Presented at "SDG Short Course I on Sustainability and Environmental Management of Geothermal Resource Utilization and the Role of Geothermal in Combating Climate Change", organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, September 4-10, 2016.

NATURE AND ASSESSMENT OF GEOTHERMAL RESOURCES

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ABSTRACT

The potential of the Earth's geothermal resources is enormous, compared to the energy needs of mankind, and they can play a role in sustainable development. They are variable in nature, classified as (a) volcanic systems with the heat sources being hot intrusions or magma, (b) fracture-controlled convective systems with deep water circulation, (c) sedimentary systems with permeable layers at great depth, (d) geo-pressured systems, (e) hot dry rock or enhanced geothermal systems and (f) shallow resources utilized through ground-source heat pumps. Geothermal systems are also classified on the basis of reservoir temperature, reservoir enthalpy and their physical state. The energy production capacity of hydrothermal systems is predominantly controlled by reservoir pressure decline caused by hot water production, which is in turn determined by the size of a geothermal reservoir, its permeability, reservoir storage capacity, water recharge and geological structure. More generally the capacity of geothermal systems is also controlled by their energy content, dictated by their size and temperature conditions (enthalpy if two-phase). Hydrothermal systems can in most cases be classified as either closed, with limited or no recharge, or open, where recharge equilibrates with the mass extraction in the long run. Modelling plays a key role in understanding the nature of geothermal systems and is the most powerful tool for predicting their response to future production, which is used to estimate their production capacity. Models are also an indispensable part of geothermal resource management during utilization. In addition to the volumetric assessment method (static modelling) different methods of dynamic modelling are the main techniques used for geothermal reservoir modelling and resource assessment, including simple analytical modelling, lumped parameter modelling or detailed numerical modelling. Thorough understanding of the nature and properties of geothermal resources, via comprehensive interdisciplinary research, as well as reliable and accurate assessment of their production capacity, through modelling, are an absolute prerequisite for sustainable utilization of geothermal resources.

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 fractured 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. The theoretical potential of the Earth's geothermal resources is, furthermore, enormous when compared to their use today and to the future energy needs of mankind. Geothermal resources should, therefore, be able to play a significant role in the essential future sustainable development of mankind.

The understanding of the nature of hydrothermal systems didn't really start advancing until deep drilling commenced and their large-scale utilization started during the 20th century. The successful exploration, development and utilization of a geothermal resource rely on comprehensive understanding of their nature as well as quantification of their response to utilization and accurate assessments of their production capacity. This, in turn, relies on efficient collaboration between various scientific and engineering disciplines during all stages. During the exploration stage of a geothermal resource research focuses on analysis of surface exploration data; mainly geological, geophysical and geochemical data, while this emphasis shifts to reservoir physics/engineering research during development and utilization. The fundamental challenge of geothermal reservoir physics/engineering is actually assessment of the long-term production capacity of geothermal resources.

This paper reviews the classification and nature of the different types of geothermal systems as well as discussing their response to utilization, which is what mainly control their production capacity. It also reviews the diverse types of model calculations, which are the principal tools of geothermal reservoir physics/engineering. Modelling is used to analyse various types of reservoir engineering data with the purpose of providing estimates of different reservoir properties (e.g. permeability). Once reservoir properties and physical conditions have been estimated, subsequent models are used to simulate the conditions and changes in the geothermal system in question, both during the pre-exploitation stage (natural state) and during utilization (production state). Modelling thus plays a key role in understanding the nature of geothermal systems as well as being the most powerful tool for predicting their response to future production and assessing their production capacity. Reliable models are also an indispensable part of successful geothermal resource management during utilization, since response predictions can e.g. aid in foreseeing the outcome different management actions.

By reviewing these subjects this paper is intended to set the stage, partly, for the subject of this short course. Sustainable production from a geothermal resource involves energy production that can be maintained for a long time, with a time-scale of 100 – 300 years having been proposed as realistic (Axelsson, 2010). Thorough understanding of the nature and properties of geothermal resources, via comprehensive interdisciplinary research, as well as reliable and accurate assessment of their production capacity, through modelling, are an absolute prerequisite for sustainable utilization of geothermal energy.

This paper reviews the subject matter only briefly, while more details on different issues can be found references sited throughout paper. The subject matter is also linked with earlier El Salvador short courses, e.g. the ones on conceptual model development in 2013 and on geothermal surface exploration in 2015 (see references later in paper). A later paper by the present author reviews the sustainable management of geothermal resources during utilization, in some detail (Axelsson, 2016).

2. GEOTHERMAL SYSTEMS OF THE WORLD

Geothermal energy stems from the Earth's outward heat-flux, which originates from the internal heat of the Earth leftover from its creation as well as from the decay of radioactive isotopes in the Earth's mantle and crust. Geothermal systems are regions in the Earth's crust where this flux, and the associated energy storage, are abnormally great. In the majority of cases the energy transport medium is water and such systems are, therefore, called hydrothermal systems. Geothermal resources are distributed throughout the planet. Even though most geothermal systems and the greatest concentration of geothermal energy are associated with the Earth's plate boundaries, geothermal energy may be found in most countries. It is highly concentrated in volcanic regions, but may also be found as warm ground-water in sedimentary formations world-wide. In many cases geothermal energy is found in populated, or easily accessible, areas. But geothermal activity is also found at great depth on the ocean floor, in mountainous regions and under glaciers and ice caps. Numerous geothermal systems probably still remain to be discovered, since many systems have no surface activity. Some of these are, however, slowly being discovered. The following basic definitions are commonly used:

- *Geothermal Field* is a geographical definition, usually indicating an area of geothermal activity at the earth's surface. In cases without surface activity this term may be used to indicate the area at the surface corresponding to the geothermal reservoir below.
- *Geothermal System* refers to all parts of the hydrological system involved, including the recharge zone, all subsurface parts and the outflow of the system.
- *Geothermal Reservoir* indicates the hot and permeable part of a geothermal system that may be directly exploited. For spontaneous discharge to be possible geothermal reservoirs must also be pressurised.

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. Table 1 summarizes classifications based on the first three aspects.

TABLE 1: Classifications of geothermal systems on the basis of temperature, enthalpy and physical state (Bödvarsson, 1964; Saemundsson et al., 2009)

<table>
<tr><td>Low-temperature (LT) systems with reservoir temperature at 1 km depth below 150°C. Often characterised by hot or boiling springs.</td><td rowspan="2">Low-enthalpy geothermal systems with reservoir fluid enthalpy less than 800 kJ/kg, corresponding to temperatures less than about 190ºC.</td><td rowspan="2">Liquid-dominated geothermal reservoirs with the water temperature at, or below, the boiling point at the prevailing pressure and the water phase controls the pressure in the reservoir. Some steam may be present.</td></tr>
<tr><td>Medium-temperature (MT) systems.</td></tr>
<tr><td rowspan="2">High-temperature (HT) systems with reservoir temperature at 1 km depth above 200°C. Characterised by fumaroles, steam vents, mud pools and highly altered ground.</td><td rowspan="2">High-enthalpy geothermal systems with reservoir fluid enthalpy greater than 800 kJ/kg.</td><td>Two-phase geothermal reservoirs where steam and water co-exist and the temperature and pressure follow the boiling point curve.</td></tr>
<tr><td>Vapour-dominated geothermal where temperature is at, or above, the boiling point at the prevailing pressure and the steam phase controls the pressure in the reservoir. Some liquid water may be present.</td></tr>
</table>

It should be pointed out that a common classification is not to be found in the geothermal literature, even though one based on enthalpy is often used. Different parts of geothermal systems may, furthermore, be in different physical states and geothermal reservoirs may also evolve from one state to another. As an example a liquid-dominated reservoir may evolve into a two-phase reservoir when pressure declines in the system as a result of production. Steam caps may also evolve in geothermal systems as a result of lowered pressure. Low-temperature systems are always liquid-dominated, but high-temperature systems can either be liquid-dominated, two-phase or vapour-dominated.

Geothermal systems are also classified based on their nature and geological setting (Figure 1):

A. ***Volcanic systems*** are in one way or another associated with volcanic activity. The heat sources for such systems are hot intrusions or magma. They are most often situated inside, or close to, volcanic complexes such as calderas and/or spreading centres. Permeable fractures and fault zones mostly control the flow of water in volcanic systems.
B. In ***fracture-controlled convective systems*** the heat source is the hot crust at depth in tectonically active areas, with above average heat-flow. Here the geothermal water has circulated to considerable depth (> 1 km), through mostly vertical fractures, to extract the heat from the rocks.
C. ***Sedimentary systems*** are found in many of the major sedimentary basins of the world. These systems owe their existence to the occurrence of permeable sedimentary layers at great depths (> 1 km) and above average geothermal gradients (> 30ºC/km). These systems are conductive in nature rather than convective, even though fractures and faults play a role in some cases. Some convective systems (B) may, however, be embedded in sedimentary rocks.
D. ***Geo-pressured system****s* are sedimentary systems analogous to geo-pressured oil and gas reservoirs where fluid caught in stratigraphic traps may have pressures close to lithostatic values. Such systems are generally fairly deep; hence, they are categorised as geothermal.
E. ***Hot dry rock (HDR)*** or ***enhanced (engineered) geothermal systems (EGS)*** involve volumes of rock that have been heated to useful temperatures by volcanism or abnormally high heat flow, but have low permeability or are virtually impermeable. Therefore, they cannot be exploited in a conventional manner. However, experiments have been conducted in a number of locations to use hydro-fracturing to try to create artificial reservoirs in such systems, or to enhance already existent fracture networks. Such systems will mostly be used through production/reinjection doublets.
F. ***Shallow resources*** refer to the thermal energy stored near the surface of the Earth's crust, partially originating from solar radiation. Recent developments in the application of ground source heat pumps have opened up a new dimension in utilizing these resources.

Numerous volcanic geothermal systems (A) are found for example in The Pacific Ring of Fire, in countries like New Zealand, Indonesia, The Philippines, Japan, Mexico and in Central America, as well as in the East-African Rift Valley and Iceland. Geothermal systems of the convective type (B) exist outside the volcanic zone in Iceland, in the SW United States and in SE China, to name a few countries. Sedimentary geothermal systems (C) are for example found in France, Germany, Central Eastern Europe and throughout China. Typical examples of geo-pressured systems (D) exist in the Northern Gulf of Mexico Basin in the U.S.A. and in SE-Hungary. The early Fenton Hill project in New Mexico in the U.S.A. and the Soultz project in NE-France, which is now in the pilot demonstration phase after 2 decades of intense research and testing, are well known HDR and EGS projects (E). Shallow resources (F) can be found all over the globe.

Saemundsson et al. (2009) discuss the classification and geological setting of geothermal systems in more detail than done here. They present a further subdivision, principally based on tectonic setting, volcanic association and geological formations. Volcanic geothermal systems (A) are e.g. subdivided into systems associated with rift-zone volcanism (diverging plate boundaries), hot-spot volcanism and subduction-zone volcanism (converging plate boundaries). The reader is referred to that reference for more details.

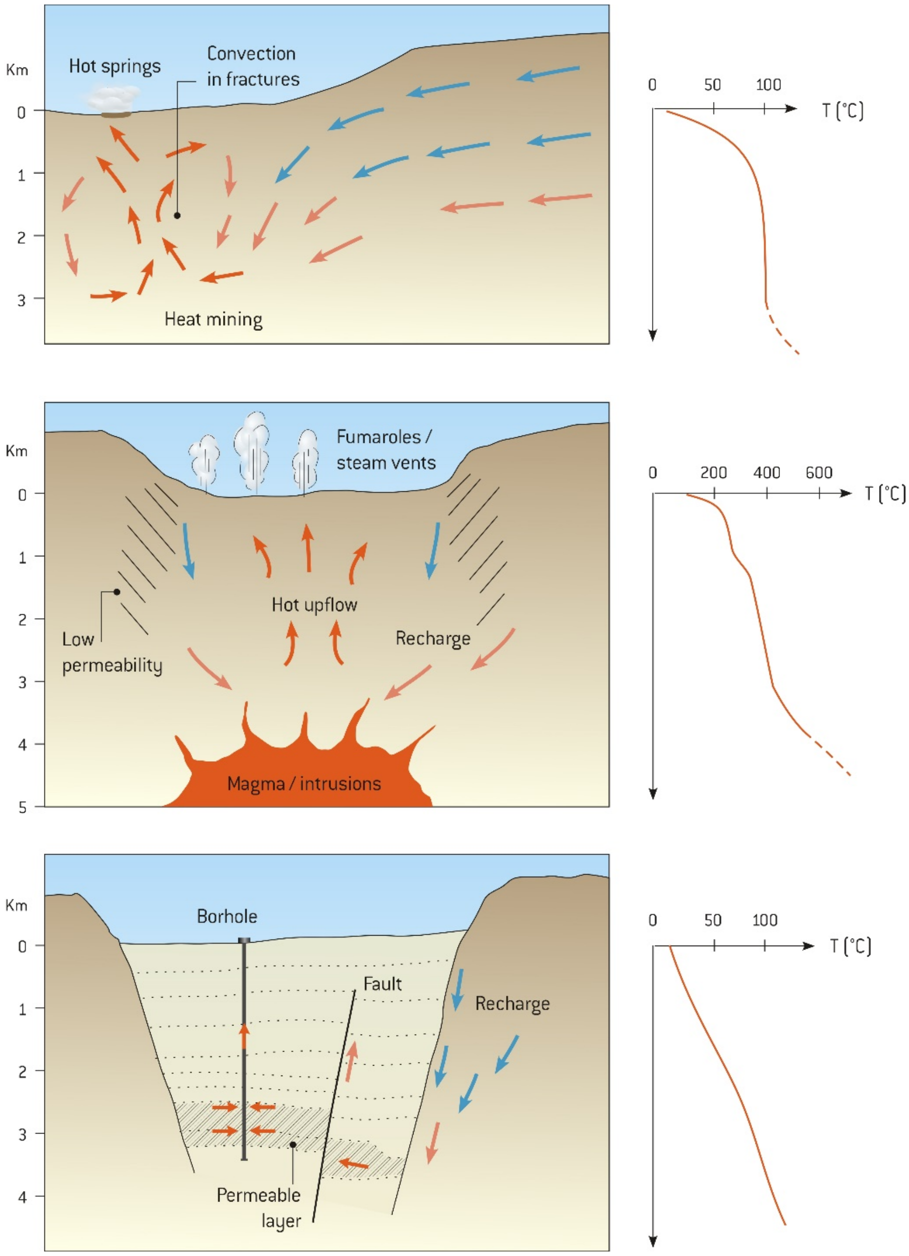

FIGURE 1: Schematic figures of the three main types of geothermal systems (A, B and C) along with typical temperature profiles

The heat source mechanism of volcanic geothermal systems and nature of the heat transfer within them, which involves flow of magma, flow of fluids, heat exchange between rocks and fluids as well as thermo-elastic rock mechanics and chemical processes, is not accurately known. This has been studied theoretically and speculated upon for more than half a century, initially through assuming heat extraction directly from deep magma chambers or hot batholiths. Bödvarsson (e.g. 1951 and 1982) and Lister (e.g. 1976) separately proposed a general process termed convective downward migration (CDM) for the heat extraction and transfer mechanism. The mechanism they envisioned does not assume a direct contact between the circulating water and the magma or hot intrusive rocks, but rather a relatively thin insulating layer between them. Heat is assumed to be transported through the layer by heat conduction. As the outer parts of the layer cool down it cracks because of thermal contraction allowing the circulating water to penetrate further downward. Through a downward migration like this, of a relatively thin conductive layer, the extremely high heat output of volcanic geothermal systems is ensured. A similar process can also be envisioned for many convective low-temperature geothermal systems (B), at least the more powerful ones, such as many systems in Iceland. Recent work suggests that smaller shallow intrusions (dykes, sills, etc.) originating in deep magma chambers, intruded intermittently in time, also play a primary role in the heat-source mechanism of volcanic geothermal systems.

Recently interest in the heat extraction and transfer mechanism of volcanic geothermal systems has increased again, with greatly increased research, mainly because of the potentially great capacity of extra deep wells drilled into such systems. This is e.g. witnessed by the IDDP deep drilling project in Iceland (http://iddp.is/), the Deep Roots Geothermal (DRG) project in Iceland operated by the GEORG research cluster cooperation (see e.g. http://www.georg.hi.is/node/255) and the recently launched European DeepEGS project (http://deepegs.eu/).

Whatever process controls the heat extraction mechanism of geothermal systems their internal heat transfer must be dominated by convection. Temperature profiles from deep wells in geothermal systems in Iceland clearly demonstrate this convective character. In addition, they demonstrate how heat has been transported from depth to shallower levels, cooling down the deeper half of the systems and heating up the upper half. Figure 2 presents a few such examples from low-temperature systems in SW-Iceland.

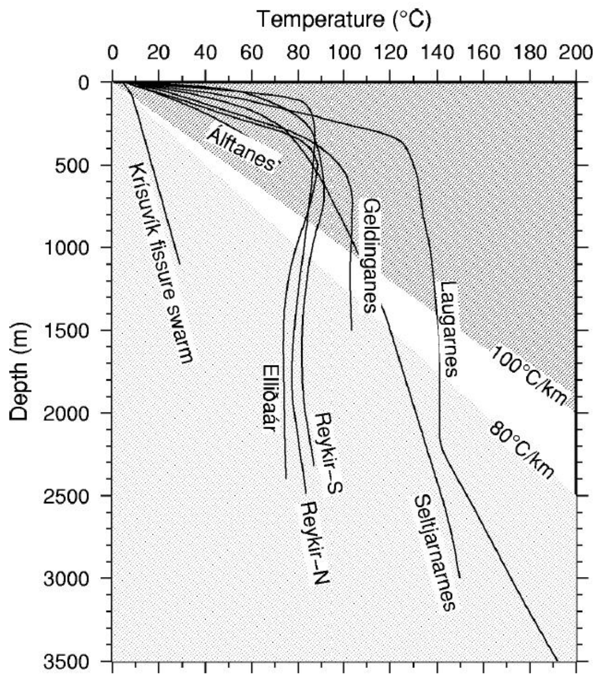

FIGURE 2: Formation temperature profiles for low-temperature systems in and around Reykjavík in SW-Iceland demonstrating the convective nature of the systems, through which heat has been transported from depth up to shallower levels (from Björnsson et al., 2000). Lighter shading denotes temperatures lower than to be expected from the regional gradient and darker shading the opposite.

Emphasis is increasingly being put on the development of conceptual models during geothermal exploration and development. These are descriptive or qualitative models incorporating, and unifying, the essential physical features of the systems, which have been revealed through analysis of all available exploration, drilling and testing data (Grant et al., 1982). Conceptual models are mainly based on geological- and geophysical information, temperature- and pressure data as well as information on the chemical content of reservoir fluids. Good conceptual models should explain the heat source for the reservoir in question and the location of recharge zones as well as describe the location of the main flow channels and the general flow pattern within the reservoir. A comprehensive conceptual model should, furthermore, provide an estimate of the size of the reservoir involved (Axelsson, 2013a). A short course comparable to the present one, devoted to conceptual models of geothermal systems, was actually held in El Salvador in 2013 (http://www.unugtp.is/en/moya/page/sc-16).

The potential of the Earth's geothermal resources is enormous when compared to its use today and to the future energy needs of mankind. Stefánsson (2005) estimated the technically feasible electrical generation potential of identified geothermal resources to be 240 GW_e (1 GW = 10^9 W), which are likely to be only a small fraction of hidden, or as yet unidentified, resources. He also indicated the most likely direct use potential of lower temperature resources (< 150°C) to be 140 EJ/yr (1 EJ = 10^{18} J). The Earth's ultimate geothermal potential is, however, impossible to estimate accurately at the present stage of knowledge and technology. Even though geothermal energy utilization has been growing rapidly in recent years, it is still miniscule compared with the Earth's potential. Bertani (2010) estimated the worldwide installed geothermal electricity generation capacity to have been about 10.7 GW_e in 2010 and Lund et al. (2010) estimated the direct geothermal utilization in 2009 to have amounted to 438 PJ/yr (1 PJ = 10^{15} J). Fridleifsson et al. (2008) have estimated that by 2050 the electrical generation capacity may reach 70 GW_e and the direct use 5.1 EJ/yr. There is, therefore, ample space for accelerated use of geothermal resources worldwide in the near future.

3. UTILIZATION RESPONSE AND CAPACITY OF GEOTHERMAL SYSTEMS

3.1 Utilization response

The long-term response and hence production capacity of geothermal systems is mainly controlled by (1) their size and energy content, (2) permeability structure, (3) boundary conditions (i.e. significance of natural and production induced recharge) and (4) reinjection management. Their energy production potential, in particular in the case of hydrothermal systems, is predominantly determined by pressure decline due to production. This is because there are technical limits to how great a pressure decline in a well is allowable; because of pump depth or spontaneous discharge through boiling, for example. The production potential is also determined by the available energy content of the system, i.e. by its size and the temperature or enthalpy of the extracted mass. The pressure decline is determined by the rate of production, on one hand, and the nature and characteristics of the geothermal system, on the other hand.

Natural geothermal reservoirs can often be classified as either ***open*** or ***closed***, with drastically different long-term behaviour, depending on their boundary conditions (see also Figure 3):

(A) Pressure declines continuously with time, at constant production, in systems that are ***closed*** or with small recharge (relative to the production). In such systems the production potential is limited by lack of water rather than lack of thermal energy. Such systems are ideal for reinjection, which provides man-made recharge. Examples are many sedimentary geothermal systems, systems in areas with limited tectonic activity or systems sealed off from surrounding hydrological systems by chemical precipitation.

(B) Pressure stabilizes in ***open*** systems because recharge eventually equilibrates with the mass extraction. The recharge may be both hot deep recharge and colder shallow recharge. The latter will eventually cause reservoir temperature to decline and production wells to cool down. In such systems the production potential is limited by the reservoir energy content (temperature and size) as the energy stored in the reservoir rocks will heat up the colder recharge as long as it is available/accessible.

The situation is somewhat different for ***EGS-systems*** and sedimentary systems utilized through production-reinjection ***doublets*** (well-pairs) and heat-exchangers with 100% reinjection. Then the production potential is predominantly controlled by the energy content of the systems involved. But permeability, and therefore pressure variations, is also of controlling significance in such situations. This is because it controls the pressure response of the wells and how much flow can be achieved and maintained, for example through the doublets involved (it's customary to talk about intra-well impedance for EGS-systems, based on the electrical analogy). In sedimentary systems the permeability is natural but in EGS-systems the permeability is to a large degree man-made, or at least enhanced.

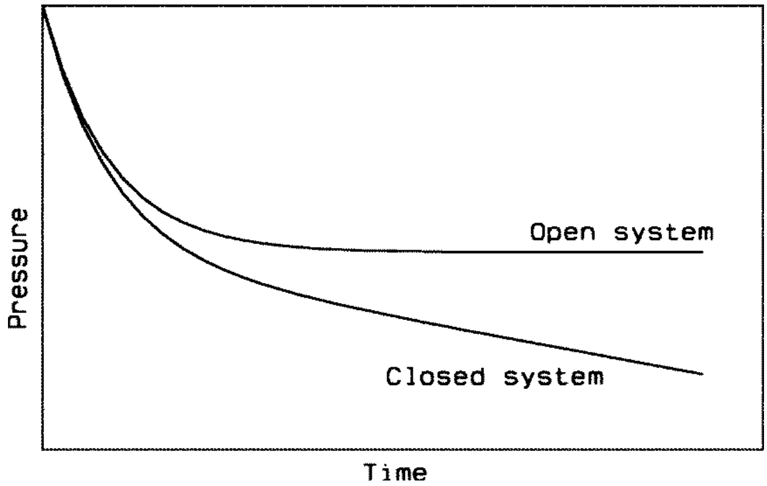

FIGURE 3: Schematic comparison of pressure decline in open (with recharge) or closed (with limited or no recharge) geothermal systems at a constant rate of production (Axelsson, 2008)

Water or steam extraction from a geothermal reservoir causes, in all cases, some decline in reservoir pressure, as already discussed. The only exception is when production from a reservoir is less than its natural recharge and discharge. Consequently, the pressure decline manifests itself in further changes, which for natural geothermal systems may be summarised in a somewhat simplified manner as follows:

I. Direct changes caused by **lowered reservoir pressure**, such as changes in surface activity, decreasing well discharge, lowered water level in wells, increased boiling (increased enthalpy) in high-enthalpy reservoirs and changes in non-condensable gas concentration.
II. Indirect changes caused by **increased recharge** to the reservoir, such as changes in chemical composition of the reservoir fluid, changes in scaling/corrosion potential, changes in reservoir temperature conditions (observed through temperature profiles of wells) and changes in temperature/enthalpy of reservoir fluid.
III. **Surface subsidence**, which may result in damage to surface installations.

Apart from the above changes caused by pressure decline due to production, reinjection causes specific changes. These include reservoir cooling and induced/triggered seismicity along with potential scaling in, and around, reinjection wells.

Axelsson (2008) presents several examples of production and response histories of geothermal systems worldwide, both high- and low-enthalpy systems, of quite contrasting nature. Some exhibit a drastic pressure draw-down for limited production while others experience very limited draw-down for substantial mass extraction. A few examples of reservoir cooling due to long-term production are also presented, even though they are relatively rare. A number of long and well documented utilization and response case histories are, in particular, available, many spanning more than 30 years, which are extremely valuable for studying the nature of geothermal systems, e.g. their renewability and potential sustainable utilization. Figures 4 – 7 show four such case histories.

Production and response histories, as discussed above, are essential for understanding the nature and estimating the properties of geothermal systems. This reflects the importance of comprehensive and careful monitoring of the response of geothermal systems to energy extraction during long-term utilization (Monterrosa and Axelsson, 2013), otherwise the relevant information is lost. The information is important for conceptual model development, for resource assessment and resource management. It is, in particular, important for model development aimed at estimating the production capacity of a geothermal system, including the assessment of the sustainable production capacity of a geothermal system. In that case the longest data-series are logically most valuable, providing the most reliable capacity estimates.

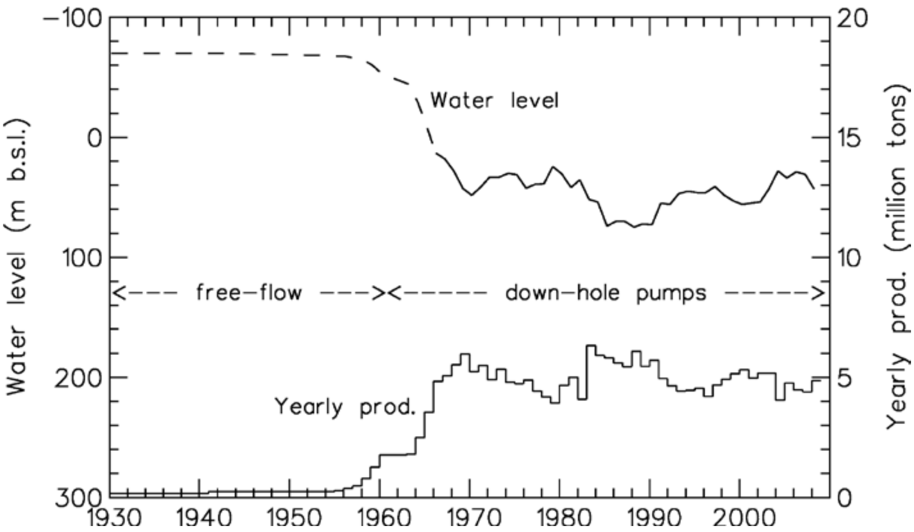

FIGURE 4: History of production and water level (pressure) response of the Laugarnes convective geothermal system in SW-Iceland from 1930 (Axelsson, 2012)

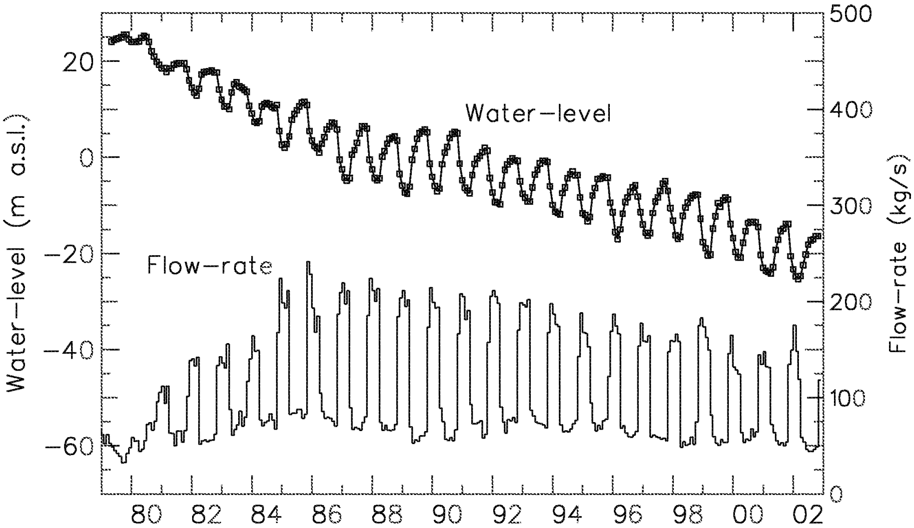

FIGURE 5: Production and water-level response history of the Urban Area sedimentary system in Beijing, China for two decades from the late 1970's (based on Liu et al., 2002)

3.2 Renewability of geothermal resources

Geothermal resources are normally classified as renewable energy sources, because they are maintained by a continuous energy current and because how enormous the energy content of the Earth's crust is compared to the energy needs of mankind. In addition, they simply don't fit well with non-renewable energy sources, like e.g. coal and oil, because of much more limited environmental load (greenhouse gas emissions, etc.).

But this classification has been disputed, by experts and laypersons alike. The author of this paper claims that this dispute simply arises from a need to force a complex natural phenomenon into an inadequate classification scheme. The claim that geothermal resources are non-renewable has, moreover, been used as an argument against increased geothermal development. The foundation for increased geothermal utilization worldwide is, however, improved understanding through intensified research.

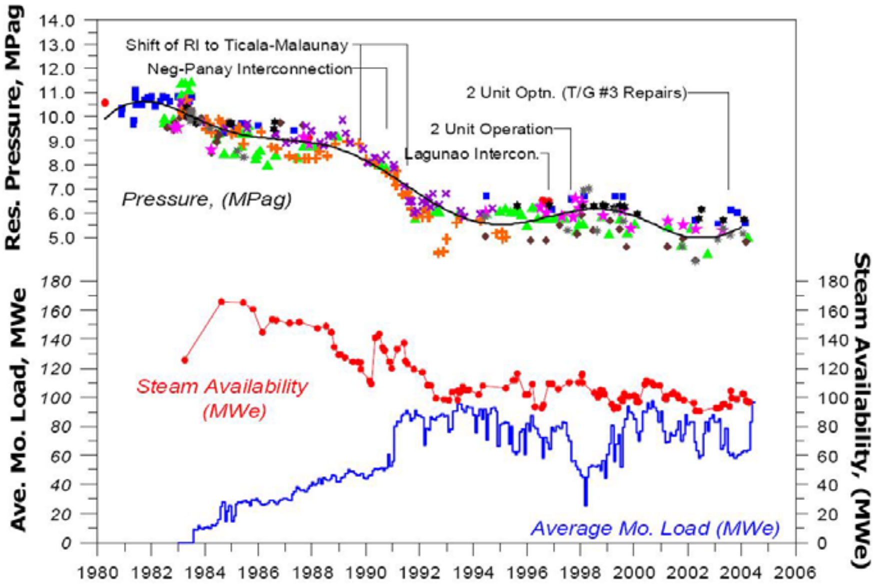

FIGURE 6: The production and pressure response history of the Palinpinion-1 volcanic geothermal system in The Philippines (Aqui et al., 2005)

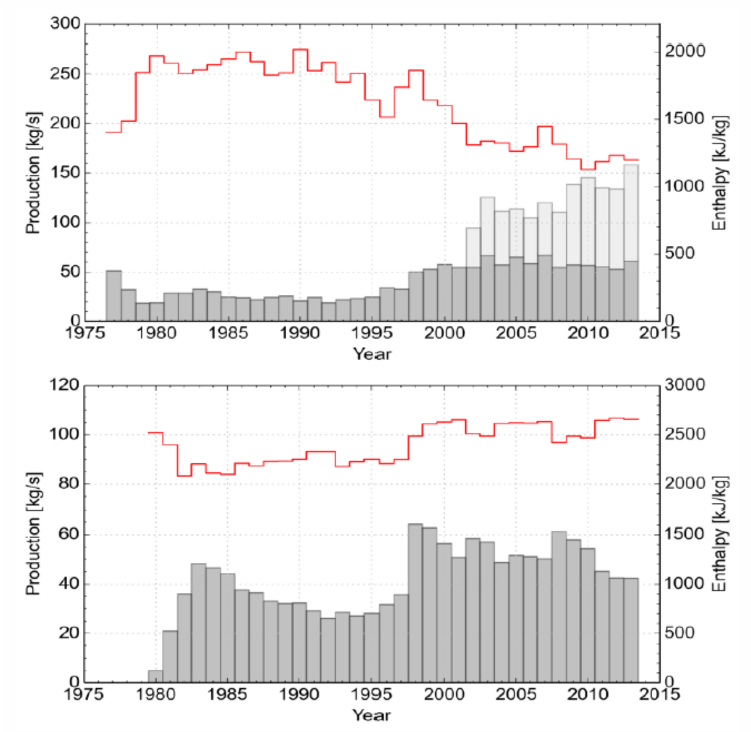

FIGURE 7: Production and enthalpy discharge histories of two sub-areas of the Krafla volcanic geothermal field in NE-Iceland (from Weisenberger et al., 2015). The upper half shows declining enthalpy due to colder recharge (inflow) and reinjection (pressure support reduces boiling) while the lower half shows increasing enthalpy due to increased boiling.

Classifying geothermal resources as renewable may also be an oversimplification. This is because geothermal resources are in essence of a double nature, i.e. a combination of an ***energy current*** (through heat convection and conduction) and ***stored energy*** (Axelsson, 2011). The renewability of these two aspects is quite different as the energy current is steady (fully renewable) while the stored energy is renewed relatively slowly, in particular the part renewed by heat conduction. During production the renewable component (the energy current) is greater than the recharge to the systems in the natural state, however, because production induces in most cases an additional inflow of mass and energy into the systems (Stefánsson, 2000).

The renewability of different types of geothermal systems is quite diverse. This is because the relative importance of the energy current compared with the stored energy is highly variable for the different types. In volcanic systems the energy current is usually quite powerful, comprising both magmatic and hot fluid inflow. In convective systems of the open type, i.e. systems with strong recharge, the energy current (hot fluid inflow) is also highly significant. But the inflow can either originate as hot inflow from depth or as shallower inflow, colder in origin. In shallow inflow situations the inflow is heated up by heat extraction from hot rocks at the outskirts of the system in question. The renewability of such systems is then supported by the usually immense energy content of the hot rocks of the systems. In convective systems of the closed type, i.e. with limited or no recharge, the renewability is more questionable. The energy extracted from the reservoir rocks through reinjection in such situations is only slowly renewed through heat conduction, but again the energy content of the systems is usually vast. They can, therefore, be considered slowly renewable in nature.

Sedimentary systems, which are mostly utilized through doublet operations, are comparable to the closed convective systems as the energy current is usually relatively insignificant compared to the stored energy. Their renewability is, therefore, mainly supported by heat conduction and hence is relatively slow. The same applies to EGS- or hot dry rock systems. Both these types can thus also be considered slowly renewable. In most such cases the stored energy component is extremely large because of the large extent and volume of the systems.

The short-course where this is presented focusses on sustainable geothermal utilization and another paper by the present author deals with the issue of sustainable geothermal utilization. Therefore, it’s important to stress the difference between sustainability and renewability, i.e. that renewability refers to the nature of the resource in question while sustainability refers to how it is utilized, a distinction which isn’t always clear to authors discussing them. Sustainable geothermal utilization depends to a large extent on the nature of the geothermal resource in question and hence its renewability. If energy production from a geothermal system is within some kind of sustainable limits (see Axelsson, 2016) one may expect that the stored energy is depleted relatively slowly and that the energy in the reservoir is renewed at a rate comparable to the extraction rate.

4. GEOTHERMAL RESOURCE ASSESSMENT

4.1 General

Various methods are available, and have been used the last several decades, to assess geothermal resources during both exploration and exploitation phases of development. These range from methods used to estimate resource temperature and resource size to complex numerical modelling aimed at predicting the production response of systems and estimating their production capacity or potential. Being able to assess a given resource during different stages of its development, as accurately as possible, is essential for its successful development, in particular for planning and managing its sustainable utilization. The main methods used are (Axelsson, 2012):

(a) Deep temperature estimates (based on chemical/gas content of surface manifestations);
(b) Surface thermal flux;
(c) Volumetric methods (adapted from mineral exploration and oil industry);
(d) Decline curve analysis (adapted from oil/gas industry);
(e) Simple mathematical modelling (often analytical);
(f) Lumped parameter modelling; and

(g) Detailed numerical modelling of natural state and/or exploitation state (often called distributed parameter models).

The first two methods are not modelling methods per se, but are the methods that can be used for resource assessment prior to extensive geophysical surveying and drilling. The remaining methods in the list can all be considered modelling methods, which play an essential role in geothermal resource development and management. These range from basic volumetric resource assessment (c) and simple analytical modelling (e) of the results of a short well test to detailed numerical modelling (g) of a complex geothermal system, simulating an intricate pattern of changes resulting from long-term production. In the early days of geothermal reservoir studies decline curve analysis (d) proved to be an efficient method to predict the future output of individual high-temperature wells (Bödvarsson and Witherspoon, 1989), but today other modelling methods are usually applied. Decline curve analysis is particularly applicable to wells in dry-steam reservoirs.

The purpose of geothermal modelling is firstly to obtain information on the conditions in a geothermal system as well as on the nature and properties of the system. This leads to proper understanding of its nature and successful development of the resource. Secondly, the purpose of modelling is to predict the response of the reservoir to future production and estimate the production potential of the system as well as to estimate the outcome of different management actions.

The diverse data/information, which is the foundation of all reservoir-modelling, need to be continuously gathered throughout the exploration and exploitation history of a geothermal reservoir. Information on reservoir properties is obtained by disturbing the state of the reservoir (fluid-flow, pressure) and by observing the resulting response, and is done through well and reservoir testing and data collection (Axelsson, 2013c). It should be emphasised that the data collected does not give the reservoir properties directly. Instead, the data are interpreted, or analysed, on the basis of appropriate models yielding estimates of reservoir properties. It is also important to keep in mind that the longer, and more extensive the tests are, the more information is obtained on the system in question. Therefore, the most important data on a geothermal reservoir is obtained through careful monitoring during long-term exploitation, which can be looked upon as prolonged and extensive reservoir testing.

The modelling methods may be classified as either ***static modelling methods*** or ***dynamic modelling methods***, with the volumetric method (c) being the main static method. Both involve development of some kind of a mathematical model that ***simulates*** some, or most, of the data available on the system involved. The volumetric method is based on estimating the total heat stored in a volume of rock and how much of that can be efficiently recovered. The dynamic modelling methods ((d) – (g) in the list above) are based on modelling the dynamic conditions and behaviour (production response) of geothermal systems.

4.2 Static modelling

The volumetric method is the main static modelling method, as already stated. It is presented and discussed in detail by Sarmiento et al. (2013). It is often used for first stage assessment, when data are limited, and was more commonly used in the past, but is still the main assessment method in some countries. It is increasingly being used, however, through application of the Monte Carlo method, which enables the incorporation of overall uncertainty in the results. The main drawback of the volumetric method is the fact that the dynamic response of a reservoir to production is not considered, such as the pressure response and the effect of fluid recharge. Reservoirs with the same heat content may have different permeabilities and recharge and, hence, very different production potentials.

The volumetric method is based on estimating the total heat stored in a volume of rock (referred to some base temperature), both thermal energy in rock matrix and in water/steam in pores. In the volumetric method the likely surface area and thickness of a resource are initially estimated from geophysical and geological data, and later from well-data as well. Consequently, likely temperature conditions are assumed on the basis of chemical studies and well temperature data, if available. Based on these, estimates of reservoir porosity and thermal properties of water and rock involved, the total energy content is estimated. The relevant equations are presented by Axelsson (2012). The reservoir temperature can either be assumed to be approximately constant, to be variable between different reservoir parts or to be a certain fraction of the boiling point curve at prevailing pressure conditions, in the calculations. The reference temperature used is the base temperature of the energy production process involved (space heating, electricity generation, etc.).

Only a relatively small fraction of the total energy in a system can be expected to be extracted, or recovered, during a several decade long utilization period. This fraction is estimated by applying two factors. First so-called surface accessibility (A), which describes what proportion of the reservoir volume can be accessed through drilling from the surface. Then the recovery factor (R), which indicates how much of the accessible energy may be technically recovered. The recovery factor is the parameter in the volumetric method, which is most difficult to estimate. The results of the volumetric assessment are also highly dependent on the factor. It depends on the nature of the system; permeability, porosity, significance of fractures, recharge, as well as on the mode of production, i.e. whether reinjection is applied. It is also to some extent dependent on utilization time. Williams (2007) provides a good review of the estimation of the recovery factor, which is often assumed to be in the range of 0.05–0.25. In recent years researchers have become more conservative in selecting the recovery factor than in the past, based on experience from long-term utilization of numerous geothermal systems worldwide.

To estimate electrical generation capacity (total energy or power potential) on basis of the recoverable energy an appropriate conversion-efficiency is used. It should incorporate the conversion of thermal energy into mechanical energy and consequently that of mechanical energy into electrical energy. The efficiency depends on resource temperature, the generation process used (conventional steam turbine, binary fluid generation, etc.) and the reference temperature.

The volumetric method can be applied to individual geothermal reservoirs, whole geothermal systems or on a regional scale, i.e. for a whole country. For individual systems the Monte Carlo method is commonly applied. It involves assigning probability distributions to the different parameters of the equations above and estimating the system potential with probability. An example of the results of such an assessment is presented in Figure 8.

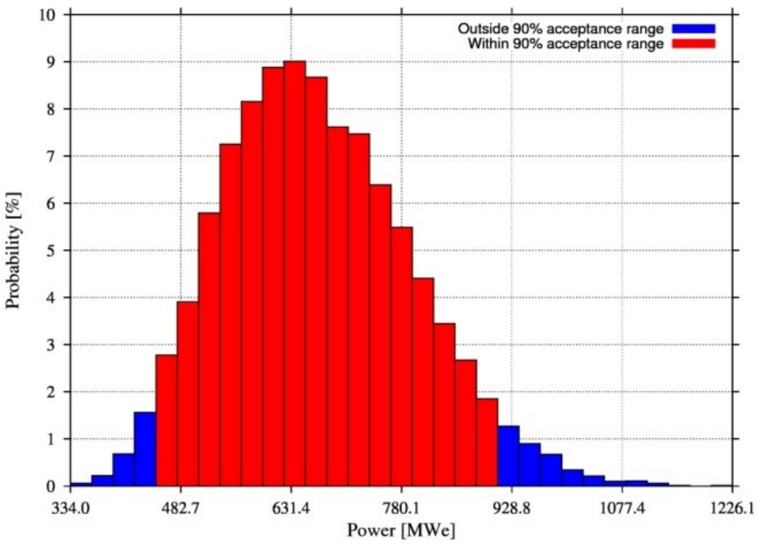

FIGURE 8: An example of the results of a volumetric resource assessment for the so-called "heavily-explored part" of the Olkaria geothermal system in Kenya for a 50-year generation period (Axelsson et al., 2013). The Monte Carlo method was applied in the assessment. Note the great uncertainty in the results (electrical generation capacity) which arises from the uncertainty in key parameters.

It must be emphasized here, in the context of the short course, that the volumetric method isn't suitable for the estimation of the sustainable production capacity of geothermal systems. This is because of its limitations mentioned above, mainly the fact that it neglects the dynamic response of geothermal systems during utilization. Thus the results of a volumetric assessment should only be considered indicative. It's also important to put emphasis on the lower limit of the Monte Carlo outcome, often referred to as the P95 or P90 value, rather than the average outcome or upper limit.

4.3 Dynamic modelling

The main dynamic modelling methods applied to geothermal systems are simple mathematical (analytical) modelling methods (e), lumped parameter methods (f) and detailed numerical modelling (g), as listed above. These are reviewed briefly below, but for more details the reader is referred to Axelsson (2013b). It should be noted that the initial phase of such model development should be always based on a good conceptual model of the geothermal system in question. Numerous examples are available on the successful role of dynamic modelling in the estimation of generation capacity of geothermal resources as well as their key role in geothermal resource management (see also Axelsson, 2013b).

In simple models, such as simple analytical models and lumped parameter models, the real structure and spatially variable properties of a geothermal system are greatly simplified so that analytical mathematical equations, describing the response of the model to energy production may be derived. These models, in fact, often only simulate one aspect of a geothermal system's response. Detailed and complex numerical models, on the other hand, can accurately simulate most aspects of a geothermal system's structure, conditions and response to production. Simple modelling takes relatively little time and only requires limited data on a geothermal system and its response, whereas numerical modelling takes a long time and requires powerful computers as well as comprehensive and detailed data on the system in question. The complexity of a model should be determined by the purpose of a study, the data available and its relative cost. In fact, simple modelling, such as lumped parameter modelling, is often a cost-effective and timesaving alternative. It may be applied in situations when available data are limited, when funds are restricted, or as parts of more comprehensive studies, such as to validate results of numerical modelling studies.

While some ***simple analytical models*** have been developed specifically for geothermal applications (see e.g. Grant and Bixeley, 2011) many of these simple models have also been inherited from ground-water science or even adopted from theoretical heat conduction treatises (because the pressure diffusion and heat conduction equations have exactly the same mathematical form). A good example of the former is the well-known Theis model, which comprises a model of a very extensive horizontal, permeable layer of constant thickness, confined at the top and bottom, with two-dimensional, horizontal flow towards a producing well extending through the layer. Geothermal well-test data are often analysed on basis of the Theis model, and its variants, by fitting the pressure response of such models to observed pressure response data.

Simple modelling has been used extensively to study and manage low-temperature geothermal systems utilised in Iceland, in particular to model their long-term response to production. ***Lumped parameter modelling*** of pressure change data, has been the principal tool for this purpose (Axelsson et al., 2005). Lumped parameter models can simulate such data very accurately, even very long data sets (several decades). Pressure changes are in fact the primary production induced changes in geothermal systems, as already emphasised. An efficient method of lumped parameter modelling of pressure response data from geothermal systems, and other underground hydrological systems, which tackles the simulation as an inverse problem and can simulate such data very accurately, if the data quality is sufficient, is available. It automatically fits the analytical response functions of the lumped models to observed data by using a non-linear iterative least-squares technique for estimating the model parameters. Today, lumped models have been developed by this method for 20 -25 low-temperature and 4 high-temperature geothermal systems in Iceland, as well as geothermal systems in China, Turkey, Kenya, Eastern Europe, Central America and The Philippines, as examples (Axelsson et al., 2005).

The theoretical basis of this automatic method of lumped parameter modelling, and relevant equations, are presented by Axelsson (1989), with a general lumped model consisting of a few tanks and flow resistors (Figure 9). The tanks simulate the storage capacity of different parts of a geothermal system and the pressure in the tanks simulates the pressure in corresponding parts of the system. The first tank of the model in the figure can be looked upon as simulating the innermost (production) part of the geothermal reservoir, and the second and third tanks simulate the outer parts of the system. The third tank is connected by a resistor to a constant pressure source, which supplies recharge to the geothermal system. The model in Figure 9 is, therefore, open. Without the connection to the constant pressure source the model would be closed. An open model may be considered optimistic, since equilibrium between production and recharge is eventually reached during long-term production, causing the pressure draw-down to stabilize. In contrast, a closed lumped model may be considered pessimistic, since no recharge is allowed for such a model and the water level declines steadily with time, during long-term production. In addition, the model presented in Figure 9 is composed of three tanks; in many instances models with only two tanks have been used.

In the lumped parameter model of Figure 9 hot water is assumed to be pumped out of the first tank, which causes the pressure in the model to decline. This in turn simulates the decline of pressure in the real geothermal system. When using this method of lumped parameter modelling, the data fitted (simulated) are the pressure (or water level) data for an observation well inside the well-field, while the input for the model is the production history of the geothermal field in question.

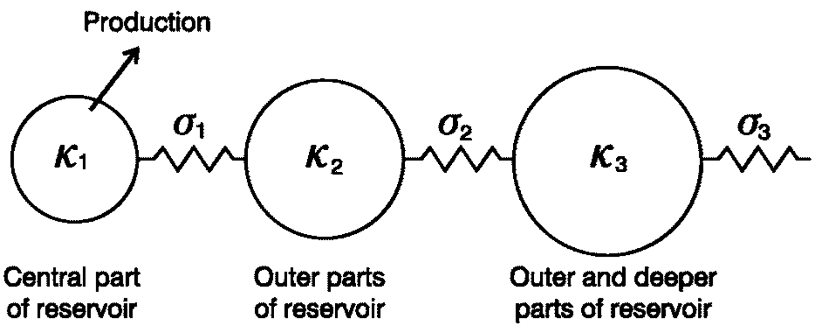

FIGURE 9: A 3-tank lumped ladder model commonly used to simulate geothermal systems (Axelsson et al., 2005)

Axelsson et al. (2005) present examples of long pressure response histories of geothermal systems, distributed throughout the world, simulated by lumped parameter models. The examples show that in all of the cases the models developed simulate the pressure changes quite accurately. Yet because of how simple the lumped parameter models are, their reliability is sometimes questioned. Experience has shown that they are quite reliable, however, and examples involving repeated simulations, demonstrate this clearly (Axelsson et al., 2005). This applies, in particular, to simulations based on long data sets, which is in agreement with the general fact that the most important data on a geothermal reservoir are obtained through careful monitoring during long-term exploitation. Lumped parameter modelling is less reliable when based on shorter data sets, which is actually the case for all such reservoir engineering predictions.

Figure 10 presents an example of a long pressure response history simulated by a lumped parameter model, the Ytri-Tjarnir low-temperature system in N-Iceland. The figure shows that the lumped parameter model developed for this system simulate the pressure changes quite accurately. Axelsson et al. (2005) present other comparable examples from a few other geothermal systems worldwide.

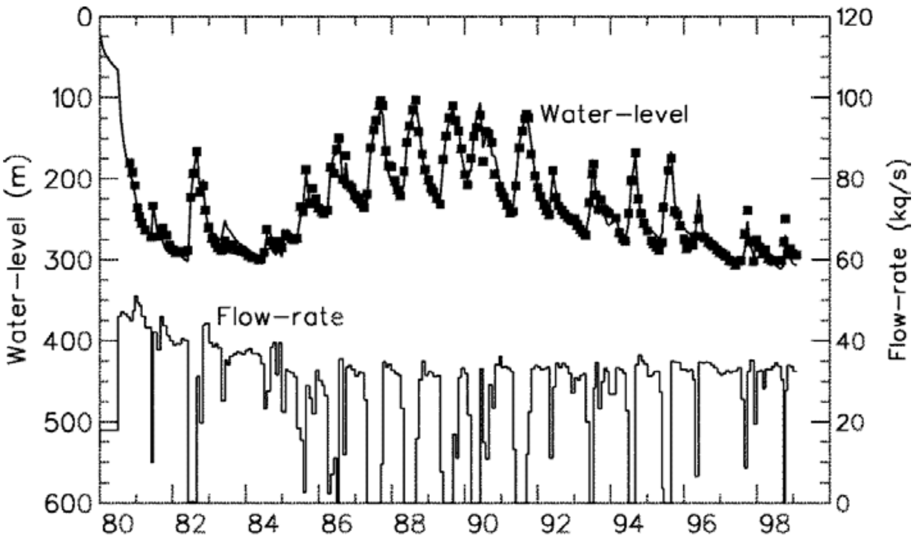

FIGURE 10: Production and water level history of the Ytri-Tjarnir low-temperature geothermal system in central N-Iceland 1980-1999. The water level history has been simulated by a lumped parameter model (squares = observed data, line = simulated data; Axelsson et al., 2005).

Once a satisfactory fit with observed pressure data has been obtained the corresponding lumped parameter models can be used to calculate predictions for different future production scenarios. Future pressure changes in geothermal systems are expected to lie somewhere between the predictions of open and closed versions of lumped parameter models, which represent extreme kinds of boundary conditions. The differences between these predictions simply reveal the inherent uncertainty in all such predictions. Real examples demonstrate that the shorter the data period a simulation is based on is, the more uncertain the predictions are (Axelsson et al., 2005). They also demonstrate that the uncertainty in the predictions increases with increasing length of the prediction period. Figure 11 below presents an example of lumped parameter model predictions for the Urban sedimentary geothermal system in Beijing, China. It involves an unusually long prediction period, as the predictions were calculated for a particular sustainability assessment. Normally such predictions are only calculated for a few decades, or ideally for a prediction period of a length comparable to the data simulation period.

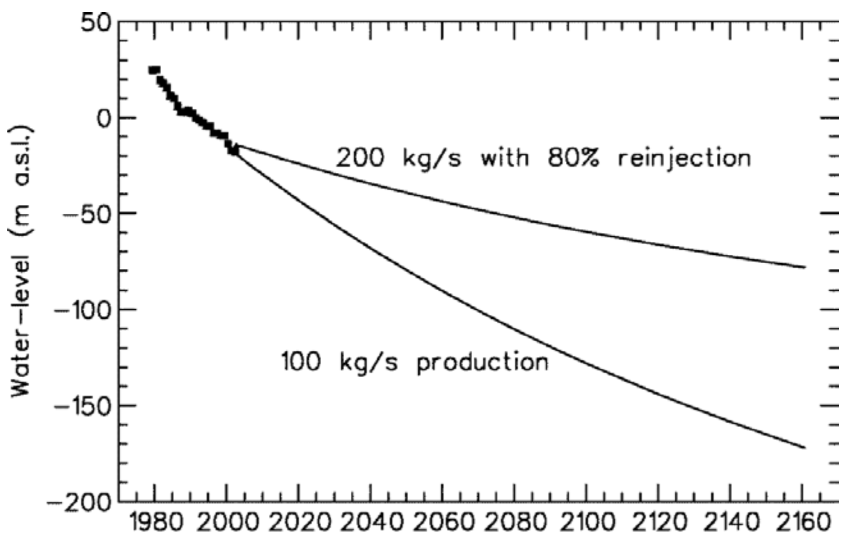

FIGURE 11: Predicted water level changes (pressure changes) in the Urban geothermal system under Beijing in China until 2160 for production scenarios with and without reinjection, averages of predictions calculated by a closed and an open lumped parameter model (Axelsson, 2010)

It should be emphasized here, that lumped parameter modelling is ideal for predicting long-term reservoir pressure changes when the sustainability of geothermal operations is being assessed. It can, in fact, simulate pressure changes as accurately as other modelling methods, in addition to providing the uncertainty bounds given by the respective open and closed models.

Detailed numerical reservoir modelling has become the most powerful tool of geothermal reservoir physics/engineering parallel with the rapid development of high-capacity modern-day computers and is increasingly being used to simulate geothermal systems in different parts of the world. This method will be reviewed briefly here, while the reader is referred to an early work by the pioneers in this field Bödvarsson et al. (1986) and a later comprehensive review by O'Sullivan et al. (2001). The numerical modelling method is extremely powerful when based on comprehensive and detailed data. Without good data, however, detailed numerical modelling can only be considered speculative, at best. In addition, numerical modelling is time-consuming and costly and without the necessary data the extensive investment needed is not justified.

The details and different aspects of detailed numerical reservoir modelling are e.g. described by Pruess (2002). The principal steps of the method involve dividing the whole volume of the reservoir/system into numerous sub-volumes (grid-blocks), today often several thousand to a few hundred-thousand blocks. Each block (or in fact families of blocks) is assigned hydrological (permeability, porosity, etc.) and thermal (heat capacity, thermal conductivity, etc.) properties. Sinks and sources are then assigned to selected blocks to simulate natural inflow and outflow as well as production wells and injection wells. In addition, appropriate boundary conditions are specified. The above is mostly based on a comprehensive conceptual model of the geothermal system and to some extent on well-test data. Finite-difference methods, or finite-element methods, are subsequently used to solve relevant equations for conservation and flow of mass and heat.

The most elaborate part of the modelling process then involves varying the model properties listed above until the model adequately simulates all relevant data. Such models should simulate available data on pressure- and temperature conditions as well as main flow patterns in the system in question during the natural state. They also need to simulate observed changes in pressure- and temperature conditions during production as well as variations in well output (mass-flow and enthalpy) during production. It should be mentioned that simulation computer codes have been developed further to enable the incorporation of chemical data in the modelling process. Attempts have also been made to incorporate other data, such as surface deformation data, gravity data and resistivity data. In principle all such additional data should aid the modelling by helping to constrain the models and make them more reliable.

Computer codes, like the well-known *TOUGH2*-code, are used for the calculations (Pruess, 2002). The items below are varied throughout the modelling process until a satisfactory data-fit is obtained:

- Permeability distribution;
- porosity distribution;
- boundary conditions (nature/permeability of outer regions of model);
- productivity indices for wells (the relation between flow and pressure drop from reservoir into a well);
- mass recharge to the system; and
- energy recharge to the system.

The *iTOUGH2* addition to *TOUGH2* has, furthermore, enabled the use of an iterative inversion process, akin to the method used in the lumped parameter modelling method presented above, to calibrate model properties.

Various examples of small-scale and large-scale numerical modelling studies are available in the geothermal literature. Some of the smaller scale studies actually involve kinds of theoretical exercises while others involve modelling of small geothermal systems, or systems in the early phases of development. The large-scale studies mostly involve the modelling of large high-enthalpy geothermal systems where considerable drilling has been performed and some production experience has been gathered. Axelsson (2013b) presents some examples of these as well as examples of numerical modelling of fracture controlled low-temperature geothermal systems, of sedimentary geothermal systems and of small-scale ground-source heat-pump systems. Figures 12 and 13 provide glimpses into two of these studies.

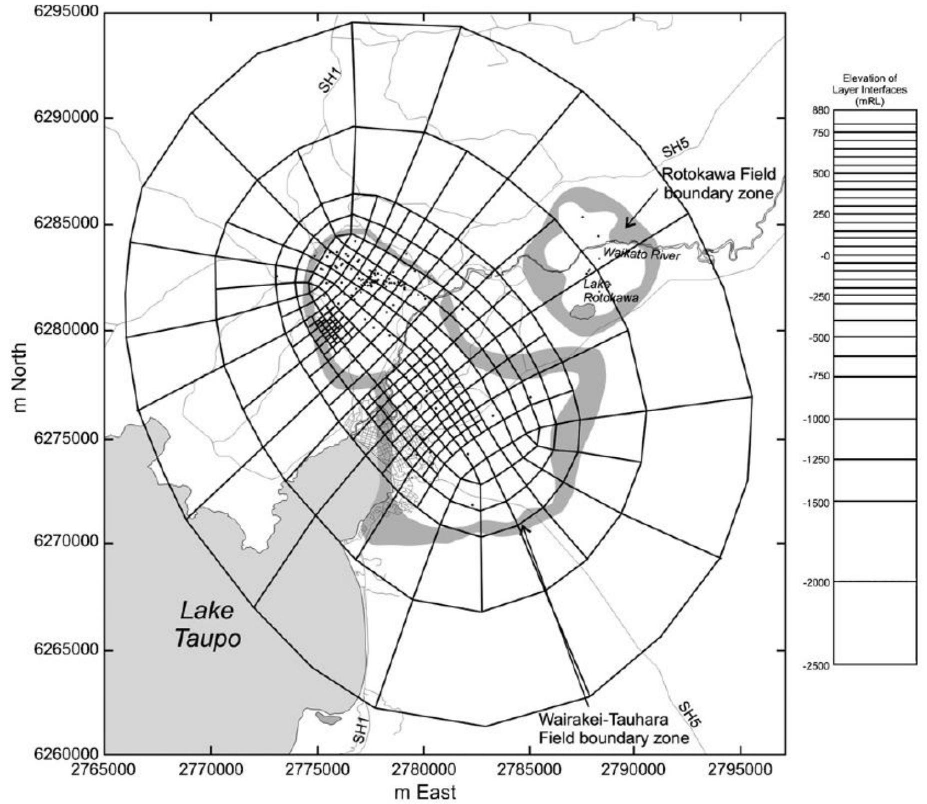

FIGURE 12: A horizontal and vertical sketch of the computational grid a recent numerical reservoir model of the Wairakei geothermal system in New Zealand (O'Sullivan et al., 2009)

The methods of geothermal reservoir modelling, in particular the methods of numerical modelling, are persistently evolving, both through the development of general modelling methods (e.g. the numerical methods applied) and advances more specific for geothermal applications. Axelsson (2013b) lists several relevant issues that will not be repeated here. Recently modelling the deep roots of volcanic systems (see above) and modelling of high temperature and pressure conditions (e.g. supercritical conditions) has received increased attention. This includes e.g. the development of a new supercritical equation-of-state module (EOS1sc) for TOUGH2/iTOUGH2 (Magnúsdóttir and Finsterle, 2015).

Finally, it should be highlighted that detailed numerical modelling is, of course, the most powerful modelling method for predicting long-term reservoir changes when the sustainability of geothermal operations is being assessed. But it must be kept in mind that if such modelling is to be reliable it must be based on very comprehensive data, ranging from exploration and well data (temperature and pressure logs, well-test data, etc.) to monitoring data collected during long-term utilization.

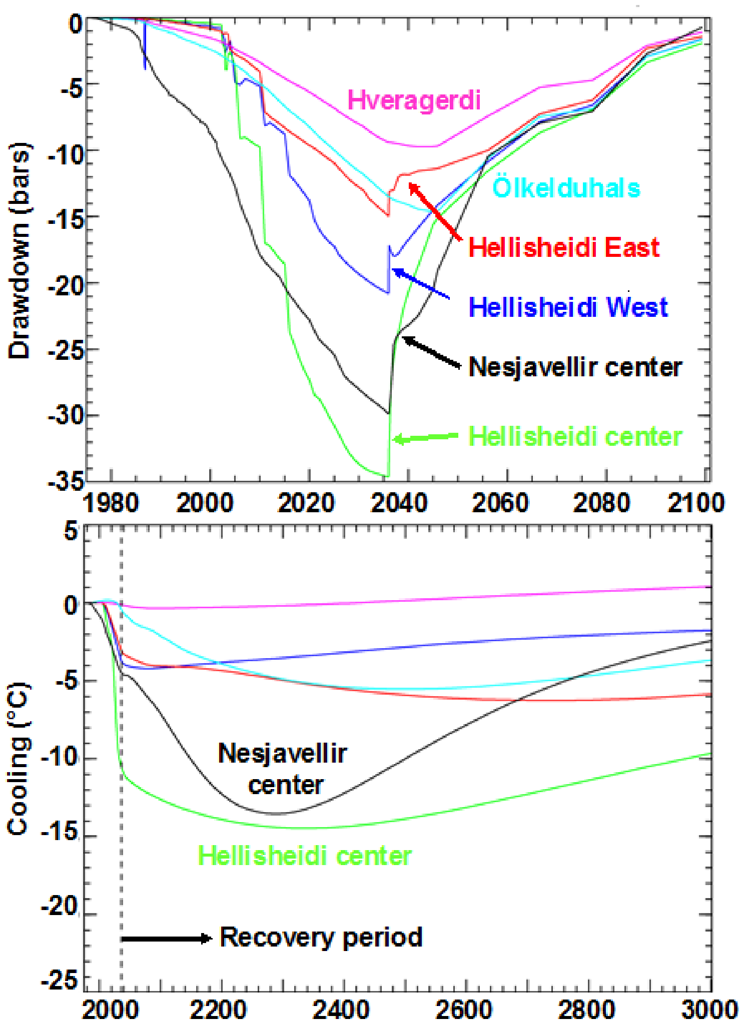

FIGURE 13: Calculated changes in reservoir pressure and temperature in different parts of the Hengill geothermal system in SW-Iceland, during a 30-year period of intense production, and for the following recovery (production stopped in 2036). Note that predicted temperature changes are not well constrained. Figure from Axelsson et al. (2010); see also Björnsson et al. (2003).

5. CONCLUSIONS

Thorough understanding of the nature and properties of geothermal resources, via comprehensive interdisciplinary research, as well as reliable and accurate assessment of their production capacity, through modelling, are an absolute prerequisite for sustainable utilization of geothermal energy. This paper has, therefore, reviewed the classification and nature of the different types of geothermal systems found throughout the Earth's crust. They include (a) volcanic systems with hot intrusions or magma as heat sources, (b) fracture-controlled convective systems with deep water circulation, (c) sedimentary systems with permeable layers at great depth, (d) geo-pressured systems, (e) hot dry rock or enhanced geothermal systems and (f) shallow resources utilized through ground-source heat pumps.

The paper has also discussed their response to utilization, which is what mainly controls their production capacity. The response primarily involves reservoir pressure decline caused by production, which in turn is determined by the size of a geothermal reservoir, its permeability, reservoir storage capacity, water recharge and geological structure. The production capacity of geothermal systems is also controlled by their energy content, dictated by their size and temperature conditions (enthalpy if two-phase). Hydrothermal systems can, furthermore, in most cases be classified as either closed, with limited or no natural recharge, or open, where recharge equilibrates with the mass extraction in the long run.

Ultimately the paper has presented the diverse types of model calculations used to simulate and assess geothermal resources. Modelling plays a key role in understanding the nature of geothermal systems and is the most powerful tool for predicting their response to future production, which is used to estimate their production capacity. Models are also an indispensable part of geothermal resource management during utilization. In addition to the volumetric assessment method (static modelling) different methods of dynamic modelling are the main techniques used for geothermal reservoir modelling and resource assessment, including simple analytical modelling, lumped parameter modelling or detailed numerical modelling. The modelling method applied should be determined by the purpose of a study and the data available for calibrating a model, as the time and cost involved are highly variable. All reliable models of geothermal systems, whether static or dynamic, should be based on an accurate conceptual model of the corresponding system.

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 and such results should only be considered indicative. This is because of its inherent limitations, mainly the fact that it neglects the dynamic response of geothermal systems during utilization.
- Lumped parameter modelling is ideal for predicting long-term reservoir pressure changes when the sustainability of geothermal operations is being assessed. It can, in fact, simulate pressure changes as accurately as other modelling methods, in addition to providing the uncertainty bounds given by the respective open and closed models.
- Detailed numerical modelling is, of course, the most powerful modelling method for predicting long-term reservoir changes when geothermal sustainability is being assessed. If such modelling is to be reliable, however, it must be based on very comprehensive data.

ACKNOWLEDGEMENTS

The author would like to acknowledge numerous colleagues for fruitful discussions and cooperation during the last three decades or so, on different aspects of the nature of geothermal systems and the assessment of their capacity. The relevant geothermal utilities and power companies are also acknowledged for allowing publication of the case-history data presented.

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