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Geothermal Activity and Utilization as the Main Attraction in a Planned Geopark in Iceland

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ABSTRACT

A Geopark is geographically confined territory with geological heritage of international importance. Every Geopark has some sites of significant geological features or sites that demonstrate outstanding archeological, ecological or cultural value. Geoparks are open to the public and emphasis is put on educational-based geo-tourism and school programs. Most Geoparks are members of the Global Geopark Network (GGN) established by UNESCO. Geoparks have to apply for a membership and fulfill the high standard set by the UNESCO organizations. The membership is valid for 4 years, after which the work taking place in the Geopark is reviewed and assessed. Only the Geoparks which currently obtain a membership are allowed to use the official logos of the mother organizations.

In Borgarfjördur Western Iceland there are plans to establish an internationally acknowledged Geopark, named SAGA-Geopark. The aim is to enhance tourism, increase the recreational activity and make geologically interesting sites accessible to the public through education and dissemination of information. The proposed Geopark will be located at the edge of the volcano rift-zone in SW Iceland, which is characterized by varied subglacial and intra-glacial volcanic formations. One of the most interesting aspects of the area is extensive geothermal activity and various utilization of geothermal energy since the early middle ages i.e. since the settlement of Iceland in the 9th century. This area is the largest low/medium enthalpy geothermal area in Iceland. Including this area into an internationally classified and acknowledged Geopark creates a unique opportunity to disseminate knowledge about the nature and economic importance of geothermal utilization to the general public. The name SAGA Geopark refers to the farm Reykholt where Snorri Sturluson, the most famous Saga-writer in Iceland, lived in the 13th century.

1. INTRODUCTION - NATURE OF A GEOPARK

A Geopark is a geographically confined territory with geological heritage of international importance. Every Geopark has some sites of significant geological features or sites that demonstrate outstanding archeological, ecological or cultural value. Geoparks are open to the public and emphasis is put on educational-based geo-tourism and school programs. Most Geoparks are members of a Global Geopark Network (GGN) established by UNESCO in 1998. Under GGN are two sub-networks, European Geoparks Network (EGN) and Asian Pacific Geoparks Network (PG). Geoparks have to apply for membership in EGN or APG and fulfill the high standard set by GGN and UNESCO. A geological report which must accompany every application is reviewed by geological scientists nominated by the International Union of Geological Sciences (IUGS). The membership is valid for 4 years after which the work taking place in the Geopark is reviewed and assessed. Only those Geoparks which obtain a membership in EGN or APG are allowed to use the official logos of the mother organizations.

One of the most interesting aspects of the area is extensive geothermal activity and various utilization of geothermal energy since the early middle ages i.e. since the settlement of Iceland in the 9th century. The Reykholt area is the largest low/medium enthalpy geothermal area in Iceland. Including this area into an internationally classified and acknowledged Geopark creates a unique opportunity to disseminate knowledge about the nature and economic importance of geothermal utilization to the general public.

2. GEOLOGICAL SETTING

Iceland is located at the intersection of the Mid-Atlantic ridge and the Greenland-Iceland-Faeroes ridge. The former lies on the diverging plate boundary of the American and the Eurasian plates. The spreading direction is N100°E. The Greenland-Iceland-Faeroes ridge is thought to be the trail of a mantle plume located beneath Iceland which has been active from the time of opening of the North-Atlantic some 50 m. y. ago (Figure 1). The plume is now situated below central East-Iceland, within the eastern branch of the volcanic rift-zone which crosses Iceland from southwest to northeast. The existence of a mantle plume is supported by a seismic anomaly and by a major Bouguer gravity-low centred above the proposed plume. The mass deficit must presumably be sought in both the elastic crust and in the under-laying asthenosphere. An anomalously low P-wave velocity of 7.0-7.6 km/s and attenuation of S-waves has been observed in the mantle beneath Iceland, indicating partial melt. This anomalous mantle terminates abruptly near the insular shelf south of Iceland where normal oceanic crust and lithosphere is found.

The spreading rate near Iceland was first estimated to be about 1cm/y in each direction, based on magnetic anomalies to the north and south of Iceland (Figure 1). Repeated regional GPS measurements have delivered similar values.

The axial rift zone crosses Iceland from the Reykjanes Peninsula where it connects with the Reykjanes Ridge (RR). Transform fault zones, the Tjornes Fracture Zone (TFZ) in the northeast and the South Iceland Seismic Zone in the south (SISZ), connect the presently active spreading zones with the submarine ridge segments (Figure 1). Tectonic earthquakes are due to relative movements of the North American and Eurasian Plates.

The biggest tectonic earthquakes in and around Iceland occur in the transverse zones in south (SISZ) and north Iceland (TFZ) and may reach at least magnitude seven. In the spreading volcanic zones magnitudes are smaller and usually do not exceed 5 (Figure 1). This is due to the fact that the elastic crust is presumably only 5-10 km thick in the volcanic rift zones and the temperature gradient is high. In the transform zones (TFZ and SISZ) the elastic crust is thicker, some 10-15km, and the temperature gradient lower.

Volcanic earthquakes located in the vicinity of the major volcanoes usually do not exceed magnitudes 4-5. Small earthquakes, which occur quite frequently in high-temperature geothermal areas, usually do not exceed magnitude three.

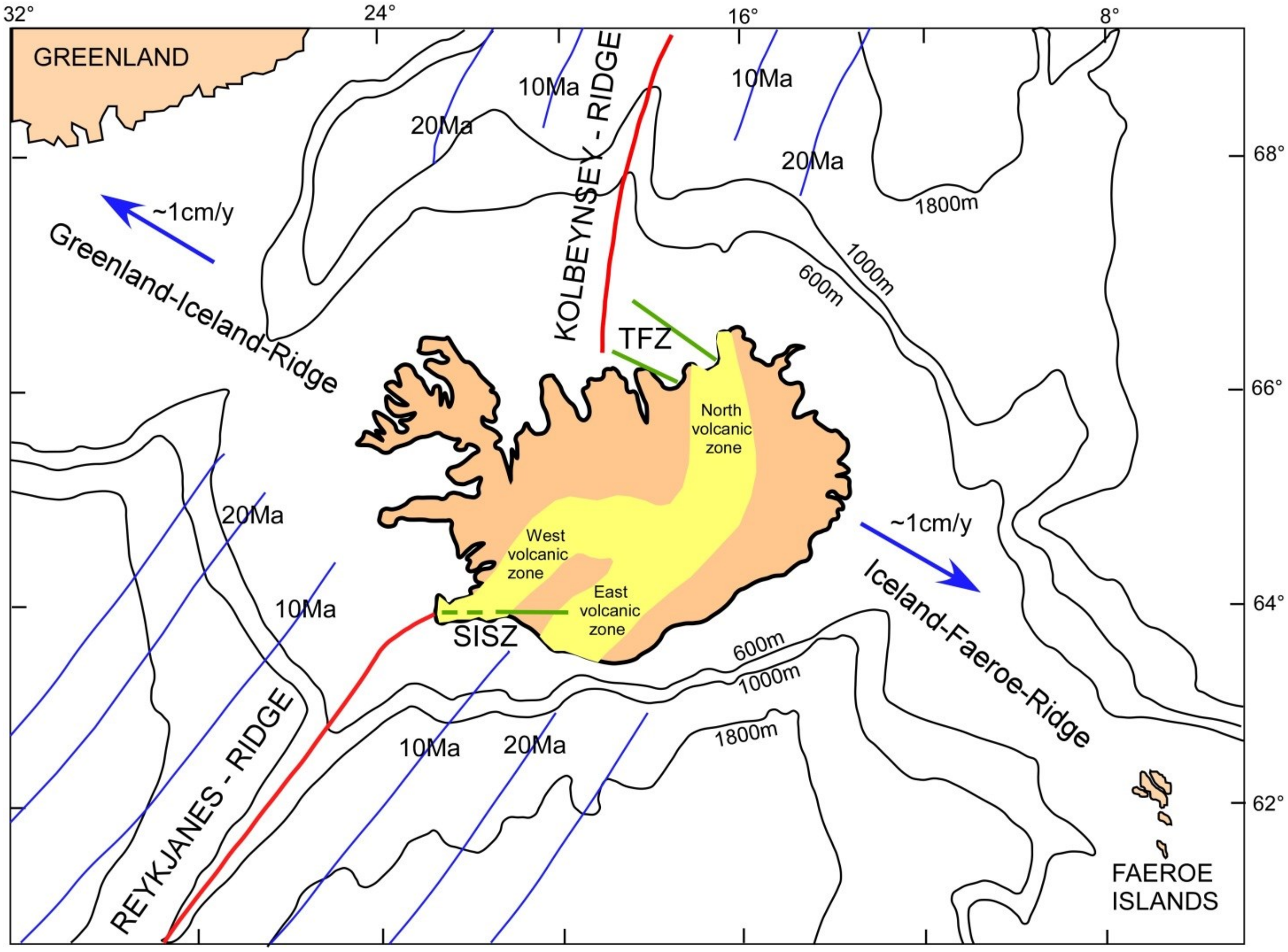

Figure 1: Iceland is an elevated plateau of volcanic basalt in the North Atlantic, situated at the junction between the Mid-Atlantic-Ridge (MAR) which characterizes the plate boundaries of the American and the Eurasian plate and the elevated Greenland–Iceland–Faeroes Ridge. The Reykjanes Ridge southwest of Iceland and the Kolbeinsey Ridge to the north are segments of the MAR. The spreading rate is around 1cm/y, indicated by blue arrows. Magnetic anomalies (blue lines) indicate increasing age in million years (Ma) of the ocean bottom with increasing distance from the rift axes. Also shown in yellow are the volcano-tectonic rift zones crossing Iceland from southwest to northeast. The rift-zone has two branches in south Iceland (East and West) and one in the north. The South Iceland Seismic Zone (SISZ) in the south and the Tjornes Fracture Zone (TFZ) in the north are transverse zones which connect the volcanic rift zones to the segments of the MAR. (Modified from Bjornsson et al., 2007)

The volcanic zones in Iceland are segmented into discrete volcanic systems (Figure 2). Most of them include a central volcano and a fissure swarm with proximal eruptive fissures and distal non-eruptive faults and ground fissures. The fissures extend far beyond the area of surface volcanism being the subsurface expression of dyke swarms (Saemundsson, 1978, 1979). Geothermal areas are an integral part of most of the central volcanoes. Sometimes subsidiary geothermal systems occur at volcanic foci on the fissure swarms, well away from the central volcanoes. The chemical compositions of lavas exhibit a wide range in most of the volcanic systems (Jakobsson, 1979). Acid volcanism is confined to the central volcanoes, rocks of intermediate composition occur around the centre, but only basalt is erupted in the fissure swarms. These features indicate shallow magma chambers at some 3-10 km depth under the central volcanoes where the magma ascending from the mantle evolves.

A second major type of volcanoes is large monogenetic lava shields and table-mountains, composed of primitive olivine-tholeiites indicating a deeper mantle magma source. Some of the volcanic shields are composed of picrite, suggesting a still deeper source. The lava shields are only found in the West Volcanic Zone (WVZ) and North Volcanic Zone (NVZ) axial rift zones, and most of them were formed during the last part of the ice age and in a short time interval after the end of the ice age. The axial rift zones are flanked by Quaternary volcanic formations and, further to the east and west, by Tertiary flood basalts as shown in Figure 2 (Saemundsson, 1978, 1979; Johannesson and Saemundsson, 1998).

The plate movements are oblique to the plate boundary and perpendicular to the individual fissure swarms. This indicates that the fissure swarms are created mainly in the upper brittle crust, by tensile crack formation perpendicular to the axis of minimum compressive stress.

The center part of the volcano-tectonic rift-zone in Iceland with rock formations younger than 0.8 m. y. is presumably the best example and the best preserved one in the world for various subglacial and intra-glacial rock formations with a wide range of chemical composition and morphological structure.

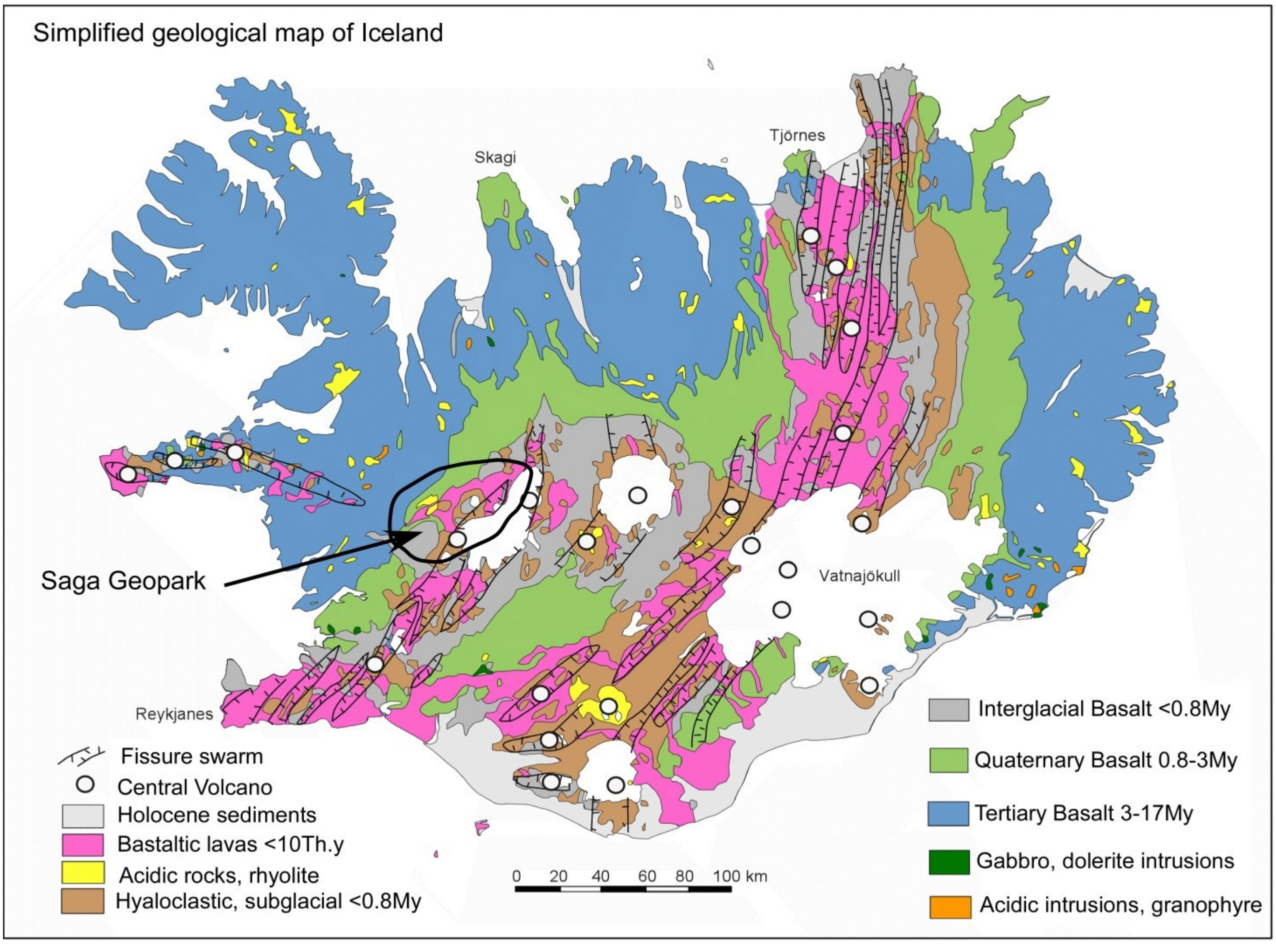

Figure 2: Simplified geological map of Iceland. The pink, grey and brown areas indicate the volcano-tectonic zone younger than 0.8 Ma. The green area shows bedrock 0.8-3.3 Ma old, and the blue area indicates Tertiary bedrock with age up to 16 Ma. Open circles represent central volcanoes. Heavy black lines mark the associated fissure swarm. The proposed SAGA Geopark is shown at the edge of the volcanic zone in SW Iceland. (Figure modified from Saemundsson, 1978; 1979).

The geology of the SE part of the proposed SAGA Geopark is, like the central and youngest part of the volcanic zone in Iceland, dominated by subglacial and interglacial volcanism younger than 0.8 m. y. This interaction of ice and fire for some 3My during the ice age is what makes the geology of Iceland unique. See Figure 3. Some postglacial lava-flows, younger than 11000y are in the area. The youngest one and largest is Hallmundarhraun from about 900 AD containing some of the largest lava tubes in the world. In this area there are some large monogenetic lava shields and table-mountains, composed of primitive olivine-tholeiites indicating a deeper mantle magma source. The lava shields are created during interglacial times but similar eruption during glacial period creates stapi mountain (table mountain). Subglacial fissure eruptions form elongated ridges made of hyaloclastite. Detailed mapping and dating of lavas in the extinct Husafell central volcano, which was active about 3.2-2.4 My ago (the first 0.8My of the ice-age), shows that 8 glacial events occurred during this time. That means about one glacial event per 100.000y (Saemundsson and Noll, 1974).The NW part of the Saga Geopark is dominated by Quaternary lavas, 0.8-3My old, closest to the active rift zone and Tertiary basalts older than 3My further to the west and north.

Figure 3 is a geological map of the Saga Geopark showing the main features in bedrock geology. The extinct Husafell central volcano is delineated by a blue boundary. The Prestahnjukur central volcano is marked with a red boundary. The canter of the central volcano is most likely between Geitlandsjokull and Thorisjokull and including small mountain Prestahnjukur made of acid rocks and geothermal alternated rocks. There are some minor warm springs about 15-20°C and containing water with some CO_2. About once a year earthquake swarms are monitored in this area. The earthquakes are small and occur on lines with direction NNE-SSW parallel to the faults and fissures in the West Volcanic Zone. This all demonstrates that the area is an active volcanic centre.

Glaciers are important part of the Saga Geopark. Langjokull is the second biggest glacier in Iceland with a major ice cap and numerous glacier tongues. The southernmost part of the glacier is called Geitlandsjokull and south of it is Thorisjokull. A small glacier is on the major shield volcano OK and one of the most majestic glaciers in Iceland is Eiriksjokull on the top of major stapi volcano.

Most of the hot springs are located around Reykholt in the western part of the proposed Geopark and on a strip eastward to Husafell. See figure 4. A detailed description of the boiling low-temperature geothermal field of Reykholt and the chemistry of the water is presented in Kristmannsdottir et. al (2005). The reservoir temperature is up to 150°C and the water type is alkaline sulphate water.

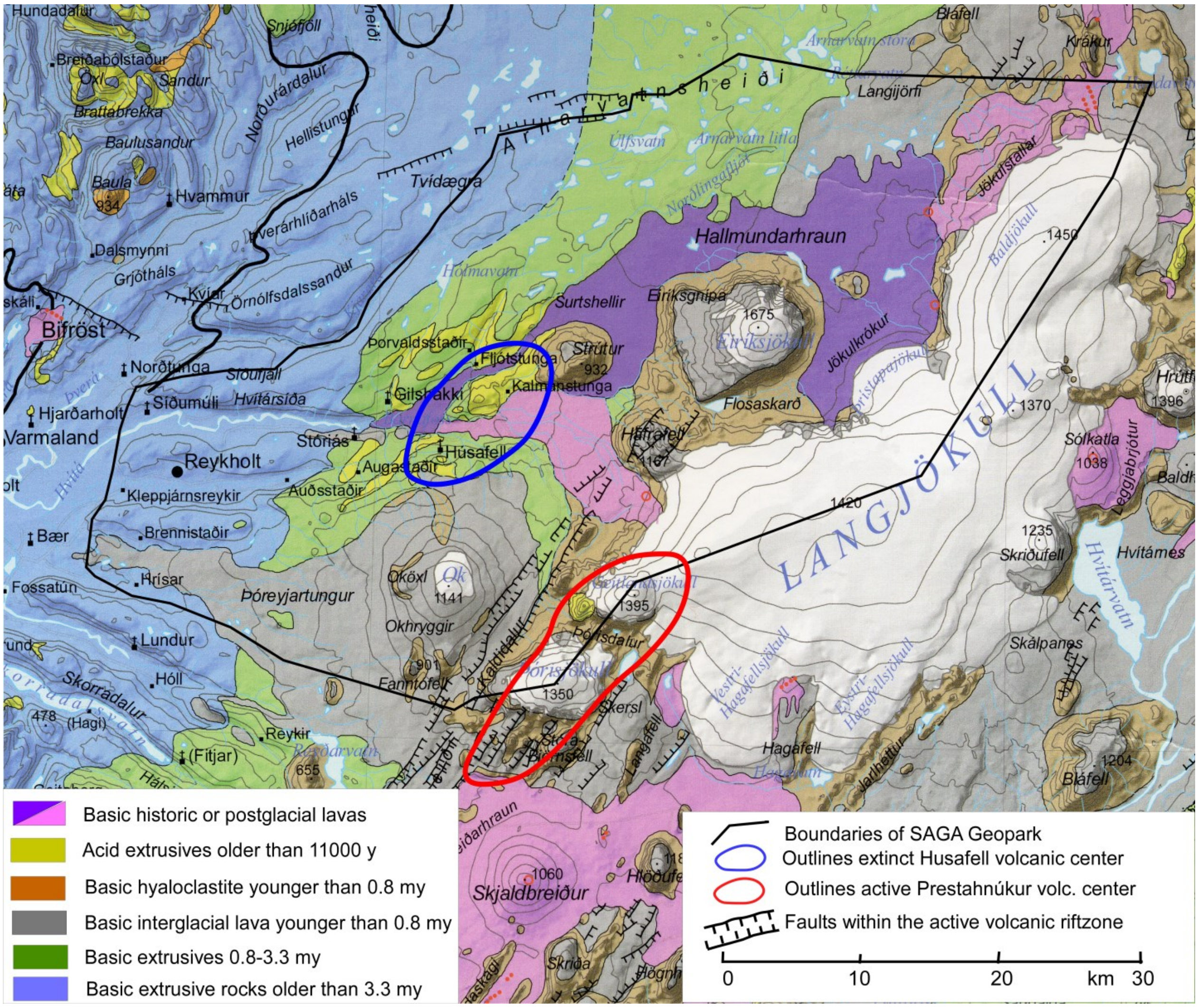

Figure 3: Simplified geological map of the proposed SAGA Geopark. The pink, grey and brown areas indicate the volcano-tectonic zone younger than 0.8 Ma. The green area shows bedrock 0.8-3.3 Ma old, and the blue area indicates Tertiary bedrock with age up to 16 Ma. Heavy black lines mark faults in the active fissure swarm. Modified from Saemundsson (1978) and Johannesson and Saemundsson (2009).

3. GEOTHERMAL SYSTEMS

There are numerous geothermal fields in Iceland. They have been divided into two different categories based on the nature of the heat source and the temperature at depth. These categories are first, the high-temperature geothermal systems (HT) with temperatures around 200-300°C at 2 km depth; and second, the low-temperature geothermal systems (LT) with temperatures lower than 150°C at 2 km depth (Bödvarsson, 1983). The HT systems are all associated with central volcanoes within the volcano-tectonic zones in Iceland. The heat-sources are shallow magma chambers or cooling intrusions in the roots of the central volcanoes. The LT systems are nearly all outside the active rift zones in the older Quaternary and Tertiary areas (Figure 4). They are created by local circulation of groundwater in confined faults and fissures extending in some cases down to at least 3 km depth. The horizontal dimensions of these convection systems are relatively small, amounting to a few km^2. The convection of the water mines the heat from the lower part of the system and carries it up to the upper part. Hence, the temperature gradient is relatively low within these LT systems. The water both in the LT and HT systems is originally meteoric water and no juvenile component has been found. The LT water is very low in dissolved solids, usually between 200-300 ppm and the pH is relatively high or around 9.5, caused by water-rock interaction with the fresh basaltic reservoir rocks. This water is used directly for cooking, bathing, washing and domestic heating. The HT water is heated up to 300-400°C or more and hence contains much more dissolved solids. It also contains some dissolved volcanic gases, like CO_2, H_2S, H_2 and CH_4, from the heat source, and SO_2 and HCl which mix with the ground water forming acidic corrosive fluids creating fumaroles and mud pools at the surface. No traces of juvenile water have been found.

The temperature of the hot water in the LT systems is defined by the maximum depth of the water circulation and by the surrounding temperature gradient (Bödvarsson, 1983). The longevity of these systems depends on the tectonic activity that is required to reopen the circulation channels that gradually are closed by precipitation of secondary minerals from the hot water (Björnsson et al., 1987, 1990). Very few LT systems are on the European plate in east Iceland. Most of them are west of the plate boundaries, indicating that the crust there is much more tectonically active than east of the plate boundaries (Björnsson et al., 1990). The LT systems can be regarded as confined local disturbances in the general heat flow from the mantle below. Outside the LT systems, the temperature gradient in wells is linear down to at least 1.5 km, which is the depth of the deepest gradient holes outside an LT system.

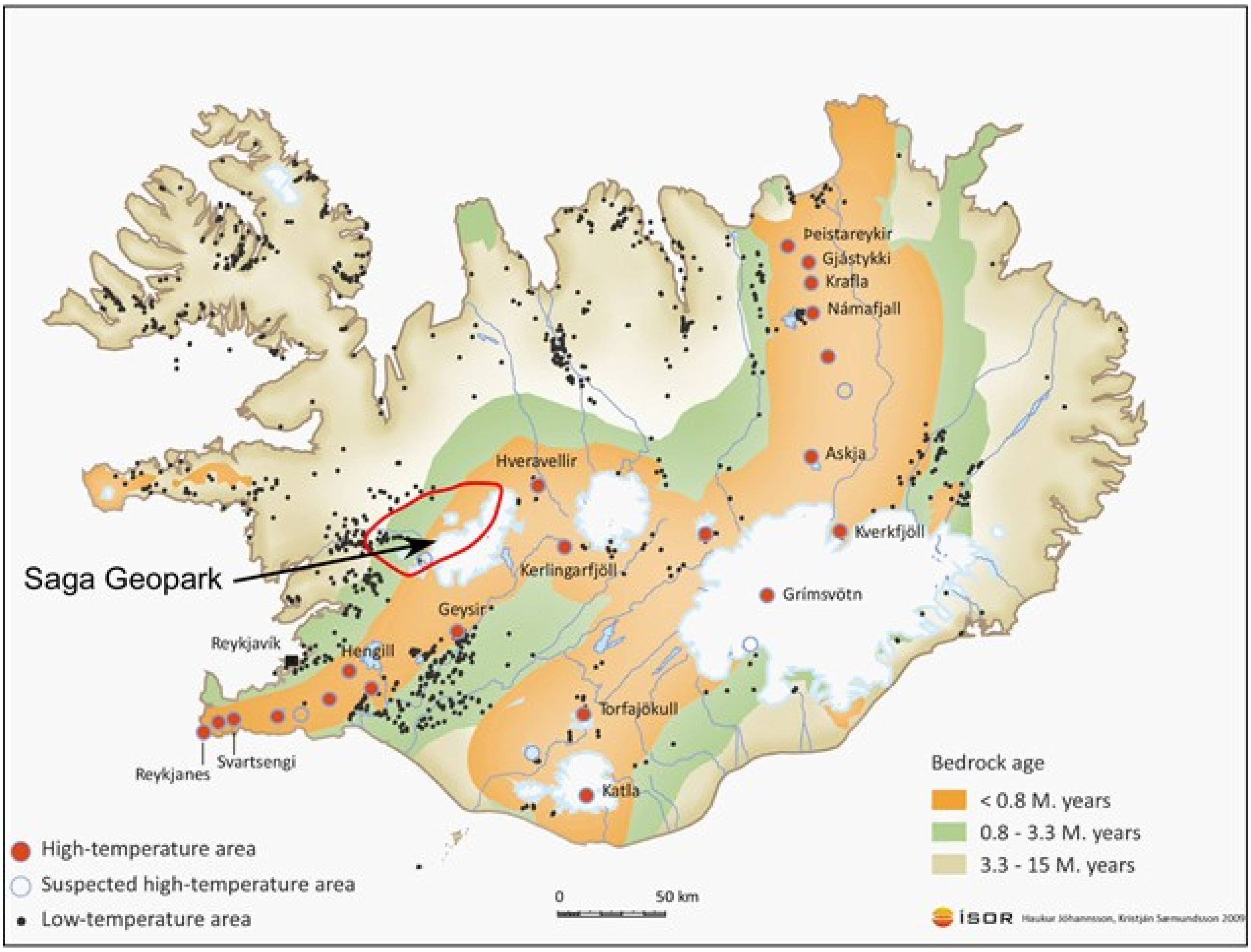

Figure 4: Geothermal fields in Iceland. The high temperature fields, marked with red circles, are all inside the volcanic rift zones. The black dots show major low-temperature fields with surface temperature above some 10-20°C. The red open circle in West Iceland shows the location of the proposed SAGA Geopark with one of the largest low temperature area in Iceland. (Map from Iceland Geo-survey).

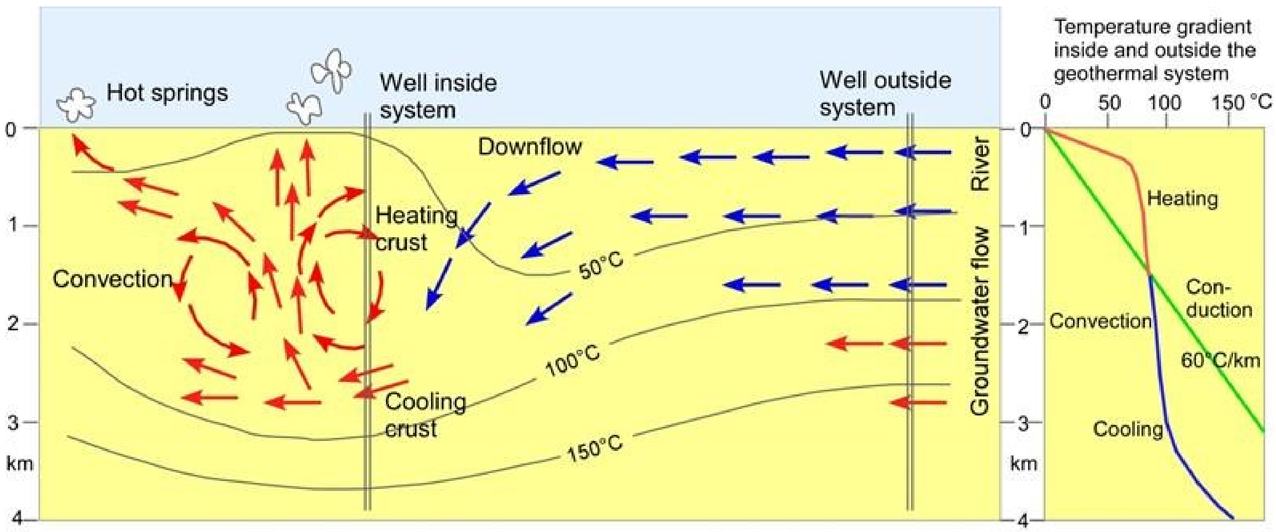

Figure 5: A schematic model of typical Icelandic low- or medium-temperature geothermal system. Local convection of groundwater in near vertical faults and fissures transports heat from the lower part of the crust up to the upper part. The right part shows a typical temperature gradient of 60°C/km outside the volcanic zone and outside geothermal systems. Typical temperature profile inside a geothermal field is also shown. There, the lower part of the crust is abnormally cool and the upper part abnormally hot. This model has been called the heat-mining model. (Modified from Bodvarsson, 1983 and Björnsson et al. 1990)

In order to keep the convection and the heat mining process going, a heat source is needed. Bodvarsson (1983) assumed that the water circulates in fissures and cracks at the boundaries of dikes and in faults. The fissures are closed below certain depths because of the lithostatic pressure. He proposed further that the cold water percolating down along the fissures of the geothermal system cools the rocks at the bottom and the contraction of the rock due to the cooling opens the fissure further down. Thus, the water continuously comes in contact with new hot rocks and the fissures migrate downwards. He named this process convective downward migration (CDM). The power of a geothermal system depends on the velocity of the downward migration, and this velocity depends on the temperature gradient of the area and the ratio between horizontal stress and vertical stress at depth. Bodvarsson points out that this model does not contradict the fact that the water in the geothermal systems is originally rain water falling on the highland. This water does not have to flow at great depth it can just as well flow in permeable layers close to the surface or in rivers to the lowlands. A schematic model of typical Icelandic LT geothermal system is shown in Figure 5.

There are no real high temperature geothermal fields within the proposed SAGA Geopark. The only indication of one is the occurrence of acid rocks in Prestahnjukur and some hydrothermal alteration within the active central volcano in the SW part of the Geopark. On the other hand there are numerous low temperature geothermal sites in the western part, especially in Reykholtsdalur which is a part of the largest low temperature geothermal district in Iceland.

4. GEOTHERMAL UTILISATION

One of the most interesting aspects of the SAGA Geopark is this extensive geothermal activity and various utilization of geothermal energy since the early middle ages, i.e. since the settlement of Iceland in the 8th century. Geothermal research has been ongoing in the area since 1960 and production has been slowly increasing through the years. The oldest space heating system in Iceland has been revealed by archeological excavations of ruins in Reykholt in Borgarfjördur, dating from the 13th century. The hot pool of Snorri Sturluson, the most famous Saga-writer in Iceland, also from the 13th century, does still exist (Figure 6). In Reykholtsdalur one of the first geothermal heating-system in modern times in Iceland was installed in 1912. There are numerous remains of early geothermal utilization all over the area, which are now being recorded and efforts are made to preserve them. In the early 1980ties one of the largest hot springs in the world, Deildartunguhver located in the area , delivering some 200L/s of boiling water, was partly exploited for a municipal district heating system for two towns in West Iceland, Akranes and Borgarnes. The hot water pipeline is about 70 km long. In Husafell in Borgarfjördur a big resort has been built up around a very special geothermal field. Most farmhouses in this part of Iceland are heated by natural hot water.

Part of the preparation and planning of the Geopark is to assemble geothermal data from the area as well as to collect and interpret new data. The Reykholt area is the largest low/medium enthalpy geothermal area in Iceland. Including this area into an internationally classified and acknowledged Geopark creates a unique opportunity to disseminate knowledge about the nature and economic importance of geothermal utilization to the general public.

Figure 6: Snorralaug at the farm Reykholt in Borgarfjördur W-Iceland, restored in 2004. One of the few constructions preserved in Iceland from early medieval times. Similar pools have been common in Iceland since the settlement in the 9th century. They were both used for washing and bathing and played the role as information centers where people from several farms gathered and used the same pool.

In the Icelandic Sagas and Annals there is extensive information about warm pools, similar to Snorralaug in Figure 6. Those pools were mainly used for bathing and washing of cloths. From this it is clear that hot geothermal water was widely used in the Middle Ages. During the early modern time, in the 15tn and 16th centuries, very little is known about use of geothermal water. Bath culture had declined and only sparse information about two bathhouses exists, without any detailed description. In the 16th to 18th centuries scientist started to get interested in geothermal activity. Several visitors came to Iceland to investigate this phenomenon. The most famous one was the chemist Robert Bunsen who spent one summer on Iceland in 1846. He wrote several scientific articles about the nature of the geothermal fields in Iceland. With this work he earned the title to be the founder of geothermal sciences (Bjornsson, 2005). At that time there was no progress to utilize the geothermal water in Iceland. Many farmers looked at the hot springs as a disadvantage that spoiled good grazing land for sheep and cows. Most people were not able to swim and the leisure bathing culture had vanished.

It was not until in the late 19th century that Iceland's isolation broke and new ideas and knowledge spread to Iceland. Many people had gone abroad and learned various handicraft and new building materials were imported. One of the most important building materials for exploitation of geothermal water was the concrete. Concrete made it possible to master the boiling hot springs, to build water containers and to pipe hot water and steam into houses. In Borgarfjordur farmers built special houses of concrete with washing facilities and kitchens with stoves made of concrete that were heated by 100°C hot steam from a boiling spring. See figures 7 and 8. Only few of these constructions still exist. It is, however, important to restore those structures in order to keep them as relics of industrial development in geothermal utilization.

Figure 7: House made of concrete by Hurdarbak in Borgarfjordur W-Iceland, built around 1900. In the right part is a kitchen with stove made of concrete. Steam from the boiling spring just right of the house was piped into the house and heated the stove. In the left part are facilities for washing clothes.

Figure 8: The concrete stove in the Hurdarbak kitchen house. There are holes for three pots.

Figure 9: Deildartunguhver is a hot spring some 10km west of Reykholt. The natural flow is up to 200L/s of 100°C of hot water. The water is pure groundwater with TDS of only about 300mg/L and can be used directly for cooking and bathing. About half of the flow is used for district heating in villages up to 70km away. The spring itself is a major tourist attraction.

Figure 10: Pump station at Deildartunguhver and a pipeline feeding the hot water to villages Borgarnes and Akranes some 70 km away from the spring. This is probably the longest hot water pipeline for space heating in the world.

The use of geothermal water is of great importance for the Icelandic people and a major tourist attraction. The total population of Iceland is about 330.000 people. During the last few years there has been an explosion in the tourism and over 500 thousand guests visited the country last year. Many of the most popular touristic sites are not prepared for this sudden increase and it is clear that the government and local authorities and land owners have to regulate, invest in and organize this line of business far better.

Half of the Icelandic population is living in the capital Reykjavik í SW Iceland and neighboring villages. In this area there are some 20 outdoor swimming pools open all year round and every house in this area has a central heating system using natural geothermal water and run by the local communities. In the countryside there is a swimming pool in nearly all towns and villages and geothermal heating nearly everywhere were hot water has been found. This has not always been the case. Around 1970 only 40% of the Icelanders had geothermal space heating. During the oil crisis in the early 70ties the government bought a new big drilling rig and hired all available earth scientists to start exploration of geothermal areas and drill for water. This major effort was very successful and in 1980 about 75% of the population had got geothermal heating in their houses. In 1990 the number had grown to 85% and now in 2014 geothermal heating is in 90% of all houses in Iceland. The National Energy Authority (Orkustofnun) has estimated that the total savings for the nation to use geothermal for space heating instead of imported oil. It was 67 billion IKR in the year 2009 which is equivalent to a family of four saving about 6800 US$ in the year 2009 alone.

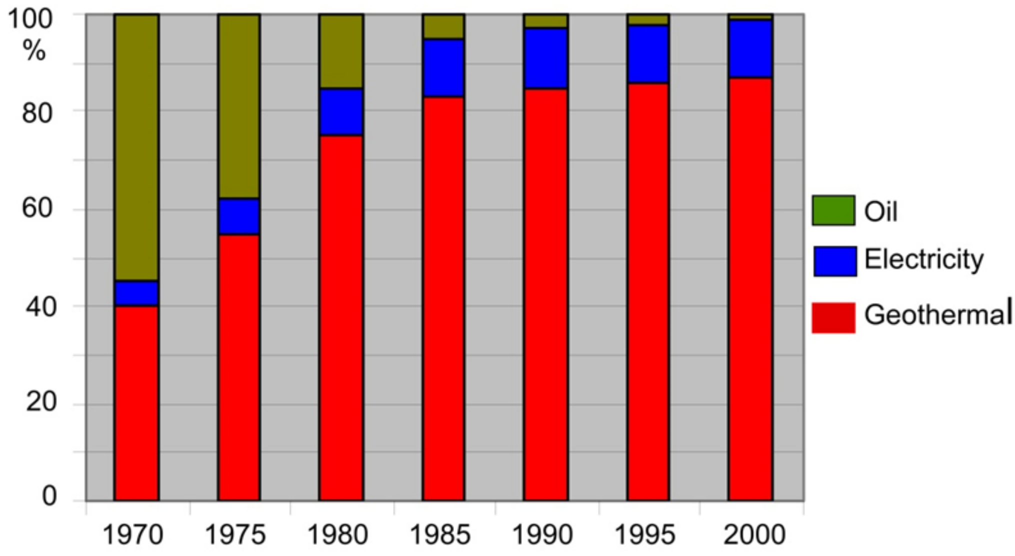

Figure 11: Elimination of imported oil for house heating in Iceland. Around 1970 only 40% of houses used geothermal water for heating. In 1980 the number was 75% and in 1990 around 80%. Today 90% off all houses are heated by geothermal. Oil is only around 1%.

6. CONCLUSIONS

A Geopark is geographically confined territory with geological heritage of international importance. The area must have some sites of significant geological features or sites that demonstrate outstanding archeological, ecological or cultural value. Geoparks are open to the public and emphasis is put on educational-based geo-tourism and school programs as well as nature conservation. Most Geoparks are members of a Global Geopark Network (GGN) established by UNESCO. The membership is granted for 4 years at a time, after which the work taking place in the Geopark is reviewed and assessed.

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