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The Isotopic and Chemical Characteristics of Geothermal Fluids in Hengill Area, SW-Iceland (Hellisheidi, Hveragerdi and Nesjavellir Fields)

Marietta W. Mutonga, Arny Sveinbjornsdottir, Gestur Gislason and Halldor Amannsson

P.O.BOX 785-20117 Naivasha/20253-00100Nairobi-Kenya, Arny Sveinbjornsdottir, Science Institute, University of Iceland,
Gestur Gislason Rekjavik Energy, Iceland, Halldor Orkustofnun, Grensásvegur 9IS-108 Reykjavík, Iceland.

mariettamu@yahoo.com, **mmutonga@kengen.co.ke**, **Arny@raunvis.hi.is**, **h@isor.is**, **gesture.gilason@or.is**

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ABSTRACT

Results of geochemical and isotopic investigations in the Hengill Geothermal area are presented. The area can be regarded as typical of Icelandic high temperature areas. It's mainly built up of pillow lavas and hyaloclastites, which were piled up in sub glacial eruptions. Part of the area is transversed by a very active NE-SW trending fault zone about 5km broad, within which are several eruptive fissures of postglacial age. The volcanic rocks are basalts of various kinds, but minor occurrences of intermediate and rhyolitic rocks are also found.

The study was based on chemical and isotopic the analyses of fluid samples from Nesjavellir prior to production, and the results data collected in the years 2000-2007 from the exploited geothermal fields. In addition, new fluid samples were collected for the present from the Nesjavellir and Hellisheidi fields. These samples were analysed for chemistry and stable isotopes at the institute of Earth Sciences, University of Iceland. Grapher and Surfer were the main programs used to plot the data.

The results indicated that the Nesjavellir and Hellisheidi thermal fluids do not share the same origin. In Nesjavellir the water comes from a distant source the glacier Langjökull whereas in Hellisheidi the water is of local origin identical to the isotopic composition of the Hveragerdi thermal water. According to the deuterium isotope values well HE.1 in Hellisheidi is closer in origin to the Nesjavellir thermal fluid than the fluid circulating the Hellisheidi system. The Hellisheidi system is younger than the Nesjavellir system as suggested both by stable isotopes and chemistry of the thermal fluids (Cl-SO_4-HCO_3 plot). In Nesjavellir the fluid is richer in ^{18}O and chemically more mature than in Hellisheidi, due to more intense water-rock interaction. Thermal fluids in Hveragerdi are of local origin as the Hellisheidi waters.

1. INTRODUCTION

Iceland is located at the junction of the Mid-Atlantic Ridge and the Greenland-Iceland-Faeroe Ridge, the former being a part of the global mid-oceanic ridge system. Iceland is regarded as being a hot sport above a mantle plume, and has been piled up through emissions of volcanic material, grown by rifting and crust accretion through volcanism along the NE-SW axial rift zone. This is sometimes referred to as the Neovolcanic zone (Figure.1). Currently, the plume channel reaches the lithosphere below the north-western part of the glacier Vatnajökull. The buoyancy of the Icelandic plume leads to dynamic uplift of the Icelandic plateau, and the high volcanic productivity over the plume produces a thick crust. The western part of Iceland lies west of the volcanic zones and belongs to the North American plate whereas the eastern part belongs to the Eurasian plate. As necrustis created along the rift zone, old bed rock moves further from the plate boundary. Therefore, the oldest rocks exposed on the surface in Iceland, formed about 16million years ago, occur in the eastern most and western most parts of the country. The volcanic zone is connected to the Atlantic ridge across transform faults in both North and South Iceland. In SW-Iceland, the volcanic rift zone is divided into two separate parallel zones characterized by several fissures and fault swarms. The two branches are connected by the E-W trending South Iceland Seismic Zone (Saemundson, 1978). The Hengill area is located just north of a ripple junction where an oblique spreading ridge, tensional spreading axes and a major seismic zone meet (Figure.1). It is part the Neovolcanic zone in SW Iceland about 40km east of Reykjavik.

The Hengill area contains three economical geothermal fields which are already being exploited for heating water and power production. These are Heillisheidi, Hveragerdi and Nesjavellir (Figure.2). At the Nesjavellir field north east of Mt. Hengill, 26 wells have been drilled, but 5 of them have been permanently closed. The depth of these wells ranges from 1000 to 2200m and temperatures of up to 380°C have been measured. The average thermal power from these wells is 60Mwt and 9MWe. The total electricity production is 120Mwe and 1640l/s of water at 83°C. In Heillisheidi which is to the south of Mt.Hengill, 28 wells have been drilled to date at 2-3 km depth; 25 out of these are deviated wells mainly targeting volcanic fractures and graben boundaries. A power plant is hosted in this field producing 90MW, soon to be 120MW (Gislason, 2007.per com). Hveragerdi is located some 50km from Reykjavík; mainly for heating purposes. Measured temperatures in this field range from 170-185°C.

1.1 Purpose of the Study

The harnessing of geothermal heat from the Hengill area has been going o for atleast more than two decades. Steam and water samples are taken several times during the discharge period to establish the chemical characteristics of the wells and to monitor any changes (Gíslason, 2007 per com). The present study is based on the analysis of fluid samples and on the results of previous work in the exploited geothermal fields. Chemical and isotopic evaluation of geothermal fluids within the Hengill area will be carried out to study if mixing of thermal fluid takes place in these fields, to evaluate chemical characteristics of the thermal fluid, to determine subsurface fluid flow paths, the origin of geothermal fluids and heat in the Hengill geothermal area. In addition to distinguish and classify thermal fluids in the fields. In so doing, I hope to use this to monitor any possible changes due to production/exploitation or otherwise now and in the future.

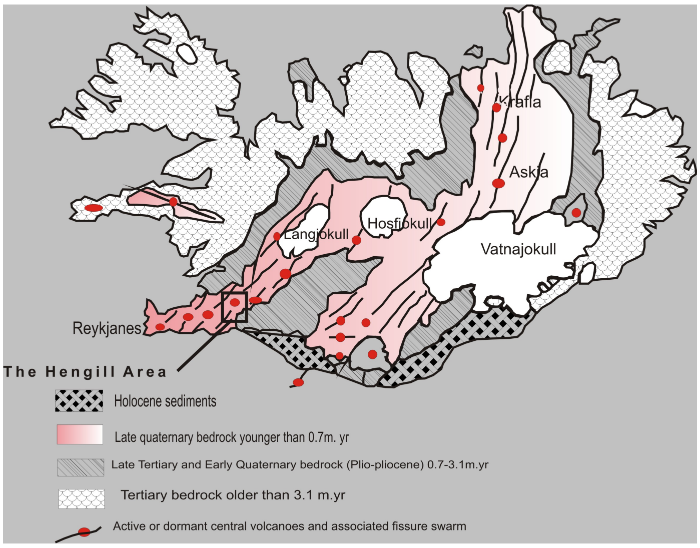

Figure 1: The Hengill area in relation to the Icelandic Neovolcanic zone and main rock types.

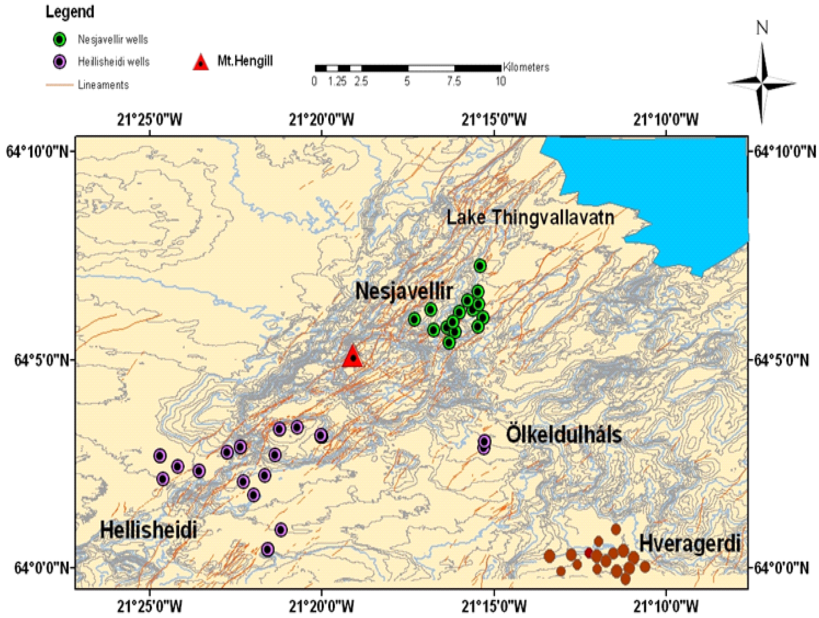

Figure 2: Location of geothermal fields in the Hengill area

2. GEOLOGICAL SETTINGS

A great deal of research work has been done in the Hengill area by different scientist in relation to the geology, geophysics, geothermal activity and geochemistry. Saemundsson (1967) mapped the Hengill Mountain and produced a 1:25,000 scale geological map. The bedrock in the Hengill area is composed of basaltic lava layers, thick sequences of hyaloclastites, and vertical intrusions. Two NNE-striking volcanic fissures, which intersected the Hengill volcano 2,000 and 5,500 years ago, act as primary conduits for sub-surface fluid flow in both Hellisheidi and Nesjavellir.

The geothermal reservoirs are liquid dominated and commonly sit on the boiling-point-with-depth profile. Reservoir fluid is 240-330°C fresh water, low in total dissolved solutes (TDS) and gas.

The geology is characterized by the active Hengill central volcano, a major fissure swarm and the extinct Hveragerdi volcanic centre hosting geothermal resources.

It is one of the largest high-temperature areas in Iceland, extending over some 50km^2. The geothermal activity is believed to be connected to three volcanic systems. 1) The Grensdalur system is the oldest system and gives heat to the Hveragerdi field. 2) North of this is a volcanic system named after Mt.Hrómundartindur, which last erupted about 10,000 years ago. The geothermal area in Ölkelduhals is connected to that system. 3)West of these volcanic systems lies the presently active Hengill volcanic system, with intense tectonic and volcanic NE-SW fractures and faults extending from Lake Thingvallavatn to Nesjavellir and further to the SW through Innstidalur, Kolvidarholl, Hveradalur(hot spring valley) and Hellisheidi (Saemundsson,1979). The area is almost entirely built up of volcanic rocks of late Quaternary and postglacial age (Saedmundsson, 1967). These are mostly basalt flows and hyaloclastites but small amounts of intermediate rocks and rhyolites occur as well.

3. USE OF ISOTOPES AND CHEMISTRY IN GEOTHERMAL, INVESTIGATIONS

Geochemistry including isotope geochemistry has greatly contributed to the present understanding of geothermal systems. Ellis (1977) suggests that the detection of even small changes in the chemical composition of a geothermal fluid enables a precise assessment of the long term stability of the field. The chemical and isotopic composition of geothermal fluid components provides information on their origin, their recharge area and flow patterns, and may allow an evaluation of subsurface temperatures. In addition, cooling processes of the fluid during ascent to the surface, due to heat conduction, admixtures with cold waters or steam losses, can be studied by means of the changes introduced in the chemical and isotopic composition of the thermal fluid.

3.1 Sampling

Sample collection, chemical analysis and data interpretation are the three main steps involved in geochemical studies of geothermal fluids. A brief description of the sampling techniques, sample treatment and analytical techniques adopted for this is given in this section. For detailed sampling and analytical techniques see Olafsson (1988); Paces (1991) and Arnorsson (1991).

The types of samples used in the study are water samples from hot water wells, water samples from wet-steam water wells.The collection of representative gas samples from a discharging well involved the collection of dry gas (non-condensable gases), condensate, steam (in NaOH solution) and hot water. It was conducted with the aid of a Webre separator and a cooling device. Great care was taken to separate steam completely from liquid.

Sample treatment was specific for particular analytical methods. The samples were collected in several fractions. Ru samples are raw and untreated for CO_2 and H_2S analysis ,Rd ones are raw and diluted on site with de-ionized water to bring SiO_2 below 100ppm for SiO_2 analysis, Fu ones are filtered and untreated for anion analysis, Fp ones are filtered and precipitated for SO_4 analysis and Fa ones are filtered for anions analysis. Samples for isotope analysis were collected in 500ml small bottles they were also raw and untreated.

The analytical methods used to obtain the data for the report included Atomic absorption methods for cations e.g. Mg.Na,K,Fe,Al; Cl and SO_4 Ion chromatography finally for δ^{18}O, δD Mass spectrometry.

3.2 Results of Chemical Analysis

The present results are based on the analyses of fluid samples and on the results of previous work from 00-07 in the exploited geothermal fields (Table.1, 2, 3 & 4). The fluid samples were collected between July-August 2007 was also analyzed for stable isotopes in the University of Iceland using the Delta-V-Advantage thermo.

4. CHEMICAL AND ISOTOPIC CHARACTERISTICS OF THE THERMAL FLUIDS

Chemical and isotopic data have been compiled and contoured on maps in order to study the chemical and thermodynamic properties of the field.

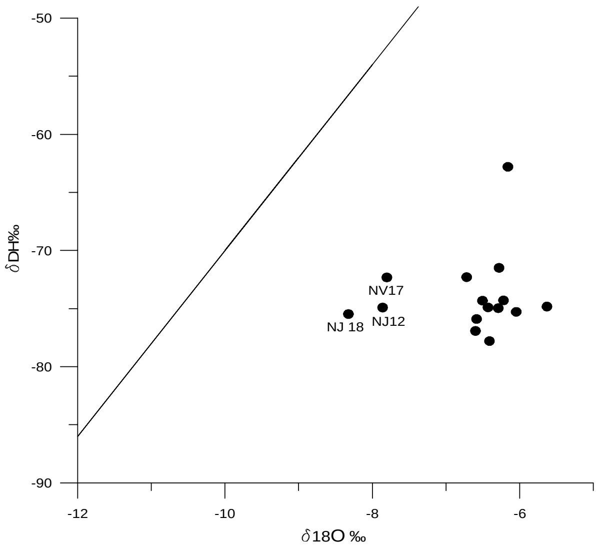

Figure 3: Nesjavellir wells in the 80's δ^{18}O Vs δ^2H

4.1 Natural Isotopes

Isotope techniques are a valuable tool in geothermal prospecting as well as studying the evolution of geothermal fields as a consequence of exploitation. Among the various isotopes, the variations of stable isotopes of oxygen, hydrogen and carbon in major fluid components provide the most useful results. In this study both hydrogen and oxygen isotopes were used. In the years 1985-1989 stable isotope measurements were performed on hydrothermal fluids from 15 wells in the Nesjavellir area (Sveinbjörnsdöttir, 1989). The measurements were done on the Finnegan MAT 251 mass spectrometer of science Institute, University of Iceland. Exploitation of the Nesjavellir field had not begun at that time. Figure.3 shows the $\delta^{1\ 8}$O values for the thermal fluid at Nesjavellir. The mean δ^{18}O values for wells east of the youngest fissure eruption were –6.5‰ whereas for wells situated west of the fissure it was -8.0‰. No difference was observed in the δD values in wells east and west of the fissure, indicating the same fluid within theproduction area. The difference in δ^{18}O could be explained if the geothermal activity within the area west of the fissure was considerably older than the activity east of it (Sveinbjörnsdöttir, 1989**).**

Figure.4 shows the spatial distribution of δ^{18}O in Nesjavellir in the 1980´s before exploitation of the field began. High values of δ^{18}O -5.9 ‰ and -6.5 ‰ are observed in the NE-SW direction of the field. Low values are observed in the NW part of the field.

Figure.5 we see the cold water wells of Hellisheidi plotting directly on the global meteoric water line as was expected while the hot wells plot to the left of the global meteoric water line they group around ^{18}O δ-7.3‰ to δ^{18}O 6.5‰ and δ^2H 62.0 ^{18}O‰ and δ^2H 65.0 ‰ respectively. Hveragerdi hot wells plot very close to the Hellisheidi wells.While the Neshjavellir wells both hot and cold wells plot quite apart from the wells Helisheidi and Hveragerdi.

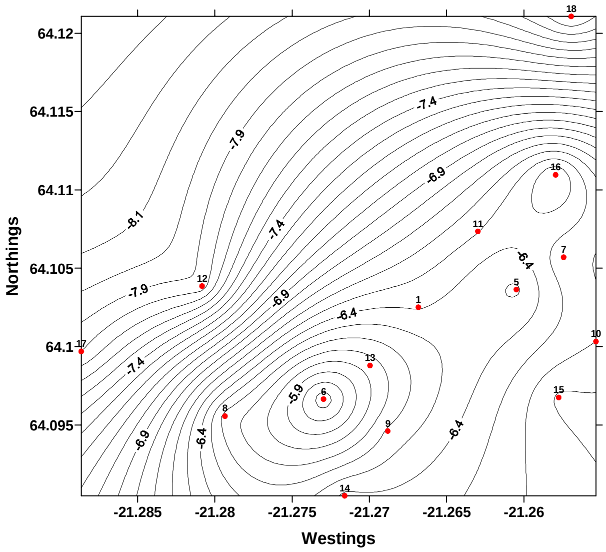

Figure 4: The distribution of δ18O in the Nesjavellir field in the 1980´s before exploitation of the field.

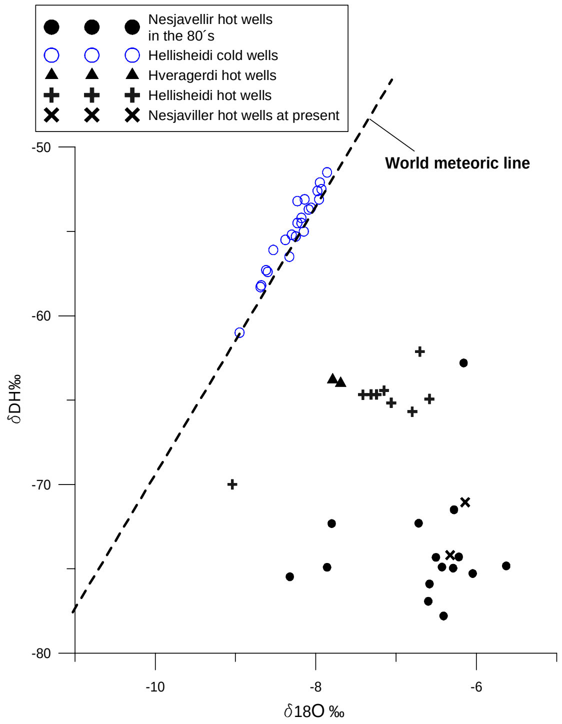

Figure 5: A graph showing $\delta^{18}O$ Vs $\delta^{2}H$ for all available data for the Hengill area.

4.2 Chemistry

4.2.1 The Nesjavellir Field

4.2.1.1 Chloride

Chloride is an example of conservative (non-reactive) constituents in geothermal systems. Once added to fluid phase they remain there. Conservative components have not equilibrated in a thermodynamic sense. They are externally fixed i.e. by their sources of supply of the geothermal fluid. Their contents along the flow path are changed only by mixing and steam loss. The chloride distribution during the production years in the 80s (Figure 6a) shows a smooth distribution with the maximum values on the eastern side of the production field and the lowest values in the North and Western side of the field and highest values in the eastern part of the field. During the production years between 00-07 the chloride concentration Values seem to have increased with high values being observed in the southern part of this field. The Nesjavellir reservoir shows great variation in initial Cl concentrations and important changes due to utilization(Figure.6b). Initially the Cl concentration in the wells closest to the young eruptive fissure was unusually low, often below 10ppm, but higher concentration was found in the lower enthalpy wells in the eastern part of the field There is certainly due to an increase in the mineralization of the fluids due to mixing or boiling or water maybe be coming from a different source with a high concentration of chloride ions.

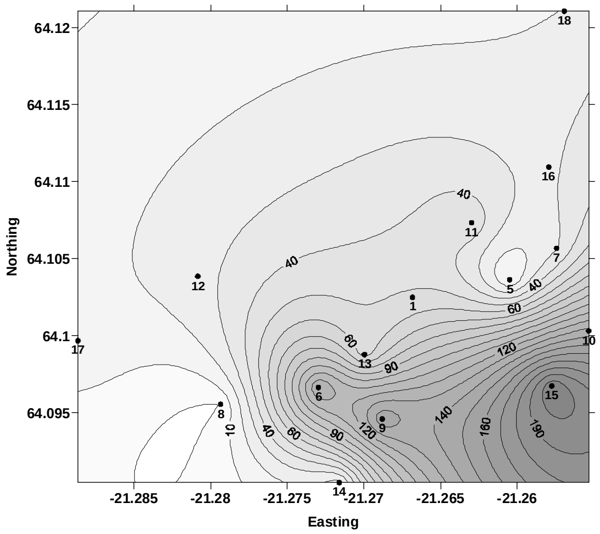

Figure 6a: Nesjavellir Cl distribution in the 80’s

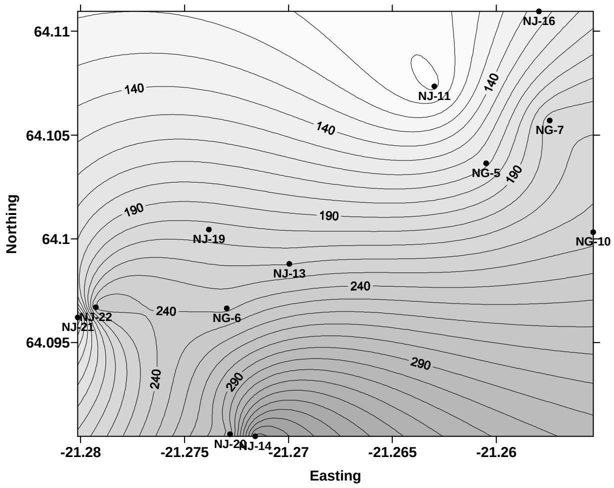

Figure 6b: Nesjavellir Cl distribution from00-07

4.2.1.2 Enthalpy

A comparison is made in the 80’s (Figure.7a) and it shows that the enthalpy distribution prior to exploitation is smooth with high values of around 2100-2700 kJ/kg being observed in the NE-SW direction of the field. The same pattern is observed for the δ^{18}O distribution shown in (Figure.4). This is the same direction as the NE-SW fissures and faults that go into the Lake Thingvallatn. The data from the year 2000-2007 suggest a change in the distribution of the enthalpy (Figure.7b) where the enthalpy seems to be increasing outwards from the centre with a notable increase being observed in the NW direction. This is a clear indication of an increase in temperature from the centre of the field outwards. As to be expected when production is forced, an enthalpy rise is predicted over time.

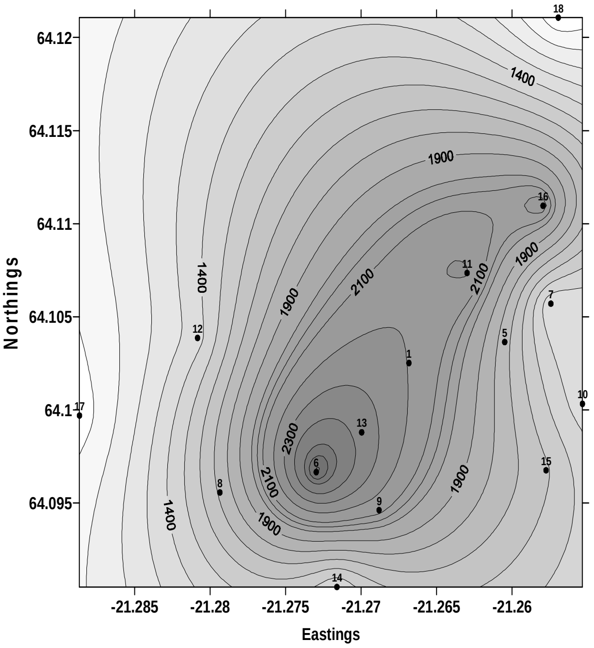

Figure 7a: Enthalpy (KJ/Kg)values in the 80´s

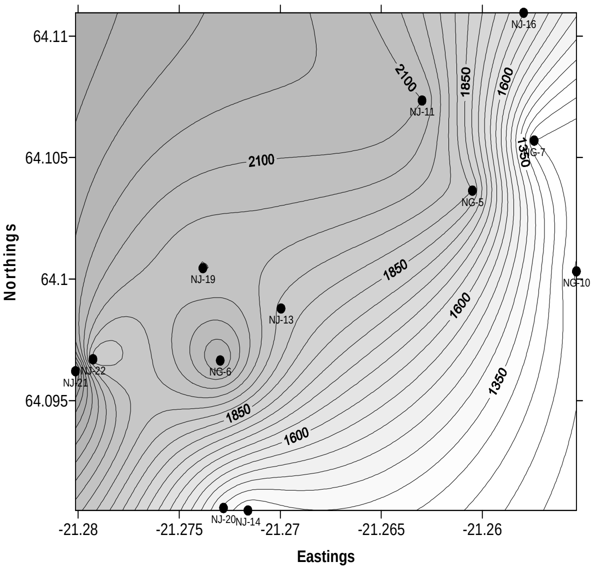

Figure 7b: Enthalpy(KJ/Kg)values from 00-07

4.2.1.3 Carbon Dioxide Distribution (CO2)

Figure.8a shows the distribution of CO_2 in the Nesjavellir field before and after production before production there is a high in the southern(Figure.8a) part of the field and after some years of utilization high CO_2 values are observed in the opposite direction(Figure 8b). High gas concentrations are mainly due to flashing in the reservoir fluid (Grimur per comm. 2007). In response to production there is increased flashing in the north western part of the field.

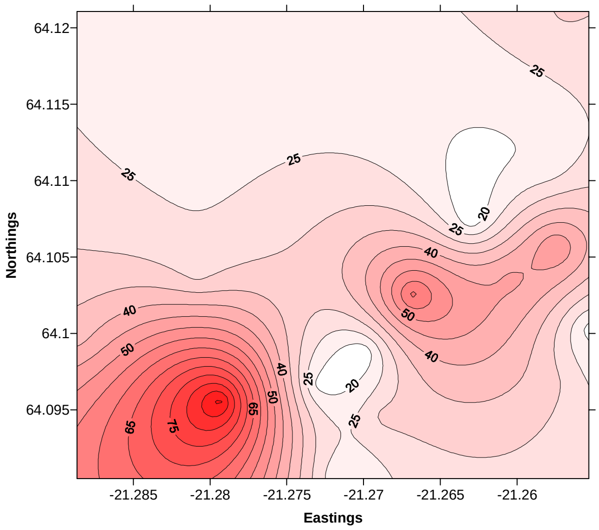

Figure 8a: CO_2 distribution before utilisation Nesjavellir

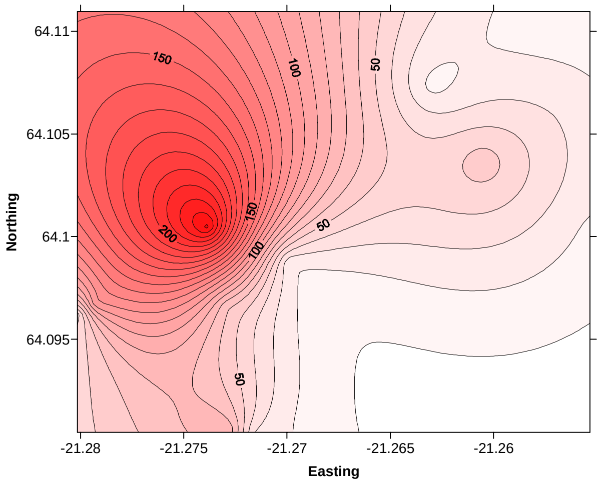

Figure 8b: CO_2 distribution after Utilisation Nesjavellir

4.2.2 The Hellisheidi Field

The samples for isotopes in this field were collected in the month of Aug-2007 from both condensate and steam. The results indicated that the isotopic composition ranged from -7.3‰ to -6.5‰ and -62.0‰ and -65‰ in the δ^{18}O and δ^{2}H respectively.

Figure.9a shows the distribution of δ^{18}O isotopes collected this year in Aug-2007 for the wells in Hellisheidi. High values of δ^{18}O are observed in the SW of the study area with a decrease being observed in the north. The highest value is δ^{18}O -6.5‰ in the south and the lowest value δ^{18}O -7.3‰ in the north. The wells 24 and 25 were producing from the steam cap, which means that the steam is much lighter in isotopes than in wells 7 and 17where we have both steam and water.

Quite high concentrations chloride ions are observed in this field with the highest Cl values coinciding with the highest values of Oxygen isotopes (Figure 9a and 9c). High enthalpy values are generally observed on the Hellisheidi field, however they seem to increase in the NE-SW direction.

4.3 Classification of Thermal Fluids

4.3.1 The Na-K-Mg Ternary Diagram

The Na-K-Mg ternary diagram (Giggenbach et al., 1988) can be used to classify waters into full equilibrium, partial equilibrium and immature waters (dissolution of rock with little or no chemical equilibrium). The full equilibrium curve is for reservoir water composition corrected for loss of steam owing to decompression boiling. Uncorrected boiled waters will generally plot slightly above the full equilibrium line.

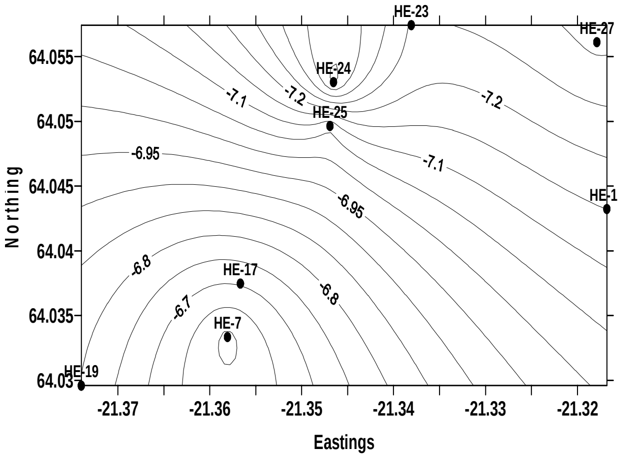

Figure 9a: Hellisheidi isotope distribution 2007

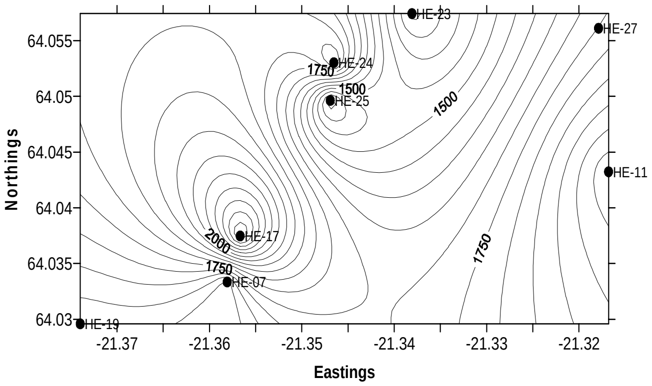

Figure 9b: Enthalpy distribution in Hellisheidi field from 00-07

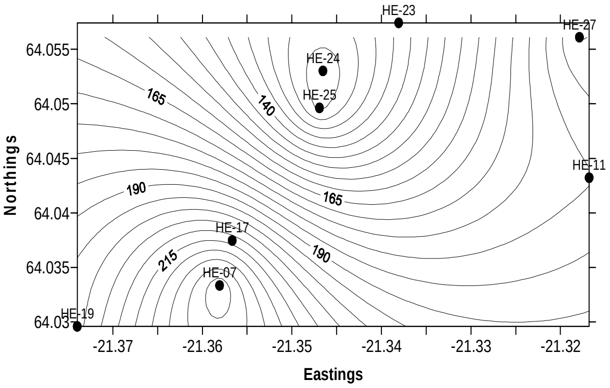

Figure 9c: The distribution of chloride in Hellisheidi field from 00-07

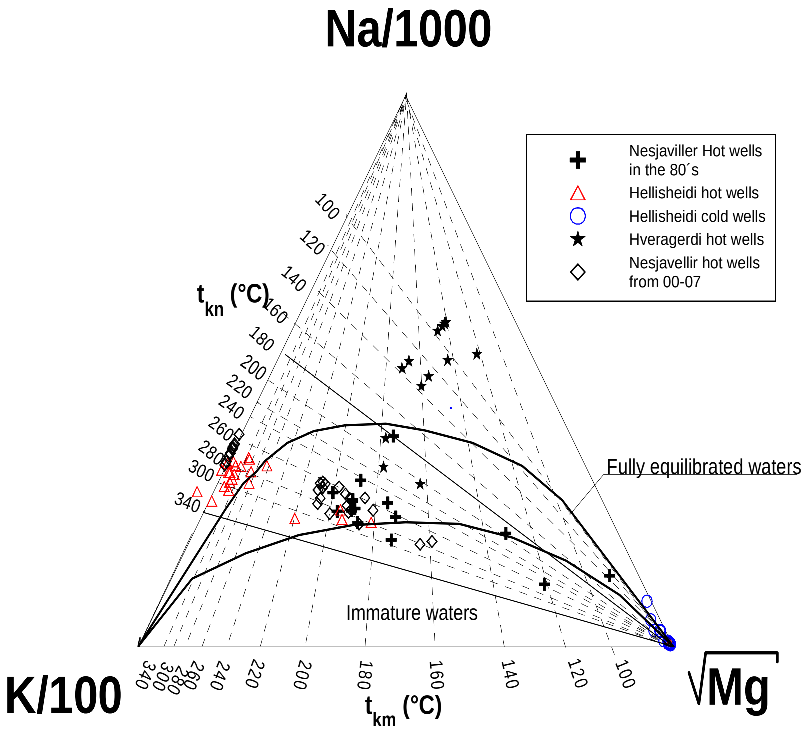

Figure 10:The Na-K-Mg diagram for the Hengill

The diagram be used to better clarify the origin of the waters, and then determine whether the fluid has equilibrated with hydrothermal minerals and to predict the equilibrium temperatures.

The thermal waters in Nesjavellir fall in the partially equilibrated and mixed waters (Figure.10). There is not much change from the 1980´s period prior to production and in the period 2000-2007 when the field was fully exploited. Most samples fall in the temperature range of 260°C-300°C except for a few that fall above the fully equilibrated line probably because of the removal of Mg from the waters.

The wells in Hveragerdi fall within the partially equilibrated waters and the mixed waters section, but most samples above the fully equilibrated waters line. The waters seem to have low temperatures ranging from 140°C-100°C, with only a few samples suggesting temperatures above 200°C(Figure 9). Most of the waters in the Hellisheidi field fall in the partially equilibrated waters (Figure.9) with only a few samples above the fully equilibrated waters line this probably de to flashing. That could be due to removal of Mg ions (very low concentration of the ion probably because of boiling). All the cold well samples plot in the √Mg –corner of the diagram which means that these waters have not attained equilibrium.

4.3.2 The Cl-SO_4-HCO_3 Diagram

Giggenbach (1991) proposed a SO_4-Cl-HCO_3 ternary diagram for initial classification of geothermal solutions to identify whether the geothermometers are applicable for the given water sample, as most solute geothermometers work only for neutral waters. According to Giggenbach (1991), solute geothermometers can only be applied to what is referred to as “mature waters”, characterized by high Cl and low SO_4. This diagram is also helpful in providing an initial indication of mixing relationships or geographic groupings.

The chemical composition of the fluids from the Nesjavellir wells in the period 2000-2007 is classified as Cl-rich geothermal water (Figure.11a). In contrast to the period in the 1980´s where there is a scatter with most samples falling in the Cl-rich section and some within the HCO_3 rich section. The pH range of most of the samples was in the ranges between 9 to 8.

Hellisheidi hot wells plot on the mature water quadrant while most (Figure.11a) cold wells plot on the peripheral waters quadrant with some samples plot volcanic mature waters section. This shows that the cold waters have probably mixed with the hot well waters. The waters in Hveragerdi probably C-type waters mature as indicated in Figure.11c.

5. DISCUSION

Figure.5 shows deviation of most of the thermal fluids from the world meteoric water line. The waters range in δH between -62‰ and -78‰ and in $\delta^{18}O$ between -5.5‰ and -7.8‰. This is consistent with the observations of Sveinbjönsdottir and Johnsen (1992) who observed that a deviation of the Nesjavellir fluid from the meteoric line was due to an oxygen isotopic exchange with the bedrock. This exchange is slow when T ≤ 200°C but at higher temperatures it increases sharply. As basaltic rocks contain very little hydrogen there is hardly any hydrogen isotopic exchange between rock and water and therefore the deuterium value for thermal water still characterizes that of the original fluid.

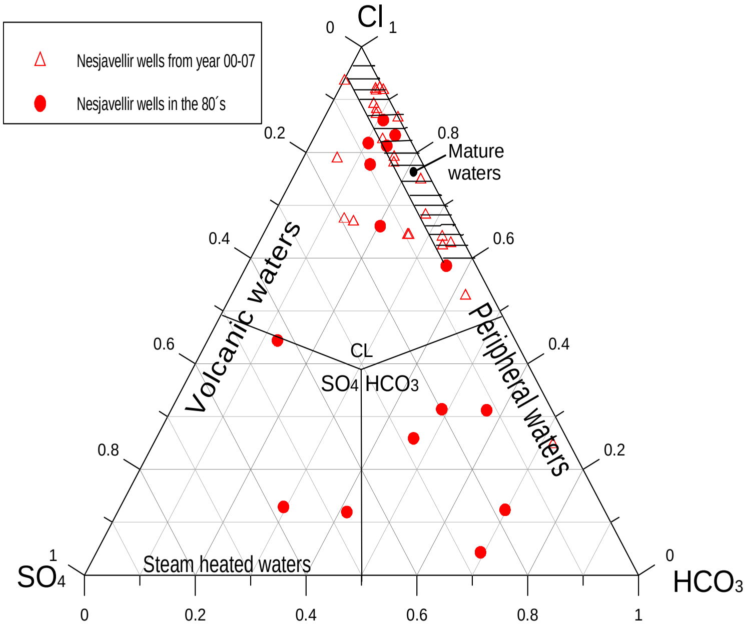

Figure:11a The nesjavellir CL-SO_4-HCO_3 diagram for Wells in the 80’s and from 00-07

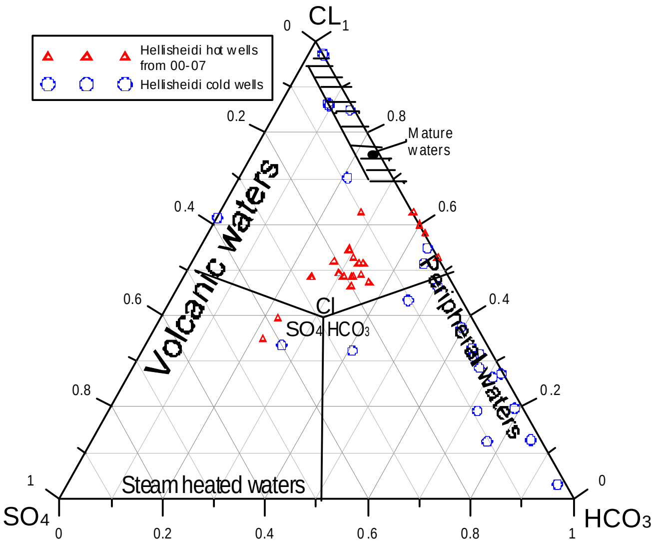

Figure 11b: The Cl-SO$_4$-HCO$_3$ diagram for the Hellisheidi field.

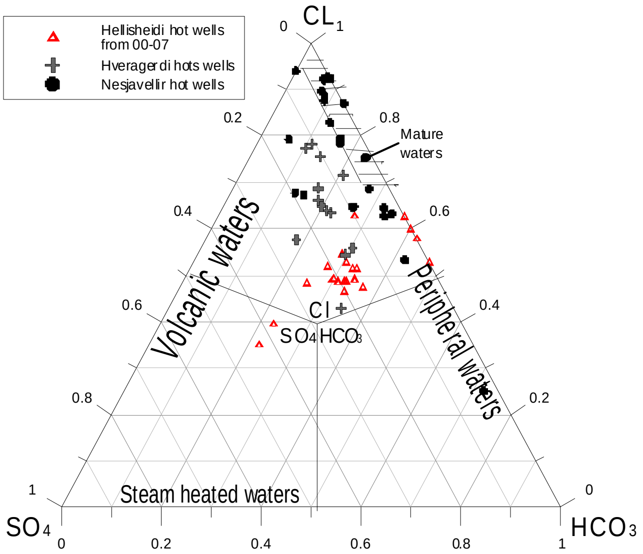

Figure 11c: The Cl-SO$_4$-HCO$_3$ diagram for the Hellisheidi field.

According to Árnason (1976) and Sveinbjornsdottir and Johnsen (1992) the geothermal water circulating in the Nesjavellir field originates as does some of the cold water in the Thingvellir area, from the glacier Longjökull ice cap the water percolates into the bedrock and flows underground to Nesjavellir field which is located south of the lake Thingvallavatn without being disturbed by the lake. The δD value of the local precipitation in Nesjavellir (-58‰) is also (SMOW) is plotted on Figure.5.So are the cold waters from Hellisheidi ranging in δ^{2}H from -60‰ to -52‰. This value is considerably higher than in the Nesjavellir thermal fluid which is between δH- 72‰ and δH -78‰ (Sveinbjörnsdottir, 1989). Water samples from drill holes and hot springs in Hveragerdi have a mean value of -65.4 ‰ which is similar to the mean value of the Hellisheidi thermal water ranging in δ^{2}H from -62‰ to δ^{2}H-65‰.While the deuterium content of the thermal fluids in Hellisheidi and Hveragerdi suggest similar origin the origin of the thermal fluid in Nesjavellir is different.

The Na-K-Mg ternary diagram provides a clue to whether geothermal water samples have been affected by mixing with ground water Samples that fall in the immature field of (Figure.10) such waters do not represent equilibrium conditions and are generally interpreted to have been affected by mixing with cold water, as Mg concentration decreases dramatically with increasing temperature (Fournier and Potter, 1982). Figure.10 shows that the cold Hellisheidi water samples plotting on the Mg corner as would be expected of these waters have not matured. Nesjavellir thermal waters from 2000-2007 and the Hellisheidi thermal waters follow a similar trend. Some samples fall in the partially equilibrated water section and some above the fully equilibrated water section. They have very little magnesium or no magnesium at all. The Hveragerdi waters plot above the full equilibrated waters line and most of the samples range in temperature from 140-100°C (Figure.10). The thermal fluids in hveragerdi are also

Cl type fluids. (Figure.11c)this can be interpreted as a mature system that is cooling.

High CO_2 gas is due to reservoir flashing, the in-situ fluid has a small concentration of dissolved CO_2. When flashed, all these CO_2 molecules will boil into the stream phase and flow rapidly to the wells downstream. That explains rise in CO_2. As the pressure stabilizes, CO_2 levels decline again. This can be seen in Nesjavellir field data (Figure.8a&8b).

Most of the wells in the Nesjavellir and Hellisheidi geothermal fields have excess enthalpy, i.e. the enthalpy of the discharged fluid is higher than that of steam saturated water at the respective aquifer temperature. This causes uncertainty as how to obtain aquifer water composition from analysis of water and steam samples collected at the wellhead. Excess enthalpy may be a consequence of several processes (Arnórsson et.al.,1991). It involves partial segregation of the water and steam phases in the depressurization zone around the wells so that the water fraction is partially retained in the aquifer, while the steam flows into the wells. 2) Processes involving flow of heat from the aquifer rock in the depressurization zone to the fluid flowing into the wells. The pressure drop causes boiling of the liquid phase, which results in cooling, and hence a positive temperature gradient is created between the aquifer rock and the flowing fluid. 3) Excess enthalpy could also be a reflection of high steam fraction of the initial aquifer fluid.

In Hellisheidi field there is no clear relationship between the $\delta^{18}O$ isotopes and enthalpy (Figure.9a&9b). However it seems that samples with high enthalpy values have low $\delta^{18}O$ values while those with low enthalpy values have $\delta^{18}O$ high values.

Ivarsson, (1998) used fumarole gas chemistry to estimate subsurface temperatures in this area, the highest temperatures were consistently found to be at the utilised Nesjavellir field, while progressively low temperatures were found at the Ölkelduhals and the Hveragerdi field. Both gas chemistry and resistivity measurements suggest that the Nesjavellir and Ölkelduhals fields are not connected at lower levels.

According to (Bjornsson et al, 2006) Hellisheidi and Nesjavellir are subfields of the Hengill system. The conceptual reservoir model suggests an upflow zone of hot fluid resides beneath the summit of the Hengill volcano. A gradual rise in temperature is observed with depth in Nesjavellir, whereas temperatures are reversed at Hellisheidi, the reversal is explained by a lateral, cooler fluid recharge from the south. The ascending fluid then flows diagonally or laterally into both the Nesjavellir and the Hellisheidi fields (Bjornsson et al, 2006). However the isotopes suggest a different story. They suggest that the fliud circulating the Nesjavellir system comes from a distant source with δ^2H ranging from -72‰-78‰ being very similar with the local precipitation at the glacier Langjökull some 100km north of Nesjaviller. The Hellisheidi thermal fluid is very similar in δ^2H to the Hveragerdi waters. There is therefore a high probability that these systems share a similar origin i.e. local precipitation.

6. CONCLUSIONS

The Nesjavellir and Hellisheidi waters do not share the same origin. In Nesjavellir the water comes from a distant source the glacier Laungjökull whereas in Hellisheidi the water is of local origin, identical to the isotopic composition of the Hveragerdi thermal water.

According to the deuterium isotope values well No.1 in Hellisheidi is closer in origin to the Nesjavellir thermal fluid than the fluid circulating the Hellisheidi system.

The Hellisheidi system is younger than the Nesjavellir system as suggested both by stable isotopes and chemistry of thermal fluids ($Cl-SO_4-HCO_3$ plot). In Nesjavellir fluid is richer in ^{18}O and chemically more mature than in Hellisheidi, due to more intense water-rock interaction. Thermal fluids in Hveragerdi are have a close origin as the Hellisheidi waters.

There is invasion of a different fluid with a high concentration of chloride ions in the Nesjavellir field, there is also increased boiling in this field generally probably in response to production.

There is a pressure drop in both fields which causes boiling of the liquid phase which results in cooling, and hence a positive temperature gradient is created between the aquifer rock and the flowing fluid. Evidence of boiling can be seen in both Nesjavellir and Hellisheidi by high CO_2 values. However boiling is more pronounced in the Hellisheidi field as indicated by the Na-K-Mg.

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Table.1 Stable istopes values (1985-1989) before utilisation of Nesjavellir(Sveinbjornsdottir,1989)

DEG_West	DEG_North	Well.No	δ^{18}O g	δ^{18}O v	Steam ratio	δ^{18}O	T sep °C	δDg	δDv	δD	T sep °C	Enthalpy(kJ/kg)	CL
-21.26683	64.10251	1	-6.6	2.8	1.0	-6.4	142.0	-79.0	-54.9	-77.8	112.0		
-21.26049	64.10364	5	-7.8	-5.1	0.8	-6.3	137.5	-74.5	-69.1	-71.5	190.5	1744.0	7.6
-21.27297	64.09665	6	-6.0	-4.0	0.4	-5.6	223.8	-75.0	-73.1	-74.8	211.3	2627.0	81.1
-21.25743	64.10570	7	-8.3	-5.6	1.0	-6.6	189.3	-79.6	-73.7	-75.9	189.5	1307.0	27.6
-21.27935	64.09556	8	-6.4	-2.6	1.0	-6.2	146.0	-63.2	-73.7	-62.8	181.0		
-21.26881	64.09461	9	-6.7	-3.4	0.8	-6.2	173.4	-75.4	-64.9	-74.3	156.5	2126.8	126.0
-21.25534	64.10032	10	-8.2	-5.7	0.4	-6.6	198.7	-80.0	-75.0	-76.9	193.0	1335.7	83.2
-21.26298	64.10735	11	-6.8	-4.2	0.9	-6.5	190.7	-74.9	-69.1	-74.3	190.3	2211.3	43.9
-21.28083	64.10386	12	-9.4	-6.8	0.4	-7.9	178.6	-78.0	-72.8	-74.9	192.3	1355.5	16.5
-21.26996	64.09879	13	-6.2	-4.0	0.8	-6.0	203.7	-75.9	-72.1	-75.3	198.9	2356.5	47.2
-21.27160	64.09048	14	-8.2	-5.2	0.4	-6.4	176.0	-79.2	-71.7	-74.9	188.0	1397.0	9.8
-21.25775	64.09675	15	-7.9	-5.5	0.5	-6.7	210.2	-74.5	-70.0	-72.3	196.4	1617.7	141.4
-21.25795	64.11096	16	-6.9	-4.3	0.8	-6.3	193.8	-76.2	-71.0	-75.0	191.4	2142.2	23.2
-21.28865	64.09969	17	10.1	-7.1	0.2	-7.8	175.0	-79.2	-70.3	-72.3	172.3	940.3	10.8
-21.25694	64.12107	18	-11.0	-7.6	0.2	-8.3	158.0	-84.3	-73.0	-75.5	162.0	916.0	11.4

TABLE 2: Nesjavellir wells from 00-07

Well No	Date	Sample No	Ps	Ave.Ps	Ts	H0	pH	/°C	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl	F
NG-5	16.3.2000	5048	15.8	15.8		1900.0	8.59	24.0	56.7	85.3	694.8	152.2	27.8	0.26	0.01	18.9	114.7	1.0
NG-6	4.10.2000	5095	16.2	16.0	195.2	2235.0	8.36	22.0		66.9	773.0	143.3	27.5	0.18	0.00		198.0	
NG-6	27.8.2004	5092	15.8			2193.0	8.75	21.8	17.8	51.1	636.9	154.5	29.3	0.28	0.01		167.5	0.7
NG-7	25.2.2000	5044	15.5	15.0		1050.0	9.18	20.2	56.2	96.4	662.0	165.2	27.4	0.38	0.00	44.1	113.0	1.3
NG-7	7.6.2006	5085	13.7			1343.0	9.02	23.6	70.9	91.7	672.9	173.2	30.6	0.56	0.02	15.6	113.7	
NG-10	25.2.2000	5045	15.5	15.5		1140.0	9.36	21.3	32.0	75.3	715.0	163.3	29.1	0.35	0.01	21	121.6	1.7
NJ-11	16.3.2000	5049	15.8	15.5		1900.0	8.76	24.1	20.8	121.0	764.7	133.4	23.8	0.39	0.00	54.2	75.5	1.1
NJ-11	28.9.2000	5094	15.5		192.8	2247.0	9.08	22.0	14.6	111.0	804.0	145.5	24.6	0.41	0.02		67.5	
NJ-13	4.10.2004	5093	16.6	16.6	196.6	1936.0	8.71	22.1	16.1	62.2	700.6	141.2	28.1	0.14	0.02		152.6	0.9
NJ-14	4.2.2000	5018	15.5	15.0		1400.0	9.27	23.0	26.0	43.6	716.0	162.8	30.2	0.27	0.00	22.7	206.7	1.3
NJ-14	22.7.2003	5117	14.0		190.7	1195.0	9.3	22.7	21.9	32.5	707.1	163.7	30.2	0.3	0.00	3	232.1	
NJ-16	16.3.2000	5050	16.2	14.1		1650.0	8.86	24.2	27.4	138.0	720.0	148.2	26.7	0.35	0.00	88.5	115.0	1.2
NJ-16	9.11.2000	5097	4.3		153.4	1520.0			17.6	112.0	791.0	154.7	27.2	0.34	0.01		94.0	
NJ-16	12.6.2006	5086	14.1			1784.0	8.82	23.1	44.5	124.0	697.6	160.3	29	0.5	0.02	33.7	88.6	
NJ-19	4.5.2000	5070	16.2			2000.0	8.05	22.0	11.0	67.6	815.3	119.1	25.1	0.09	0.00	58.8	116.3	1.1
NJ-19	8.2.2002	5034		17.4	199.8	1993.0	8.41	21.4	0.0	74.3	908.0	131.2	26.9	0.09	0.00	25.6	144.4	1.3
NJ-19	4.10.2004	5094	17.4		187.8	73.0	8.61	22.2	19.1	62.7	692.4	142.4	28	0.09	0.00		159.4	1.0
NJ-19	14.8.2006	5094	13.6			1954.0	8.43	22.6	13.7	65.9	825.8	144.7	32	0.3	0.03	6.3	152.7	
NJ-20	4.2.2000	5017	9.0	9.0		1386.0	9.02	23.1	32.3	54.6	725.0	173	31.7	0.42	0.00	27.3	173.5	0.1
NJ-21	27.3.2001	5060	14.0			2265.0	9.19	22.7	109.5	108.8	878.7	195.4	33.4	0.81	0.02	29	166.4	0.7
NJ-21	2.5.2001	5068	3.7	14.0	151.1	2627.0	9.47	22.0	217.6	11.3	1069.0	207.5	37.9	0.87	0.05	52.2	221.4	1.0
NJ-21	7.2.2002	5033			151.1	2348.0	6.18	22.0	402.8	166.4	759.0	160.9	28.1	0.36	0.01	35.9	113.2	1.4
NJ-21	27.6.2006	5090	14.0			2528.0	8.67	22.7	77.6	99.8	747.3	151.7	29.5	0.48	0.02	11.4	114.4	
NJ-22	27.3.2001	5058	14.0			1781.0	8.61	21.5	24.1	86.7	771.1	139.9	28.8	0.74	0.02	18.8	203.2	0.7
NJ-22	2.5.2001	5067	13.2	14.0	194.3	1967.0	8.71	22.0	76.5	8.8	771.9	133.4	28.4	0.26	0.01	12.5	200.7	0.7
NJ-22	7.2.2002	5032			194.8	2102.0	7.87	22.4	42.2	47.9	875.0	138.7	29.4	0.23	0.07	25.1	167.4	1.2
NJ-22	19.4.2002	5067			200	1881.0	8.85	24.3	16.9	39.4	770.0	138.5	27.9	0.16	0.01	15.1	163.2	1.2
NJ-22	29.6.2006	5091	14.2			1646.0	8.98	22.8	14.6	48.0	852.2	158.2	35.3	0.18	0.02	6.6	170.4	
NJ-23	17.3.2004	5070	6.0	6.0	163.9		7.1	22.7	106.4	255.0	763.4	159	30.6	0.62	0.09		98.3	1.4

TABLE 3: Hellisheidi wells from 00-07

Well No	Date	Sample No	Ps	Ave.Ps	Ts	H0	pH	/°C	CO2	H2S	SiO2	Na	K	Ca	Mg	SO4	Cl
HE-3	16.4.2002	5062	4.3		153.5	1199	9.14	24	18.3	14.1	736.3	218.6	32.3	4.67	0		289.8
HE-3	14.6.2002	5086	5.2	5	157.8	1330	9.32	24.6	16.4	19.3	599.4	237.7	35.1	1.81	0	44.6	316.5
HE-3	10.9.2002	5092	5.5		159.6	1396	9.37	22.6	15.2	19.6	658.4	240.1	39.6	0.99	0	22.5	333
HE-4	16.4.2002	5063	6		163.5	1234	9.46	24.3	19.4	30.5	759.2	175.9	24	1.09	0		244.3
HE-4	14.6.2002	5087	7	7.5	168.9	1226	9.58	24.9	14.6	31.4	595.8	194.7	26.3	0.77	0	37.8	228.1
HE-4	10.9.2002	5093	7.5		171.5	1358	9.49	22.7	18.4	35.6	609.4	188.1	27.1	0.6	0	19.2	206.3
HE-4	1.4.2003	5078	8.7		172	1288	9.44	23.2	13.9	39.6	648.3	187.9	25.7	0.57	0	24.3	257.1
HE-5	31.10.2002	5107	6.3		161.2	1017	9.6	21.7	83.7	18.7	561	185.8	26.8	0.61	0	39.1	115
HE-5	26.11.2002	5108	5.9		163.5	1127	9.56	21.4	77.3	26.7	582	150.1	24.5	0.79	0	22.6	125.9
HE-5	28.3.2007	5044	8.4	8.4		1194					695.9	1717.9	30	0.36	0	20.2	78.3
HE-6	11.3.2003	5064	5		158.8	1318	9.29	24				181.7	26.2	1.38	0	60.4	167.8
HE-6	19.5.2003	5101	7.2	7.2	164.9	1354	9.38	20.7	85.6	32.4	587	175.2	25.6	0.58	0	27.4	200.4
HE-6	15.7.2003	5106	6.8		165.3	1397	9.28	22.9	51.7	38.6	625.2	171.3	26.5	0.6	0.01	23.2	193.9
HE-6	12.4.2007	5047	11			1522					806.6	180.1	29.2	0.28	0.01	24.6	119.3
HE-7	18.12.2002	5109	10.4		177.9	1414	9.6	21.8	0	72.7	629	182	28.5	0.75	0.01	20.6	172.5
HE-7	11.3.2003	5065	12.5		187.1	1429	9.11	24.1				196.6	21.1	0.48	0	25.2	216.4
HE-7	19.5.2003	5102	11.5		187.6	1459	9.19	21.3	36.8	56.3	540	189.6	28.9	0.46	0.01	22.3	298.9
HE-7	15.7.2003	5105	10.5	10	182.5	1239	9.22	22.9	32.8	56	685.3	194.9	31	0.4	0.09		203.9
HE-7	30.8.2006	5097	6.5			1255				45.6	748.3	203.1	35.7	0.48	0.02	9.5	227.9
HE-7	26.4.2007	5061	10.1		181.9	1423					712.2	215.8	35.8	0.37	0	95	209.2
HE-7	17.7.2007	5117	9.3		180.5	1523					728	217.3	36.7	0.36	0.01	10.3	219.8
HE-8	23.6.2004	5072	2.4	2.4		1213	9.54	22.7	108.3	15.7	649.6	161.8	25.7	2.7	0.1		110.5
HE-9	17.11.2003	5125	7.2		166.9	2633	8.74	22.2			793.6	175.8	30	1.08	0.01		202.5
HE-9	18.4.2007	5050	9	9		2757					101.2	87.9	13	0.32	0.01	32.5	56.8
HE-11	21.10.2004	5100	14.7		191.8	1295	8.66	22	41.2	48.6	728.6	175	31.4	0.55	0.01		186.6
HE-11	6.12.2006	5133	9.8	11.56	180.1	1836			46.7	59	786.2	179.1	35.2	0.41	0	16.3	173.1
HE-11	12.4.2007	5048	11.2			1839					715.5	187.8	36.2	0.27	0	49.2	179.5
HE-12	9.3.2005	5056	11.8	11.8	189.5	1292	9.24	21.8	28	56.1	686.2	176.6	32.9	0.61	0.01		267.3
HE-13	12.5.2005	5078	5	5		965	9.67	23.2	32.4	33.2	603.4	151	23.6	1.45	0.01		125.5
HE-15	12.5.2005	5077	8.8	8.8		1174	9.35	22.8	20.7	21.5	640.5	186.1	31.7	0.62	0.01		191.7
HE-15	15.6.2005	5081	8.8			1241	9.39	24.6	17.2	47.8	651.1	189.3	32.3	0.64	0.01		195.9
HE-16	9.5.2006	5080	4.2	4.2		1124	9.32	24.4	33.6	45	622.2	201.7	31.9	1.91	0.01	23.6	193.5
HE-17	15.12.2005	5107	12			1326	9.1	23.3	29	42.6	819.2	182.9	36.2	0.39	0.01		199.8
HE-17	7.2.2006	5058	10.8			1579	8.88	23		45.9	796.8	176.8	37.8	0.33	0.05		205.5
HE-17	7.12.2006	5134	11.3	12	187.8	2533	7.95	22	39.5	72	797.5	164.2	32.9	0.69	0	15.8	170.6
HE-17	3.7.2007	5101	12.5		187.3	2319					848.7	195.9	38		0.01	8.3	203.8
HE-18	19.4.2006	5077	7.8	21		1236	9.55	22.7	35.6	37	737.7	189.4	33.6	1.37	0.1	9.7	238
HE-18	18.4.2007	5049	21			1433					119.1	190.5	32.3	0.37	0.01	10.6	157.6
HE-19	29.3.2007	5045	8.6			1584					642.3	219.4	33.7	0.57	0	10.5	207.8
HE-19	17.7.2007	5116	8.8	8.8	178.7	1560					640.6	217.1	33.6	0.56	0.01	12.4	208.8
HE-20	30.5.2006	5083	5	5		1059	8.53	23.5	102.8	44.1	550.3	235.8	32.7	5.29	0.02	37.1	228.7
HE-20	29.8.2006	5095	4.7	5		1053	8.43	23.7	99.5	44.9	579.1	236.2	32.7	3.38	0.03	50.8	230.2
HE-20	30.10.2006	5103	8			1069	8.82	23.3	103	52.3	570	232.1	32.5	3.14	0.02	41.5	223.8
HE-21	30.5.2006	5084	6	6		1885	8	23.8	39.3	8.3	975.8	262.5	59.3	0.67	0.01	5.2	400.2
HE-21	30.8.2006	5096	5.1			1815	7.87	23.7	34	6.6	1035.5	276.5	65.4	0.6	0.02	6.5	438.5
HE-22	1.12.2006	5132	3.2	3.2	140	902	9.23	23.2	24.1	47.4	442	221.4	24.7	3.16	0	73.1	217
HE-23	19.6.2007	5083	2.8	2.8		1279					508.6		171.7	0.93		37.7	111.4
HE-24	19.6.2007	5084	8	8	171.1	1918					600.1	171.7	25.6	1.22	0.01	46.2	119
HE-25	20.6.2007	5085	3.9	3.9	142.7	1310					652.5	202.1	28.9	1.1	0.01	47.3	144.6
HE-27	26.6.2007	5088	5	5	154.9	1752					598.4	227	29.4	5.7	0.01	95	202.8

TABLE:4Hellisheidi samples 2007															
Easting	**Northing**	**Sample no**	**Well no**	**18O (l)**	**DH(l)**	**18O (s)**	**DH (s)**	**Enthalpy(HO)**	**HO(I)**	**HO(s)**	**18O**	**DH**	**Ps**	**Steam ratio**	**Cl**
-21.3179	64.0561	5088	HE-27	-5.53	-59.36	-8.88	-69.34	1752.0	623.224	2744.0	-7.313	-64.672	4.50	0.532	190.25
-21.3567	64.0375	5101	HE-17	-4.89	-59.32	-7.25	-62.97	2319.0	782.979	2781.0	-6.704	-62.126	11.10	0.769	212.96
-21.3740	64.0296	5116	HE-19	-5.67	-63.64	-8.44	-68.66	1560.0	727.736	2769.8	-6.799	-65.686	8.30	0.408	198.26
-21.3581	64.0333	5117	HE-07	-5.61	-63.33	-8.16	-67.52	1523.0	746.845	2773.9	-6.586	-64.934	9.20	0.383	239.10
-21.3168	64.0432	5129	HE-11	-5.63	-62.62	-8.04	-65.49	2047.0	789.988	2782.3	-7.151	-64.431	11.50	0.631	179.50
-21.3381	64.0574	5130	HE-23	-5.9	-59.97	-9.91	-74.00	1279.0	551.462	2721.7	-7.244	-64.673	2.80	0.335	
-21.3469	64.0496	5131	HE-25	-5.97	-61.67	-9.27	-72.24	1310.0	604.723	2738.1	-7.061	-65.164	4.00	0.331	118.35
-21.3465	64.0530	5132	HE-24	-5.87	-60.94	-8.51	-67.34	1908.0	702.117	2763.9	-7.414	-64.683	7.20	0.585	116.90