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Development of Thought on the Nature of Geothermal Fields in Iceland from Medieval Times to the Present

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ABSTRACT

Since the settlement of Iceland in the ninth century AD, people have used geothermal water for bathing, washing, cooking and even house heating. In spite of this utilization, only few speculative thoughts appear in the Sagas and contemporary records on the origin and nature of the hot water. In the 18th century, the first visitors with some scientific training came to Iceland and research on geothermal activity began. One of the first ideas was that the heat and fumarolic activity was caused by fermentation in surface layers. It was a breakthrough when the German scientist and father of modern chemistry, Robert Bunsen, came to Iceland in 1846. He investigated several geothermal fields in Iceland and took samples for later analysis. He came to the conclusion that the geothermal water was originally rainwater which had precipitated deep into the earth and been heated by the surrounding rocks. He and his colleagues explained the chemical composition of the geothermal water solely as water-rock interactions. Very soon, these findings of Bunsen were forgotten or were never absorbed by the geological scientific community. In the late 19th and early 20th centuries, most geologists thought that geothermal water was mostly juvenile water originating in magma. However, in the first decades of the 20th century, most researchers returned to the conclusion that it was originally rainwater but was heated either by magma or by cooling intrusions at depth, as Bunsen had proposed. Around 1940, Icelandic geophysicist Trausti Einarsson criticized this heating-mechanism. He argued that the convecting water was heated by the surrounding rock. Einarsson thought that the geothermal water and the crust were in steady-state equilibrium with the flow of heat from the mantle up through the crust. This model of a geothermal system is called the "steady-state model". Another Icelandic geophysicist, Gunnar Bödvarsson, demonstrated around 1950 that the steady-state heat flow is not sufficient to maintain the power of all the geothermal systems in Iceland; and he proposed that the geothermal systems are a transient phenomena created by local circulation of groundwater in faults and fissures. Thus, the circulating water was mining heat from the lower part of the crust and transferring it to the upper part, creating the hot spring areas. This model is called the "heat mining model". Strangely enough, the steady-state model was generally accepted in the geothermal community in Iceland but the heat-mining model was forgotten for 30-40 years until Bödvarsson republished his work in an international journal in 1984. Now the "heat mining model" is generally accepted and explains all the major features of low-temperature geothermal systems in Iceland. It is interesting to compare this erratic development of thought on the nature of geothermal systems with the discovery, rejection and re-discovery of other ideas in geology such as Wegener's continental drift theory.

1. INTRODUCTION

In this paper, an attempt is made to follow the development of thoughts on the nature of geothermal fields in Iceland, from medieval time to the present. Geothermal energy has been utilized since the settlement of Iceland in the 9th century AD; and modern scientific research of the geothermal activity started in the early 19th century. The name of the hot spring, Geysir, in S-Iceland became an international synonym for hot springs all over the world. Since the beginning of the 20th century, utilization of geothermal water for bathing, washing, space heating and electricity production has made geothermal an integrated and significant part of the Icelandic culture and identity. Thus, Iceland is an ideal place to investigate this development of thought; explore how the ideas have changed during the centuries; and see how conflicting ideas have been competing for decades. Here, Iceland is taken as an example to investigate the problem, but similar development did take place in other countries and the ideas and results presented here should be applicable to other countries with geothermal activity as well. By investigating the development of ideas about geothermal activity, it is strange to find that sometimes a self-consistent model based on solid systematic measurements is rejected and eclipsed by a vague hypothesis which is accepted mistakenly for decades by the scientific community. This development of thoughts with alternating setbacks and progresses is not confined to geology.

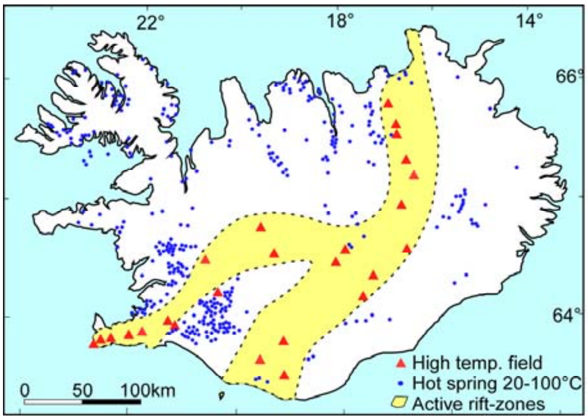

Figure 1: Geothermal fields in Iceland. The high temperature fields marked with red triangles are all inside the volcanic rift zones. The blue dots show major low-temperature fields with surface temperature above 20°C.

It is worth mentioning that most of the 19th century and the early 20th century literature on geothermal research in Iceland is in German and few key articles are written in Danish and France. The majority of papers and reports from the second half of the 20th century are written in Icelandic. Only a few key articles are written in the present day scientific language i.e. English. Thus, in order to trace the history of thought on geothermal development the last two centuries, it is essential to have a reading knowledge in five languages. English alone would give a very biased and incomplete picture.

In this paper, the development of ideas on geothermal activity are analyzed, but first it is essential to present the geological setting of Iceland and the latest picture of the nature of geothermal fields on the island.

2. THE PRESENT PICTURE

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 some 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 1). 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 convecting systems are relatively small, amounting to a few km^2. The convecting 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°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. Based on the chemical content, the hot springs have often been classified as acidic springs corresponding to the HT fields, and basic or alkalic springs corresponding to the LT fields.

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 some 1.5 km, which is the depth of the deepest gradient holes outside an LT system.

3. SETTLEMENT AND MEDIEVAL TIME

The first settlers of Iceland came from Norway and from the Celtic areas in Ireland and Scotland in the 9th century AD. Natural warm water and boiling springs were new to these people. They named hundreds of places after these phenomena like Reykir (e. smoke or steam), Gufudalur (e. steam valley), Laugar (e. warm spring), Varmá (e. warm river) and Reykjavik (e. steam bay) just to mention a few. The Icelanders soon learned to use the hot water for washing clothes, for bathing and for relaxing and healing during the cold winter months. In many of the old Sagas, which deal with the lives of people in the 9th to 11th centuries, there are numerous narratives on bathing activities (Thordarson, 1998). The Sagas were written in the 12th and 13th centuries, and contemporary literature from that time also contains reports on utilization of warm springs.

The most famous of the old bathing pools is Snorralaug (Snorri's pool, Figure 2) at Reykholt in Borgarfjördur, W-Iceland. The historian and politician Snorri Sturluson lived at the farm from 1206 to 1241. He wrote the book Snorra-Edda - a textbook on old Nordic mythology and poetry, several biographies of Norwegian kings, and presumably one or more of the most famous Sagas. Snorralaug is one of few constructions preserved in Iceland from medieval times. It is built of hand-hewn rocks and the water is fed a few hundreds of meters from a boiling spring in a closed channel made of rocks. Ongoing archaeological excavations in Reykholt have further shown that in the 13th century steam was fed in a stone channel a few hundred meters uphill into a living house presumably for heating purposes.

Figure 2: Snorralaug at the farm Reykholt in Borgarfjördur W-Iceland, restored in 2004. One of the few constructions preserved in Iceland from medieval times. Photograph from the Archaeological Heritage Agency of Iceland.

In spite of this utilization of geothermal water and all the geothermal place names, nowhere in the Sagas is any discussion about the nature of the geothermal activity or discussion on the origin of the hot water. The Icelanders of these days knew how lava layers were formed because they had observed numerous eruptions. But the nature of the warm springs and the boiling mud pools was not an issue worth describing or discussing in writing. It is possible that the expensive calfskin leather used for books in those days was just too expensive to spend it on a well-known and common phenomenon.

4. THE FIRST SCIENTIFIC OBSERVATIONS

The 16th century was the birth era of modern sciences. Galileo (around 1600) is often called the father of modern science and the scientific method. The development of science during this century culminated in the fundamental laws of Newton (around 1700). During this whole century, very little was written about geothermal activity. Geology was not born as a scientific discipline and most philosophers and thinking people accepted the creation of the Earth as described in the Bible. It could even be dangerous to present ideas, which were controversial to the ideas accepted by the church.

In Iceland, the 17th century was an era of setbacks and decline. The climate became colder, epidemic diseases plagued the nation and volcanic eruptions killed a large percentage of the livestock. Superstition increased and the educational standard moved lower along with the living standard. Nevertheless, there exist a few valuable geographical descriptions of natural phenomena in Iceland from this time. Bishops, who received their education abroad, wrote most of these reports. Icelandic self-learned individuals wrote some. One of these geographical reports is a description of Iceland written in Latin by Oddur Einarsson who was bishop in Skalholt in S-Iceland. This Latin text named *Qualiscunque descriptio Islandica*, written around 1598, has been translated into Icelandic (Einarsson, 1971). It contains a detailed description of a volcanic eruption and describes some geothermal fields where sulfur was mined and exported to Denmark. Further, the author gives a detailed description of a natural steam bath (sauna) in Namafjall, one of the high-temperature fields in N-Iceland, where the local inhabitants came for relaxation and bathing. The descriptions of the author are realistic and he tries to explain the phenomena without superstition. For explanation, he goes back to the ancient Greek philosophy where volcanic eruptions and geothermal activity were thought to be caused by burning sulfur in huge cavities within the Earth.

In the early 18th century, there was a turning point in thinking in Europe with the beginning of the so-called Enlightenment era. This philosophical movement questioned traditional doctrines and values, put an emphasis on individualism, human progress, empirical methods in science and free use of reasoning. In this era, scientific work was formed into well-defined scientific disciplines like chemistry, astronomy and geology; and the first thoughts on the theory of evolution were presented. Many governments and monarchs adopted these thoughts, and the movement came through Germany to Denmark where it was well received by the kings and the administration. The Royal Danish Academy of Sciences was founded in 1742, and it soon started organizing scientific work in Iceland, which was in a union with Denmark at that time.

The main goal of the research in Iceland was to collect and analyze all kinds of scientific data describing the nature, the weather, measure geographic location etc. Special emphasis was put on possible natural resources which might be utilized to improve the living conditions in the country. Numerous expeditions to Iceland were financed by the Academy over the whole century. In addition to these Danish-Icelandic expeditions, both individuals and groups from other countries visited Iceland. Here, only three of these expeditions will be mentioned in order to demonstrate the ideas people of those days had about geothermal water.

In 1750, two Icelandic students at the University of Copenhagen - Eggert Olafsson who studied natural sciences; and Bjarni Palsson who studied medicine were selected by the King to go to Iceland and start research in natural sciences. This journey was so successful that they received a research grant to visit Iceland every summer from 1752 to 1757, and to write a book about their research. The book was published in Danish in 1772, and later translated into Icelandic (Olafsson and Palsson, 1975). This was the most comprehensive work up to then, written about geography, flora and fauna and various natural phenomena in Iceland. This book is not a systematic description of Iceland's natural phenomena. It is built up as a diary in chronological order and similar phenomena are described in various parts of the book. The authors investigated several low-temperature and high-temperature geothermal fields, measured temperature and drilled several shallow drill-holes using hand-driven drilling devices in two geothermal fields to investigate the conditions below the surface, and they measured the temperature gradient in these wells. They found maximum temperature at shallow depth and cooler layers below. Their drill-holes were clearly located at the boundaries of the geothermal fields they drilled, where the temperature distribution was characterized by lateral flow. They concluded that the heat was caused by fermentation in shallow clay layers.

In the years 1791-1794, a young Icelandic scientist Sveinn Palsson made a similar survey of Iceland as his colleagues Olafsson and Palsson 40 years before. Sveinn Palsson mapped volcanic lava-fields and crater rows in great detail. He was the first to discover the continuous volcanic fissure zone crossing Iceland from SW to NE (the present volcanic rift zone) and presumably the first scientist to discover the visco-elastic nature of glaciers. It is justified to call Sveinn Palsson the first Icelandic geologist. His misfortune was that he lost his research grant and most of his work was not published until early in the 20th century (Palsson, 1983).

Figure 3: The hot spring Geysir (Great Geysir) in S-Iceland. The international word geyser comes from the Icelandic name of this particular spring. Drawing from a 19th-century picture atlas.

During his field excursions, he spent some days in the Geysir geothermal field in S-Iceland (Figure 3) but in spite of his ability to see the general picture in all things he investigated, he did not add much to the former ideas of Olafsson and Palsson (1975). He accepted their idea about fermentation and thought that the difference between low-temperature fields and high-temperature fields was just the thickness of the fermentation-clay layer the water was flowing through on its way to the surface. Most of the foreign scientists who visited the geothermal fields in Iceland at the end of the 18th and beginning of the 19th centuries tried to explain the nature of the geothermal activity. A young English nobleman and geologist Mackenzie (1811) visited Iceland in 1810. He spent some days observing Geysir and presented in his book a hypothesis about the nature of eruptive hot springs. He thought that steam was collected in subsurface cavities close to the bottom of the vent and an eruption would happen when the steam suddenly was pushed into the main vent of the spring.

It was generally assumed, among geologists in Europe in those days, that geothermal water was juvenile water, i.e. water coming from magma in magma chambers at depth. Water in cold springs was on the other hand assumed to be meteoric water (vadose water) pressed to the surface by hydrostatic head.

5. BUNSEN – BIRTH OF GEOTHERMAL SCIENCE

In 1845, a violent volcanic eruption started in the volcano Hekla in S-Iceland. The monarch of Denmark was King Christian VIII. He was not born as a crown prince and presumably therefore got a good education in history, fine arts and science. As a young man, he traveled for years around Europe and visited numerous universities and got involved in the democratic movement of that time (Lauring, 1991). When he heard of the eruption in Iceland, he invited four excellent young scientists to go to Iceland to study the eruption and the hot springs, thought to be due to the same causes. It is obvious that the King had a good nose for where the best science was done in Europe. The group consisted of a well-known traveler and geologist Sartorius von Waltershausen, professor in Göttingen; Descloizeaux, a French mineralogist; Robert Bunsen, professor in chemistry in Marburg; and his colleague the mineralogist Bergmann.

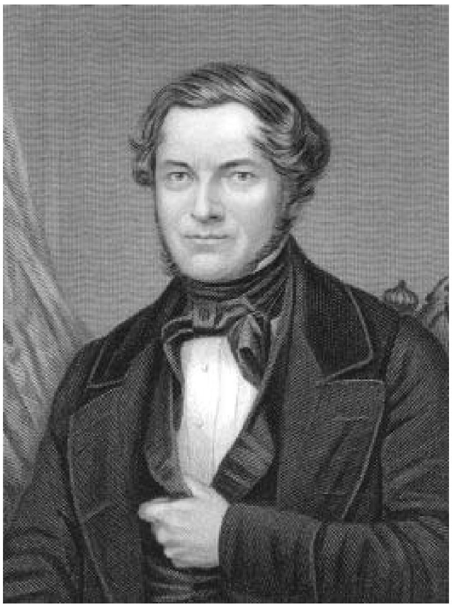

Figure 4: Robert Bunsen as a young man. He was professor in chemistry in Marburg, Germany, when he visited Iceland in 1846 at the age of 35.

The fifth member was a Danish lieutenant and geologist Mathiesen who was ordered by the King to prepare the expedition. The King received the scientists personally, supplied them with all facilities, and they were brought to Iceland by a brig from the Danish fleet (Oesper and Freudenberg, 1941).

This group of scientists was well equipped with scientific instruments and devices to collect samples of gas, water and rocks. Bunsen and Descloizeaux were top scientists in the fields of chemistry, mineralogy and physics. It is therefore justified to call this journey the first modern scientific expedition to Iceland. Bunsen is sometimes called the father of modern chemistry and he is definitely, along with his colleague Kirchoff, the father of spectrometry. This expedition to Iceland made him father of geothermal research. In 1860, Bunsen won the Copley medal of the Royal Society in London, presumably the highest honor a scientist could get before the foundation of the Nobel prize (Figure 4).

The volcanic eruption had ceased when Bunsen and his colleagues arrived in Iceland in the middle of May in 1846, but they started soon to investigate geothermal fields near Reykjavik and then went on a trip to Hekla to investigate the new lava. Bunsen stayed two weeks at Geysir and investigated the eruptive mechanism and traveled to the high-temperature geothermal fields at Namafjall and Krafla in N-Iceland. They collected over a hundred gas samples and an adequate number of various rock and water samples for later analysis in their laboratories. Some of these samples were sent to various laboratories in Europe in order to get the best results and control the findings. The results were published soon after their return in numerous articles. See, for example, Bunsen (1847a, 1847b, and 1851), Descloizeaux (1847), and Waltershausen (1847).

The most important result of this work was the manifestation that geothermal water, both in the low-temperature (alkalic) springs and the high-temperature (acidic) springs, is meteoric water. No traces of juvenile water was found or needed to explain the chemical content of the water. The chemical content could be explained solely by water-rock interaction. Bunsen proved this in numerous laboratory experiments by cooking various types of rock in water. He observed the hydrothermal alteration of rocks in the hot springs and precipitation of secondary minerals. He used this observation to explain the formation of secondary minerals in the old basaltic lava-pile and in the hyaloclastic rocks. This was a brilliant conclusion, especially if one considers that many geologists at that time did not distinguish between rocks and minerals. In this matter, Bunsen and Waltershausen did not agree. Their discussions demonstrate that Bunsen always made a clear distinction between scientific results based on observations and experiments on the one hand and untested hypotheses on the other hand. He warns the geologists and mineralogists to jump to conclusions and accept or reject chemical results especially if they are presented in a mathematical form.

During a two-week stay at Geysir, Bunsen and Descloizeaux measured the temperature at various depths in the 33m deep tube of Geysir, and for different time intervals before an eruption. The temperature was closest to the boiling curve at some 23m depth and reached the boiling temperature periodically due to lateral heating or inflow of hot water at this depth. The start of boiling then triggered an eruption. This geyser action theory of Bunsen is still generally accepted.

Bunsen observed a close correlation between volcano-tectonic lineaments and distribution of geothermal fields. He also saw a close link between high-temperature fields and volcanism. He concluded that magma or cooling intrusions were the heat source of the high-temperature fields. He extended this thought to the low-temperature fields and assumed that ancient volcanism was the heat source for these geothermal systems as well. This conclusion was logical, as all rocks in Iceland are of volcanic origin, and no information was available on temperature distribution at depth.

6. SETBACKS AND STAGNATION

A great number of scientists and visitors investigated the geothermal fields in Iceland in the 19th and the early 20th centuries after Bunsen and his colleagues finished their pioneering work. For review, see e.g. Thoroddsen (1925). But nobody took over where Bunsen stopped and continued his work with similar scientific enthusiasm. The situation got even worse. Some authorities and leading scientists in geology either ignored or did not know of the excellent scientific work of Bunsen, which was based on his own field observations and systematic laboratory work. One of the leading geologists in the second-half of the 19th century was Eduard Suess, professor in Vienna. He was an expert on the geography of the Alps and presented a theory of mountain folding, which is a precursor of the continental drift theory, and he proposed the existence of the Tethys ocean and Gondwanaland. He published his ideas in a monumental four-volume book named *Das Antlitz der Erde*. It was translated into English as *The Face of the Earth* and used as a textbook for many years. Craters on the Moon and Mars are named after Suess and he won the Copley medal in 1903, the same prize as Bunsen won in 1860. In 1902, Suess wrote a review article about geothermal springs of the world (Suess, 1902). He discussed all types of warm and hot springs and stated that all these hot springs contain only juvenile water and no component at all of meteoric water. He claimed that this is true both for the high-temperature mud-pools and geysers in Iceland, and for the classic low-temperature springs in central Europe like in Karlsbad. In the article, there are no real arguments or data supporting his assertion. About Iceland, he asserted that there the situation is so clear that nobody ever has doubted that all thermal springs could contain anything else than pure juvenile water. Suess was never in Iceland and in his article he did not cite anyone who had been there, not even Bunsen. A young German geologist von Knebel made two journeys to Iceland in 1905 (Knebel, 1906) and again in 1907. He made detailed studies of volcanoes and geothermal springs. After the first journey, he wrote an article and opposed the hypothesis of Suess. Knebel discusses in detail all arguments pro and contra juvenile water, and he came to the conclusion that the majority of the Icelandic geothermal water must be of meteoric origin (Knebel, 1906). During his second trip, Knebel drowned in the caldera-lake of Askja in central Iceland and his colleague Reck published his work (Knebel and Reck, 1912). Knebel observed that hot springs in Iceland are usually linked to faults, fissures or dikes. He collected information from written material, and found out that earthquake activity often caused a sudden increase in the temperature and flow rate of many of the springs, which on the other hand declined slowly over decades and centuries in the periods in between earthquakes. This observation supports the idea that the water is flowing in small fissures and cracks, which are filled slowly by precipitation of secondary minerals from the water, and reopened in tectonic movements and shaking of the rocks in earthquakes.

Many geologists accepted the hypothesis of Suess, which is rather strange considering the fact that it was not based on recent observations. It is obvious that people tend to believe what well-known and respected authorities present. But why did Suess write this paper, which seems to be based on 50-100 year old ideas? The answer is not clear. In those days in Europe, there was often a very limited communication between the various disciplines of science. This was even the case in many European countries during the second-half of the 20th century. It is possible that the geographical and geological community lived in a closed isolated world where new ideas from other disciplines like chemistry, mineralogy and physics were not absorbed.

The Icelandic geologist Thorvaldur Thoroddsen compiled the first geological map of Iceland in 1901. He investigated numerous geothermal fields and wrote a summary article on all research done on hot and warm springs in Iceland (Thoroddsen, 1910). He stated in one of his papers that, since Bunsen, no systematic research has been done on the nature of hot springs in Iceland (*"Seitdem sind keine systematische Untersuchungen der physischen und geologischen Verhaeltnisse der warmen Quellen vorgenommen worden"*) (Thoroddsen, 1925). Thorkell Thorkelsson measured the gas content and radon in warm and hot springs in Iceland (Thorkelsson, 1910, 1930, 1940). He found that in the low-temperature (alkalic) springs, the gas was 98-99% N_2 and that the argon/nitrogen ratio was the same in the atmosphere as in the cold water. Gas in the high-temperature (acid) springs was mainly CO_2 but also some H_2S, CH_4 and H_2. He concluded that the gas in the LT-springs was from the atmosphere, and gas in the HT water came from magma. Thorkelsson found some radon in the water and concluded that radioactivity could possibly play a role as a heat source. Further research was done by Barth (1939, 1950) and by Sonder (1941).

All these scientists who investigated the hot springs in Iceland in the first half of the 20th century came to a similar conclusion. The water is mainly meteoric water, but some discussed the possibility of a minor juvenile component. The springs are usually connected to dikes or tectonic lineaments and appear in groups. The heat source of the HT-fields are cooling intrusions or magma herds at great depth, and the heat source of the LT-fields are old intrusions and dikes which have cooled considerably.

The conclusion, which can be drawn from those findings, is that the general picture the geothermal society formed of the nature of geothermal fields around 1940 is nearly the same as Bunsen presented some 100 years earlier.

7. A STEADY STATE HEAT-FLOW MODEL

A young Icelandic geophysicist Trausti Einarsson studied in Germany before the Second World War, and came to Iceland in the 1940s. He started to investigate the eruption mechanism of Geysir in 1937, and used the temperature measurements of Bunsen because no better data had been collected. Geysir had stopped erupting in the early 20th century, but Einarsson got permission to lower the water-level in the spring by cutting an open channel into the cinder cone, and the eruptions started again. He collected more temperature data during those new eruptions, and came to a similar conclusion about the eruption mechanism as Bunsen did nearly one century before (Einarsson, 1938a).

Einarsson started to investigate the geological history of Iceland; i.e. the formation of the basalt layers and the hyaloclastites and tectonic movements. Very little had been written about those fundamental geological structures and the ideas, discussed at that time, were far from the present plate tectonics picture. Einarsson was especially interested in the nature of the hot springs, and started a very detailed mapping of dykes and distribution of low-temperature springs in N-Iceland (Einarsson, 1937, 1938b). He found that the majority of the warm springs were connected to dykes, and very often warm springs were close to the intersection of two dykes, or a dyke and fault or fissure. See Figure 5. This demonstrated that the permeability of fissures and cracks played a key role in the nature of hot springs. At the beginning, he proposed that the cold ground water percolated down along dipping lava layers, was heated on the way down, and forced up to the surface when it hit a dyke or a fault.

Figure 5: Trausti Einarsson proposed a model of the geothermal systems in Iceland where the water was heated solely by the steady state heat flow from the interior of the Earth. He rejected magma and cooling intrusions as a heat source.

He published his observations and conclusions in a paper named *Ueber das Wesen der heissen Quellen* Islands (Einarsson, 1942). He described the geothermal systems as local convection cells where the driving force is both hydrostatic head from surrounding mountains, and the difference in specific weight between cold and hot water. The surrounding rocks heat the water, and the temperature of the rocks at depth is solely controlled by the continuous heat-flow from the interior of the earth. The greatest novelty in his model is that he completely rejects magma and cooling intrusions as heat sources; and he goes one step further in assuming that the water is heated by the general heat-flow from below, and that there is steady-state equilibrium between this heat-flow from below and the heat the water transports up to the surface. Thus, the water convection does not cool the reservoir rocks, and there is a thermal equilibrium in the crust. This model is mainly based on observations of low-temperature fields in central N-Iceland, and Trausti Einarsson assumed that the convection of the water is a local phenomena confined to some tens of km^3 on the surface to a few km depth. At this time, nothing was known about the temperature gradient in Iceland, but Einarsson assumed it was at least similar to the value 30°C/km, known from the continents. He did some theoretical calculations and compared the assumed heat-flow from below with the total flow rate from the springs. His conclusion was that this mechanism could at least explain all the LT-activity in Iceland. In this paper, Trausti Einarsson does not deal in any detail with the high-temperature fields; but he points out that most or all of them are in areas which are intersected by major faults and fissures, and he indicates that this fact might play a much more important role for the heating mechanism than hot intrusions or magma at depth.

After the Second World War, another Icelandic scientist who had studied civil engineering and physics in Germany came to Iceland. This was Gunnar Bödvarsson, who had worked as a civil engineer in Denmark during the war and then became the director for the new Geothermal Department of the State Electricity Authority in Iceland. He was responsible for prospecting, drilling and development of utilization of geothermal energy in Iceland. He had a solid background and work experience in applied mathematics, physics and engineering. He wrote a milestone report named *On geothermal activity in Iceland* (Bödvarsson, 1948). In one chapter of this report, he investigates theoretically the heat transfer between rocks and water and compares his quantitative calculations with available observations and various proposed heating mechanisms. He was aware of the fact that his calculations were based on assumptions and, thus, were only an experiment to find a likely model for the geothermal phenomena. The last proof had to come from geological, geophysical and chemical observations. And he said "*But the geologists cannot observe the heat balance and the temperature field, so the problem must be treated in this way*". This was a completely new approach and a novelty in geothermal exploration in Iceland and a major step forward. The main conclusions of this work (Bödvarsson, 1948 and 1950a) are that it is possible to explain the smallest LT-geothermal systems with the steady-state model. In order to explain the energy of the larger systems, an additional transient heat source is needed. He proposed an intrusion, or that the larger systems were new and mined the heat from the surrounding rocks. In order to explain the larger LT-systems with the steady-state model, the contact surface between rocks and water would have to be several hundred km^2. According to Bödvarsson, the only realistic heat sources for the HT-systems were cooling intrusions and direct contact between the surface of the intrusion and the water.

In the years 1947-1948, a major exploration survey was done in the Hengill high-temperature field east of Reykjavik. Both Gunnar Bödvarsson and Trausti Einarsson were involved in this research and interpreted the data. Bödvarsson (1951) thought that the heat source was a cooling intrusion on the order of 50km^3 in size, and that the water was heated by flowing along the solidified upper part of the intrusion. He assumed that there was no chemical interaction between fluid magma and the water. In order to heat the thermal water by the steady-state model, he calculated that the contact surface had to be more than 2000 km^2; what he thought to be unrealistic. Trausti still believed in his model from 1942, and extended it to the HT-fields. In order to obtain more heat from the crustal rocks, he had to extend the dimensions of his convection cells. He assumed that a regional deep ground water flow from the central highland towards the coast absorbed the heat coming from below and, thus, was a source for the geothermal systems. His calculations showed that the total estimated heat flow from the whole island is just enough to heat the water flowing from hot springs in Iceland. A simplified sketch of his model is shown in Figure 6.

The findings of Bödvarsson were published in an engineering journal in 1951 (Bödvarsson, 1951); but the results of Einarsson not until 1966 (Einarsson, 1966). At that time, some preliminary results from deuterium measurements in geothermal water and rainwater were available. They showed that the deuterium content of geothermal water in springs from the lowlands was the same as in rainwater falling in the central highlands. Arnason (1976) continued this research and concluded that the deuterium content in rainwater and geothermal water proved the model of Einarsson, i.e. the geothermal water is rainwater falling in the central highlands and heated at great depth by the steady heat flow through the crust. The temperature of water in a geothermal spring should, therefore, depend on the depth of the flow channels feeding that spring.

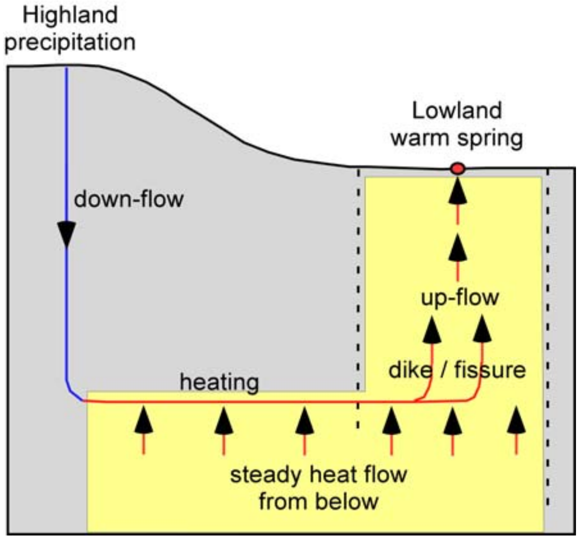

Figure 6: The steady-state model of Trausti Einarsson. Modified from Bödvarsson (1983).

The majority of the geothermal community in Iceland accepted the model of Einarsson to explain the nature of the LT-fields, and it was widely used in geothermal research. See, for example, Fridleifsson (1979) and Björnsson (1980). The ideas of Bödvarsson were not investigated much further, and were nearly forgotten for some 30 years in a similar way as the ideas of Bunsen a century before.

The interesting question arises: How did the geothermal community select between these two models? Around 1950, the data were scarce. Only few shallow drill-holes had been drilled in geothermal fields, and no deep holes existed that could give information on temperature in the deeper parts of the geothermal systems or thermal gradient at depth outside the systems. The model of Einarsson was simple and presented without complicated mathematics. The mathematics used by Bödvarsson was standard mathematics used in theoretical physics and engineering, but complicated enough to make his articles unreadable for most geologists, geochemists and even some of the geophysicists of the geothermal community. Bödvarsson moved to America in 1963 and did not have many opportunities to follow up his thoughts in discussions with Icelandic colleagues after that. Around 1970, the number of working geoscientists in Iceland increased considerably. Most of them were educated and grew up with the steady-state model as granted. These people were working on exploration and exploitation of geothermal resources with great success. In the 1980s, the number of houses using geothermal energy for space heating increased from 45% to 85%. It may have been limited time for these young people to think about fundamental problems, but numerous data piled up, which could have been used to revise the standard picture.

The development of thought on the HT-geothermal systems was somewhat different from the discussion on the LT-systems. Around 1970, some thought that circulation of water in deep faults and fissures could explain the heating of the geothermal water, according to the model of Einarsson. Others thought it was essential to include magma and cooling intrusions in order to explain the high energy transport from these systems. This discussion stopped during a major volcano-tectonic rifting episode that took place in the Krafla volcanic system, N-Iceland, from 1975-1989. A magma chamber was delineated beneath the central caldera by seismic and geodetic measurements. A 100 km long fissure swarm intersecting the central volcano rifted up to 8 m in about 20 rifting events. During the rifting events, magma flowed horizontally into the fissure swarm and formed dykes and eruptions occurred eight times. The surface geothermal activity was increased considerably, especially in the Namafjall HT-geothermal field some 10 km south of the central caldera. This influenced the deep geothermal wells and a few m^3 of scoria came up through one of the wells, creating the only man-made volcano in the world. See for example Björnsson (1985) and Einarsson and Brandsdottir (1980). Similar rifting episodes seem to take place every few hundred years in most of the HT fields in Iceland. After observing this close correlation between rifting, magma intrusions and HT geothermal activity, there is no doubt that the main heat source of the HT geothermal fields is periodically intruded magma at shallow depth.

8. THE HEAT MINING MODEL

In the 1960s, the Icelanders started to drill deep wells, >1500 m, in the LT geothermal fields in and around Reykjavik. The first deep wells in W and N Iceland were drilled in the mid-1970s both inside LT fields and as exploration wells outside LT fields. Numerous shallow wells were drilled to map the temperature gradient and estimate the heat flow through the crust (Palmason and Saemundsson, 1979).

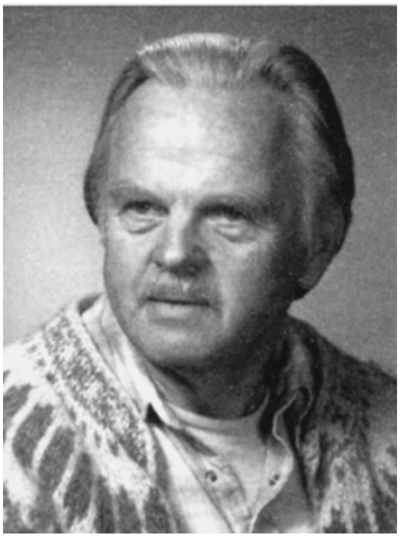

Figure 7: Gunnar Bödvarsson proposed a new heat-mining model for geothermal systems.

The most interesting result was that the temperature gradient within the geothermal fields was quite different from the normal gradient outside geothermal areas. The upper parts of the geothermal systems were hotter than the proposed one from the regional linear gradient, and the lower parts of the geothermal systems were much colder. Typical temperature gradients are shown in Figure 8. These temperature profiles demonstrate a strong convection within the geothermal fields where heat is transported from the lower parts to the upper parts. Thus, the he geothermal systems are cold spots within the lower part of the crust.

In 1982 and 1983, Gunnar Bödvarsson (Figure 7) published two papers on the nature of geothermal activity in Iceland (Bödvarsson, 1982 and 1983). He pointed out that the heat mining demonstrated by the temperature gradients is in clear contrast to the steady-state heat flow model. According to that model, the temperature gradients within the geothermal fields should be linear, and the temperature at each depth should correspond to the normal temperature gradient outside the geothermal systems. He compared also the flow rate from LT fields and the temperature in the springs and found that the temperature increased clearly with the flow rate. According to the steady-state model, this should be the other way around. He calculated the total heat flow from the crust and estimated it to be in the range of 5-10 GW. Only a small part of this is utilized to heat the ground water. The total flow rate from all LT fields in Iceland (before drilling) is around 1800 l/s corresponding to 0.5 GW. Hence, it is very unlikely that the heat-flow is high enough to maintain the LT geothermal fields.

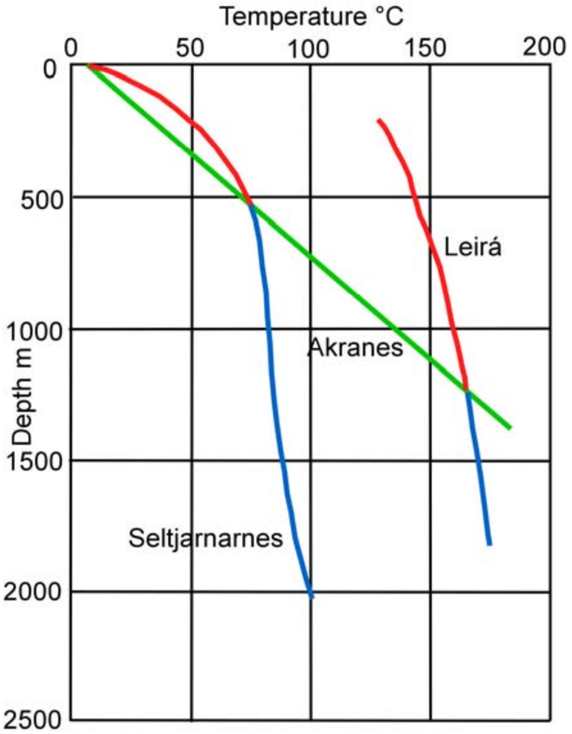

Figure 8: Temperature gradient profiles from wells inside and outside low-temperature fields in Iceland. The green line from a well in Akranes outside geothermal activity shows a linear gradient, not disturbed by water convection. The profiles from the geothermal areas at Leira and Seltjarnarnes show abnormally high temperatures in the upper parts of the geothermal systems (red lines) and abnormally low temperatures at depth (blue lines) indicating strong vertical convection transporting heat to the surface. Redrawn from Björnsson et al. (1990).

In order to keep the convection and the heat mining process going, a heat source is needed. Bödvarsson 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 cool 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.

According to this convective downward migration model or the heat-mining model, as it has been called, the geothermal systems are transient phenomena and do not live forever. Bödvarsson proposed that this process had started during the rapid deglaciation at the end of the last ice age when land was elevated tens or hundreds of meters. The vertical movements depend on the glacial load and crustal thickness. These movements could have created fissures and cracks along weaknesses in the crust and hence, started the geothermal process.

After Bödvarsson (1982 and 1983) published his papers in 1982 and 1983, the convective downward migration model was accepted in the geothermal community. Björnsson and Stefansson (1987) incorporated it into a paper on heat and mass transport in geothermal reservoirs. Björnsson et al. (1987 and 1990) used it to reevaluate some thoughts on LT geothermal activity and discuss some new data supporting this model. They reevaluated the permeability of the basaltic lava pile around some LT fields using long-term production and draw-down data from wells. They found that the permeability was about 5 times lower than previously assumed. This meant that deep continuous ground water flow from the highlands to the lowlands is only about 400 l/s; which meant that the low-temperature fields with their total production rate of about 2000 l/s could not be fed from this regional deep ground water current. They also reported on local tracer tests from a LT area which demonstrated that the circulation time in the system was on the order of weeks, i.e. very short time compared to some thousand years it takes the deep ground water to flow from the highlands to the lowlands.

Axelsson (1985), a student of Bödvasson made an attempt to calculate the opening velocity of fissures and the thermal power of a CDM geothermal system. He found that the ratio between horizontal and vertical stress has to be lower than 60% for CDM to start. The power increases with the temperature gradient. It is realistic that the power can be around 10 MW per kilometer length of a fissure. Thus, it is easy to explain the biggest LT fields in Iceland, which produce about 200 MW with this mechanism. Only a few geothermally active fissures, each a few km long, are needed to deliver this power. It is, on the other hand, impossible to explain this power by the steady-state model.

A similar downward migration mechanism has been proposed in order to explain the heat transfer from solidifying magma into circulating cold water in the roots of HT geothermal systems and on the Mid Oceanic Ridges (Lister, 1974, 1976; Bödvarsson 1951, 1982; Björnsson et al., 1982). The main difference is that in this case the cooling is strong enough to crack new fissures in the solid crust of the magma chamber but in the LT model of Bödvarsson the cooling mechanism is only opening old cracks along dykes, fissures and faults.

Bödvarsson (1982) assumed that tectonic movements at the end of the ice age initiated the LT geothermal activity. This is most likely true, and it is well known that volcanic activity was much higher during this time than some thousands of years later. Björnsson et al. (1990) showed that there is a close relationship between local earthquake activity in Iceland and the number of LT hot springs. This demonstrates that earthquakes and minor tectonic movements play a key role in reopening fissures and cracks, maintaining the LT geothermal fields. This is also in agreement with the CDM model because earthquakes are more likely to occur where horizontal stress is low.

Figure 9 shows a schematic drawing of the heat mining model of Bödvarsson (1983) which he calls the dyke convector model and is characterized by convective downward migration of fissures and cracks.

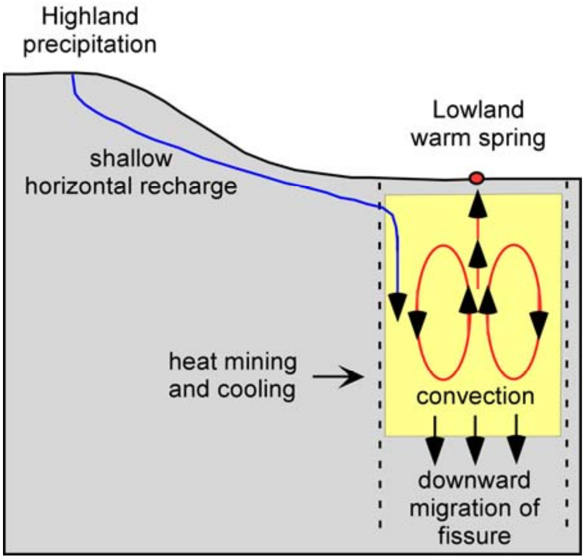

Figure 9: The heat mining model. Modified from Bödvarsson (1983).

To conclude this discussion, it seems to be clear that this model is capable of explaining the nature and power of the largest low-temperature fields in Iceland, and is in agreement with all available data. According to the model, the power of the low-temperature systems is controlled by the temperature conditions in the crust and, in particular, the local stress field. Given the thermal conditions in the crust, it appears that the regional tectonics and the resulting local stress field control the low-temperature activity.

This model is generally accepted in the geothermal community in Iceland, and it is used to perform more purposeful exploration and drilling in the LT fields than was done some 20 years ago.

9. DEVELOPMENT, STAGNATION AND DECLINE OF THOUGHT IN GEOTHERMAL

Looking back some two centuries on the development of thought on the nature of geothermal fields in Iceland, it becomes clear that this period is not characterized by continuous progress. The development is more characterized by a few new ideas, rejection of good ideas, and stagnation for long periods of time. Why did the geoscience community forget or ignore the ideas of Bunsen, which were based on new observations and experiments? Why did it take 30 years for the Icelandic geothermal community to realize that the model of Bödvarsson was the only model which could explain the nature of the LT geothermal fields? This development resembles the evolution of Wegener’s continental drift /plate tectonic theory, which was formally rejected and nearly forgotten for some 50 years. Is this back and forth process something which characterizes the geological sciences? Is geology *"ein Denksport am Rande der Wissenschaften"* (brain gym at the border of science)? The answer to the last two questions is no. Rejection of new revolutionary ideas also happens in the so-called exact sciences. A good example is the Swedish physicist Hannes Alfven, who around 1940 wrote several milestone papers about the magnetosphere and cosmology. His ideas were dismissed by the leading authorities in the field like Chapman in the USA, and Bartels in Germany, and he was forced to publish his work in obscure Swedish journals. His work was continuously disputed for decades, but suddenly the scientific community turned around and Alfven won the Nobel Prize in physics in 1970. Similar examples are known, e.g. from theoretical research in quantum mechanics; and a recent paper by Wilcox (1999) describes the development of ideas on magma mixing and the struggle for its acceptance, starting with Bunsen in 1851 to the present day.

The question remains, why does the scientific community sometimes accept mistakenly for decades an idea, which later is proved to be wrong, and rejects the correct idea? There is probably no single answer to this question. It is clear that the scientific community is reluctant to accept ideas, which conflict with the general accepted or standard theories. This may happen if the author of the new idea is far ahead of his time and the scientific community is not ready for the new thought. Sometimes, a wrong or limited idea is presented in such an elegant way that further progress toward solution of a problem is interrupted.

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