The roots of volcanic geothermal systems – their birth, evolution and extinction.

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ABSTRACT

It appears common to assume that magma represents the heat source to hydrothermal systems in young volcanic provinces. Measurements and estimates of the natural heat loss from such systems indicate that they are convection systems and that the heat source is very hot. Yet, it need not be magma. It may be igneous rocks that have not cooled much down subsequent to consolidation of the parent magma. It is considered important to introduce the concept of time into studies of geothermal systems. Volcanic geothermal systems are born, they develop and become extinct. Their characteristics, such as renewability, intensity of hydrothermal alteration and temperature distribution all change as these systems evolve. In the crustal spreading geological environment of Iceland, it is particularly convenient to study volcanic geothermal system that range from being young to ones that have become extinct and exhumed by erosion. When a geothermal system is cut from its magma heat source, as a consequence of crustal accretion, its renewability is reduced to zero. It represents a mine of heat and being hotter than the enveloping rock, it will start to cool down by conduction and groundwater circulation. It will develop into a low-temperature system with fossil high-temperature alteration mineralogy and finally become extinct.

1. INTRODUCTION

On the geological time scale, the lifetime of magmatic hydrothermal systems is short, may be $10^4$ to $10^5$ years. Each system is expected to have its history. Some may be short-lived, others long-lived. They are born, they develop and become extinct. At present, the production characteristics of individual systems will be affected by their evolutionary stage.

When magma is intruded into permeable rocks at shallow crustal levels, a geothermal system likely develops above it through density driven groundwater convection. The rising hot fluid will transport heat from the heat source to shallower crustal levels and gradually heat up the rock, possibly until the boiling point curve is reached at all depths. At this point the heat extracted from the magma heat source is mostly lost through the surface into the atmosphere.

Studies of eroded fossil hydrothermal systems provide information about the nature of intrusions (size and shape) that once constituted their heat source. Many fossil hydrothermal systems are exposed in the Tertiary formations in Iceland and even more deeply eroded ones in other parts of the North-Atlantic Tertiary Igneous Province, such as in Scotland and Greenland. It is considered that studies of fossil volcanic geothermal systems will provide much information about the roots of presently active systems.

2. VOLCANIC GEOTHERMAL SYSTEMS

Iceland is part of the North-Atlantic Volcanic Province. Volcanism started in the area in early tertiary times during the opening of the Atlantic Ocean. Early tertiary rocks belonging to this Province are exposed in western Scotland and East Greenland, represented by both lava flows and minor and major intrusions, the best known little doubt being the layered gabbro at Skærgaard in eastern Greenland with an estimated volume of 270 km$^3$. It has been estimated that this intrusion formed at 5-8 km depth below the surface at that time (McBirney, 1984). Layered intrusions are also exposed in Scotland, their depth of intrusion being 3-5 km.

Central volcanic complexes, like those found in Scotland, are abundant in Iceland, ranging in age from ~15 million years to present but they are less deeply eroded, 0-2 km. Within the active volcanic belts in Iceland a total of 26 volcanic geothermal fields are known and one offshore (Fig. 1). Most of them are located close to or at the lithosphere plate boundaries where volcanic systems with their associated fissure swarms intersect the plate boundary. In the eastern volcanic belt they coincide with central volcanic complexes but in the western volcanic belt there are no central volcanic complexes except for Hengill.

In Iceland, hydrothermal systems have been classified as high and low-temperature. By the definition of Goff and Janik (2000), the term high-temperature area is a synonym with systems in young volcanic terrain, i.e. volcanic geothermal system, while low-temperature areas correspond with tectonic systems as defined by Goff and Janik (2000). Here, the terms volcanic and tectonic systems will be used.

Known fossil volcanic geothermal systems in quaternary and upper-tertiary rocks (up to 15 million years old) in Iceland that have been exhumed by erosion are 50 (Fig. 2). In addition, two developed low-temperature systems are old volcanic systems that have cooled down as reflected by the hydrothermal alteration mineralogy. Forrester and Taylor (1977) and Taylor and Forrester (1979) have demonstrated that large quantities of meteoric water have reacted extensively with the deep-seated intrusions in Scotland and the Skærgaard intrusion in East-Greenland as witnessed by the low $^{18}$O content of the rocks forming these intrusions. Yet, the rock is very fresh. If through flow of liquid water was responsible for the low $^{4}$H, one would expect that the rock was intensely altered hydrothermally. A plausible explanation is that the fluid was low-density vapor, possibly low-density supercritical H$_2$O.
Figure 1: Active volcanic (high-temperature) fields in Iceland.

Figure 2. Known fossil volcanic (high-temperature) geothermal systems in Iceland.
Central volcanic complexes in Iceland are not only characterized by hydrothermal activity but also with occurrences of silicic igneous rocks. Multiple evidence indicates that the parent magma of these rocks represents partially melted hydrothermally altered basaltic rock. It thus appears that some volcanic geothermal systems may subside at plate boundaries under the growing pile of volcanic rocks instead of drifting out of the volcanic belts as a consequence of crustal accretion in which case they would be in the end brought back to the surface by erosion. This could explain the observation that volcanic geothermal systems are relative more abundant in the volcanic belts than in older formations. A low-density trap for rising basaltic magma formed by low-density subglacially erupted quaternary rocks may also contribute.

The crust below Iceland has been divided into 5 layers on the basis of seismic velocities (Pal'mason, 1973). Drillholes have penetrated the three topmost layers (0 to 2) and a little bit into layer 3. This layer is built up of gabbro intrusions but the three above are composed of sediments, lavas and hyaloclastites. The depth to layer 3 in the volcanic zones is generally 3 to 4.5 km. It is, however, shallower below eroded tertiary volcanic complexes. Flóvenz (1980) considers that the crust above layer 3 does not form distinct layers, rather that there is a gradual depth-related variation of increased density of the rock.

3. FORMATION AND RISE OF MAGMA

Basaltic magma that forms by partial melting of ductile mantle rock does not rise continuously from its source to shallow crustal levels and the surface. First the magma, which is less dense than the source rock, must segregate into sufficiently large pockets to give it enough buoyancy to rise by pushing aside the mantle rock. Whether or not the magma reaches the surface is affected by density traps on the way and several other characteristics of the magma itself and the host rock. Thus, at the boundary between mantle and lower crustal rocks, the magma has tendency to form large intrusive bodies (Gudmundsson, 1987) but also at higher levels, particularly on top of seismic layer 3, because basalt magma is less dense than gabbro but more dense than volcanic basaltic rock. As a consequence of this, Walker (1974) proposed that layer 3 grows from above and older gabbro bodies subside correspondingly, just like a lava succession. A sill-like body of magma intruded at the boundary of layers 2 and 3 may develop into a major stock-type intrusion by swallowing later batches of rising magma from the mantle, that is if the sill body was still molten when new magma rose. Shallower minor intrusions, dykes and small sills are relatively frequent at 1000-2000 m depth in both fossil and presently active volcanic systems in Iceland. They may enhance fumarolic activity for a relatively short period of time, as was observed at Námafjall and Krafla during the 1724-29 and 1975-84 volcanic episodes but the deeper major intrusions are considered to act as the main heat source to the above-lying geothermal system, also causing partial melting of hydrothermally altered basalt to form silicic magma.

4. TRANSFER OF HEAT FROM HEAT SOURCE AND CONVECTION

In order to explain the high heat output from, at least many volcanic geothermal fields worldwide, it is necessary to assume a very hot heat source, either magma or recently consolidated magma. As the temperature of the heat source is higher than that of the surrounding rock, its heat is transported into this rock by conduction and radiation. The same applies to heat transfer to the high-temperature geothermal system above its heat source. For this reason, the only renewal of the heat source is by magma intruded into the roots of the geothermal system. This renewal is not a continuous process. The time between eruptions of active central volcanos in Iceland ranges from decades to thousands of years. At Krafla, e.g. three volcanic eruptions have occurred within the Krafla caldera over the last 1000 years. Likely intrusive activity is more frequent than volcanic eruptions. Yet, flow of magma into the roots of volcanic geothermal systems appears to be very variable and it is not continuous.

A volcanic eruption took place on Heimaey (one of the Vestmanna Islands) in 1973. Seawater was pumped onto the lava with the purpose of diverting its flow away from the close-by town or stopping it. Several holes were drilled into the new lava with the purpose of seeing the effect of seawater pumping on its cooling. A temperature profile of one of the holes is shown in Fig. 3. In the uppermost 4 m, temperature is ~100°C, controlled by rising steam formed by vaporization of the seawater. Between ~4-6 m depth temperatures rise from ~100 to ~900°C and below is molten lava. The layer with the very steep temperature gradient represents a conductive layer between magama and the convecting seawater. When pumping was reduced or stopped, the conductive layer became thicker and vice versa. Thus a balance of heat flow was established between the conductive layer and the rising steam. With time this layer migrated down through the molten lava (see Jónsson and Matthíasson, 1974 and Björnsson et al., 1982).

It is considered that consolidation of magma in the roots of hydrothermal systems is comparable with that just described for the 1973 lava on Heimaey. The conductive layer, as calculated by the lateral extent of some hydrothermal systems in Iceland and the natural heat flow through the surface may be quite thin, as low as some 50-300 m in some systems (Krafla, Námafjall, Grímsvötn and Reykjanes).

Recharge to volcanic geothermal systems is expected to be shallow groundwater in the immediate vicinity or within these systems. The convection is density driven. At the base of the convection cell, the fluid may be sub-boiling water, two-phase, or steam only. Some of the deeply drilled volcanic geothermal fields in Iceland contain sub-boiling water below some depth (Reykjanes, Eldvörp, Svartsengi, Kriosvik and Hveragerdi), others are two-phase, at least to the depth penetrated by the deepest wells (Námafjall, Hellisheidi) and still other have superheated steam at drilled depths (~2,000 m), at least locally (Nesjavellir, Krafla). Likely, superheated steam forms by complete evaporation of the recharging water. If this is so, the deuterium content of the steam would be the same as the deuterium content of the recharging water.

If vertical permeability is sufficiently high, the convection may be one-dimensional and the temperature at the base of the convective cell tends to be just below the critical point (Coumo et al., 2008). Also, if temperature follows the boiling point curve with depth to the critical point, temperature must increase very sharply with depth beyond the critical point to maintain density driven convection, i.e. decreasing fluid density with depth. There is thus little room for supercritical H2O in such systems.
Exploitation of magmatic hydrothermal systems may enhance the crystallization and cooling of the magma heat source by successively deeper fluid convection in a manner described by Lister (1976) and in line with the observed cooling mechanism of the 1973 Heimaey lava. If this happens in a hydrothermal system under exploitation, it may last considerably longer than predicted from the heat content of fluid and rock in the hydrothermal system at the beginning of exploitation. Unfortunately data of the roots of volcanic geothermal systems are inadequate to do anything more than speculate on this issue.

5. ESTIMATION OF RESOURCE SIZE AND GENERATING CAPACITY

The so-called volume method has been used to estimate the heat stored in volcanic (high-temperature) hydrothermal systems in Iceland (Pálason et al., 1985). By evaluating the heat recovery factor, the estimated stored heat was considered to be sufficient to generate ~3,600 MW over a period of 50 years. A more recent estimate yields 4,250 MW, also for a 50 year production period (Ketilsson et al., 2009).

The early estimate of Pálason et al. (1985) was based on estimation of the volume of individual systems from distribution of thermal manifestation, DC Schlumberger soundings, evaluation of subsurface temperatures and assuming that permeability extended to 3 km depth. The more recent estimate of Ketilsson et al. (2009) was based MT-soundings in four fields and Monte Carlo statistics and the results from these four areas were considered to represent all known high-temperature fields in Iceland.

Bödvarsson (1982) estimated the heat loss through the earth’s crust in Iceland to be 30,000 MW. Of this heat flow 50% was by conduction and ~25% each through erupting volcanoes and volcanic geothermal systems. Conversion of the heat flow through the geothermal systems into conventional power generation translates to 900 MW. The natural heat loss need not be renewable. The renewability depends on the evolutionary stage of each hydrothermal system.

The volume method was developed at the United States Geological Survey in the 1970’s. The basic assumption made in using this method is that a geothermal system is represented by a certain volume of hot fluid and hot rock. Enhanced fluid withdrawal by exploitation causes reservoir pressure drawdown that was considered to lead to enhanced recharge of cold groundwater into the system. To begin with this water gained temperature when flowing through the hot rock of the geothermal system. With time, however, the enthalpy of fluid entering wells would decrease. This response of hydrothermal systems to exploitation is best reflected in decrease in Cl in water discharged from wells that is followed by cooling as Cl concentrations are low in cold groundwater but typically high in geothermal waters. Such pattern has been observed at Krafla (Fig. 4) but also in many fields in different parts of the world, such as at Wairakei (New Zealand) and Momotombo (Nicaragua).

The liquid-dominated geothermal system at Wairakei was the first of such systems to be exploited in the world and it is probably the one that has been most intensively investigated. Power generation started in 1958 so the field has been operated for almost 60 years. Glover and Mroszek, 2009 and references therein) have shown how Cl concentrations in well discharges have decreased with time. In 2000, about 1/3 of the water discharged from production wells was rapidly heated cold groundwater. The cause is enhanced recharge by the exploitation and the heat source is the hot reservoir rock. Manningon et al. (2004) have evaluated cooling of the reservoir rock by enhanced cold water recharge and concluded that usable heat (>180°C) for power generation will be exhausted after ~150 years of exploitation (production of ~250 MW). The investigations at Wairakei demonstrate that this geothermal system is not renewable in the sense that it is renewed at a rate equal to or higher than it is consumed. As discussed in the following section, recovery of the Wairakei reservoir after 100 years of exploitation is ~400 year for a production of 250 MW (O’Sullivan et al., 2010).
Figure 4: Decrease in chloride concentration (calculated at 10 bar abs. vapor pressure) in water discharged from well 21 at Krafla reflecting increasing cold water recharge into the producing aquifer.

6. RENEWABILITY

Stefánsson (2000) concluded that volcanic geothermal systems in Iceland are renewable and that recharge of the thermal energy takes place by hot fluid. Yet, it is universally accepted that the source fluid of geothermal systems is mostly if not solely cold water, seawater or meteoric water or mixtures there of. Thus, a heat source is needed to heat this water. Further, Stefánsson (2000) concludes that hot-dry rock systems are not renewable to any extent, and most likely also geothermal systems in sedimentary basins.

Bertrani and Lund (2013) state in their book World Energy Resources, 2013 Survey that:

‘Geothermal energy is generally classified as a renewable resource, where ‘renewable’ describes a characteristic of the resource: the energy removed from the resource is continuously replaced by more energy on time scales similar to those required for energy removal (Stefánsson, 2000). Consequently, geothermal production is not a ‘mining’ process.’

and quote Stefánsson (2000) to substantiate this statement.

Stefánsson (2000) considers that extraction of fluid by exploitation in excess natural heat output enhances hot fluid recharge into the hydrothermal system because aquifer fluid cooling has not been observed. This deduction is not correct. As already mentioned, decrease in Cl in water discharged from production wells and later cooling has been observed in many fields, such as Krafla (Gudmundsson and Arnórsson, 2002) and Wairakei (Glover and Mroczek, 2009). Cold groundwater is low in Cl whereas geothermal water is typically high in this constituent. For that reason the decrease in the Cl-cooling pattern is indicative of enhanced cold water recharge. To begin with the recharging cold water picks up heat from the hot rock of the geothermal system but gradually this heating process becomes less efficient as the wallrock of permeable channels conveying the recharging water cool down.

Contrary to Stefánsson (2000), Sanyal (2005) and O’Sullivan et al. (2010) consider that recharge of thermal energy into hydrothermal systems is not affected by exploitation. For this reason, they consider that the recovery time of a particular hydrothermal system after a period of exploitation would be proportional to the ratio of heat extraction during production divided by the natural heat loss. Recovery time so calculated is minimal. It assumes that the heat flow from the heat source is constant and that all this heat is used to heat up rock that cooled during the exploitation period. One would expect that reservoir pressure recovery was faster than thermal recovery and, if this is the case, surface activity would be renewed before thermal recovery. The outcome is that some of the heat from the heat source would be lost into the atmosphere and not be used to heat up cooled rock.

Sanyal (2005) estimated the renewability of geothermal systems that were exploited for power generation at the time. He observed the heat extraction during exploitation was often tenfold the natural heat output. Assuming that the natural heat output is made use of during exploitation and the total heat extraction tenfold this heat output, recovery time would be 9 times the production time. For the existing 60 MW geothermal plant at Krafla, recovery period after 100 years of production would be 900 years.

In the UN report ‘Our Common Future’ energy resources have been classified as renewable and non-renewable. By definition, the former are renewed at a rate equal to or higher than they are consumed. They cannot be exhausted (Girardet and Mendonça, 2009). By contrast, non-renewable resources are depleted as they are consumed. This classification is a simplification. The European Union classifies geothermal energy among renewable energy sources and so does the Department of Energy of U.S.A. In Directive 2009/28/EC of the European Parliament and the Council, April 23, 2009, L 140/27, Article 2 it states:

‘Energy from renewable sources’ means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogasses’
It seems clear that this classification does not imply that geothermal energy is renewable by its nature. In 1985, the National Energy Authority of Iceland estimated the heat stored in high-temperature hydrothermal systems in the country as ~3,500 MW, over a production period of 50 years and an updated estimate in 2009 yielded 4,250 MW, also over a 50 year period. Williams et al. (2008) at the United States Geological Survey have estimated that exploitable heat in identified high-temperature geothermal resources in U.S.A. is equivalent to ~9,000 MW, over a 30 year period. All these results clearly imply that the resource is viewed as a mine of heat.

In the mentioned Directive, geothermal energy is defined as:

‘…energy stored in the form of heat beneath the surface the solid earth’

It is quite clear that geothermal energy as defined by the European Union is not a renewable energy source as has pointed out in many publications (e.g. Duffield and Sass, 2003) Also, practically all of it is not even a resource by present-day technology. It seems that the classification of geothermal energy by the European Union and the Department of Energie, U.S.A. is environmental. Any environmentally benign energy resource should be developed with the purpose of reducing as much as possible combustion of fossil fuel.

The renewability of volcanic geothermal systems depends on the nature of the heat source, fluid withdrawal by exploitation in excess of natural heat output and permeability. The heat source to mature volcanic geothermal systems may be hot rock only. Hveragerdi, the Geysir field and Hveravellir in central Iceland probably represent such systems. On the other hand young volcanic hydrothermal systems are likely to have a magma heat source. The existence of shallow magma has been proven at Krafla and Námafjall and likely also in parts of the Hengill systems (Nesjavellir and Hellisheiði). Their renewability is affected by the frequency and amount of new magma intruded into their roots. The recharging fluid at the base of the convection cell is superheated steam in the case of Krafla and likely also at Nesjavellir. Other fields may be two-phase to fluid convection base depth or sub-boiling below a certain depth, as determined by the relative flows of fluid and heat. The rising hot fluid looses heat by heating of groundwater and rock at shallower levels and through the surface. It may take a long time for the fluid to reach the boiling point at all depths and thermal equilibrium to be attained between fluid and rock. In young systems limited heat may have cumulated in fluids at shallow depths and especially the rock but as they mature more heat has cumulated in both fluid and rock. Taking into account rock type, the intensity of hydrothermal alteration is a measure of the maturity of volcanic geothermal systems.

7. EFFICIENCY OF HEAT EXTRACTION

Porosity has been measured in rocks from fossil volcanic geothermal systems in Iceland. By comparison with measurements in these fossil systems, porosity in presently active systems is likely to be most commonly in the range of 10-20% (Franzson et al., 2010). These numbers suggest that ~75-90% of the heat in these systems is in the rock, therefore 10-25% in the fluid (Fig. 4).

Exploitation of the heat in the rock can be achieved in three ways: conductive flow of heat from depressurized (cooled) fluid flowing into wells, enhanced boiling of fluid in micro pores and capillary water and by heating of cold groundwater recharging the reservoir. The first two of these processes will be operative only in the depressurization zones around wells but the third one around the periphery of wellfields and along the most permeable aquifers. Injection of spent fluid with somewhat elevated temperature will reduce mining of heat from the rock and counteract reservoir pressure drawdown. The latter effect may reduce boiling of immobile pore water and capillary water and in this way reduce use of heat in the rock. On the other hand, keeping up reservoir pressures will both improve yield and longevity of production wells. These effects should be taken into account when a decision is taken to inject spent fluid from power stations, either within or outside production wellfields.

In their evaluation of size of high-temperature geothermal resources in the United States, Muffler (1979) assumed that 25% of the heat in the heat could be made use of for production. From studies of exploited high-temperature fields in California and Nevada Lovekin (2004) concluded that the number was lower, 5-20%. No estimates of this kind exist for the Icelandic volcanic geothermal fields presently under exploitation.

The efficiency of heat extraction is affected by the processes listed above but also by the spacing of permeable fractures. Larger spacing means less effieive conductive heat transfer from rock to fluid (Williams et al., 2007). Intensive exploitation from a given wellfield tends to reduce this efficiency. Conservative production improves it.

If it assumed for demonstration purposes only that all the hot fluid in 1.5 km³ of reservoir rock (areal extent 1 km², thickness 1.5 km) can be made use of for conventional 15 MW, power generation, this fluid will last for 32-64 years if porosity is 10-20% and reservoir temperature 250°C. The corresponding numbers for a 300°C reservoir are 46-92 years. If it is assumed that 20% of the heat in the rock can be extracted to produce steam, the longevities of reservoirs with the volumes and temperatures the lifetime would become ~240 (250°C) and ~260 (300°C) years. This amount of heat extraction from the rock corresponds to reservoir rock cooling to 200°C and 240°C for reservoirs initially at 250°C and 300°C, respectively. The above numbers clearly demonstrate that mining of heat from the reservoir rock is the most important parameter in determining the lifetime of wellfields.

As demonstrated by drilling into the lava formed in 1973 on Heimaey (Vestmann Islands), enhanced “recharge” by increasing pumping of seawater onto the lava enhanced its cooling by downward migration of the conductive layer between magma and the bottom of the convecting seawater. These results are in line with those of Lister (1976) who postulates that cooling of the roots of convective hydrothermal systems may create permeability at successively greater depths through cracking or widening of cracks in the rock by its thermal contraction. If this is real, the 15 MW per km² “rule” is always conservative although one would expect that its importance will vary from wellfield to wellfield, both within and between hydrothermal fields.

8. MAIN CONCLUSIONS

The European Union and the Department of Energy in U.S.A. classify geothermal energy among renewable energy resources. Apparently, this classification is not based on the nature of the resource but concern with the global environmental changes associated with combustion of fossil fuel.
Every volcanic geothermal system has its geological history. Such systems are born, they develop and become extinct. The production characteristics of these systems are expected to be affected by their evolutionary stage. Volcanic geothermal systems need not have a magma heat source. It may be very hot igneous rock body that has not cooled much down since its consolidation. Some volcanic geothermal system may have significant renewability. Others represent mines of heat depending on their evolutionary stage. If renewable, the renewability of systems under exploitation is affected by the extent and timespan of exploitation. A minimum recovery time equals the excess heat extraction divided by the natural heat output.

Volcanic geothermal systems form if magma is intruded into permeable crust. Cooling of the magma and its consolidation in the roots of such systems is considered to be similar to the cooling of the lava that formed in 1973 on Heimaey (Vestmann Islands), Iceland. A relatively thin conductive layer forms between the magma and the base of the convecting fluid. This layer migrates downward with time. Exploitation of a geothermal system that involves substantially increased heat withdrawal from the system may enhance cooling of the heat source without any renewal.

Convection in volcanic geothermal systems is density driven. If permeability if sufficiently high and the heat source of very high temperature, the base of the convection cell tends to be at temperatures just below the critical point. Recharge is expected to be in the vicinity of the system, even within it. Depending on porosity, far the larger part of the heat stored in geothermal systems is in the rock, at least if they are mature. Efficient extraction of this heat to produce steam is the most important factor in determining the productive lifetime of both wellfields and geothermal fields as a whole. Exploitation of the heat in the rock can be achieved in three ways: conductive flow of heat to depressurized (cooled) fluid flowing into wells, enhanced boiling of water in micropores and capillary water and heating of cold groundwater recharging the reservoir. The first two of these processes will be operative only in the depressurization zones around producing wells but the third one around the periphery of wellfields and along the most permeable aquifers. Injection of spent fluid with elevated temperature will reduce mining of heat from the rock relative to cold groundwater recharge but at the same time, by maintaining reservoir pressure, it may reduce boiling of immobile pore water and capillary water and in this way reduce use of heat in the rock.

If it assumed for demonstration purposes only that all the hot fluid in 1.5 km$^3$ of reservoir rock (lateral extent 1 km$^2$, thickness 1.5 km) can be made use of for conventional 15 MWe power generation, this fluid will last for 32-64 years if porosity is 10-20% and reservoir temperature 250°C. The corresponding numbers for a 300°C reservoir are 46-92 years. If it is assumed that 20% of the heat in the rock can be extracted to produce steam, the longevity of the same reservoir with the same volumes and temperatures would increase by some 150%, i.e. a factor of 2.5. This amount of heat extraction from the rock corresponds to reservoir rock cooling to 200°C and 240°C for reservoirs initially at 250°C and 300°C. The above numbers indicate that volcanic geothermal systems can be expected to last for a long time, even if they are not renewable.

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