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CO_2 EMISSIONS FROM THE KRAFLA GEOTHERMAL AREA, ICELAND

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ABSTRACT

Geothermal resource utilization, although widely accepted as a clean energy source, has also contributed to a decrease in air quality due to hydrogen sulphide and carbon dioxide emissions. Several studies have shown that CO_2 emissions from geothermal/volcanic systems occur naturally and in some cases these natural emissions exceed the amount of CO_2 emitted from the geothermal power plant utilizing the geothermal resource. This study was carried out to quantify the natural CO_2 soil flux emissions from the Krafla geothermal field, identify the relationship between soil gas emission and the structural geology, and compare the results to the CO_2 emissions from the Krafla power plant. The results of this study show that the total CO_2 flux from soil degassing is approximately 14.13 tons/day for a survey area of 2.5 km^2, a positive correlation between CO_2 soil flux emissions and the structural geology of the area. CO_2 emission from natural sources exceeds the emission from the power plant by approximately 3 times.

1. INTRODUCTION

1.1 Background

Geothermal resource utilization in Iceland has shown significant benefits in the form of supplying clean, renewable energy and has made the country´s capital, Reykjavik, one of the cleanest cities in the world. Although widely accepted as a clean energy source, geothermal utilization, especially high-temperature utilization for generating electricity, has contributed to decreasing air quality due to hydrogen sulphide and carbon dioxide emissions despite the fact that these are much lower than emissions from fossil fuel combustion power plants (Giroud and Arnórsson, 2005). The latter is known as a greenhouse gas and with the implementation of the Kyoto protocol and awareness of global warming becoming stronger amongst environmentalists and the general public on a global scale, this issue has become more important. Several studies have shown that CO_2 emissions from geothermal/volcanic systems occur naturally and, in some cases, these natural emissions exceed the amount of CO_2 emitted from the geothermal power plant utilizing the geothermal resource (e.g., Seaward and Kerrick, 1996; Delgado et.al., 1998; Bertani and Thain, 2002). A study in the Lardarello field in Italy has shown a noticeable and measurable decrease in the natural release of CO_2 from the ground as a result of geothermal power development (Bertani and Thain, 2002), while a study in New Zealand has shown that the exploitation of the Wairakei system significantly increased diffuse surface heat flow which, if heat flow is considered as a proxy for CO_2 emissions, could lead to conclusions that exploitation has increased natural CO_2 emissions (Sheppard and Mroczek, 2004). The conclusion of a study in the Reykjanes geothermal area in SW-Iceland was that the planned power plant (which is now operating) will significantly increase CO_2 emissions from the geothermal system (Fridriksson et al., 2006). In addition, they found that the natural emissions were predominantly soil diffuse emissions (Table 1) as had been suggested by other workers in other areas (e.g. Favara et al., 2001; Sorey et al., 1998; Evans et al., 2002; Gerlach et al., 2001). Studies of CO_2 emissions from geothermal power plants and natural geothermal activity in Iceland have also been conducted by Ármannsson et al. (2005), as shown in Table 2.

TABLE 1: Reykjanes, SW-Iceland, different conduits (modified from Fridriksson et al., 2006)

	CO_2 (tons/day)	Steam (tons/day)	Heat flow (MW)
Soil	13.5	4150	108
Steam vents	0.23	72	1.9
Steam heated pools	0.15	46	1.2

CO_2: Soil – 97.3%; Steam vents – 1.6%; Pools – 1.1%

TABLE 2: CO_2 and S (expressed as SO_2) emissions per kWh from Iceland´s major geothermal power plants in 2000 (Ármannsson et al., 2005)

Plant	**From electricity generation only**		**From electricity and heat production**	
	CO_2 ($gkWh^{-1}$)	**S as SO_2 ($gkWh^{-1}$)**	**CO_2 ($gkWh^{-1}$)**	**S as SO_2 ($gkWh^{-1}$)**
Krafla	152	23	152	23
Svartsengi	181	6	74	2
Nesjavellir	26	21	10	8

So, summing up these studies, there is still some controversy on this issue. We could say that different areas will show different behaviour in CO_2 emissions affected by geothermal utilisation and they should be assessed for each area. The main controversy is whether the emissions from geothermal plants is an addition of gas to the atmosphere or whether they are just a transfer from natural emissions to plant emissions. There is some evidence that in vapour-dominated systems the emissions are large to start with but then will decrease and, if averaged over some years, they can be treated as just a transfer; the same does not apply to liquid-dominated systems. Ármannsson and Fridriksson (2008) presented results for CO_2 emissions from two geothermal plants, Krafla and Svartsengi, along with the total emissions from all geothermal plants in Iceland (Figure 1).

In the early 1990s a steam pillow had developed in the Svartsengi area and CO_2 emissions had increased substantially. In 1996, however, the gas emissions were waning again despite continued production. In 1998-2000 more wells were drilled into the steam pillow and a substantial increase in gas emissions was observed. By 2003 the emissions had decreased again. In Krafla several wells were drilled in 1997-1999 to increase the installed power of the power plant from 30 to 60 MW.

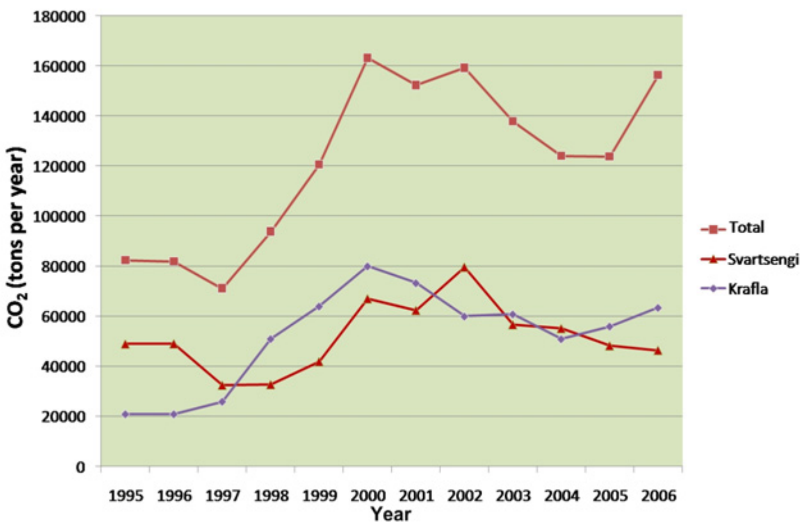

FIGURE 1: CO_2 from Icelandic geothermal plants 1995-2006 (Ármannsson and Fridriksson, 2008)

Most of the wells were high-enthalpy or close to being vapour-dominated. This resulted in a considerable gas increase; this decreased in 2003 although production had not been decreased. This supports the view that the gas content of high-enthalpy steam will decrease after an initial increase. The increase observed for the total emissions from geothermal plants in Iceland in 2006 is due to the commissioning of two new geothermal power plants, Hellisheidi and Reykjanes.

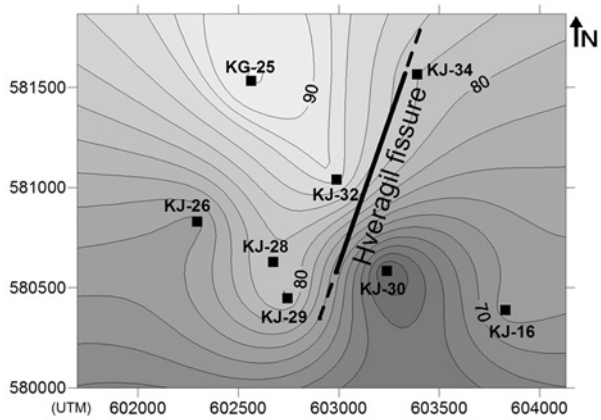

FIGURE 2: Krafla CO_2 fixed in bedrock in tons/m^2 (Ármannsson et al., 2007)

Ármannsson et al. (2007) studied the concentration of carbonate in cuttings from the drilled part of the Krafla area and obtained an apparently inverse relationship between the amount of carbonate fixed in rock and soil diffuse CO_2 emissions, also suggesting that a substantial part of the CO_2 flux from the magma is bound in the rocks close to the surface (Figure 2).

1.2 CO_2 emissions from the Krafla geothermal area

The Krafla geothermal area is located within the neovolcanic zone in NE-Iceland (Figure 3). It consists of the Krafla central volcano and a 100 km long N-S transecting fissure swarm. It has a 10 km wide caldera that was formed about 100,000 years ago by a violent rhyolitic tuff-forming eruption. Krafla has been the source of many rifting and eruptive events during the Holocene, including two in historical time. The Mývatnseldar eruptions (the "Mývatn fires") in 1724 began with a great volcanic explosion which formed the crater Víti. In the following years, a series of earthquakes and eruptions occurred in the vicinity of Krafla mountain. The greatest eruption took place in 1729, when lava flowed from Leirhnjúkur mountain down to Mývatn lake. Eldhraun is the name of the lava field formed during the eruptions. This system was last active between 1975 and 1984 when lava erupted from, and to the north of, the central volcano, and dykes were injected along most of the fissure zone (Saemundsson, 1991; Björnsson et al., 1979). This event is now known as the Krafla fires, and it significantly increased the gas emissions (dominantly CO_2) from the area due to magmatic intrusion.

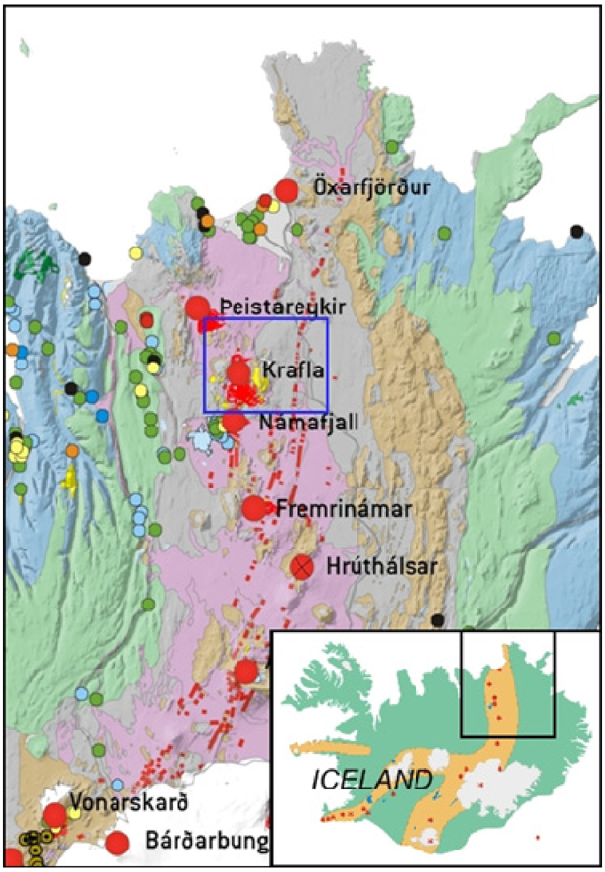

FIGURE 3: Map of the Krafla geothermal area

Drilling started in Krafla in 1974 but the power plant was commissioned in 1978, then only producing 7 MW. Drilling was halted due to the Krafla fires but was resumed in 1980 until 1982 after which the plant produced 30 MW (Ármannsson et al., 1987). The second turbine was commissioned in 1999 after which the plant has produced 60 MW (Júlíusson et al., 2005).

Some wells in the Leirbotnar field, which in the beginning of the Krafla fires was the only field that had been drilled, were blocked due to the formation of deposits of pyrite and pyrrhotite in the course of the magmatic gas passage to the surface. The gas concentration has been carefully monitored and the pattern has been similar for wells in the affected Leirbotnar field, i.e. a maximum in 1977/1978, a secondary maximum in 1980 and a steady decline since (Figure 4). In Figure 4, changes that were first observed in well 3 were, subsequent to that well's collapse, followed in nearby well 7, both wells being in the Leirbotnar field (Ármannsson et al., 1989).

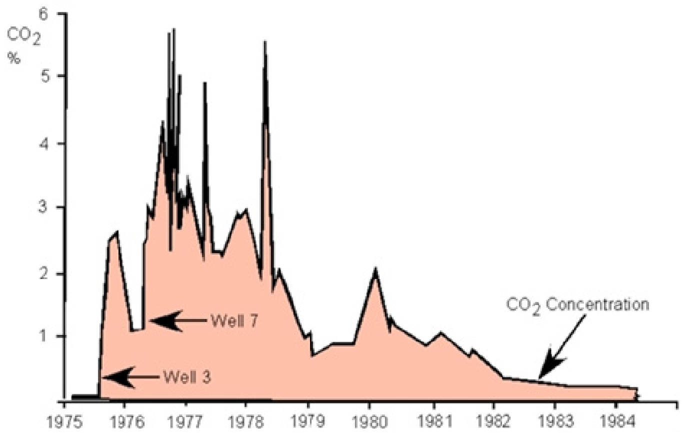

FIGURE 4: Changes in CO_2 concentrations in well 3 and later neighbouring well 7 during the Krafla fires 1975-1984

In a previous study of the CO_2 budget of the Krafla geothermal system carried out by Ármannsson et al. (2007), soil CO_2 flux emissions and CO_2 concentration in drill cuttings were determined. The result of their study showed that the mean flux of the geothermal population is about 115 g/m^{2}day and emanates from about 10% of the total area. The total CO_2 flux from the eastern Krafla caldera is about 120 kton/yr and about 70% of that is of geothermal origin (Ármannsson et al., 2007).

In this study, the research area is north and west of where Ármannsson et al. (2007) had already collected data, now extended by an additional area of approximately 1 km^2. In the area of study, only CO_2 soil flux was taken into account since there were no boreholes present there. It is hoped that the results of this study will complement the previous study and show the relationship between soil gas emissions and the structural geology of the Krafla geothermal area.

2. METHODOLOGY

2.1 CO_2 flux measurements

The CO_2 flux measurements are carried out directly with a closed-chamber CO_2 flux meter from West Systems. The flux meter is equipped with a LICOR LI-820 single-path, dual wavelength, non-dispersive infrared gas analyser (Figure 5). The flux meter has a 3.06×10^{-3} m^3 internal volume. The flux measurement is based

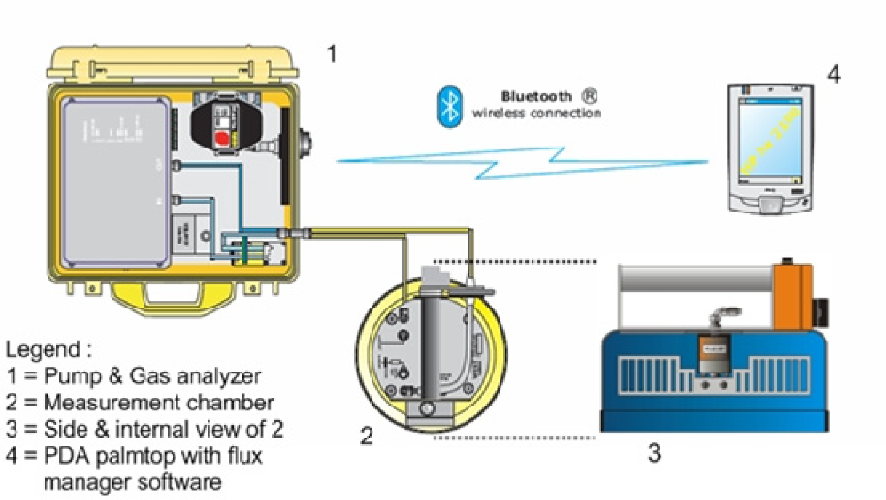

FIGURE 5: Flux meter from West systems (model)

on the rate of CO_2 increase in the chamber; the measurement lasts for approximately 2 minutes at each location.

CO_2 flux through soil was measured over a rectangular grid with intervals of 25 m N-S and 50 m E-W with some exclusion in areas not suitable for measurement. Data from previous measurements were also included in the analysis, comprising a total area of 2.5 km^2 and 3095 measurement points (Figure 6).

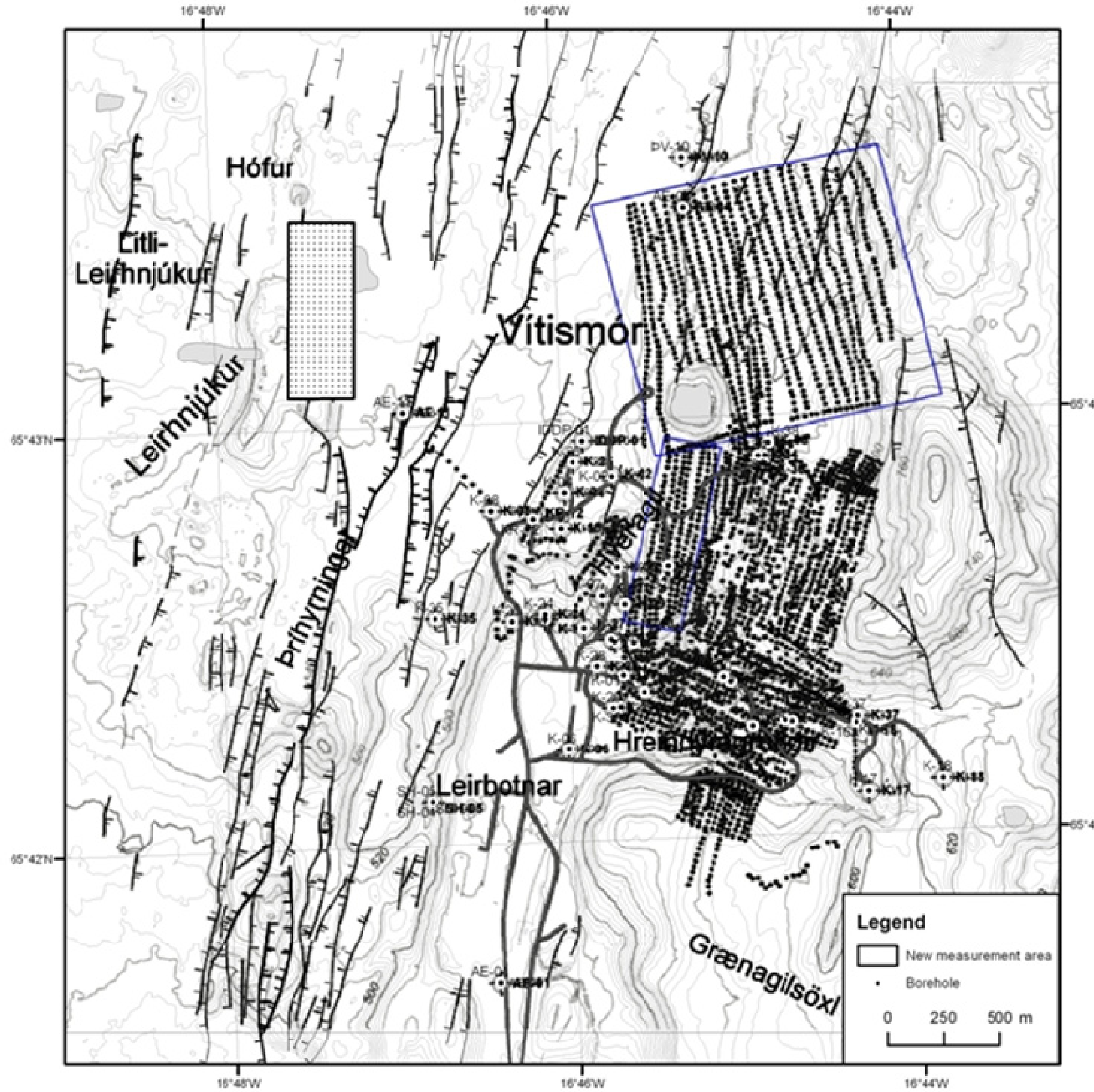

FIGURE 6: CO_2 flux measurement points in the Krafla geothermal area

Figure 7 shows typical results of a CO_2-soil flux measurement. Initially, the CO_2 concentration inside the cell is constant at about 700 to 900 ppm, but after approximately 40 seconds the CO_2 concentration starts to increase linearly with time. The slope of the curve defined by the CO_2 concentration as a function of time is a measure of the CO_2 flux through the soil. Other parameters that need to be accounted for when evaluating the flux from the concentration as a function of time are temperature inside the chamber, air pressure and the internal volume of the system.

The relationship between these parameters and the flux is defined by the following equation:

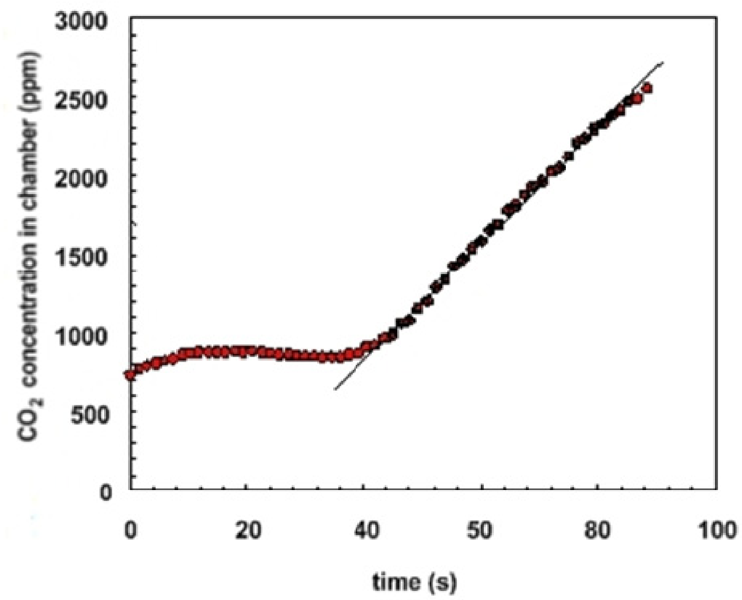

FIGURE 7: Typical raw data from a soil flux measurement

$$K = \frac{86400 \cdot P}{10^6 \cdot R \cdot T_k} \cdot \frac{V}{A} \tag{1}$$

where K = Accumulation chamber factor;
P = Barometric pressure [mBar (HPa)];
R = Gas constant [0.08314510 bar $LK^{-1}mol^{-1}$];
T_k = Air temperature [Kelvin];
V = Chamber net volume [m^3];
A = Chamber inlet net area [m^2].

The dimensions of K are:

$$K = \frac{moles \cdot meter^{-2} \cdot day^{-1}}{ppm \cdot sec^{-1}}$$

The values of K can be obtained from the table provided by the equipment manufacturer.

2.2 Sampling procedure

The flux meter chamber is pressed firmly against the ground and loose soil is packed (if necessary) around the outside. This is done to seal the measurement unit and prevent atmospheric air from entering the system and affecting the measurement. The CO_2 flux measurements are conducted in dry weather conditions only that have prevailed preferably for 2 days. This is to avoid potential effects of water saturation of the soil pores.

The appropriate distance between measurement points varies but the general rule of thumb is that at least three or four measurements are needed in order to define the anomalies. So if the widths of the anomalies are of the order of 100 m, the grid spacing can be of the order of 25 to 30 m between points. Flux measurements on a grid allow the construction of diffuse soil degassing maps. These maps can also be used to discover "hidden" geothermal systems for which hydrothermal surface features (e.g. hot springs, elevated ground temperatures, hydrothermal alteration) are not present (Lewicki and Oldenburg, 2004).

2.3 Data interpretation

Collected CO_2 flux data is in ppm/s, and is converted into g/m^{2}day using Equation 1. The data is then analyzed using the graphical statistical analysis (GSA) method of Sinclair (1974) to identify different populations within the samples and distinguish between background and anomalous CO_2 flux populations, and to determine the mean flux value and the standard deviation of the population (Ármannsson et al., 2007). Sinclair's procedure is based on a detailed analysis of the distributions in probability plots.

3. RESULTS AND DISCUSSION

The CO_2 flux measurements were carried out according to the procedures described above. The CO_2 flux contours are shown in Figure 8 below. Previous results for the Leirhnúkur area are shown in Figure 9.

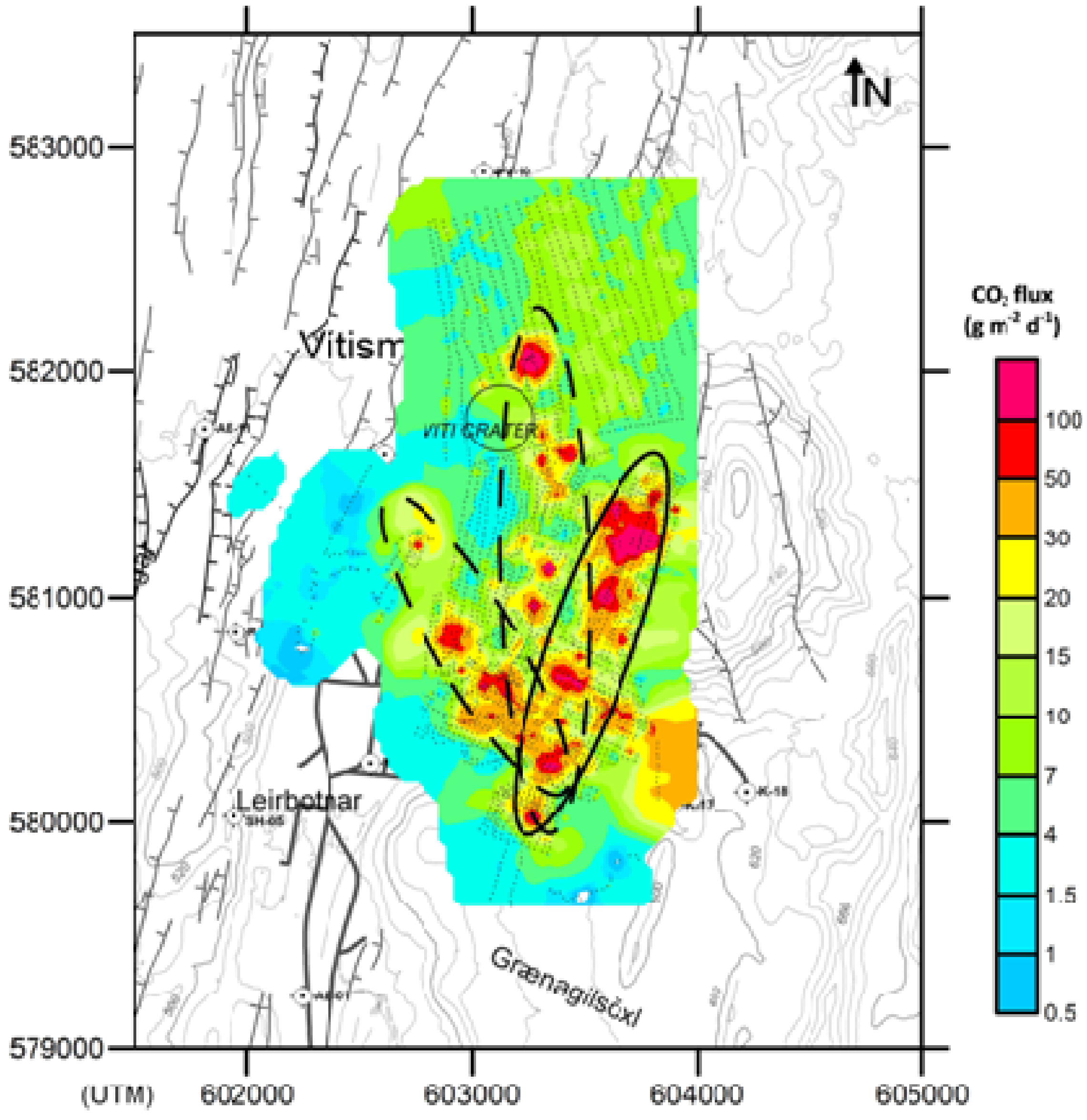

FIGURE 8: Contour map of CO_2 flux from measured points

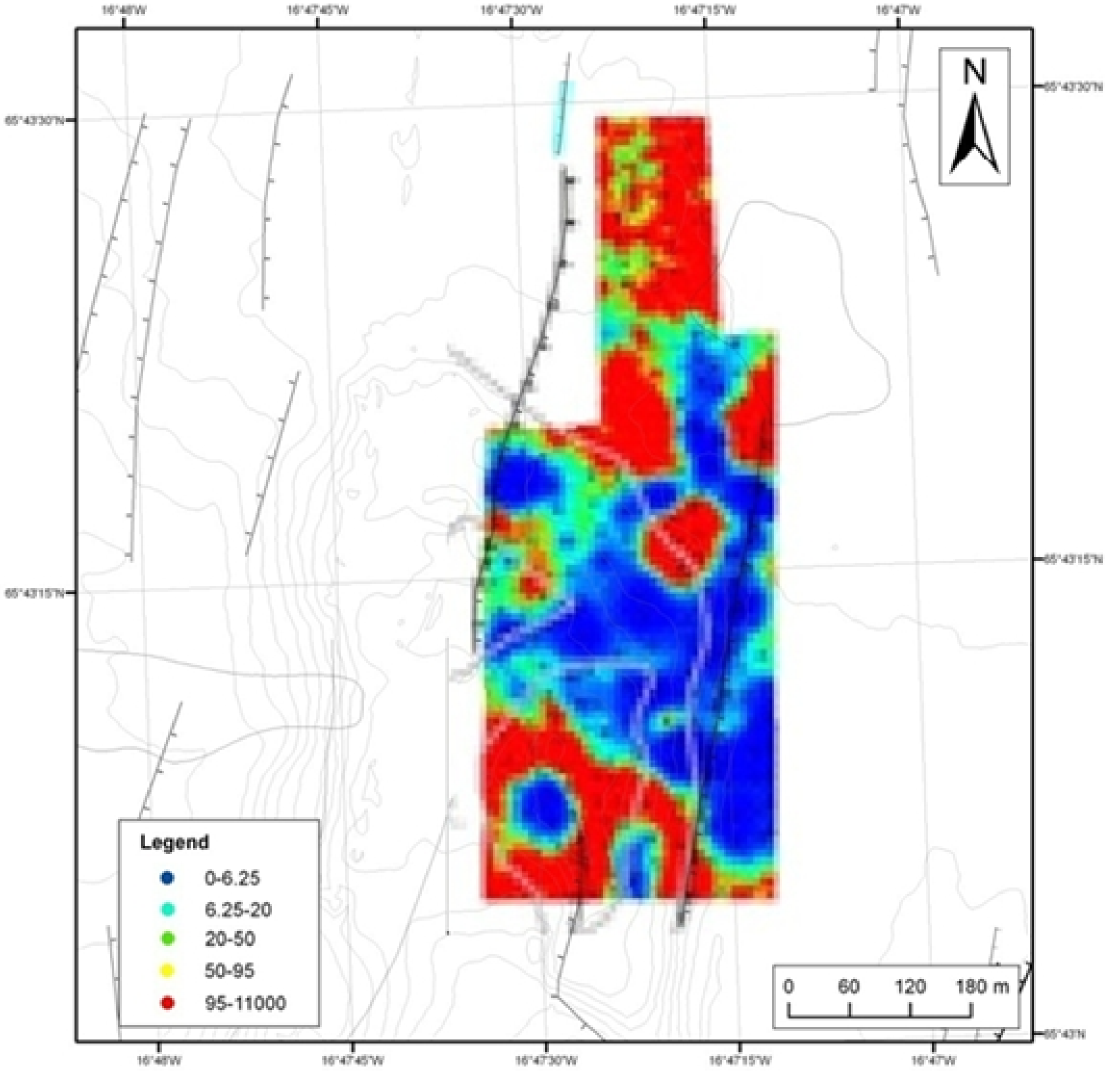

FIGURE 9: Results of soil diffuse CO_2 flux measurements in the Leirhnúkur area (from Ármannsson et al., 2007)

From the collected data, the GSA method of Sinclair (1974) was used to partition the population. This method has been successfully applied to the results of CO_2 flux campaigns in order to both separate background populations from anomalous CO_2 flux populations (i.e. where the fluxes originate in deep volcanic-hydrothermal CO_2) and to compute the total CO_2 output, and relative uncertainties, from the different sources active in areas surveyed (Fridriksson, et al., 2006).

The logarithmic probability plot in the Krafla geothermal area (Figure 10) shows that the entire data set has a polymodal density distribution. The plot forms a curve with two inflexion points (marked with arrows) dividing the populations into three theoretical populations with log normal distributions, A, B, and C with proportions (*fi*) of 25%, 71.5%, and 3.5%, respectively.

This result is then used to determine the mean (M_i) and standard deviation (σ_i) of each population by plotting the 50% cumulative probability to the log φ CO_2 intersecting each population line for the mean, and the 84% subtracted by 50% plotted values for the standard deviation. The results are seen in Table 3.

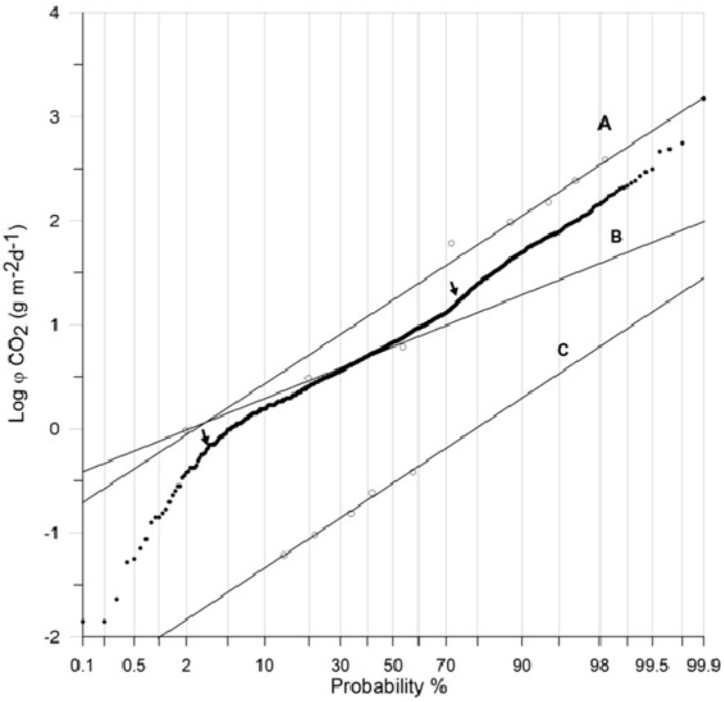

FIGURE 10: Logarithmic probability plot of CO_2 through soil at Krafla; arrowhead shows inflexion points dividing the population into three at 3.5% and 75% cumulative probability; a theoretical population of A, B, and C was obtained following the graphical statistical method of Sinclair (1978)

TABLE 3: Estimated parameters of the partitioned populations and diffuse CO_2 output

Population	f_i (%)	$M_i \pm \sigma_i$	MN_i (g/m²day)	No. of points	S_i (m²)	Source	FCO_2 (tons/day)
A	25	1.27 ± 0.62	22.6 (23.9-21.4)	774	625,000	Hydrothermal	14.13 (14.94-13.38)
B	71.5	0.8 ± 0.39	6.81 (7.03-6.45)	2213	1,787,500	Background	12.17 (12.57-11.53)
C	3.5	-0.5 ± 0.65	0.39 (0.44-0.35)	108	87,500	Background	0.0341 (0.0385-0.0306)
Total	**100**			**3095**	**2,500,000**		**26.33 (27.5-24.9)**

95% confidence interval of the estimations are given in parentheses

Because the mean and standard deviations refer to the logarithm of the values, the estimation of the mean soil φ CO_2 value (*MNi*) and the 95% confidence interval of the mean for each population is found by means of the Sichel´s *t*-estimator (David, 1977). The area covered by each population (*Si*) is estimated by multiplying *fi* with the total surveyed area (S = 2,500,000 m²). The CO_2 output from each population is then obtained by multiplying S_i with MN_i. Finally, the total CO_2 output from the surveyed area is calculated by summing the CO_2 output from each population. It can be seen from Table 3 that the total CO_2 output is 26.33 tons/day (9610 tons/year) with the estimated maximum and minimum values 27.5 and 24.9 tons/day, respectively. From this output, about 54% is from population A (geothermal origin) and 46% is from background emissions.

These results are lower than those reported by Ármannsson et al. (2007) for which the calculated mean flux from the geothermal population was about 115 g/m²day and the total CO_2 flux from the eastern Krafla caldera was about 120×10^3 tons/year. This is not surprising since the recently surveyed area generally showed a low CO_2 flux except for some points northeast of the Víti lake crater where there are surface manifestations of geothermal activity such as steam vents and mud pools. Background concentrations in the range of 0.5-15 g/m²day (Figure 8) were mostly observed in the other areas. The sampling points in the older study are also skewed towards areas with visible geothermal manifestations while in this study the sampling points are more uniform, covering a certain area but not taking into account whether there are geothermal manifestations present or not. The pattern of the CO_2 flux shows a NE-SW trend which confirms the fault trending of the Krafla geothermal area (parallel with the Hveragil fissure).

The estimated output from the surveyed area is only 0.0096×10^9 kg/year, relatively low when compared to most of the other volcanic and geothermal areas shown in Table 4. If we take this result and do an extrapolation to the estimated total area of natural CO_2 degassing in Krafla which is about 50 km^2 (Ármannsson, 2003), this will give a result of 192,210 tons/year. The CO_2 emissions from the Krafla power plant were reported as 63,500 tons in the year 2006 (Ármannsson and Fridriksson, 2008). We can see that the amount of the natural emissions exceeds the emissions from the power plant by approximately 3 times. These natural amounts only encompass emissions from soil and not from focussed degassing and other natural conduits which add a small amount to this natural emission, if we assume that soil diffuse emissions are the dominant natural source of CO_2 emissions in the area.

TABLE 4: CO_2 output from some volcanic and geothermal areas (Ármannsson et al., 2005, original sources can be found there)

Area	**CO_2 output (10^9 kg/year)**
Pantellera Island, Italy	0.39
Vulcano, Italy	0.13
Solfatara, Italy	0.048
Ustica Island, Italy	0.26
Popocatepetl, Mexico	14.5-36.5
Yellowstone	10-22[a]
Mammoth Mountain, USA	0.055-0.2
White Island, New Zealand	0.95
Mt. Erebus, Antarctica	0.66
Taupo Volcanic Zone, New Zealand	0.44
Furnas, Azores, Portugal	0.01
Mid-Ocean Volcanic System	30-1000
Total	**200-1000**

[a] Diffuse degassing only

4. CONCLUSIONS

The soil CO_2 flux concentration contours conform to the fault trends of the area (NE-SW) and high concentrations are found in areas where surface manifestations are present.

The study shows that CO_2 emissions in geothermal areas occur naturally, even without visible surface manifestations, through soil diffuse degassing. In this particular case, the amount well exceeds the CO_2 emission from the power plant utilizing the geothermal energy in the area. The amount of soil diffuse CO_2 flux from geothermal origin is estimated to be around 14.13 tons/day for a survey area of 2.5 km^2, while the total emissions from natural sources are estimated to be around 192.21×10^3 tons/year for a 50 km^2 area, compared to CO_2 emission from the Krafla power plant of about 63×10^3 tons/year.

It is beneficial to see the CO_2 emissions trend over time from both natural sources and geothermal utilization to see if there is a relationship between the two; a periodic monitoring of CO_2 soil flux emissions would give us an opportunity to understand better the impact of geothermal utilization on CO_2 emissions. This could be accomplished by placing automatic continuous monitoring stations which measure soil CO_2 flux and various environmental parameters which can potentially affect the soil gas flux at selected sites, along with more detailed periodic measurements at fixed points that are repeated several times per year. Granieri et al. (2003) reported the results of a continuous CO_2 soil flux measurement in the Solfatara crater (Phlegreaan fields, Italy) for a period of 4 years (1998-2002) through a combination of an automatic continuously operating station at a selected site and periodic measurements of flux over an array of sites.

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