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Geothermal Surface Manifestations at the Hengill Volcanic System and Neighbouring Volcanic Systems in Southwest Iceland.

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ABSTRACT

Modern geological research in the larger Hengill region dates back to the early 1960's and continues to this day. Much of this interest is associated with the utilization of the Hengill Volcanic System for electrical and space heating purposes. Two large co-generation geothermal power plants having been commissioned in the last 30 years. An intricate part of geothermal power production is geothermal surface monitoring, as well as regular gas sampling of fumaroles for reservoir temperature estimates. This has been conducted in the larger Hengill region since the early eighties and continues to this date. A large effort was made in 2007 – 2010 to map the entire region with respect to geothermal manifestations, eventually published in four large reports in 2011. The results presented here build upon these reports and include surface geothermal mapping with GPS tracking, physical measurements, gas collection, calculated reservoir temperatures, heat flux and gas flux.

1. INTRODUCTION

The larger Hengill geothermal field is a geographically continuous geothermal region with surface geothermal manifestations encompassing three volcanic systems on the southwestern volcanic zone in Iceland (Fig. 1). The Hengill volcanic system (active), the Hrómundartindur volcanic system (dormant) and the Grændalur volcanic system (extinct). Surface geothermal activity covers 60 km^2 but actual fumaroles, steaming ground, hot springs and mud pools cover less than 0,5 km^2 (less than 1%). The Hengill volcanic system has been extensively studied since the sixties using geological, geochemical and geophysical methods, especially in connection with future geothermal exploitation of the area. Two co-generation geothermal power plants (electricity and hot water for space heating), at Nesjavellir (1990) and Hellisheiði (2006), have been commissioned. Today Nesjavellir produces 120 MW_e and 300 MW_t, while Hellisheiði produces 303 MW_e and 133 MW_t.

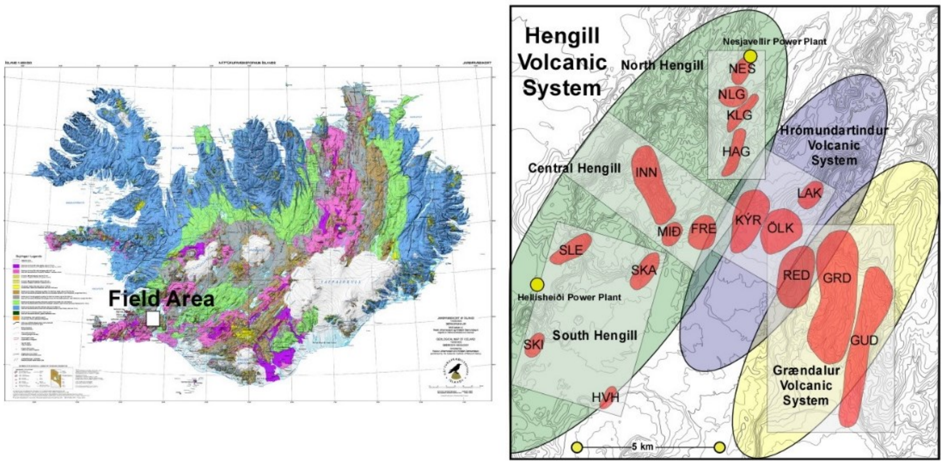

Figure 1: Field location map. The three volcanic systems are shown, as well as the subdivisions of the geothermal areas. Power stations are shown as yellow dots.

2. METHODOLOGY

The methodology used was to use handheld GPS to map all surface geothermal manifestations. Divided into fumaroles, steaming ground, springs and mud pools, all were GPS tracked, temperatures measured including soil temperatures, steam/gas samples collected and pH of water measured. Discharge was measured or estimated. The results include reservoir temperatures, based on CO_2 and H_2S geothermometers (Arnórsson and Gunnlaugsson, 1985), natural thermal heat loss and amount of gas released from geothermal areas. Considerable amount of field experiments where conducted over a period of many years to simplify a relatively complex and slow process into a viable working field methodology (Ívarsson 1996; Ívarsson 1998; Ívarsson 2006; Ívarsson 2009). The three volcanic systems were subdivided into 17 large geothermal regions and they contain more than 350 individual small geothermal fields or single springs/fumaroles (Ívarsson et al. 2011, part I, II, III and IV).

3. General Discussion

Reservoir temperatures, based on surface fumarole sampling, indicate an average temperature of 309°C (average of CO_2 and H_2S geothermometers) in the northern part of the Hengill volcanic system. The central parts of Hengill show an average temperature of 300°C and the southern part of Hengill 310°C. The Nesjavellir power plant is associated with the northern part of Hengill and the Hellisheiði power plant to the southern part. The dormant Hrómundartindur volcanic system has an average reservoir temperature of 291°C and the extinct Grændalur volcanic system an average temperature of 272°C. A small municipal district heating system is operating in the southern part of the Grændalur system and has been operating for the last 70 years.

The total area of surface geothermal manifestations mapped was 415.000 m^2. Calculated heat loss from the natural geothermal output of the whole area amounted to 360 MW_t. 75 MWt from the Hengill volcanic system, 70 MWt from the Hrómundartindur volcanic system and 210 MWt from the Grændalur volcanic system. The reason for the very high heat loss in the extinct Grændalur volcano is the earthquake on May 29th, 2008, measuring around M6.4, which caused a massive rejuvenation in the geothermal output in that area. This activity has since subsided to perhaps 30% of what it was, making the present heat loss about 63 MW_t. Compared with the heat extraction of both power plants in the Hengill Volcano of 2600 MW_t (flow rate 1660 kg/s and average enthalpy of 1570 kJ/kg), the natural heat flow of 75 MW_t is relatively miniscule. It might come as a surprise that only 10% of the heat flow from individual fields comes from strong fumaroles, 10 – 30 % from springs and mud pools and 60 – 80% from steaming or hot ground.

Gas emissions from natural geothermal fields and power stations is an environmental concern. Approximately 0,5% of the steam are non-condensable gases, consisting about 80% CO_2 and 15% H_2S in the borehole steam (the rest Ar, CH_4, H_2, N_2), but varies considerably in the natural fumaroles. CO_2 is a greenhouse gas and H_2S is a highly toxic corrosive gas. Using the calculated heat loss from natural fumaroles and measured CO_2 and H_2S in the steam it is possible to calculate the gas release from natural geothermal fields. The results show that Hengill volcano releases about 5.300 tons/year of CO_2 and 400 tons/year of H_2S through naturally occurring geothermal manifestations. Comparing that with the two power stations at Hengill volcano, combined they extract 50.000 tons/year of CO_2 and 16.000 tons/year of H_2S, of which 12.000 tons/year CO_2 and 7.000 tons/year of H_2S is being presently reinjected into the geothermal field again. Comparing the gas flux between the power plants and natural output, nature is only a few percent of the total gas output. For the other two volcanic systems in the larger Hengill region, Hrómundartindur natural gas flux amounts to 4.100 tons/year of CO_2 and 100 tons/year of H_2S, and Grændalur to 1.600 tons/year of CO_2 and 40 tons/year of H_2S.

Decades of monitoring natural surface geothermal manifestations have taught us that natural changes occur both with the slow progress of time and in almost immediate responses to earthquakes. In our experience shallow earthquakes under the size 5 tend to have little or no effect on the geothermal field. Larger earthquakes generate large fracture that penetrate deep into the reservoir, allowing acid fluids to ascend to the surface. In some cases up to two years passed before the full effects of the earthquake had materialized on the surface as geothermal activity. Most of the activity then subsides to normal within the next 5 to 10 years.

Power plants can easily affect nearby geothermal fields or generate new ones. This is usually due to aggressive steam extraction, causing a rapid pressure drop in the geothermal reservoir and resulting in boiling, possibly creating a steam pillow at shallow levels. This can increase the activity in preexisting geothermal areas or create new ones. This steam usually does not contain an acidic deep rooted component. This process is now occurring in two locations at the Hengill volcano and both are due to power production.

Figure 2: Part of Hagavíkurlaugar field (HAG) showing, side by side, a shallow source mineral spring (center) and deep source fumaloes (left). Picture by Gretar Ívarsson, May 28th 2018.

4. HENGILL VOLCANIC SYSTEM

The Hengill volcanic system consists of the central volcano Hengill and a 50 km long fissure swarm running through it from south-southwest to north-northeast (Sinton et al. 2005). Three basaltic eruptions have occurred on the fissure swarm on both sides of the Hengill central volcano in postglacial times, forming extensive lava fields, albeit of relatively small volume. No eruption has occurred in the Hengill volcano massif itself in the last 12.000 years. Both geothermal power stations, at Nesjavellir and Hellisheiði, have their production fields on the fissure swarm on the northeastern and southwestern perimeter of the central volcano where recent activity has occurred. The heat source is apparently shallow magmatic intrusions related to these surface eruptions and other intrusive events. The western part of the fissure swarm has been more productive in the last 8.000 years, but prior to that in fini-glacial times (8 – 12.000 years ago) the eastern part was more productive, producing two shield volcanoes. This recent shift in activity is reflected in slightly lower reservoir temperatures in eastern part of the Hengill volcanic system compared to the western part.

4.1 North Hengill

The north Hengill region is divided into 4 subsections, Nesjavellir (NES), Nesjalaugagil (NLG), Köldulaugagil (KLG) and Hagavíkurlaugar (HAG). The first three are utilized by the Nesjavellir power plant and represent the area of the most recent volcanic activity. The fourth belong a slightly older volcanic swarm and has yet to be fully researched. Reservoir temperature average 309°C (302 – 317°C), surface manifestations cover 58.000 m^2 with an estimated heat loss of 52 MW$_t$. Nesjavellir power plant extracts 750 MW$_t$, so the surrounding natural geothermal manifestations only emit 7% compared to the power plant. The calculated CO_2 and H_2S emission from the natural field is approximately 3.100 ton/year and 290 ton/year, respectively. Comparing this to the emissions from the Nesjavellir power plant of 14.000 ton/year CO_2 and 7000 ton/year H_2S this only amounts to 22% and 4%, respectively.

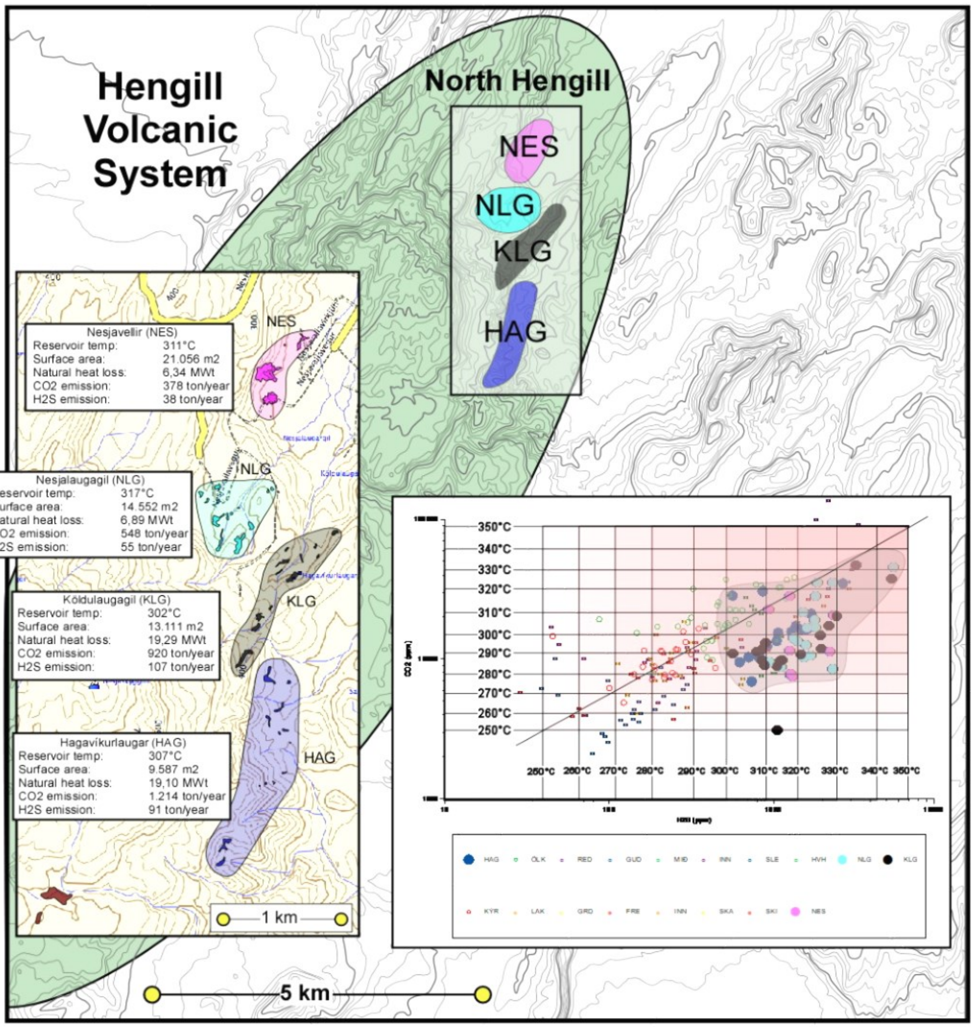

Figure 3: North Hengill surface geothermal manifestations. Insert shows more details and info on calculated reservoir temperature, surface area, heat loss, CO_2 and H_2S emissions for each section. Chemical insert shows CO_2/H_2S concentrations on log scale and calculated reservoir temperature. Shaded area represents north Hengill samples.

Figure 4: Nesjavellir power plant and parts of the NES, NLG and KLG geothermal fields. Picture by Gretar Ívarsson, August 25th 2010.

4.2 Central Hengill

The central Hengill region is divided into 3 subsections, Innstidalur (INN), Miðdalur (MIÐ) and Fremstidalur (FRE). Reservoir temperature average 307°C (278 – 333°C), the highest temperatures being connected with the recently more active westerly part of the Hengill volcanic system. Surface manifestations cover 33.000 m^2 with an estimated heat loss of 18 MW_t. The calculated CO_2 and H_2S emission from the natural field is approximately 1.900 ton/year and 80 ton/year, respectively.

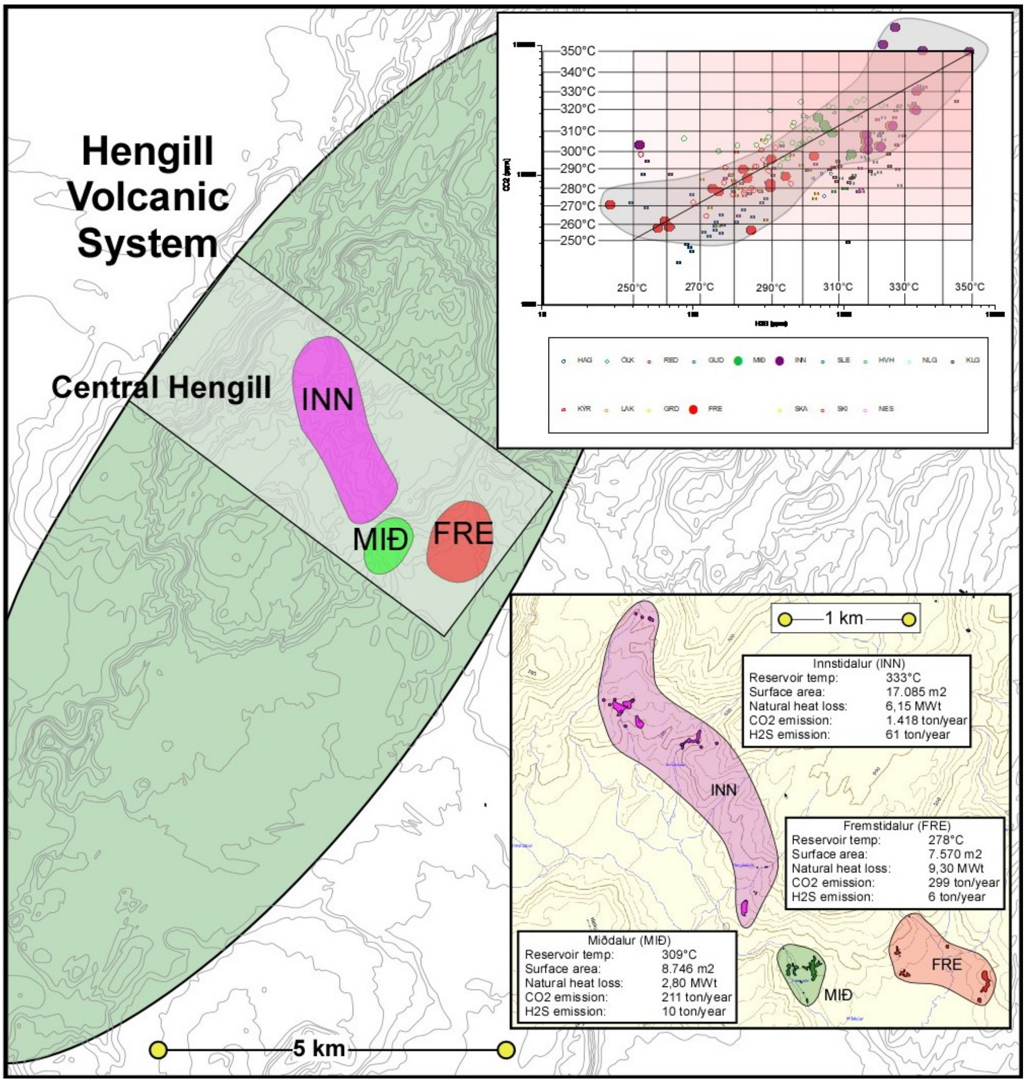

Figure 5: Central Hengill surface geothermal manifestations. Insert shows more details and info on calculated reservoir temperature, surface area, heat loss, CO_2 and H_2S emissions for each section. Chemical insert shows CO_2/H_2S concentrations on log scale and calculated reservoir temperature. Shaded area represents central Hengill samples.

Figure 6: Part of Innstidalur (INN) geothermal field. Picture by Gretar Ívarsson, July 17th 2018.

4.3 South Hengill

The south Hengill region is divided into 4 subsections, Sleggjubeinsdalur (SLE), Skarðsmýrarfjall (SKA), Skíðaskáli (SKI) and Hverahlíð (HVH). The two western areas reflect the area of the most recent volcanic activity, while the other two represent the older postglacial volcanic activity. Reservoir temperature average 308°C (295 – 323°C), surface manifestations cover 15.600 m^2 with an estimated heat loss of 6 MW_t. The calculated CO_2 and H_2S emission from the natural field is approximately 300 ton/year and 30 ton/year, respectively.

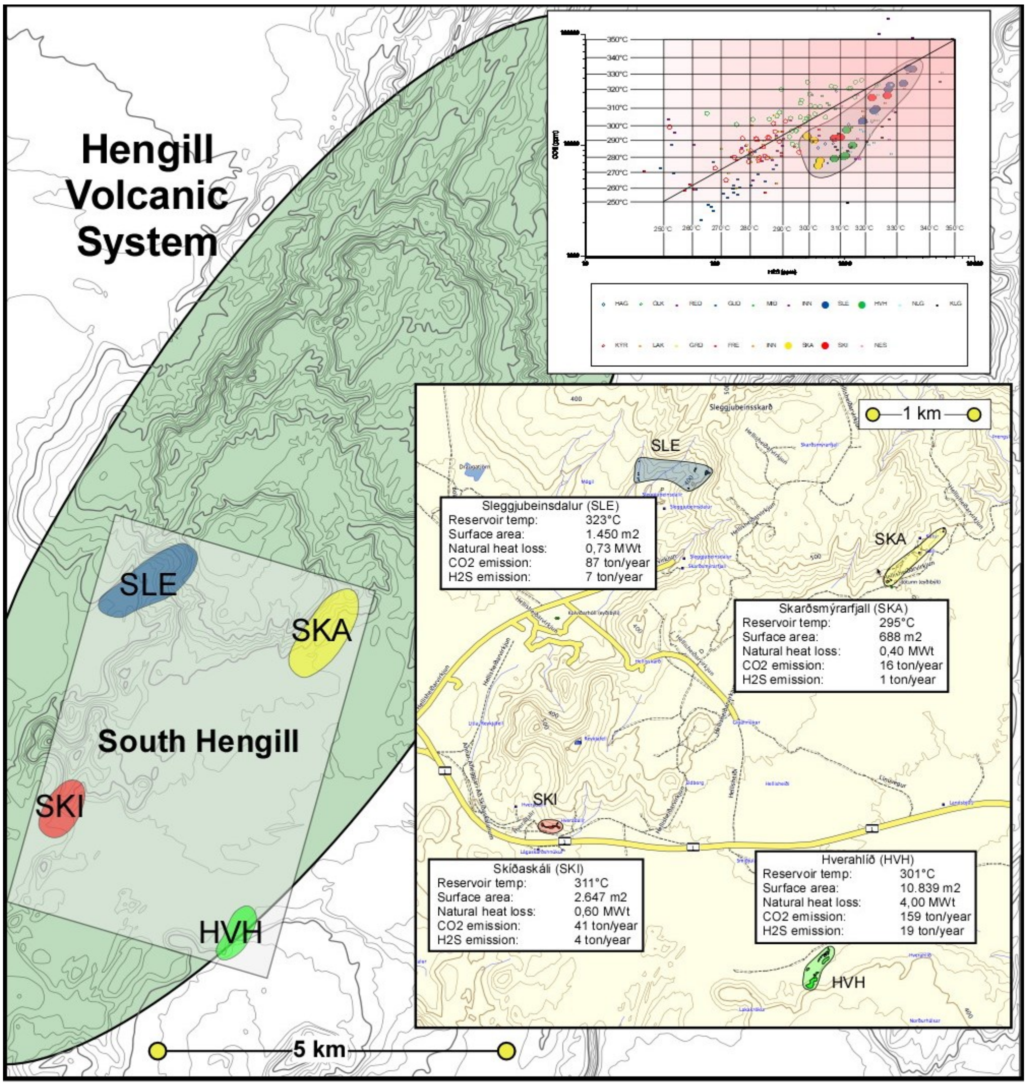

Figure 7: South Hengill surface geothermal manifestations. Insert shows more details and info on calculated reservoir temperature, surface area, heat loss, CO_2 and H_2S emissions for each section. Chemical insert shows CO_2/H_2S concentrations on log scale and calculated reservoir temperature. Shaded area represents south Hengill samples.

Figure 8: Aerial view of the Hverahlíð (HVH) geothermal field (lower right) on the perimeter of the Skálafell fini-glacial shield volcano. Picture by Gretar Ívarsson, August 29th 2016.

5. HRÓMUNDARTINDUR VOLCANIC SYSTEM

The Hrómundartindur volcanic system is divided into 3 subsections, Kýrgil (KÝR), Ölkelduháls (ÖLK) and Lakaskörð (LAK). The dormant system was last volcanologically active about 9 – 11.000 years ago and modern geothermal surface manifestations in ÖLK and LAK closely follow this activity. An earthquake swarm in 1994-1998 with more than 12.000 registered earthquakes, indicates magmatic intrusions at 8 km depth, but with no apparent effect on the surface activity nor chemical composition of fumaroles. Reservoir temperature average 290°C (282 – 301°C), surface manifestations cover 60.000 m^2 with an estimated heat loss of 70 MW$_t$. The calculated CO_2 and H_2S emission from the natural field is approximately 4.100 ton/year and 100 ton/year, respectively.

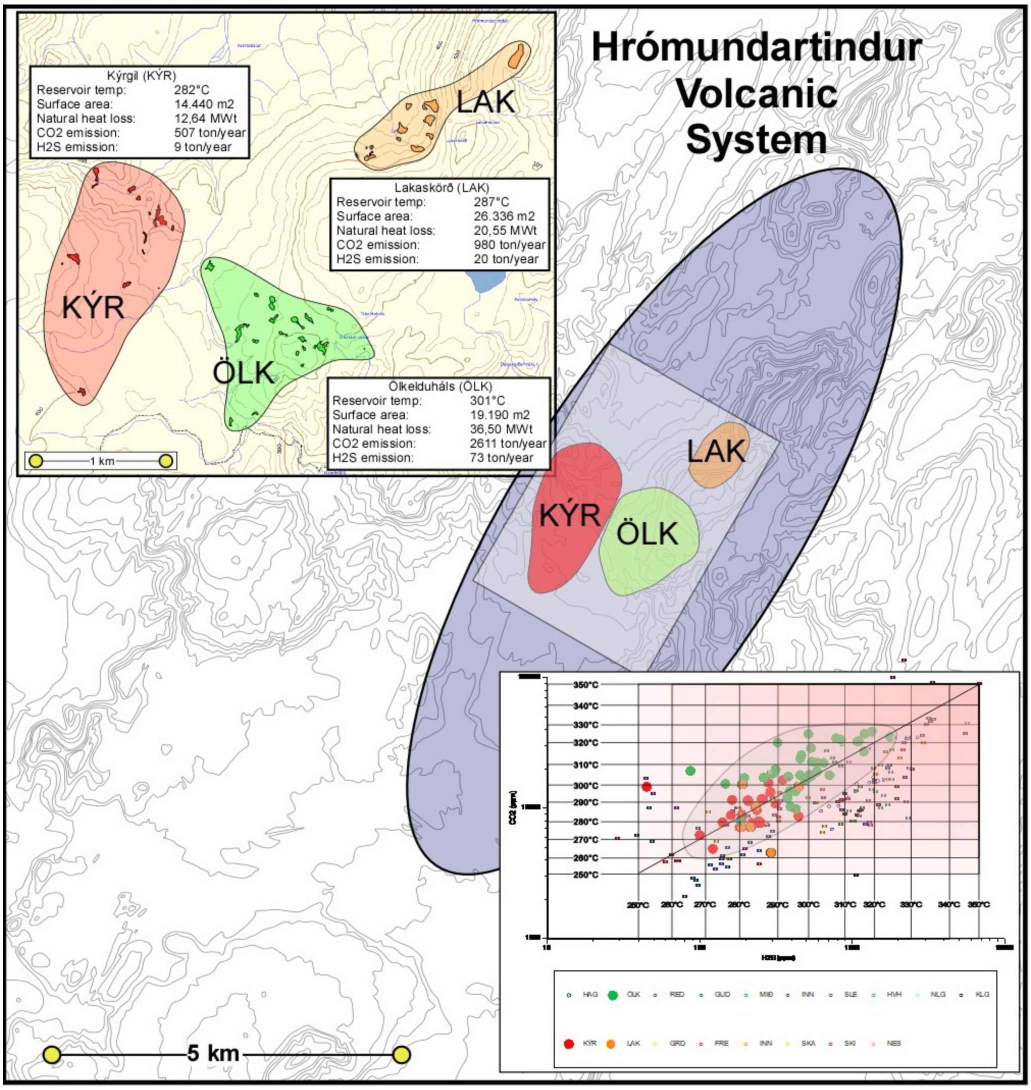

Figure 9: Hrómundartindur surface geothermal manifestations. Insert shows more details and info on calculated reservoir temperature, surface area, heat loss, CO_2 and H_2S emissions for each section. Chemical insert shows CO_2/H_2S concentrations on log scale and calculated reservoir temperature. Shaded area represents Hrómundartindur samples.

Figure 10: Ölkelduháls geothermal field (ÖLK). Picture by Gretar Ívarsson, September 5th 2013.

6. GRÆNDALUR VOLCANIC SYSTEM

The Grændalur volcanic system is divided into 3 subsections, Reykjadalur (RED), Grændalur (GRD) and Gufudalur (GUD). This area has not experienced any postglacial volcanic activity, is extensively eroded and considered to be extinct. Reservoir temperature average 274°C (261 – 287°C), surface manifestations cover 25.000 m^2 with an estimated heat loss of 59 MW$_t$. The calculated CO_2 and H_2S emission from the natural field is approximately 1.600 ton/year and 40 ton/year, respectively.

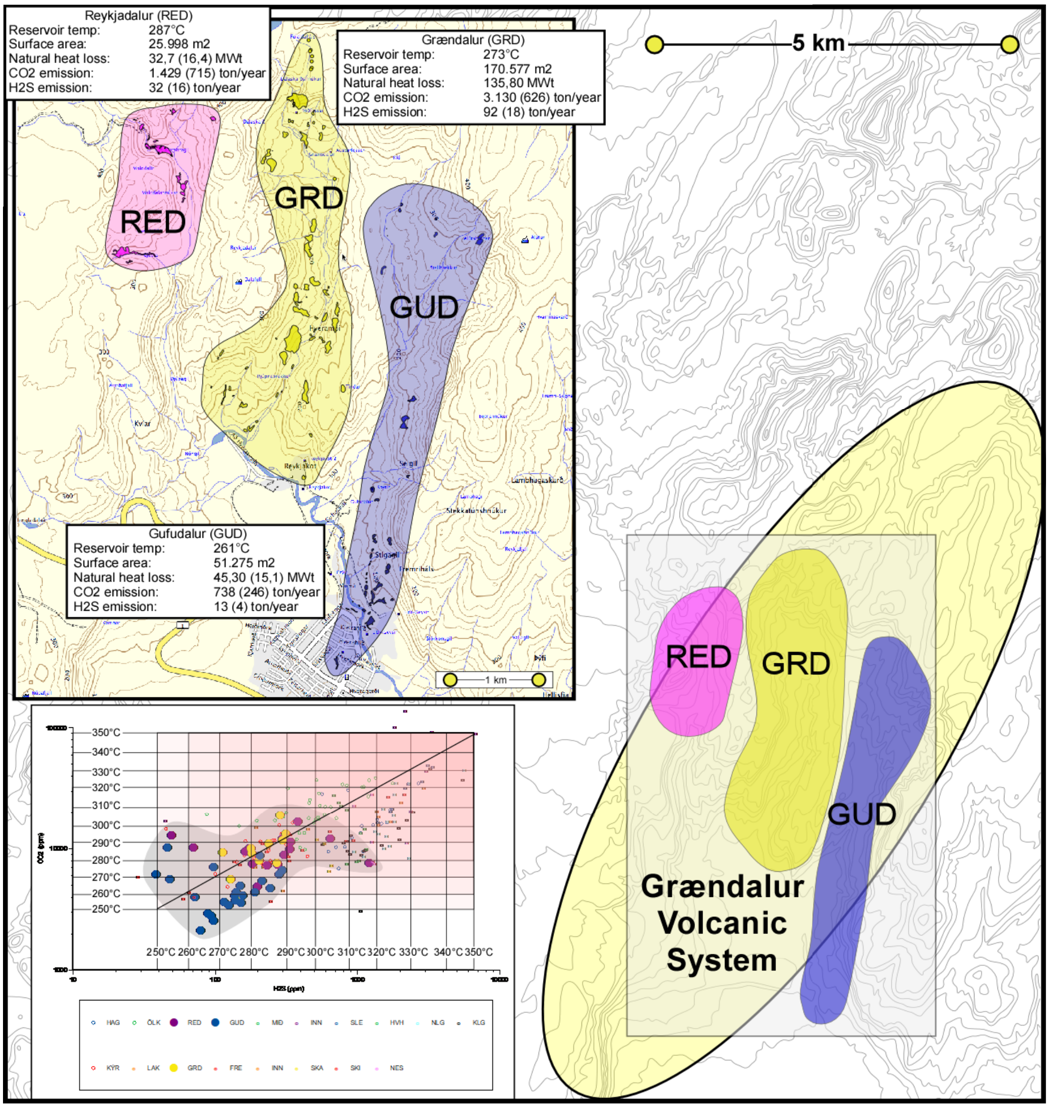

Figure 11: Grændalur volcanic system surface geothermal manifestations. Insert shows more details and info on calculated reservoir temperature, surface area, heat loss, CO_2 and H_2S emissions for each section. Chemical insert shows CO_2/H_2S concentrations on log scale and calculated reservoir temperature. Shaded area represents Grændalur samples.

Figure 12: Grændalur (GRD) to the left and Gufudalur (GUD)to the right. Picture by Gretar Ívarsson, August 30th 2012.

4. CONCLUSION

The Hengill volcanic system consists of the central volcano Hengill and a 50 km long fissure swarm running through it from south-southwest to north-northeast (Sinton et al. 2005). Three basaltic eruptions have occurred on the fissure swarm on both sides of the Hengill central volcano in postglacial times, forming extensive lava fields, albeit of relatively small volume. No eruption has occurred in the Hengill volcano massif itself in the last 12.000 years. Both geothermal power stations, at Nesjavellir and Hellisheiði, have their production fields on the fissure swarm on the northeastern and southwestern perimeter of the central volcano where recent activity has occurred. The heat source is apparently shallow magmatic intrusions related to these surface eruptions and other intrusive events. The western part of the fissure swarm has been more productive in the last 8.000 years, but prior to that in fini-glacial times (8 – 12.000 years ago) the eastern part was more productive, producing two shield volcanoes. This recent shift in activity is reflected in slightly lower reservoir temperatures in eastern part of the Hengill volcanic system compared to the western part.

The results are summarized in the last two figures (Fig. 13 and 14). The highest reservoir temperatures are recorded in the present day active Hengill volcanic system (305-310°C), especially in its western part (310-330°C) where volcanic activity has concentrated in the last 8.000 years. It´s eastern part was more active prior the that and today records lower reservoir temperatures (278 -307°C). The dormant Hrómundartindur, not active since fini-glacial times, has still lower reservoir temperatures (282-301°C°C) and the extinct Grændalur between 261-287°C.

The reservoir temperature does not necessary reflect the amount of surface geothermal manifestations, its heat flux or gas flux. Two other functions can overshadow the temperature effect, and that's surface geology and tectonic activity. The Grændalur volcanic system experienced a shallow M6.4 earthquake on May 29th 2008. This earthquake totally changed the complexity of the neighboring geothermal fields, releasing deep seated geothermal fluids into the upper crust and to the surface. This increased the heat and gas flux by some unknown factor but had no effect on the gas geochemistry or calculated temperature. Later estimates have lowered the original heat and gas flux to more represent the situation today and prior to the earthquake in 2008. These revised estimates are given in parentheses for the Grændalur volcanic system. Neither Hengill nor Hrómundartindur geothermal fields were affected by the earthquake. Apart from tectonic movements surface geology affects where geothermal manifestations are found. Porous lava flows tend not to develop geothermal fields, probably due the large inflow of cold groundwater that condenses uprising geothermal fluids, while older subglacial hyaloclastites, being non-porous, commonly develop powerful "everlasting" geothermal fields. The lack of surface geothermal manifestations, therefore, does not exclude a geothermal reservoir below.

Figure 14 compares the natural gas flux from the three volcanic systems and compares them to the two geothermal power stations at Nesjavellir (120 MW_e and 300 MW_t) and Hellisheiði (300 MW_e and 133 MW_t), both on the perimeter of the Hengill central volcano. Natural surface geothermal manifestations at Hengill volcanic system only release about 10% of the CO_2 compared to the two power stations and 3% of the H_2S. Apparently the more reactive H_2S-gas has a more difficult time reaching the surface in fumaroles than CO_2 and therefore gives a lower percentage. While geothermal power plants have a relatively small environmental atmospheric impact compared with many other means of energy production, they, at least in the case of Hengill, dominate the gas flux compared to the natural geothermal field.

Volcanic System	Locality	Surface Geothermal Manifestation (m^2)	Calculated Heat loss (MW_t)	Calculated Average Reservoir temp (°C)	Calculated CO_2 loss (ton/year)	Calculated H_2S loss (ton/year)
North Hengill	Nesjavellir (NES)	21056	6,34	311	378	38
	Nesjalaugagil (NLG)	14552	6,89	317	548	55
	Köldulaugagil (KLG)	13111	19,29	302	920	107
	Hagavíkurlaugar (HAG)	9587	19,10	307	1214	91
	Sum/Avr	**58306**	**51,62**	**309**	**3060**	**291**
Central Hengill	Fremstidalur (FRE)	7570	9,30	278	299	6
	Miðdalur (MIÐ)	8746	2,80	309	211	10
	Innstidalur (INN)	17085	6,15	333	1418	61
	Sum/Avr	**33401**	**18,25**	**307**	**1928**	**77**
South Hengill	Sleggjubeinsdalur (SLE)	1450	0,73	323	87	7
	Skarðsmýrarfjall (SKA)	688	0,40	295	16	1
	Skíðaskáli (SKI)	2647	0,60	311	41	4
	Hverahlíð (HVH)	10839	4,00	301	159	19
	Sum/Avr	**15624**	**5,73**	**308**	**303**	**31**
Hrómundartindur	Lakaskörð (LAK)	26336	20,55	287	980	20
	Ölkelduháls (ÖLK)	19190	36,50	301	2611	73
	Kýrgil (KÝR)	14440	12,64	282	507	9
	Sum/Avr	**59966**	**69,69**	**290**	**4098**	**102**
Grændalur	Reykjadalur (RED)	25998	32,7 (16,4)	287	1429 (715)	32 (16)
	Grændalur (GRD)	170577	135,8 (27,2)	273	3130 (626)	92 (18)
	Gufudalur (GUD)	51275	45,3 (15,1)	261	738 (246)	13 (4)
	Sum/Avr	**247850**	**213,8 (58,7)**	**274**	**5297 (1587)**	**137 (38)**
	Sum	**415200**	**359,1 (203,9)**	**294**	**14686 (10976)**	**637 (538)**

Figure 13: Surface area, calculated heat loss, average reservoir temperature and calculated CO_2/H_2S gas flux. For Grændalur volcanic system the numbers in parentheses are recent estimates following rejuvenated activity after the earthquake 2008.

	Calculated CO_2 loss (ton/year)	Calculated H_2S loss (ton/year)
Hengilll Volcanic System	5300	400
Hrómundartindur Volcanic System	4100	100
Grændalur Volcanic System	1600	40
SUM	11000	540
Nesjavellir Power Plant	14000	7000
Hellisheiði Power Plant	37000	9000
SUM	51000	16000

Figure 14: Natural gas flux from the three volcanic systems compared with the two geothermal plants.

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