Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-1119

XVII European Conference
ECSMGE 2019
Reykjavík
on Soil Mechanics
and Geotechnical Engineering

Geothermal exploitation in Iceland – Success and Challenges

Exploitation de la géothermie en Islande – Succès et Enjeux

Ó.G. Flóvenz
ÍSOR – Iceland GeoSurevy, Reykkjavík, Iceland

ABSTRACT: : Iceland is blessed with favourable geological conditions to produce and utilize geothermal energy. It provides low cost energy to heat about 90% of houses in Iceland and about 27% of the electricity. In addition, the geothermal energy is used for various other applications including swimming pools and spas, fish- and greenhouse-farming and various industrial processes. The geothermal energy is the key to convenient and enjoyable life in Iceland and it affects greatly our culture and living standards. During 90 years of geothermal development in Iceland a lot of challenges has been faced, and problems have always been solved.

The crustal rock in Iceland is usually of low general permeability at reservoir depth and the geothermal fluid flow is confined to subvertical fractures formed by tectonic activity. A well is only productive if it is drilled into an open fracture. The geothermal utilisation has a huge environmental benefit for the society, it has low CO_2 emission and creates local jobs. There are, however, several challenges still to deal with. induced seismicity due to reinjection of fluid, reduction of gas emission from power plants, extraction of energy from superhot roots of the high temperature systems, methods to prevent casing damages due to high thermal stresses in the casing pipes and ways to find a reasonable balance between the renewable geothermal power production and nature protection. Several pioneering projects are now running to address these challenges. The Icelandic success in geothermal utilisation is an incentive for many other countries to increase the share of renewable energy in their energy production.

RÉSUMÉ: L'Islande a la chance de disposer d'un contexte géologique favorable à la production et l'utilisation d'énergie géothermique. L'exploitation de la géothermie fournit une énergie à faible coût, qui permet de chauffer 90% des maisons en Islande et de produire 27% de l'électricité consommée dans le pays. En outre, la géothermie est utilisée pour d'autres applications : piscines et spas, aquaculture et serriculture, ainsi que différents procédés industriels. La géothermie, qui impacte fortement notre culture et notre niveau de vie, est la clef pour une vie confortable et agréable en Islande. De nombreux obstacles ont été rencontrés pendant les 90 années où la géothermie s'est développée en Islande et les problèmes ont toujours été résolus.

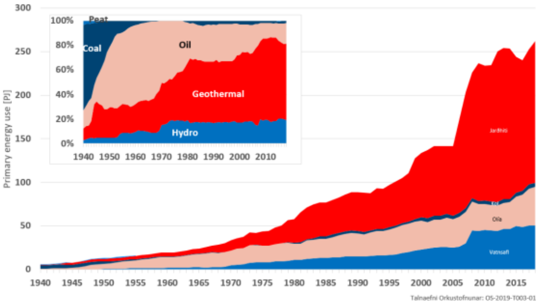
La croûte islandaise a, dans l'ensemble, une faible perméabilité aux profondeurs habituelles des réservoirs. Par conséquent, les écoulements de fluides géothermaux sont confinés dans les fractures sub-verticales créées par l'activité tectonique ; un puits n'est productif que s'il est foré dans une fracture ouverte. L'utilisation de la géothermie présente des avantages environnementaux considérables, tels que de faibles émissions de CO_2 et la création d'emplois locaux. Plusieurs enjeux de taille persistent cependant: surveiller la sismicité induite due à la réinjection de fluides, réduire les émissions de gaz à la sortie des centrales géothermiques, extraire l'énergie à la source-même – extrêmement chaude – des systèmes haute-température, limiter l'endommagement des revêtements de forages lié aux fortes contraintes thermiques dans les conduits et enfin trouver un compromis entre la production d'énergie renouvelable par géothermie et la protection de la nature.

Keywords: Geothermal energy, Induced seismicity, CO_2 sequestration, casing damages, superhot systems

1 RENEWABLE ENERGY

Access to energy at affordable prices is a prerequisite for a modern society. Since the first settlement of the island and until the 20th century, people lived mostly in turf houses where peat was the main source of heating and fish oil the main energy source of indoor light. When houses of concrete and wood became common at the end of the nineteenth century the energy for heating changed to imported coal and later oil. Despite numerous hot springs around the country they were only used for bathing and washing but not for house heating, probably due to lack of technical know-how. In the 1920´s drilling for hot water started in Iceland and the first district heating system was operative in 1928. The development was however rather slow until in the 1970s. Figure 1 shows the development of the primary energy use in Iceland and the dominant share of the geothermal in the energy budget. It show that about 80% of the primary energy use in Iceland comes from renewable energy resources, hydro and geothermal. Fossil fuel is only used for cars, ships, mostly the fishing fleet, and for airplanes.

We can identify three jumps in the geothermal development, the first one in the 1940s when large parts of Reykjavík got geothermal water from a resource 15 km away, the second one in from 1970 to 1980 when a major step was taken by the government to exclude fossil fuel from the heating sector and finally from 1995 to 2010 where major steps were taking in geothermal power production. Figure 2 shows the development in the house heating sector from 1970 when over 50% of the houses were heated by oil to 2018 when the house heating was over 99% from renewable sources, 90% directly from geothermal and 9.3% from electricity. The electricity in Iceland is produced by hydro (73%) and by geothermal energy (27%) with a minor production from wind power.



Talnaefni Orkustofnunar: OS-2019-T003-01

Figure 1 The development of primary energy consumption in Iceland from 1940 to 2018. Geothermal energy stands for about 67% of the primary energy. (Source: Orkustofnun)

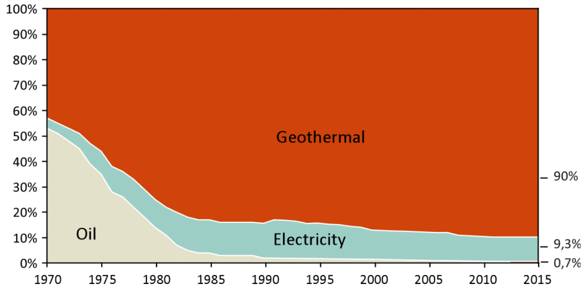


Figure 2 Development of the energy used for house heating in Iceland from 1970 to 2018.

This development in Iceland was driven by two factors, economy and energy security rather that environmental factors. Figure 3 show comparison of heating cost in the Nordic capitals.

Reykjavík, heated by geothermal energy has far the lowest energy cost which is extremely important when heating is necessary all the year.

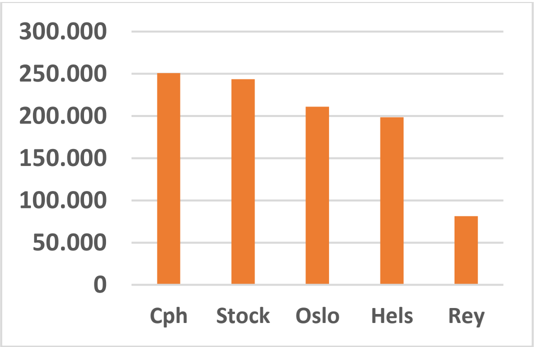


Figure 3 Comparison of calculated cost for heating a 100m^2 flat in the Nordic capitals, assuming the same energy need everywhere. VAT is not included. Source: Samorka, Federation of Energy and Utility Companies in Iceland www.samorka.is

2 THE GEOTHERMAL SYSTEMS

Iceland is the only place in the world where an active oceanic spreading ridge is above sea level. The reason for this is the presence of a low-density mantle hot spot, centered below central Iceland, that increases the magmatic production rate compared to normal oceanic ridges. This leads to abnormal crustal thickness beneath Iceland of 20-40 km (Bjarnason et al 1993, Kaban et al, 2002) compared to normal oceanic crust of 10 km or less.

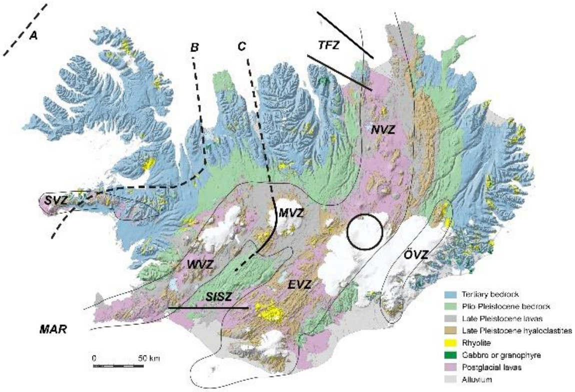


Figure 4 The rift zones of Iceland. The black circle shows the centre of the hot spot and the dotted lines show ancient and extinct rift zones. From Hardarson et al, 2008.

The spreading axis of the Mid-Atlantic Ridge (MAR) crosses the island as a zone of active spreading and volcanism, referred to as the axial volcanic zone (AVZ). It is composed of several segments named the Westeren Volcanic Zone (WVZ), the Eastern Volcanic Zone (EVZ) and the Northern Volcanic Zone (NVZ). The measured half spreading rate in Iceland is close to 1 cm/year. The axis rises from sea on the Reykjanes peninsula on the south-west corner of the country and submerges again at the north-eastern coast (Fig.4). The AVZ does not form a straight line through the country but is shifted about 150 km eastwards, close to the southern coast (The South Iceland Seismic Zone, SISZ) and back in a westerly direction at the northern coast (The Tjörnes Fracture Zone, TFZ). In the southern part of Iceland, the AVZ is composed of two parallel axial segments. Throughout the almost 20 m.y. of the exposed geological history of Iceland the AVZ has shifted eastwards a few times, leaving behind traces of ancient spreading axis and related transform tectonics, especially on the American plate (e.g. Sæmundsson, 1979).

The subaerial volcanism of the country resulted in extensive eruption of flood basalts that characterizes the pre-glacial and interglacial periods. During the glaciation periods, when the country was mostly covered with ice, elongated hyaloclastite ridges or table mountains were formed and accumulated above the volcanic fissures. The glaciation and deglaciation furthermore lead to large vertical crustal movements that might have contributed to the formation of fracture dominated hydrothermal fields outside the rift zones (Böðvarsson, 1982).

The crustal accretion process in Iceland has been modelled and described by Pálmason (1973). His model assumes a simple spreading axis and spreading rate, where new crust is partly formed by dyke injection into the existing crust and partly by surface volcanism. The eruptions cause the lava to accumulate at certain rate, normally distributed around the spreading axis, and the crust subsides by the same amount as the overlying erupted mass. This means that lava that

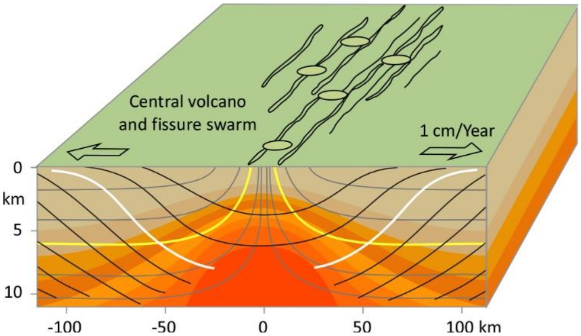


Figure 5. Pálmason´s crustal accretion model. The yellow and the tiny blue lines show the trajectories of the lava material from the surface away from the rift axis and downwards. The white line and the tiny black lines show the isochrones and the temperature is shown with the colour scale.

solidifies on the surface moves horizontally away from the spreading axis, with half spreading rate of 1 cm/year, but simultaneously moves vertically down due to the load of lava that accumulates on the surface at a later time. The trajectories of the lava successions are shown in figure 5. The magma that cool on the surface at the spreading axis move vertically down with time, whilst those which accumulate outside the spreading axis move both laterally and downwards. When lava has left the volcanic zone it only moves laterally away from the spreading axis with time.

A consequence of this process is that the lava becomes reheated as it moves to greater depth, pores close due to external pressure and it undergoes hydrothermal alteration which finally makes the rock almost impermeable. Close to the spreading axis the subsiding crust can even be reheated to solidus of certain minerals so it starts to melt partially and create silicic magma.

Fresh lava on the surface has very high porosity (~30%) and primary permeability. Therefore, there is practically no conductive heat transport in the near surface lava pile, all heat from below is removed by groundwater flow. As the lava becomes buried the porosity and permeability reduce with depth because of the burial pressure and the precipitation of secondary minerals from geothermal fluids. Temperature logs in boreholes in the volcanic zones in Iceland indicate that primary permeability has been reduced enough at around 1 km depth to let thermal conduction dominate the heat transport. A result of this is that the uppermost 1 km of the volcanic crust in Iceland should have very high permeability. But since repeated glacial erosion has removed the uppermost 1-2 km of the crust at present sea level outside the volcanic zone, the general permeability of the basaltic crust outside the volcanic zone is low.

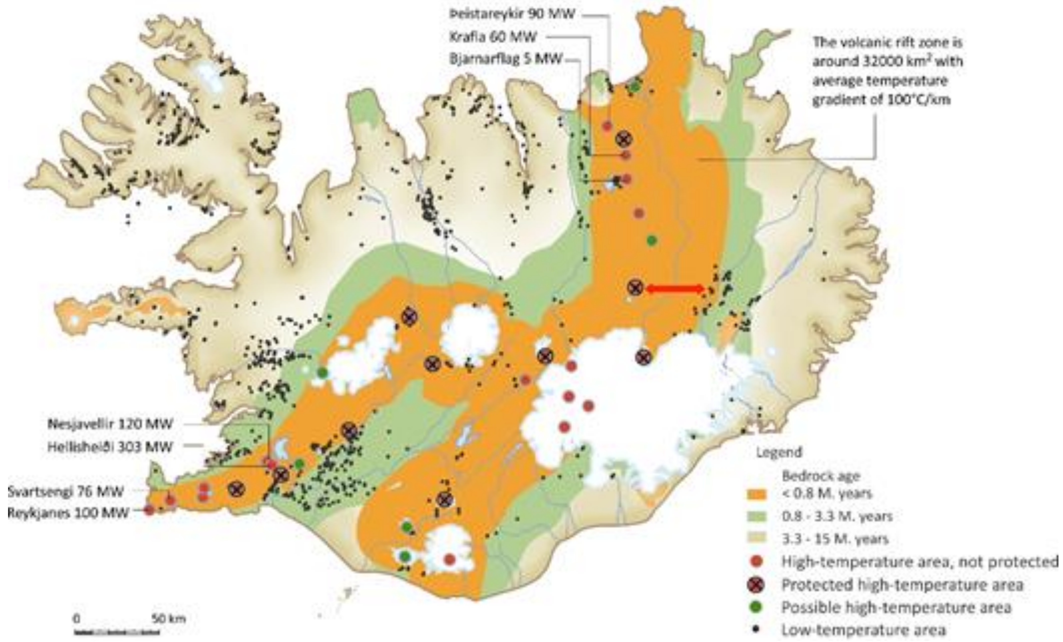


Figure 6. A simplified geological map of Iceland showing the location of the geothermal fields and the present geothermal power plants. The volcanic rift zones are almost identical to zones of bedrock of age less than 0.8 M.Y. The red arrow shows the approximate location of the resistivity section in Figure 11.

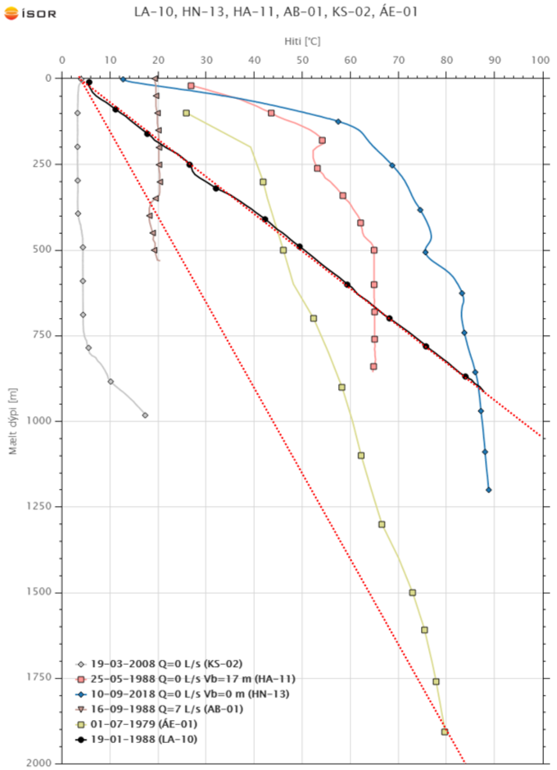


Figure 7. Typical temperature logs from boreholes in Iceland outside the high temperature fields. The background temperature gradient outside geothermal areas is shown by two red dotted straight lines. The other logs are from geothermal fields and show typical convection profiles with different reservoir temperature where the shallow part is abnormally hot but the lower part is abnormally cold. The coldest log is from the volcanic rift zone.

Heat flow in Iceland is high compared to continental areas. The heat flow is basically controlled by two processes. One is a background heat flow, originating from the cooling crust moving away from the spreading axis like at the mid-oceanic ridges. The other is local high or low heat flow anomalies caused by convection of water in vertical fracture systems, the high values corresponds to the upwelling part, while the low values relate to the down flow pattern. Since the crust in Iceland is fairly homogeneous with respect to thermal conductivity (1.6-1.9 W/m°K), the near surface temperature gradient is frequently used as a proxy for heat flow. The typical background values of the temperature gradient in Iceland is 80-100°C/km at the boarder of the volcanic rift zone to 40-50°C/km in the oldest crust that is farthest away from the rift axis. Within the volcanic zone, however, the uppermost 1 km of the crust consists of highly permeable young volcanics, where all conductive heat from below is transported away by large groundwater currents. Therefore, almost a zero temperature gradient is observed in the uppermost 1 km within the volcanic rift zone (Fig.7), with the exception of the high-temperature hydrothermal fields associated with the volcanic centres.

Geothermal surface manifestations are very common in Iceland. They appear as hot springs, fumaroles, steam vents or simply as geothermal alteration minerals on the ground. Geothermal areas in Iceland are basically of two different types, high-temperature fields and low-temperature fields, but areas with intermediate reservoir temperatures (150-200°C) are rarely found. The locations of the high and low temperature fields in Iceland are shown in figure 6. There are fundamental differences between high and low temperature fields. The high-temperature fields have reservoir temperatures of 200-340°C and are exclusively located within active volcanoes or recent post-glacial volcanism in the axial rift zone. Their surface manifestations are hot springs and fumaroles and high-temperature rock alteration, resulting in colourful and picturesque landscapes (Fig.8). The geothermal fluid is usually acidic and the rather high chemical content prevents direct use of the fluid.

The low-temperature fields in Iceland show quite a different character from those in the high-temperature fields. Their location is also shown in figure 6. The low-temperature geothermal systems are almost all outside the axial rift-zone. Their reservoirs are fracture dominated in otherwise low permeability basaltic lavas or hyaloclastites. The heat is extracted from the relatively high background temperature gradient by fluid convection in permeable fracture systems (Flóvenz and Sæmundsson, 1993). This is explained in Fig.7. In most cases the surface expressions of the low-temperature fields appear as hot springs on the surface. Sometimes, the low-temperature fields are hidden with no expression of geothermal activity at the surface (Axelsson et al, 2005). In these cases, the geothermal fields are discovered by geophysical measurements of heat flow, or electrical resistivity of the subsurface, or simply by tectonic data.

Figure 8. Hot springs in Krýsuvík, SW-Iceland surrounded by grey and yellow coloured clay minerals formed by hydrothermal alteration.

The tectonic origin of the permeable fractures are not always obvious. In some cases they are clearly linked to the shear zones of the transform faults between rift segments, like in the South Iceland Seismic Zone. There are also examples of low-temperature fields where recent or active fissure swarms of the volcanic centres penetrate the older rocks without any surface volcanism. It has also been suggested that the geothermal fractures are a consequence of the postglacial rebound of the crust (Bödvarsson, 1982).

As expected for a region where the Mid Atlantic Ridge interferes with a hot spot, the overall seismicity in Iceland is high. Figure 9 shows a map of the seismicity of Iceland for the period 1995 to 2016, embedded on a simplified geological map. The seismicity shows clearly the main tectonic and geological patterns of the country; the volcanic centres in the axial rift zones, the axial part of the MAR, and the transform faults and oblique rift zones in North and South Iceland which connect the rift segments in Iceland. The eastern part of Iceland outside axial rift-zone, i.e. that belonging to the European plate, is almost devoid of seismicity as well as surface geothermal activity. On the contrary, the part that belongs to the American plate outside the axial rift-zone, is characterized by both intraplate earthquakes and hydrothermal systems supporting the hypothesis of tectonic origin of the low-temperature systems.

The chemical content of the geothermal fluid within the low-temperature system is usually quite low, typically with total dissolved solids of less than 300 mg/L. At a few places, the reservoir fluid is slightly seawater contaminated giving rise to total dissolved solids of over 1000 mg/L. The quality of the geothermal water is indeed mostly within drinking water standards. The fluid is eminently suitable for domestic use and provides tap water and water for radiator systems.

3 THE BENEFIT OF UTILISATION OF GEOTHERMAL ENERGY

Economy and energy safety have been the primary drivers for the development and use of renewable energy in Iceland. But the side effects are huge, resulting in health, environmental, and social benefits.

3.1 Economical benefit

There are several ways to estimate the economical benefit of the geothermal utilisation in Iceland. Firstly it is the pure effect of the low energy prices compared to alternative energy sources. Orkustofnun, the National Energy Authority, calculates annually the avoided cost of using geothermal instead of oil for house heating. For the year 2014 this amounts around 730 million USD or over 2200 USD per person per year. This avoided cost equals 4,5% of GNP (Orkustofnun 2015). These numbers can vary considerbly with time due to fluctuations in oil prices and in the exchange rate of the Icelandic krona. This avoided cost might however be an oversetimate as higher prices would eventually lead to lower consumption. Secondly, the geothermal industry creates well paid jobs in Iceland and in many cases rural jobs.

3.2 *Environmental benefit*

The main environmental impact of the geothermal production in Iceland is the positive influence on the quality of the atmosphere with reduction in carbon dioxide emission and other pollutants from burning of fossil fuel.

The effect on public health was striking in Reykjavík when largest parts of Reykjavík were connected to geothermal district heating system in 1943-1945 (Baldur Johnsen, 1962). Prior to 1940 about 80% of the heating in Reykjavik was by coal that was reduced to about 45% in 1945 and replaced by geothermal and oil. Prior to 1940, the incidences of cold were 50-100% higher in city of Reykjavik compared to rural areas but after the geothermal heating was initiated the incidences in Reykjavik dropped to less than half of the cases in the rural areas. The reason for this positive change is might be a combination of lower air pollution since the smoke from coal heating was strongly reduced and improved indoor heating.

The use of geothermal strongly reduces the CO_2 emission from the energy sector in Iceland. In 2017 the calculated annual CO_2 savings by using geothermal energy for heating and electricity production instead of oil is 8,1 Megatonn. Almost half of is due to the geothermal heating (Orkustofnun, 2018)

3.3 *Social benefit*

Nowadays, geothermal energy is an integrated part of everyday life in Iceland and has created a special culture that marks the society in many ways. About 90% of all buildings in Iceland are heated directly by geothermal energy, both in urban and rural areas and in most cases at very low price. The abundance of hot water affects everyday life. All parts of the houses are heated throughout the year and the typical room temperature is 22°C, even in the garage. You can take a long hot shower with high flow rate without worrying much about your energy bill. And you can, without any additional energy cost, use the return water from your radiator system to heat up the pavement outside your house and keep it free of snow. You can go to the one of the numerous outdoor warm and comfortable geothermally heated public swimming pools and enjoy swimming, both on beautiful summer days as in winter snowstorms; or enjoy sitting outdoors in a hot tub with friends, participating in discussions and debates on politics or simply the life. You can also visit geothermal spas or buy fresh vegetables throughout the year which are grown in geothermally heated greenhouses under lightning produced by renewable electricity. People who enjoy sports can utilise some of the numerous heated sports halls for exercising. In recent years, six full size geothermally heated indoor football grounds have been built, and also numerous large sports halls for football, handball and basketball, providing excellent facilities for the development of youth sport skills.

4 THE MAIN CHALLENGES TO-DAY

4.1 *Carbon and sulfur emission*

The production of hot water from low-temperature fields is practically without any emission of gasses. The CO_2 emission is negligible. Slight content of hydrogen sulphide (H_2S) is usually observed in the low-temperature geothermal water and gives a faint smell when the hot water is used directly for bathing and washing. The inhabitants are used to this smell and do not even notice it on daily basis, but foreign guests may notice it. The concentration of H_2S is far below all health limits but our nose detects the H_2S in extremely low concentrations. In case of oxygen contamination of the hot water the H_2S in it reacts with the oxygen to produce sulphate and has therefore a corrosion preventing effect for pipes and radiators. Therefore, H_2S is sometimes deliberately mixed into the hot water if its concentration is negligible.

Emission of CO_2 and H_2S follows the geothermal steam produced in geothermal power plants but in different concentrations from one field to another. In case of Icelandic power plants the emission of CO_2 per electricity produced is in the range 26 -181 g/kWh$_e$ (Ármannsson et al, 2005, Sigurdardottir and Thorgeirsson, 2016). This is of the order of 4-25% of similar values for oil driven power plants. Although the concentration of H_2S from the power plants in the atmosphere is far below environmental limits it may be quite annoying and cause damages to electronic equipment and corrode metals like copper and silver. In case of, the 303MW$_e$ Hellisheiði power plant, the largest geothermal power plant in Iceland, ongoing research and demonstration projects called Carbfix and Sulfix show that it is possible to collect and reinject the CO_2 and H_2S into the shallower part of the reservoir where it fixes permanently in minerals as calcite and pyrite. In 2015 over 10% of the emitted CO_2 was reinjected and research indicates that at least 90% of it is fixed in mineral form within a year from reinjection. At the Hellisheidi Power plant about 30% of the H_2S was reinjected in the SulFix project in 2015 whereof about 75-80% is sequestered in the form of minerals like pyrite within six months. (Sigurdardottir and Thorgeirsson, 2016). These leading experiments of Reykjavik Energy are paving the way for future zero emission geothermal power plants. An alternative solution to deal with the CO_2 emission is to use it for production of synthetic fuel or to fix it in plants in greenhouses.

4.2 Induced seismicity

Induced seismicity is commonly a concern for geothermal energy production in the world, especially where hydraulic stimulation is applied. In general, this was not the case for Iceland until recently. Earthquakes are quite common in Iceland and people living close to the plate boundary and geothermal fields are used to observe small earthquakes now and then (Fig. 9). Therefore, it was generally presumed that induced seismicity would just occur as small additional noise to the background seismicity and not disturb the public seriously.

Monitoring of earthquake have shown that production related earthquakes, usually less than magnitude 2.0, are common at all the high-temperature fields and at the low-temperature fields that are located directly at plate boundaries (Flóvenz et al., 2015).

Larger earthquakes with magnitude in the interval 5.8 to 7.0 have been observed in relation the transform zones where strike slip earthquakes prevail, 21 events in the South Iceland Seismic Zone during the past three centuries (Halldórsson et al, 2013a). and 9 events close to and offshore the north coast over two centuries (Halldórsson et al, 2013b).

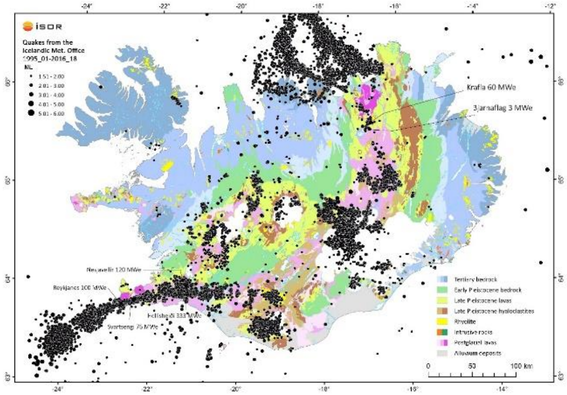


Figure 9. Seismicity in Iceland from 1995 to 2016 showing earthquakes of magnitude 1.5 and larger (Flóvenz and Jónsdóttir, 2016). Data are from the Icelandic Meteorological Office.

The production of geothermal fluid from the ground disturbs the hydraulic pressure in the geothermal reservoir and deforms the local stress field. The production itself lowers the fluid pressure and should therefore increase the overall rock strength and possibly delay impending earthquakes. Sometimes the production is periodic within the year causing sinusoidal variation in the fluid pressure that might modulate the seismicity and affect the timing of an impending large earthquake. A 6.6 earthquake in Iceland in the year 2000 might have been an example of such an effect. (Flóvenz, et al., 2015). Furthermore, the production itself leads sometimes to land subsidence that might cause earthquakes. On the contrary, fluid injection into the reservoir, elevates the reservoir fluid pressure and can lead to earthquakes. This applies to reinjection of geothermal fluid to counteract the pressure drop caused by the production or to stimulate a reservoir to increase the well productivity or to dispose effluents from the a power plant.

All major geothermal power plants in Iceland are located within high temperature fields that are associated with active volcanoes on the plate boundaries. They all have high natural seismicity due to tectonic and volcanic activity and injection induced earthquakes are recorded in all cases where reinjection is practiced. The level of the induced seismicity is however different from one field to another. The expected maximum magnitude for a natural earthquake is between 4.0 and 6.0 for the different fields. Therefore it is possible that medium to large magnitude earthquakes might be triggered by injection of fluid into the high temperature fields. This happened in the fall of 2011 when a large-scale reinjection was initiated at the Hellisheiði power plant. It triggered repeatedly intense swarms of earthquakes up to magnitude 3.9 (Bessason et al., 2012) that were strongly felt in neighboring village and annoyed people severely but did not cause any damage. Prior to that induced earthquakes up to magnitude 2.5 were observed during circulation loss when the injection wells were drilled (Ágústsson et al., 2015) witnessing that the crust was critically stressed.

The experience has shown us that the presumption of neglecting the potential of annoying or damaging earthquakes triggered by reinjection is not valid. Therefore, the geothermal operators must manage their geothermal reservoirs with the possibility in mind that their activity can trigger impeding medium to large magnitude earthquakes, especially if injection by hydraulic stimulation is applied. Based on this experience the authorities have introduced guidelines for reinjection operations in line with what is being done in the international community.

To deal with this challenges ÍSOR has in co-operation with Reykjavík Energy and other energy companies participated in international projects. They aim to mitigate the risk of damaging induced seismicity and perform well stimulation under strict control using a sort of traffic light system to manage the stimulation. Example of such projects are the EU-supported projects GEISER (see geiser-fp7.fr/default.aspx), DESTRESS (destress-h2020.eu/en/home/) and COSEISMIQ (geothermica.eu/projects/coseismiq/).

4.3 Thermal casing damages

High temperature wells might experience large variation in temperature during their lifetime. The temperature is often 300-340°C in conventional reservoirs but can be 450-500°C in superhot wells that exploits the deeper part of the high temperature systems. Conventional high temperature wells are typically cased with steel casing to 1000-1500m dept and in extreme cases to 3000m depth. The steel casings are cemented to the surrounding rock. When they heat up the steel pipes are subject to large thermal stresses that may lead to irreversible plastic deformation of the casings and even cause a collapse with buckling of the casing itself. If the casing is cooled down again, which sometimes is necessary, it contracts, and large tensile stresses occur which can lead to tensile rupture of the casing that mostly occur at casing joints. Consequently, the wells might be destroyed and abandoned as they might leak and cause steam explosions in the wellfield. Such casing damages are common and is one of the main obstacles for utilization of superhot geothermal systems in the roots of the high temperature fields.

It is of utmost importance for the geothermal industry to solve this casing problem if superhot systems are going to be exploited in the future. The most promising concept is that of flexible couplings that are used to connect individual casing pipes (Thorbjörnsson et al. 2017). This solution was proposed and patented by the expert team of ISOR. It enables well designers to account for thermal axial stresses without designing for plastic strain and thereby reduce the risk of plastic deformation or collapse during warm up and production of the well. The basic concept is to allow each casing segment to expand into the coupling during the warm-up of the well and the coupling will close after reaching calculated temperature for the given coupling and build up pressure to ensure tight connection. If the wells cool down later the coupling will open again and prevent tensile rupture.

The casing damage problem is presently being dealt with by several collaboration projects supported by the Horizon 2020 program of the European Union. (e.g. projects GEOWELL http://geowell-h2020.eu/, DEEPEGS https://deepegs.eu/work-packages/, GeConnect https://www.geothermalresearch.eu/geconnect/about/) The laboratory tests of the concept have been quite successful and a full-scale demonstration test will be performed in the near future.

4.4 Nature conservation

The geographic location of Iceland together with its spectacular landscape formed by interaction between glaciers, water, plate movements and volcanic activity make the Icelandic nature unique. This applies not the least to the high temperature areas of Iceland that are usually a part of a magnificent landscape of the volcanic zone where the surface expression of geothermal activity forms of colourful alteration minerals, hot springs, mud pools and steam vents.

Figure 10 Boiling ground in Grensdalur in S-Iceland, a popular tourist attraction.

Consequently, the Icelanders faces the dilemma of the nature conservation versus exploitation of benign renewable energy resources. Harnessing the high temperature fields has considerable visual impact in form of power plants, drilling pads, pipelines, roads and powerlines. The production itself has only minor effect on the surface and visible geothermal activity will rather increase than decrease. Therefore it is important to design the constructions, pipes and power lines with respect to the landscape, avoid to damage geological formations or vegetation, reduce the number of drill pads by drilling several wells from each pad, and minimize the effect of hot brine and gas disposal.

Already seven major high-temperature fields have been harnessed, most of them close the habituated areas and outside the central highlands. To build power plants in the central highlands will be controversial as there is a strong will to protect the highlands from further human activity apart from tourism. Some of the larges known high temperature fields are already in protected areas and there are plans to extent the present national parks to cover most of the central highlands. This will put tight constraints on possible new geothermal power plants in Iceland. The main challenge for the future is to find a reasonable balance between nature conservation and harnessing the renewable energy resources of Iceland.

5 THE FUTURE OF GEOTHERMAL ELECTRICITY PRODUCTION

5.1 The geothermal potential in Iceland

The volcanic rift zone of Iceland (Fig.6) covers 32,000 km^2 where only 600 km^2 belongs to known high temperature geothermal systems. The remaining part of the volcanic rift zone was defined as 2,150 km^2 of active areas with recent tectonic or volcanic activity and 29,250 km^2 belong to non-active areas. Pálmason et al. (1985) made a volumetric assesment of the geothermal potential in Iceland and by taking into account the accessibility factor, likely recovery and utilization factors, the stored energy above 3 km depth was estimated to give 3500 MW$_e$ for 50 years from the known high temperature sytems alone. Similar values are 8400 MW$_e$ for the active areas and 24,100 MWe for the non-active areas within the volcanic rift-zone (Pálmason et al. 1985). Until now power production has been limited to the known high temperature fields where the total installed power is presently 752 MW$_e$ from 7 power stations in 6 defined high temperature fields. The limits of 3 km depth in the assessment in 1985 was based on the geothemal drilling technology at that time. Now, over thirty years later, it is quite possible to drill to 5 km depth or even greater in Icelandic geothermal areas. This almost double the potential of the volcanic riftzone (Flóvenz, 2018).

There are in principle four ways to increase the electricity production from geothemal resources in the volcanic zone of Iceland:

Firstly, to increase production in the presently utilized fields and their pheriphery. This is a possibility in some cases but it is considered only to offer a moderate increase in the energy production.

Secondly, to start production in new and unexploited fields. This could lead to considerable increase in electricity production but as most of these fields are on areas that are already protected or are likely to be protected soon this possibility is not realistic.

Thirdly, to extract energy from deep roots of the present utilized systems by drilling to 4-5 km depth for superhot steam, even at near-magmatic temperature.

Fourthly to drill to 4-5 km depth in the active areas of the volcanic riftzone but in areas outside the known high temperature fields.

The two last possibilities are discussed in the following sections.

5.2 Exploiting the deep roots og volcanoes

The Icelandic geothermal industry has put considerable effort into exploration of the deeper part of the already harnessed high temperature fields. There, very high temperatures are expected, even close to magmatic conditions, and the extracted fluid might be superheated or in supercritical state. Alternatively, the deep superhot wells could be used as reinjection wells where the cold injected fluid extracts the energy from 3-5 km depth and is captured in shallower wells. The aim is to respond to the increasing environmental awareness and to utilize better the infrastructure at each power plant. The Iceland Deep Drilling Project (IDDP), a joint effort of the main power companies and the government of Iceland, has been the core of this development. Friðleifsson et al (2014) have described the concept of IDDP. The project has gained high international attention where a large number of scientist and international funding bodies have participated.

Two wells have already been drilled under the IDDP project, the IDDP-1 in Krafla (Friðleifsson et al. 2015) and the IDDP-2 in Reykjanes (Friðleifsson et al. 2017). Although number of problems rose during drilling and testing of the wells, these projects have tough many lessons. They have visualized challenging problems and confirmed that it is a realistic option to extract energy from the superhot roots of the high temperature geothermal systems.

The main lesson learned are at present:

- It is possible to drill into magma bodies beneath the high temperature reservoirs.

Well IDDP-1 penetrated a magma body just below 2 km depth.

- A zone of high permeability was found at the top of the magma body yielding 450°C hot superheated steam that could give up to 36 MW_e from the single well. (Friðleifsson et al. 2015)
- The steam contained chlorine gas that makes the fluid extremely corrosive when it starts to condense into small droplets. Experiments to scrub the fluid at the surface were promising (Markusson and Hauksson, 2015).
- Due to corrosive failure in wellhead equipment, it was necessary to kill the well after 28 months of flow testing. Then serious casing damages were observed that are most likely due to thermal expansion and contraction of the casing, probably also due to corrosion and improper cementing of the casing. It was not possible to repair the well and it was cemented and abandoned.
- Well IDDP-2 was successfully drilled to a depth of 4.6 km. No magma was detected which was in agreement with the geophysical exploration prior to drilling.
- Loss of circulation or feed zones were observed as deep as 4.5 km in IDDP-2 according to temperature logs (Friðleifsson et al. 2017).
- Casing damages occurred also in IDDP-2, most likely due to thermal stresses in the casing. This has prevented further testing of the well and reliable measurement of the bottom hole temperature, but it is clearly well above 430°C (Friðleifsson et al. 2017). These lessons are source of optimism for future energy extraction from the deep roots of the high temperature fields in Iceland and have a world-wide relevance. At the same time, they tell us that we have technical and scientific challenges to meet in order to realize the dream of this kind of projects.

5.3 Exploring the deep volcanic riftzone

The idea of exploring for applicable geothermal resource at 2-5 km depth in the volcanic rift zone is based on the assumption of high temperature gradients of (>100°C/km) beneath the permeable zone that cover the uppermost 1-2 km within the volcanic rift-zone. Furthermore, the existence of active fault systems within the volcanic rift-zone indicate high possibilities for considerable fracture permeability. If this is true the ideal reservoir temperature of 230-300°C can be expected between 2 and 5 km depth. Then the obvious question is how we can estimate the real temperature in this depth interval and its spatial variations within the rift-zone. To do it by drilling numerous 1-2 km wildcat exploration wells would be far too expensive so it is necessary to rely on the geophysics, especially resistivity measurements and earthquake seismology.

The best method to measure the resistivity of the crust down to 5-10 km depth in the volcanic rift-zone is to use a combination of time-domain electromagnetic soundings (TEM) and magnatotelluric soundings (MT).

Assuming that the inversion process of the TEM/MT data gives us reliable resistivity models, the next step is to interpret the resistivity structure in terms of relevant geothermal parameters. It is a complicated task and requires understanding of the still debated conduction mechanisms in porous rock and its dependence on various parameters. The process of electrical conduction in basaltic crust has been investigated for a long time, both experimentally and theoretically and still is (e.g. Levy et al. 2018 and references there in). The highlights of these research activities are the complex role of smectite and other clay minerals (e.g. Levy et al. 2018, Flóvenz et al. 1985, Árnason et al. 2000), the dominance of surface or interface conduction

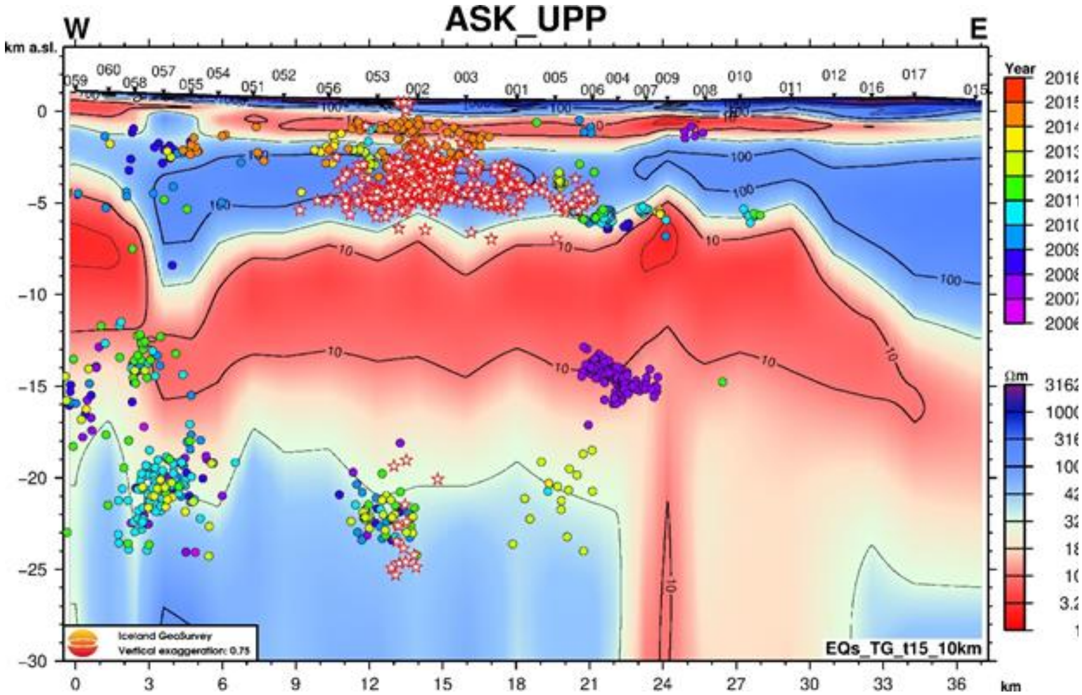


Figure 11. A West-East resistivity cross section from the Askja high temperature field in the west to the eastern border of the volcanic rift-zone. The dots are the seismic events. Note the absence of seismicity within the deep conductive layer and up-doming of it under the high temperature field in Askja. Figure from Vilhjálmsson and Flóvenz (2017).

and its high temperature dependence (e.g. Kristinsdóttir et al, 2010) and the measurements of resistivity of porous rock above 300°C (e.g. Nono et al. 2018).

Most of the known high temperature fields in Iceland have been mapped by resistivity soundings (e.g. Árnason et al. 2010). They show generally a very typical structure of a shallow up-doming layer of very low resistivity covering a core of higher resistivity. It has been explained as a layer of high smectite content of the basaltic rock caused by hydrothermal activity. The increase in resistivity below corresponds to the top of the more resistive chlorite alteration zone (e.g. Árnason et al. 2000). It is known that this change in mineralogy occur at temperature close 230°C. Therefore, we can map the 230°C isothermal surface in the high temperature system provided that it has not cooled at later time.

Outside the known high temperature fields but within the volcanic rift-zone, another layer of low resistivity has been observed at 5-10 km depth, deepening further away from the rift axis. (e.g. Beblo and Björnsson, 1980). This structure has been mapped in more details in a small part of the volcanic rift zone of NE-Iceland as shown in Figure 6 (Vilhjálmsson and Flóvenz, 2017). It extends eastwards from the eastern boarder of the Askja central volcano and high temperature system to the boarder of the volcanic rift-zone.

The section shows the typical resistivity structure of the volcanic rift-zone;

- High near surface resistivity of the ~1 km thick permeable fresh basaltic material,
- A conductive layer at roughly 2 km depth showing the smectite alteration zone,
- A more resistive layer, starting from 2-3 km depth, corresponding to the chlorite alteration zone.

- A deep conductive layer at roughly 7-15 km depth, doming up below Askja.
- Elevated resistivity below roughly 15 km dept.
- Possible a column of low resistivity extending further downwards.

The dots on the figure denote hypocenters of microearthquakes (Soosalu 2009 and Greenfield 2016). They show that the deep conductive layer appears aseismic but at the same time S-waves from location beneath the layer propagate normally through it. This can be interpreted as the layer is close to the brittle ductile boundary but far below the solidus of the material. The estimated temperature of the top of the deep conductive layer is therefore likely to be close to or above 500°C (Vilhjálmsson and Flóvenz, 2017). Hence, mapping the top of the deep conductive layer puts constraints on the temperature in the upper crust of the volcanic rift-zone.

Another constraint on the temperature distribution can be estimated from the top of the chlorite zone as represented by the bottom of the upper conductive layer. This temperature is close to 230°C provided that the alteration minerals are in thermal equilibrium (Flóvenz et al, 2012).

These two constraints on the temperature distribution open up the possibility to use TEM/MT soundings to map the spatial temperature distribution within the volcanic rift zone. By systematic mapping of the resistivity it is possible to explore for the best sites for future development of the geothermal power sector in Iceland.

6 CONCLUSIONS

Almost one century of geothermal development in Iceland has led to great success where 90% of houses in the country are heated by geothermal water at very low cost. The households in Iceland pays only 30-40% of what they would have to pay for same amount of energy in the other Nordic Capitals. Geothermal energy is also used to produce 27% of the electricity produced in Iceland at competitive cost. The success in Iceland is a result of combination of favourable geological conditions and continuous research and development activity over long time.

The Icelandic geothermal industry has faced many challenges on its way to the present stage and has still challenges to meet. They include development of methods to extract energy from the superhot roots of the volcanic geothermal systems where magmatic conditions might be faced, sequestration of CO_2 and H_2S in order to create zero emission power plants, mitigation of induced seismicity, development of methods to prevent casing damages in high temperature wells and finding ways to combine geothermal energy production with nature conversation..

7 ACKNOWLEDGEMENTS

The author thanks Dr. Léa Levy for the French translation.

8 REFERENCES

Ágústsson, K., Kristjánsdóttir, S., Flóvenz., Ó.G., Guðmundsson, Ó. 2015. Induced Seismic Activity during Drilling of Injection Wells at the Hellisheiði Power Plant, SW Iceland. *Proceedings World Geothermal Congress 2015 Melbourne, Australia*, 10p.

Ármannsson, H., Fridriksson, Th.,. Kristjánsson, B.R., 2005. CO_2 emissions from geothermal power plants and natural geothermal activity in Iceland. *Geothermics* **34**. 286–296

Árnason, K., Karlsdóttir, R., Eysteinsson, H., Flóvenz, Ó.G. and Gudlaugsson, S.T. 2000. The resistivity structure of high temperature geothermal systems in Iceland. *Proceedings: The World Geothermal Congress*, 923-928.

Axelsson, G., Bjornsson, G., Egilson, Th., Flovenz, Ó.G., Gautason, B., Hauksdottir, S., Olafsson, M., Smarason, O.B., Saemundsson, K. 2005. Nature and Properties of Recently Discovered Hidden Low-Temperature

Geothermal Reservoirs in Iceland. 2005 Anatlya, Turkey, 10p.

Beblo, M. and Björnsson, A. 1980. Model of electrical resistivity beneath NE-Iceland and correlation with temperature. *Journal of Geophysics*, **47**, 184-190

Bessason, B., Ólafsson, E.H., Gunnarsson, G., Flóvenz, Ó.G., Jakobsdóttir, S.S., Björnsson, S., Árnadóttir,Þ. 2012: Verklag vegna örvaðrar skjálftavirkni í jarðhitakerfum. *Orkuveita Reykjavíkur, report*, 108p.

Bjarnason, I.Th., Menke, W., Flóvenz, Ó.G., Caress, D., 1993. Tomographic image of the mid-Atlantic plate boundary in southwestern Iceland. *J. Geophys. Res*., **98**, 6607–6622.

Bödvarsson, G, 1982. Glaciation and geothermal processes in Iceland. *Jökull, 32*, 21-28.

Flóvenz, Ó.G., Georgsson, L.S. and Árnason, K. 1985. Resistivity structure of the upper crust in Iceland. *Journal of Geophysical Research*, **90**, 10136-10150.

Flóvenz, Ó.G., Sæmundsson, K, 1993. Heat flow and geothermal processes in Iceland. *Tectonophysics*, **225**, 123-138,

Flóvenz, Ó.G., Hersir, G.P., Sæmundsson, K., Ármannsson, H. and Friðriksson Þ., 2012. Geothermal Energy Exploration Techniques. In:. (ed) *Comprehensive Renewable Energy*, (ed.: Sayigh A) **7**, 51-95, Elsevier, Oxford.

Flóvenz, Ó.G., Ágústsson, K, Guðnason, E.Á., Kristjánsdóttir, S. 2015. Reinjection and Induced Seismicity in Geothermal Fields in Iceland. *Proceedings World Geothermal Congress 2015 Melbourne, Australia*, 15p.

Flóvenz, Ó.G., Jónsdóttir, B. 2016. The Icelandic Experience on Integrated Geothemal Utilization. *Perspectives for Geothermal Energy in Europe* (Ed. Bertani, R.) 77-126. World Scientific Publishing Europe, Ltd, London.

Flóvenz, Ó.G 2018. Expanding the resource base for high temperature geothermal power production in Iceland. GRC Transactions, **42**, 15p.

Friðleifsson G.Ó., Elders, W.A. and Albertsson, A., 2014 “The concept of the Iceland deep drilling project.” *Geothermics*, **49**, 2–8.

Friðleifsson G.Ó., Pálsson B., Albertsson, A., Stefánsson, B., Gunnlaugsson, E., Ketilsson, J. and, Gíslason, Þ., 2015. IDDP-1 Drilled Into Magma – World’s First Magma-EGS System Created. *Proceedings World Geothermal Congress*, 12p

Friðleifsson G.Ó. and Elders, W.A., 2017. “Successful Drilling for Supercritical Geothermal Resources at Reykjanes in SW Iceland.” *GRC Transactions*, **41**, 1095-1107.

Halldórsson, P., Björnsson, S., Sólnes, J., Bessason, B. 2013a. Suðurland. *Náttúrvá á Íslandi* (Eds. Sólnes, J., Sigmundsson, F., Bessason, B.), 591-609 Viðlagatrygging Íslands/Háskólaútgáfan.

Halldórsson, P., Brandsdóttir, B., Sólnes, J., Stefánsson, R. 2013b. Norðurland. *Náttúrvá á Íslandi* (Eds. Sólnes, J., Sigmundsson, F., Bessason, B.), 591-609 Viðlagatrygging Íslands/Háskólaútgáfan.

Harðarson, B.S., Fitton, J.G., Hjartarson, Á. 2008. Tertiary volcanism in Iceland. *Jökull* **58**, 161-178.

Johnsen, B. 1962. Úr heilbrigðisskýrslum. *Fréttabréf um heilbrigðismál*, **11**, 3-5.

Kaban,M.K., Flóvenz, Ó.G., Pálmason, G., 2002. Nature of the crust-mantle transition zone and the thermal state of the upper mantle beneath Iceland from gravity modelling. *Geophys. J. Int.* **149**, 281–299.

Kristinsdóttir, L.H., Flóvenz, Ó.G., Árnason, K., Bruhn, D., Milsch, H., Spangenberg, E. and Kulenkampff, J. 2010. Electrical conductivity and P-wave velocity in rock samples from high temperature Icelandic geothermal fields. *Geothermics*, **39**, 94-105

Levy, L., Gibert, B., Sigmundsson, F., Flóvenz, Ó.G., Hersir, G.P., Briole, P. and Pezard, P. 2018. The role of smectites in the electrical conductivity of active hydrothermal systems: electrical properties of core samples from Krafla volcano, Iceland. *Geophys. J. Int*. **214**, 1558-1552.

Markusson, S.H. and Hauksson, T., 2015. Utilization of the Hottest Well in the World, IDDP-1 in Krafla. *Proceedings World Geothermal Congress*, 6p.

Nono, F., Gibert, B., Parat, F., Loggia, D., Cichy, S.B. and Violay, M. 2018. Electrical conductivity of Icelandic deep geothermal reservoirs up to supercritical conditions: Insight from laboratory experiments. J.Volcanol.Geotherm.Res.,15p. https://doi.org/10.1016/j.jvolgeores.2018.04.021.

Orkustofnun, 2015. OS-2015-T009-01: Economic benefits of using geothermal energy instead of oil for space heating [data file].

Orkustofnun, 2018. OS-2018-T004-01: CO_2 savings using renewable energy instead of oil [data file].

Pálmason, G., 1973. Kinematics and heat flow in a volcanic rift zone, with application to Iceland. *Geophys. J. R. Astr. Soc.*, **33**, 451–481.

Pálmason, G., Johnsen, G.V., Torfason, H., Sæmundsson, K., Ragnars, K., Haraldsson G.I. and Halldórsson, G.K., 1985. Mat á jarðvarma Íslands (Geothermal Assessment of Iceland). *Orkustofnun Report, OS-085/JHD-076*, (1985), 136p. (In Icelandic with English summary).

Sæmundsson, K. 1979, Outline of the geology of Iceland, *Jökull* **29**, 7-28.

Sigurdardóttir, H., Thorgeirsson, Th.A. (ed), 2016. OR Environmental Report 2015. Orkuveita Reykjavíkur, 91 p

Soosalu, H., Key, J., White, R.S., Knox, C., Einarsson, P. and Jakobsdóttir, S.S. 2009. Lower-crustal earthquakes caused by magma movement beneath Askja volcano on the north Iceland rift. *Bulletin of Volcanology*, **72(1)**, 55.

Thorbjornsson, I., Kaldal, G.S., Gunnarsson, B.S. and Ragnarsson, Á., 2017. A New Approach to Mitigate Casing failures in High-Temperature Geothermal Wells. *GRC Transactions*, **41**, 585-591.

Vilhjálmsson, A.M., Flóvenz, Ó.G. 2017. Geothermal implications from a Resistivity Survey in the Volcanic Rift Zone of NE-Iceland and Comparison with Seismic Data." *Iceland GeoSurvey, Report ÍSOR-20017/065*, 46p.