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GEOTHERMAL DRILLING TARGETS AND WELL SITING

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ABSTRACT

Increased geothermal utilization and improved understanding of geothermal systems during the last century coincided with geothermal wells becoming the main instruments of geothermal development. They enable a drastic increase in geothermal energy production, compared to natural out-flow, and provide access deep into the systems, not otherwise possible. The key to the successful drilling of any type of geothermal well (temperature gradient, exploration, production, step-out, make-up, reinjection, monitoring and unconventional wells) is correct siting and design of the well based on a clear definition and understanding of the drilling target aimed for, founded on all information available at any given time. This is best achieved through a comprehensive and up-to-date conceptual model, which is a qualitative models incorporating, and unifying, the essential physical features of a geothermal system. The principal geothermal drilling targets are in fact structures of adequate permeability and sufficiently high temperature to yield productive wells. Temperature conditions may be indirectly inferred from resistivity surveying, natural seismicity 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 have been drilled into a geothermal system. Once this structure becomes well known and clearly defined drilling success usually improves. The siting of the first well in a geothermal field depends mostly on surface exploration but once the first wells have been drilled subsurface data come into play, increasing the knowledge on a geothermal system. Most important are feed-zone, temperature-logging and well-test data.

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 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 (or boreholes/drillholes) 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 technology of geothermal well drilling is mostly derived from the petroleum industry, as well as from the ground-water and mineral industries. The technology has been adapted to different conditions, however, mostly in terms of geology, temperature, pressure and chemistry of the fluid involved. Because of the limited size of the geothermal industry, compared with e.g. the petroleum industry, advancement of the geothermal drilling technology has been relatively slow. Geothermal wells play a variable role, however, both during development of geothermal resources as well as during their utilization. The main roles are: (a) exploration wells, (b) production wells, (c) reinjection wells and (d) monitoring wells.

The key to the successful drilling of any type of geothermal well is correct siting and design of the well based on a clear definition and understanding of the drilling target aimed for. This paper discusses targeting and siting of the different types of geothermal wells with particular emphasis on how all available information and data should be used for this purpose. The cooperation of the different disciplines involved in geothermal research and development is of particular importance here. The paper starts out by reviewing briefly the types and classification of geothermal resources as well as discussing conceptual models of geothermal systems, which play a key role in targeting and siting geothermal wells. Subsequently the paper discusses the different types of geothermal wells along with different aspects of their targeting and siting. The paper is concluded by general conclusions and recommendations.

2. GEOTHERMAL SYSTEMS

2.1 Types and classification of geothermal systems

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. Axelsson (2008a) and Saemundsson et al. (2009) summarize the classifications based on the first three aspects, i.e. as high-temperature (> 200°C) or low-temperature (< 150°C) systems, high-enthalpy (> 800 kJ/kg) or low-enthalpy (< 800 kJ/kg), or liquid-dominated, two-phase or vapour-dominated systems.

Geothermal systems may also be classified based on their nature and geological setting (Figure 1) as follows:

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 *convective fracture controlled 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 systems* 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)* consist of 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 way. 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. Recent developments in the application of ground source heat pumps have opened up a new dimension in utilizing these resources.

Saemundsson et al. (2009) discuss the geological setting of geothermal systems in more detail and present a further subdivision principally based on tectonic setting, volcanic association and geological formations. Numerous volcanic geothermal systems (A) are found for example in The Pacific Ring of Fire, in countries like New Zealand, The Philippines, Japan and in Central America. 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, Central Eastern Europe and throughout China. Typical examples of geo-pressured systems (D) are found in the Northern Gulf of Mexico Basin in the U.S.A. The Fenton Hill project in New Mexico in The United States and the Soultz project in NE-France are well known HDR and EGS projects (E) while shallow resources (F) can be found all over the globe. The type of geothermal system involved of course affects the design and siting of geothermal wells to be drilled into the system.

There are definite differences between geothermal systems and their ground-water and petroleum counterparts, which are worth mentioning since they also affect the siting and design of geothermal wells. Geothermal reservoirs in volcanic (A) and convective (B) systems are in most cases embedded in fractured rocks, while ground water and petroleum reservoirs are usually found in porous sedimentary rocks. In addition geothermal reservoirs are most often of great vertical extent (from a few hundred meters to a few kilometres) in contrast to ground water and petroleum reservoirs, which have limited vertical extent, but may be quite extensive horizontally. Many geothermal systems are also uncapped and the hot fluid may be directly connected to cooler surrounding systems. Finally it should be mentioned that heat transport as well as mass transport is important in geothermal systems in contrast to ground water and petroleum cases, where only mass flow needs to be considered. Heat extraction, rather than simply fluid extraction, is in fact at the core of geothermal utilization. Moreover, two-phase conditions often prevail in high-temperature geothermal systems.

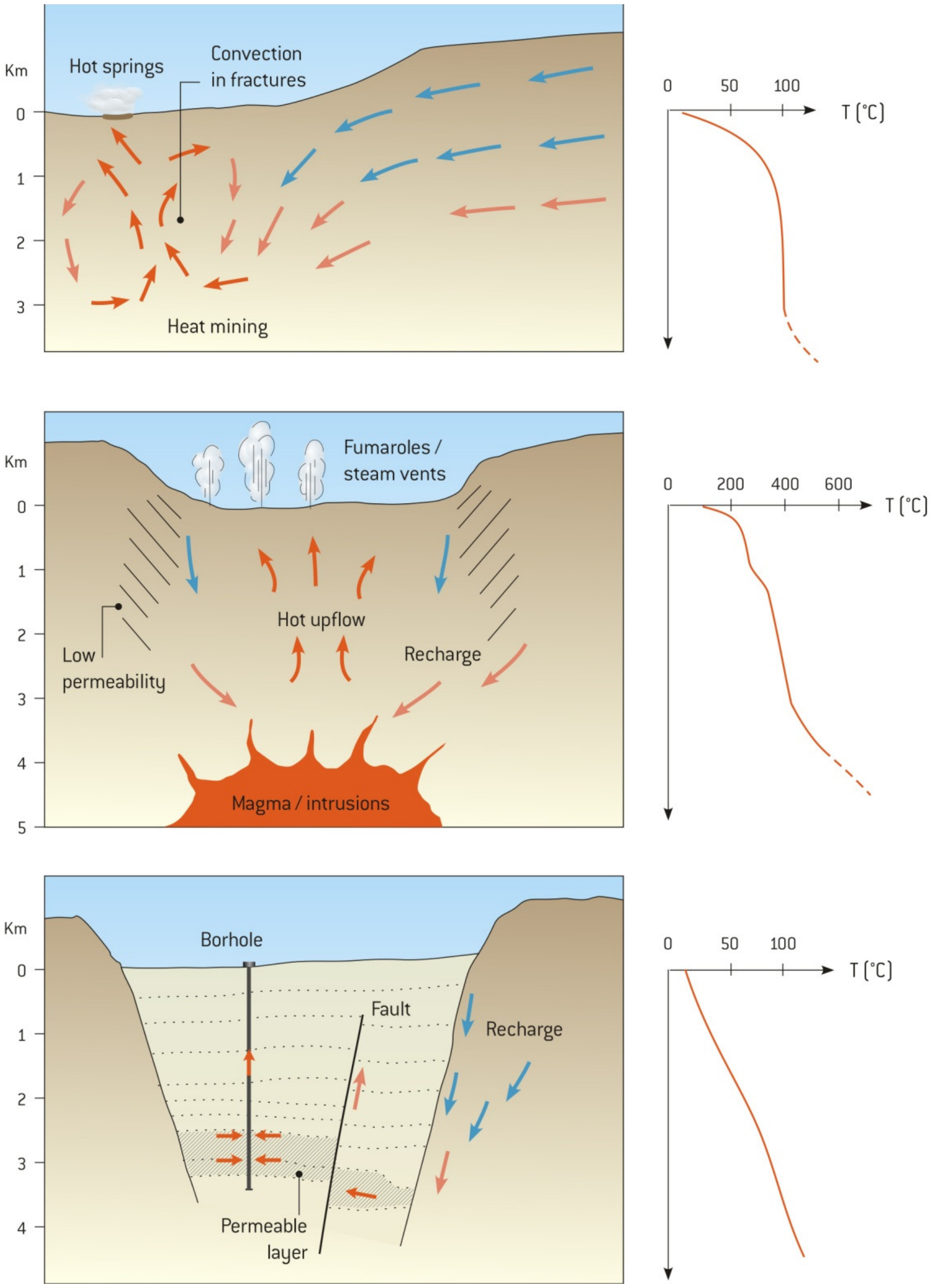

FIGURE 1: Schematic figures of the three main types of geothermal systems; a convective fracture controlled system (B) at the top, a volcanic system (A) in the middle and a sedimentary system (C) at the bottom (Axelsson, 2008a)

2.2 Conceptual models of geothermal systems

The basis of defining drilling targets and well locations is good understanding of the structure and nature of a geothermal system based on all information available at any given time. This information is increasingly being unified through the development of so-called conceptual models, which play a key role in all phases of geothermal exploration and development. This approach has obvious benefits beyond an approach where each discipline develops their own ideas independent from other disciplines. Conceptual models are descriptive or qualitative models incorporating, and unifying, the essential physical features of geothermal systems, which have been revealed through analysis of all available exploration, drilling and testing data (Grant and Bixley, 2011). Conceptual models 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
(2) Explain the heat source(s) for a system
(3) Include information on the location of the hot up-flow zones
(4) Describe the location of colder recharge zones
(5) Define the general flow pattern in a system
(6) Indicate location of two-phase zones, as well as steam-dominated zones
(7) Describe location of the main permeable flow structures (faults, fractures, horizontal layers, etc.)
(8) Indicate the location of flow barriers
(9) Define the cap-rock of the system
(10) 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, but it's really only when large-scale utilization has been on-going for quite some time, with associated monitoring, that fairly comprehensive knowledge on the items listed has become available.

Two examples of visualizations of geothermal conceptual models are presented in Figures 2 and 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 Ahuachapan geothermal system in El Salvador presented by Monterrosa and Montalvo (2010) and the conceptual model for the Hengill geothermal system presented by Franzson et al. (2005).

3. GEOTHERMAL WELLS

3.1 General

Wells or boreholes are vital components in both geothermal research and utilization, since they provide essential access for both energy extraction and information collection, as already mentioned. Deep geothermal drilling didn't really commence on a large scale until the middle of the 20th century even though some geothermal drilling had already started a century before that. Deep (150–200 m) geothermal drilling started in Larderello, Italy, in 1856 (Grant and Bixley, 2011) and the first deep (~970m) geothermal well in Hungary was drilled in Budapest from 1868 to 1878 (Szanyi and Kovács, 2010).

The design, drilling and construction of geothermal wells are discussed in other lectures at this short course. Sarmiento (2007) discusses drilling practises in The Philippines in particular, where extensive experience has accumulated during the countries extensive geothermal development. Typically the upper parts of a geothermal well are closed off by a series of casings; to stabilize the well, to close off non-geothermal hydrological systems and for safety reasons. The deeper parts of the well are either fully open or cased with a so-called liner, which is not cemented in place but perforated in selected intervals, to allow fluid (water and/or steam) to flow from the reservoir into the well. The most significant difference between geothermal and petroleum wells are the following:

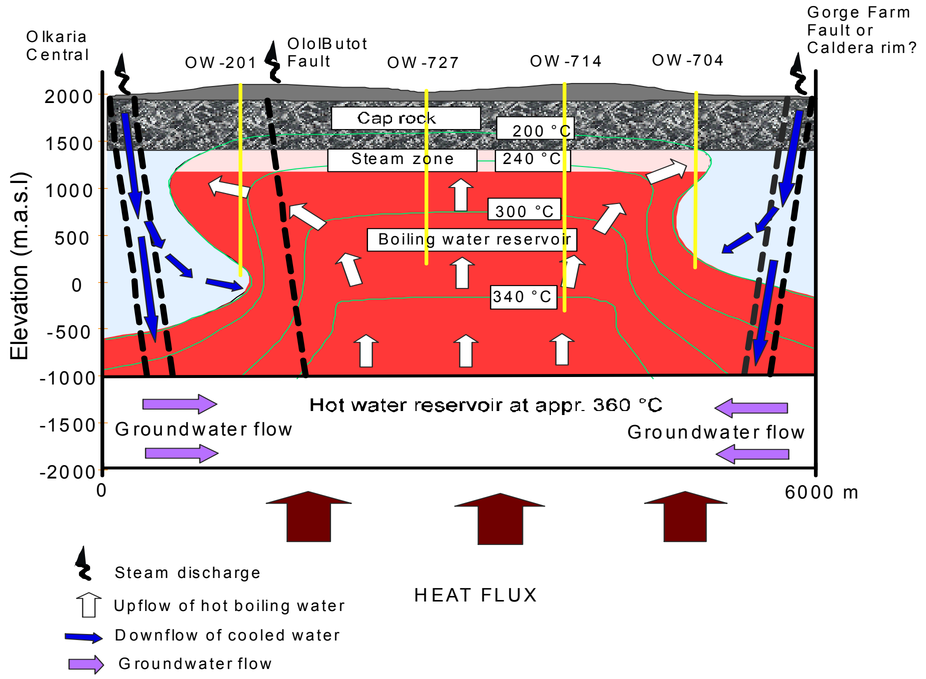

FIGURE 2: A view of the 2002 conceptual model of the Olkaria East geothermal system (Ofwona, 2002)

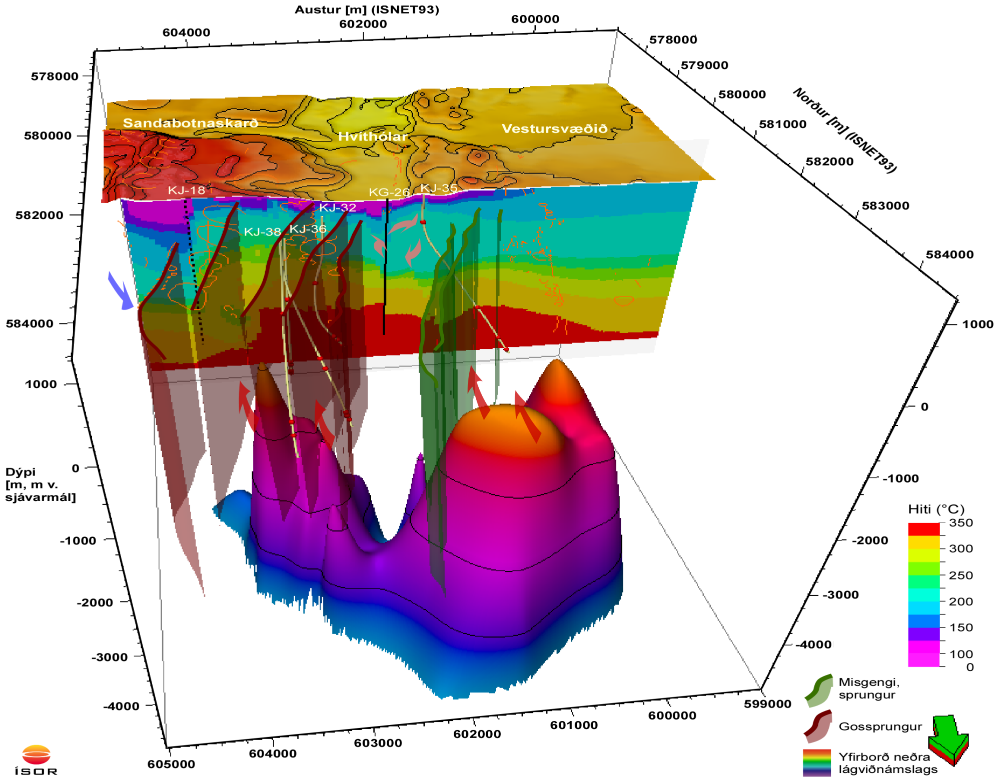

FIGURE 3: A 3-dimensional view of the current conceptual model of the Krafla geothermal system in NE-Iceland (Mortensen et al., 2009) showing a deep-seated low-resistivity anomaly reflecting a magma chamber, faults and eruption fissures as well as temperature conditions and inferred flow directions

(i) Geothermal wells are most often drilled in hard, igneous rocks, which are more difficult to drill than the sedimentary environment of petroleum wells.
(ii) The open production sections of geothermal wells are quite long in comparison with those of petroleum wells, ranging from a few hundred metres to more than 2 km.
(iii) Yet geothermal wells usually have some discrete in-flow sections (feed-zones, see below).
(iv) Geothermal wells often encounter high temperatures and pressures, sometimes associated with blow-out danger due to explosive boiling.
(v) Water is commonly used as drilling fluid for open sections in contrast with drilling mud most commonly used in petroleum wells to avoid clogging any feed-zones (also reduced pollution danger).
(vi) The drilling of successful geothermal wells often involves large, or even total, circulation losses.
(vii) Geothermal production wells are generally of larger diameter (up to a few tens of cm's) than petroleum wells, because of greater flow-rates involved.

Grant and Bixley (2011) discuss some of these in more detail.

A geothermal well is connected to the geothermal reservoir through feed-zones of the open section or intervals. The feed-zones are either particular open fractures or permeable aquifer layers. In volcanic rocks the feed-zones are often fractures or permeable layers such as interbeds (layers in-between different rock formations) while in sedimentary systems the feed-zones are most commonly associated with a series of thin aquifer layers or thicker permeable formations. Yet fractures can also play a role in sedimentary systems. In some instances a well is connected to a reservoir through a single feed-zone while in other cases several feed-zones may exist in the open section, but often one of these is the dominant one.

Geothermal wells can be classified as either:

(a) liquid-phase low-temperature wells, which produce liquid water at well-head (pressure may be higher than atmospheric, however),
(b) two-phase high-temperature wells where the flow from the feed-zone(s) is liquid or two-phase and the wells produce either a two-phase mixture or dry-steam or
(c) dry-steam high-temperature wells where the flow from the feed-zone(s) to the well-head is steam-dominated.

In the liquid-phase and dry-steam wells the inflow is single phase liquid water or steam, respectively, while two-phase wells can be furthermore classified as either liquid or two-phase inflow wells. In multi feed-zone two-phase wells one feed-zone can even be single-phase while another one is two-phase.

In general the productivity of geothermal wells is a complex function of:

(1) well-bore parameters such as diameter, friction factors, feed-zone depth and more,
(2) feed-zone temperature and enthalpy,
(3) feed-zone pressure, which depends directly on reservoir pressure and reservoir permeability,
(4) well-head pressure or depth to water level during production and
(5) temperature conditions around the well.

Most of these parameters can be assumed approximately constant for reservoirs under production, except for the reservoir pressure (3), which varies with time and the overall mass-extraction from the reservoir. The feed-zone temperature and enthalpy may also vary with time in some cases, albeit usually more slowly than reservoir pressure.

Finally it should be mentioned that geothermal wells are often stimulated following drilling (Thórhallsson, 2012a), either to recover permeability reduced by the drilling operation itself, to enhance lower than expected near-well permeability or to open up connections to permeable structures not directly intersected by the well in question. Axelsson and Thórhallsson (2009) review the main methods of geothermal well stimulation with emphasis on methods applied successfully in Iceland. The methods most commonly used involve applying high-pressure water injection, sometimes through open-hole packers, or intermittent cold water injection with the purpose of thermal shocking. Stimulation operations commonly last a few days while in some instances stimulation operations have been conducted for some months. The stimulation operations often result in well productivity (or injectivity) being improved by a factor of 2-3. Geothermal wells stimulation is discussed further in other lectures at this short course.

3.2 Types of geothermal wells

The different types of geothermal wells are listed and described briefly below:

(1) **Temperature gradient wells** are generally both slim and quite shallow, most often only around 50 m in depth, even though in some instances they may reach a few hundred metres depth. Their main purpose is to study shallow temperature conditions (temperature gradient) and estimate heat flow. In contrast with other geothermal wells temperature gradient drilling can in fact be classified as a surface exploration tool. Saemundsson (2010) discusses the use of such wells in geothermal exploration and presents example. Their use has been particularly effective in the exploration for fracture controlled low-temperature geothermal resources in Iceland, especially hidden systems (Axelsson et al., 2005).

(2) **Exploration wells** are deeper wells intended to extend into the geothermal system being explored, i.e. to reach a specific target. Their main purpose is to study temperature conditions, permeability and chemical conditions of the target. Exploration wells are either so-called slim wells with diameter < 15 cm (Thórhallsson, 2012b), which are drilled for the sole purpose of exploring conditions at the target depth, or exploration wells designed as production wells (full diameter wells). The former can be used to estimate the capacity of production wells later drilled to reach the same target(s) (Garg and Combs, 1997; Combs and Garg, 2000). The latter can later be converted to production wells, however, if successful. Slim wells are of course considerably less expensive than full diameter wells and they can be considered more appropriate when the risk involved is relatively large.

(3) **Production wells** are wells drilled with the sole purpose of enabling production of geothermal energy (as hot liquid, two-phase mixture or steam) from a specific target, or a geothermal reservoir. Their design is of paramount importance, e.g. the casing program applied. Production wells are either designed for spontaneous discharge through boiling (high-temperature reservoirs) or for the application of down-hole pumps (lower temperature reservoirs).

(4) **Step-out wells** are either exploration or production wells drilled to investigate the extent, of a geothermal reservoir already confirmed. A step-out well either approaches the edge, or boundary, of a reservoir or is drilled beyond it. A number of step-out wells in different directions may be required if a given reservoir is extensive in area.

(5) **Make-up wells** are production wells drilled inside an already confirmed reservoir, which is being utilized for energy production, to make up for production wells which are either lost through damage of some kind (collapse, scaling, etc.) or to make up for declining capacity of wells.

(6) **Reinjection wells** are used to return energy-depleted fluid back into the geothermal system in question or even to inject water of a different origin as supplemental recharge. The location of reinjection wells is variable as reinjection can either be applied inside a production reservoir, on its periphery, above or below it or outside the main production field, depending on conditions and the purpose of the reinjection (Axelsson, 2012).

(7) **Monitoring wells** are used to monitor changes in geothermal systems, mainly after utilization starts, mostly pressure and temperature changes. These are in most cases already existing wells, such as exploration wells or abandoned production wells. Active production wells are sometimes used for monitoring purposes (chemical content, temperature and pressure).

Carefully designed and comprehnsive monitoring is the key to successful management of geothermal resources during utilization (Axelsson, 2008b). Monitoring wells are also used to monitor transport of chemicals, such as during tracer tests.

(8) **Unconventional wells** are either wells of unconventional design or wells drilled into parts of geothermal systems generally not used for energy production. Good examples are the wells of the Iceland deep drilling program (IDDP, see e.g. Fridleifsson et al., 2010). The aim of the program is to drill down to 4–5 km depth in high-temperature volcanic systems, where supercritical fluid conditions are expected. The first IDDP well was, furthermore, drilled into magma at ~2 km depth, i.e. conditions which surely are unconventional.

The different types of wells play a role during different stages of geothermal development as can e.g. be seen in Figure 4, which shows an example of a geothermal development project plan. The plan includes a subdivision of well categories, beyond the one listed above, which will not be discussed here. Steingrímsson et al. (2005) and Björnsson et al. (2012) provide further information on overall plans for geothermal development in Iceland. Another example worth mentioning is the geothermal development program of the Philippines (Dolor, 2005). In addition Stefánsson (1992) analyses the success of geothermal development, which depends to a great extent on the success of drilling.

4. WELL SITING AND TARGETTING

The key to the successful drilling of any type of geothermal well is correct siting and design of the well based on a clear definition and understanding of the drilling target aimed for, as already stated. This is best achieved through a comprehensive and up-to-date conceptual model. In addition data from different sources play different roles for different types of wells. This can be seen from Table 1, which lists most of the different research methods relevant for defining geothermal drilling targets.

Discussing all these research methods is beyond the scope of the present paper, but instead the reader is referred to numerous papers in the general geothermal literature, and in particular papers presented at a number of short courses given by the United Nations University Geothermal Training Programme (available at http://www.unugtp.is/page/workshops-and-short-courses). A good review of the methods applied in geothermal well targeting during the exploration stage is e.g. given by Santos (2011).

The methods classified as primary in the table are methods which are used in most geothermal development programs worldwide, while the ones classified as secondary are methods only applied in some cases. Yet some of the latter methods are quite valuable when applicable. A case in point is e.g. passive seismic analysis; including event location (depth distribution), focal mechanism and S-wave attenuation analysis, which may add greatly to the understanding of the deeper parts of geothermal systems, in particular those of volcanic systems.

The principal geothermal drilling targets 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 involved, 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 have been drilled into a geothermal system. Once this structure becomes well known and clearly defined drilling success usually peaks. Figure 5 shows 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.

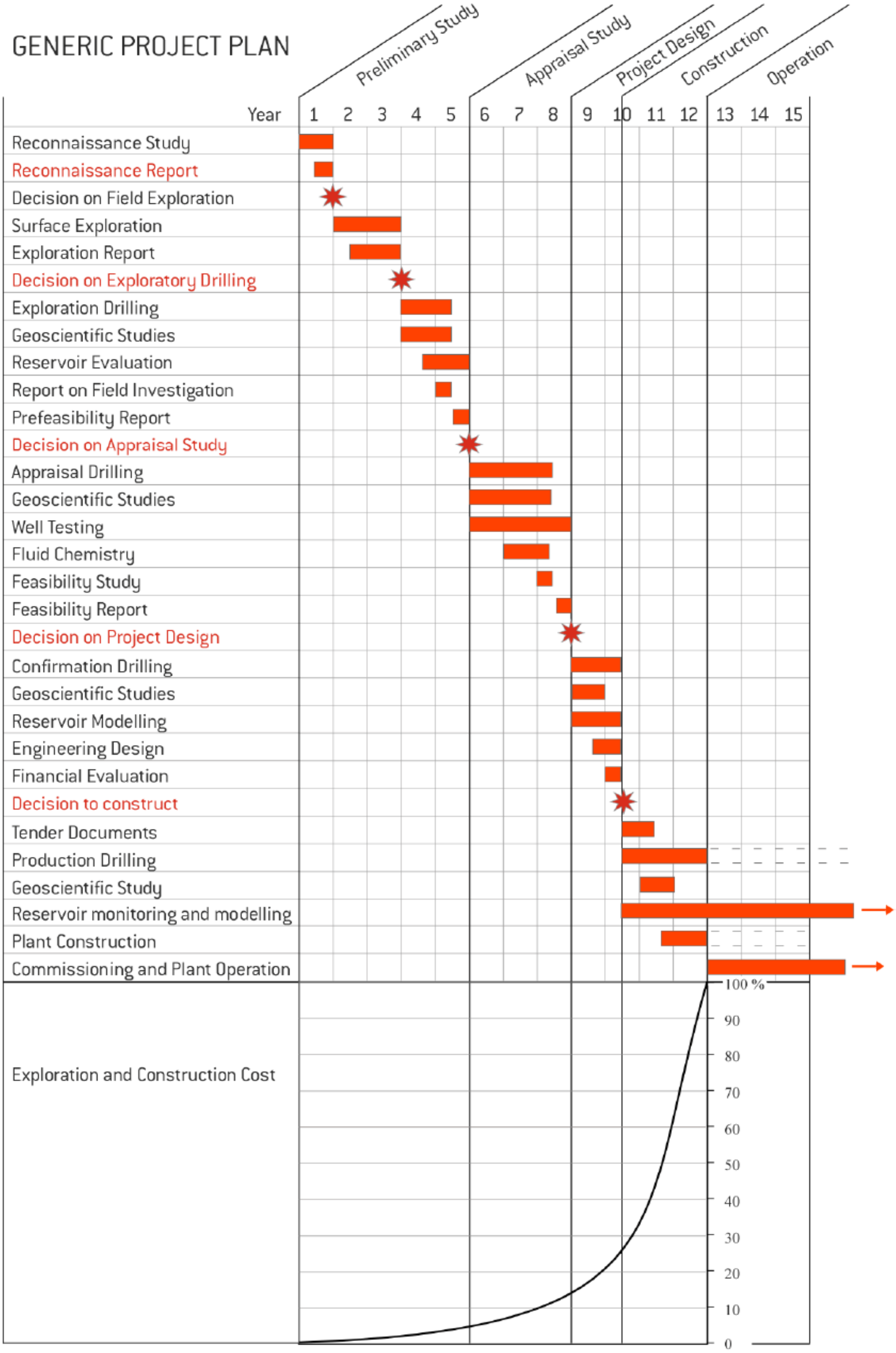

FIGURE 4: Generic project plan for phases of geothermal development proposed in Iceland in 1982 (Steingrímsson et al., 2005)

TABLE 1: Table indicating the contribution of different types of geothermal research to targeting of different types of geothermal wells. The symbol **P** indicates a primary research method most often applied while **S** indicates a secondary method, which is not applied in all cases

Research	Exploration wells	Production wells	Make-up and step-out wells	Reinjection wells
Geological mapping	**P**	**P**	**P**	**P**
Mapping of faults/fractures	**P**	**P**	**P**	**P**
Surface manifestation mapping	**P**	**P**	**P**	
Ground temperature surveying	**S**	**S**	**S**	
Chemical-content/isotope surveying	**P**	**P**	**P**	
Aerial photos and satellite imagery	**S**	**S**	**S**	**S**
Remote sensing (e.g. infrared)	**S**	**S**	**S**	
Hydrogeological studies	**S**	**S**	**S**	**S**
Temperature gradient wells	**S**	**S**	**S**	**P**
Magnetic mapping	**S**	**S**	**S**	**S**
Gravity mapping	**S**	**S**	**S**	**S**
Resistivity surveying	**P**	**P**	**P**	**P**
Seismic studies	**S**	**S**	**S**	**S**
Borehole lithology		**P**	**P**	**P**
Feed-zone inventory		**P**	**P**	**P**
Temperature/pressure logging		**P**	**P**	**P**
Borehole fracture imaging		**S**	**S**	**S**
Well testing		**P**	**P**	**P**
Discharge testing		**P**	**P**	
Temperature/pressure monitoring		**P**	**P**	
Chemical monitoring		**P**	**P**	
Gravity monitoring		**S**	**S**	**S**
Micro-seismic monitoring		**S**	**S**	**S**
Tracer testing				**P**
Reservoir modelling		**S**	**P**	**P**

The table above demonstrates that the siting of the first wells in a geothermal field, i.e. the exploration wells, depends 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. Once the first wells have been drilled 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 a separate paper at this short course. Thus target definition for production wells and other wells relies more and more on subsurface data as development progresses (Table 1).

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. what was expected. Based on this comparison the conceptual model of the geothermal system should be updated, to ensure that the next well siting will be based on the most up-to-date information and understanding.

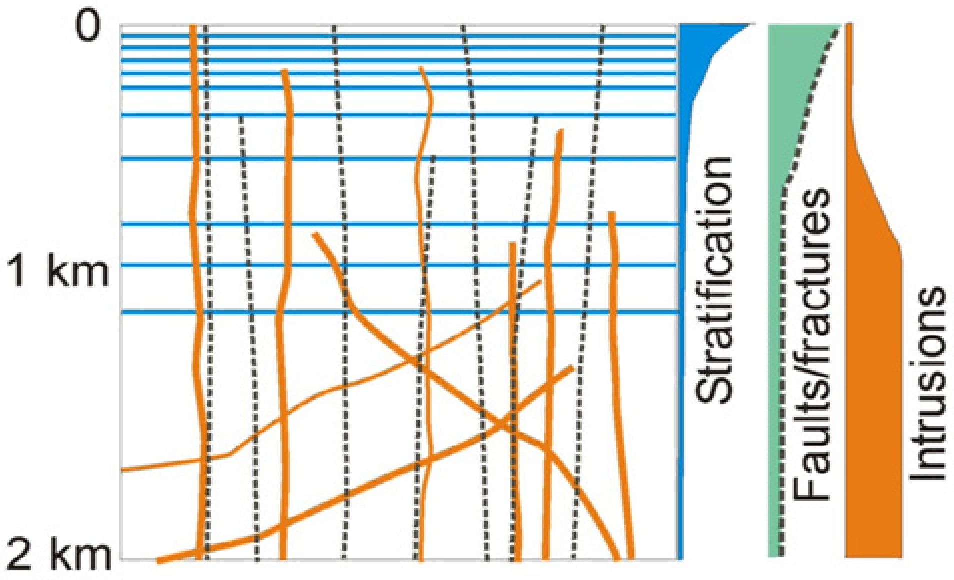

FIGURE 5: A schematic figure showing how the importance of permeability associated with different geological structures varies typically with depth in volcanic geothermal systems in Iceland. The best permeability is often found at the intersection of two such structures

Figure 6 shows an example of how both surface exploration data and well data are used to define the drilling target for a step-out well at Þeistareykir geothermal field in NE-Iceland, but the resistivity model is based on a 3D inversion of the TEM-MT survey, while the temperature and alteration model is projected from well data.

Figure 7 shows another example of how multiple data sets from surface and subsurface exploration are combined and compared with 3D visualization. These models are forming the foundation for the conceptual model of the field and for well siting. This figure is highlighting data, which are providing information about the extent of the geothermal reservoir and distribution of temperature and permeability.

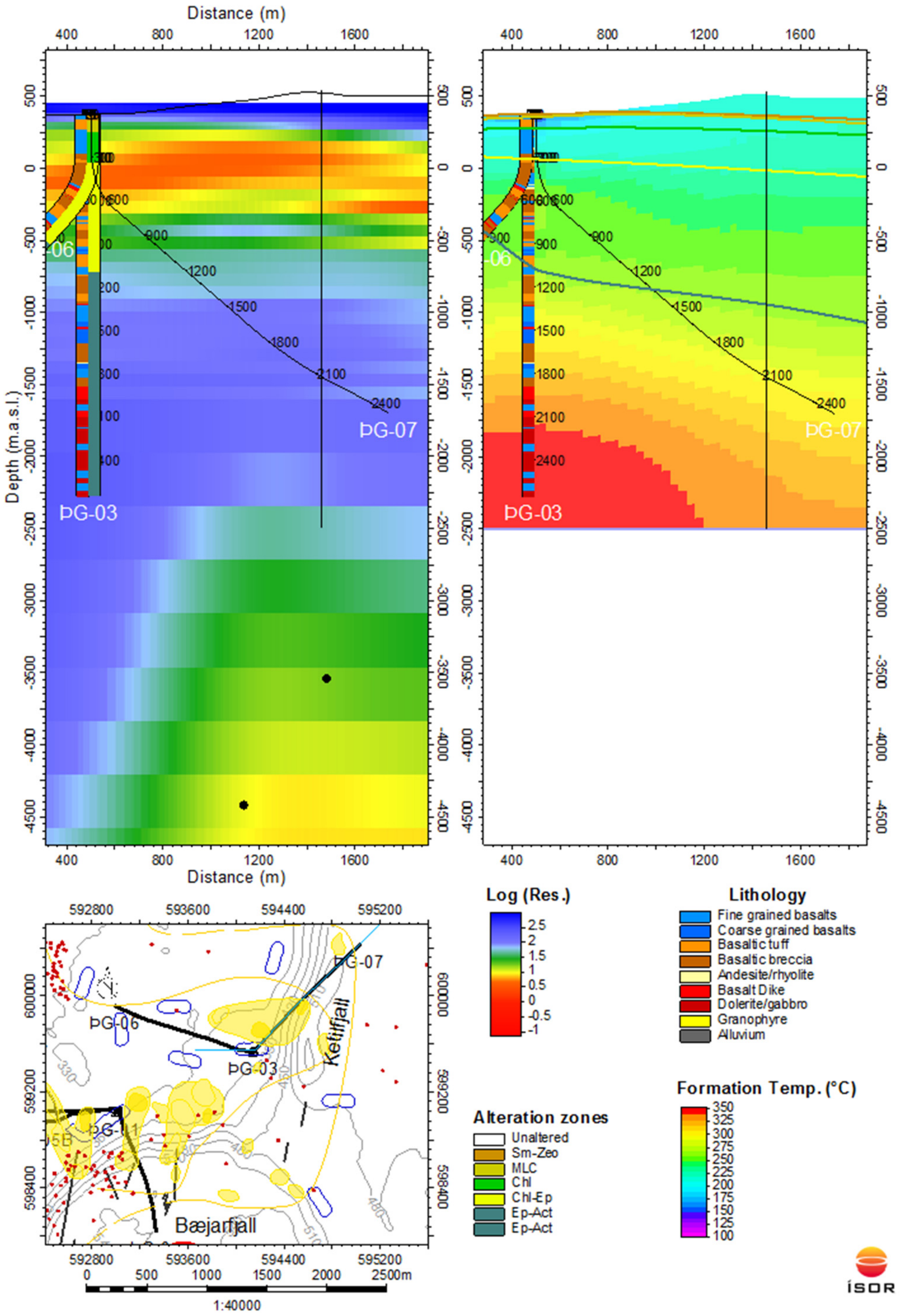

FIGURE 6: Example of projected target visualization for a step-out well at Þeistareykir geothermal field in NE-Iceland. Well trajectory is compared with 3D resistivity model (left) and to the right is comparison with temperature and alteration model. The black vertical line defines the Ketilfjall fissure, which the well is projected to intersect at ~2100 m depth. Lithology is plotted along well trajectory of well ÞG-03. The uncertainty of the temperature model is high at more than 1000 m from previously drilled wells (ÞG-03)

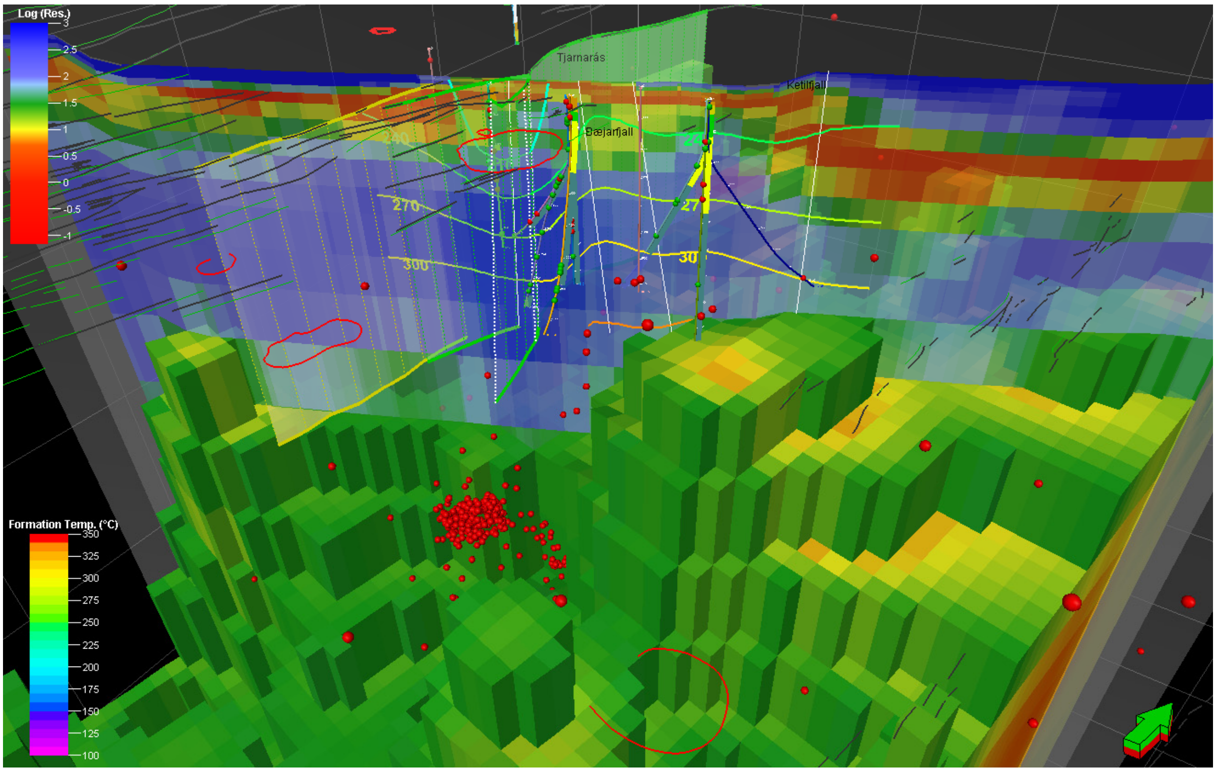

FIGURE 7: 3D visualization of Þeistareykir geothermal field combining data of resistivity, temperature, seismicity and alteration. Yellow-green 3D block model in the lower part of the figure is showing the structure if the deep conductive layer based on TEM-MT survey. On the NE-SW cross section is also projected the resistivity model, where yellow-red colours are highlighting the conductive cap above the geothermal reservoir, while the temperature model is projected as isotherm lines on the cross section. Alteration zoning is plotted along the well trajectories (green – chlorite zone; yellow: chlorite-epidote zone; blue-green: epidote-actinolite zone). The 240°C isotherm and the top of the chl-ep zone correlated with the lower part of the low resistive cap of the geothermal reservoir. Red dots indicate earthquake locations covering the time interval from 1993-2011. The Tjarnarás fault plane is marked with a light-green plane in the upper part of the figure. North arrow is in the lower right corner

In the past geothermal wells were mostly vertical and the same usually also applies to the first wells (exploration wells) in fields where development is just starting. Recently directional wells (Thórhallsson, 2012c) have become dominant in many geothermal fields in the world. The principal benefits (environmental and economic) are that fewer drill-pads and less surface piping are needed. Directional drilling also enables reaching drilling targets that are not easily accessible by vertical wells. There have been claims that directional wells are more productive in certain geological situations, in particular when near vertical fractures/faults are dominant. This has not been substantiated, however.

It should be noted that the success rate for geothermal drilling is dependent on the geothermal system involved. This is because of their individual nature and the fact that some systems are not as easily understood as others. The drilling success rate also depends on the speed of development of a given project. If the speed is too high the necessary knowledge doesn't accumulate rapidly enough (because of insufficient time for research and conceptual model updating) and the drilling is more risky.

Finally it should be mentioned that 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, as already mentioned, with the reinjection targets therefore being quite different. Sufficient permeability is, of course, also a necessary requirement for successful reinjection wells and therefore all the research methods applied to evaluate permeability are also required for reinjection wells (Table 1). 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 (for more details see Axelsson, 2012).

5. CONCLUSIONS AND RECOMMENDATIONS

This paper has discussed targeting and siting of the different types of geothermal wells with particular emphasis on how all available information and data should be used for this purpose. This is best achieved through a comprehensive and up-to-date conceptual model of the geothermal system in question. Cooperation of the different disciplines involved in geothermal research and development is of particular importance here. This approach has obvious benefits beyond an approach where each discipline develops their own ideas independent from other disciplines. The principal geothermal drilling targets are structures, or volumes, of adequate permeability and sufficiently high temperature to yield productive wells.

The nature of the permeability depends on the type of geothermal system involved, the geology of the system (formations, faults/fractures, etc.) and in-situ stress conditions. In the early stages of development knowledge on which to base well siting is limited but when development continues (with drilling) the necessary knowledge increases. Yet it's really only when large-scale utilization has been on-going for quite some time, with associated monitoring, that fairly comprehensive knowledge and understanding on the nature and structure of a system has been achieved.

The research methods applied in defining geothermal targets have been classified as primary or secondary depending on whether they are used in most geothermal development programs worldwide or only in some cases. Yet some of the methods currently classified as secondary are quite valuable when pertinent, and may add significantly to information needed for geothermal well targeting. This applies e.g. to passive seismic analysis; including event location (depth distribution), focal mechanism and S-wave attenuation analysis, which may add greatly to the understanding of the deeper parts of geothermal systems, in particular those volcanic in nature.

The principal benefits (environmental and economic) of directional drilling, compared to vertical drilling, are that fewer drill-pads and less surface piping are needed. Directional drilling also enables reaching drilling targets that are not easily accessible by vertical wells. It should be noted that, in addition to drastic differences between individual systems, drilling success also depends on the speed of development of a given project. If the speed is too high the necessary knowledge doesn't accumulate rapidly enough (because of insufficient time for research and conceptual model updating) and the drilling becomes more risky.

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