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The Evolution of CO_2 Emissions and Heat Flow through Soil since 2004 in the Utilized Reykjanes Geothermal Area, SW Iceland: Ten Years of Observations on Changes in Geothermal Surface Activity.

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ABSTRACT

For the last ten years, annual measurements on soil temperature and CO_2 flux have been done in the Reykjanes geothermal area, SW-Iceland. Each year since 2004, the soil gas and heat flow survey have consisted of ~ 450 direct measurements of CO_2 flux and soil temperature at 15 cm depth and the data has been used to create maps of the distribution and to evaluate the total CO_2 flux through soil and the total heat flow. In 2006, a 100 MW geothermal power plant started electrical energy production and the soil measurements have been used to observe changes in the geothermal area in relationship with the utilization. The soil temperature and CO_2 flux measurements have shown an increased activity both in heat flow and in CO_2 flux. The CO_2 flux has increased from 13.5 ± 1.7 tons per day in 2004 to 51.4 ± 8.9 tons per day in 2013 according to the results of the soil measurements and clear signs of stabilization in the CO_2 flux in Reykjanes have not been observed. The total heat flow has been derived from the soil temperature measurements and the values did almost triple between 2004 and 2012, though this increase has been nonlinear. Between 2012 and 2013, the heat flow did not increase and the measurements in the years to come will reveal if a peak in heat flow has been reached. The heat flow is derived from the soil temperature and the equation used is very sensitive for high temperature values. It is now known that temperature at high values in the soil in Reykjanes does vary, therefore reducing the value of the total heat flow estimate as a very precise indicator for changes in the surface activity in Reykjanes geothermal area. A thermal infrared image which was obtained in May 2011 from the Reykjanes geothermal area shows a detailed picture of the surface temperature distribution. This image provides excellent data to compare with a TIR image from April 2004, also obtained from Reykjanes. The comparison of these two images shows without any doubt that surface temperature has increased in large parts of the Reykjanes geothermal area. The changes in surface activity in the Reykjanes geothermal area are expected to approach a steady state and the measurements in future years are essential as a part of the understanding of the geothermal system and their responses to utilization.

1. INTRODUCTION

For the last decades there has been a growing interest in studying the CO_2 degassing of the Earth. It is known that CO_2 can escape from depth through different pathways, the best known way of which is through volcanoes; however, non-volcanic degassing can occur with escape of gases from the upper mantle, from carbonate bearing rocks in the crust, from hydrocarbon reservoirs in the sedimentary beds and from surface deposits and surface processes (Mörner and Etiope, 2002; Chiodini et al. 2010). In active and quiescent volcanoes, gas is released not only from craters and fumaroles but also from well-defined areas on the flanks and at the base of volcanoes where CO2 is the main component of geothermal and volcanic gas (Chiodini et al. 2001; Frondini et al. 2004). Monitoring CO_2 emissions from geothermal areas is one of the fundamental ways of understanding changes in geothermal systems. It has been demonstrated that CO_2 degassing on flanks of volcanoes is sensitive to changes in magmatic activity of the volcano itself, therefore providing one method for monitoring volcanoes. For geothermal systems, soil diffuse CO_2 degassing has been shown to be a good indicator of the energetic state of the system (Brombach et al. 2001; Chiodini et al., 2001) and monitoring changes of soil CO_2 degassing can therefore lead to better understanding of the behavior of undisturbed geothermal systems. Numerous studies have focused on CO_2 soil diffuse degassing from quiescent volcanic/geothermal areas (e.g. Brombach et al., 2001; Chiodini et al., 1998, 2001; Hernández et al., 1998; Inguaggiato et al. 2011), and studies suggest that significant amounts of CO_2 are released to the atmosphere by quiescent degassing of volcanoes and soil diffuse degassing from geothermal systems compared to the CO_2 released from fumaroles (e.g. Salazar et al., 2001; Inguaggiato et al. 2011, Fridriksson et al., 2006).

Besides CO_2 emissions, changes in temperature and the quantification of heat flow are important factors when monitoring geothermal areas, and changes in their activity. According to Dawson (1964), the natural heat discharge from geothermal areas appears as a heat flow through soil, heat loss from water surfaces, heat loss through fumaroles, through overflow from geysers and springs and seepage to lakes and rivers. This happens through three main heat transfer mechanisms: advection, conduction and radiation. According to Sorey and Colvard (1994) the dominant mode of heat loss differs between geothermal areas due to different surface characteristics, such as manifestations, alteration and ground cover. Thermal infrared data have been used as a tool for geological mapping but they only show the heat flow through radiation. This is therefore not a complete method to map the total heat flow from an area, but maps the extent of surface thermal anomalies and gives an overview of the distribution of the heat flow. Values obtained by investigations using a combination of TIR imagery and ground measurements have been shown to agree well with values obtained by direct measurement techniques (Harris and Stevensson 1996; Sorey and Colvard 1994). The TIR method can cover the observation area completely (including inaccessible features), and gives an instant overview, showing the temperature variability clearly. This method therefore represents a suitable tool to monitor changes in surface activity of geothermal systems over time (e.g. Chiodini et al., 2007).

It is known that changes in the behavior of geothermal systems and its surface activity can occur in relation with utilization of a geothermal system (Pálmason, 2005; Hunt 2001; Giroud and Arnórsson, 2005). A study in New Zealand has shown that the exploitation of the Wairakei system significantly increased heat flow through surface (Allis, 1981), which if heat flow is considered as a proxy for CO_2 emissions, it could lead to the conclusion that the exploitation has increased the natural CO_2 emissions (Sheppard and Mroczek, 2004). To be able to evaluate and quantify changes in geothermal areas due to utilization it is essential to understand natural changes in geothermal systems and then follow closely any changes in its behavior when the system is utilized.

2. GEOLOGICAL SETTINGS

The Reykjanes geothermal area is located at the Reykjanes volcanic system, on the southwestern tip of the Reykjanes Peninsula, SW-Iceland, which forms a subaerial continuation of the Reykjanes Ridge. The Reykjanes volcanic system is the westernmost system of the five active volcanic systems on the Reykjanes Peninsula. Two most recent volcanic episodes in Reykjanes occurred between 1.9 and 2.1 ka ago and in the 12th and early 13th century (Sigurgeirsson, 1995, 2004). The landscape in Reykjanes is dominated by post-glacial lava flows and volcanic craters with low hyaloclastite ridges of Pleistocene age protruding through the lava field in few places. Systematic investigations began in the area between 1960 and 1970 and since then, 30 geothermal wells have been drilled in Reykjanes, the deepest one being 3,082 m. In May 2006, a 100 MW power plant started electrical energy production.

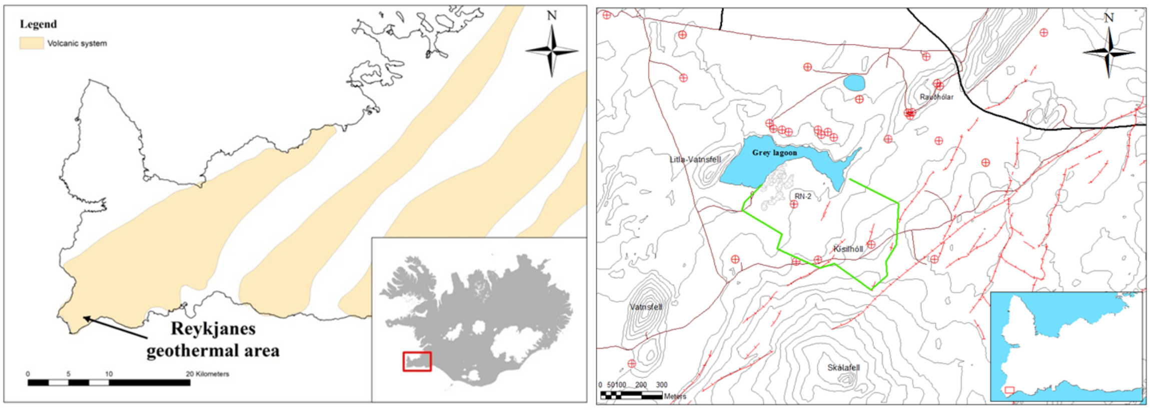

Figure 1: A map of Reykjanes Peninsula showing the location of the Reykjanes volcanic system and Reykjanes geothermal area

The extent of the geothermal manifestations in the Reykjanes geothermal system has been estimated to be around 2 km^2 (Pálmason et al. 1985) and they are closely associated with tectonic fractures (Björnsson et al. 1971). The system is surrounded by the ocean on three sides, only 1.5 km from the shoreline and extends SW to the sea (Björnsson et al., 1971; Johnsson and Jakobsson, 1985). Now, most of the current surface activity is concentrated in an area of approximately 0.3 km^2, which is characterized by extensive normal faulting and geothermal activity (Fridriksson et al., 2010). Surface manifestations are typical of high-temperature areas and include steam heated mud pools, steam vents, hot springs, fractures and warm to hot ground (Fridriksson et al., 2006). The intensity of the surface activity is known to vary over time; it increases abruptly as a result of seismic activity and decreases with time until the next seismic event. No boiling springs are currently present at Reykjanes, but seawater geysers were active on and off from 1906 to 1980 (Friðriksson et al. 2010). The intensive steam vents and steam heated mud pools are located in the two most active and intensely altered parts of the geothermal area, one at the southeastern and the other at the northwestern part. Where the geothermal activity is intense, the areas are mostly unvegetated and the soil consists of wet geothermally altered clay, but where the ground is not very much affected by the geothermal activity, the characteristic vegetation consists of green moss (*Hypnum jutlandicum*) and creeping thyme (*Thymus praecox arcticus)* (Elmarsdóttir et al., 2003). Geothermal signs are also present outside the study area, mostly warm and moist air rising through small fissures, e.g. south of the study area towards Skálafell but on the northeastern side of the Gray lagoon, around Rauðhólar, the soil is geothermally altered and also on the north side of the Grey lagoon.

3. DATA AND METHODS

3.1 Direct observations on CO_2 flux through soil from the Reykjanes geothermal system

In 2004, CO_2 emissions and heat flow through soil, steam vents and fractures and steam heated mud pools were determined in the Reykjanes geothermal system. CO_2 through soil was measured by soil flux equipment, while heat flow from steam vents and fractures was determined by quantifying the amount of steam emitted from the vents via direct measurements of steam flow rate; heat loss from the steam heated mud pools was determined by quantifying the rate of heat loss from the pools by evaporation, convection and radiation (Friðriksson et al., 2006). They stated that 5.1 x 10^6 kg year^{-1} of CO_2 were emitted from the Reykjanes system with more than 97% released through soil. Since 2004, annual measurements of soil temperature and CO_2 flux through soil have been carried out systematically every summer in the Reykjanes geothermal area. The measurements have been done on a grid covering the areas with the most significant surface activity. The size of the measured area has changed from year to year due to changes in the distribution of the surface activity but has covered on average about 0.3 km^2; annual number of measurements nodes has been around 400-500 with grid spacing about 25 x 25 m.

Surface CO_2 flux was measured using a WEST Systems fluxmeter equipped with a LICOR LI-820 single path, dual wavelength, non-dispersive infrared gas analyzer. This flux meter is based on a closed chamber method with repeatability of ± 10% (Chiodini et al., 2003) and has become a routine studying and monitoring tool at many volcanic and geothermal sites for the last 15 years (e.g. Chiodini et al., 1998; Lewicki et al., 2005; Giammanco et al., 2010; Mazot et al., 2011). The measurement is based on the rate of CO_2 increase in ppm sec^{-1} inside a 3.06 x 10^{-3} m^3 chamber. According to Granieri et al. (2003), various external factors can influence the CO_2 soil flux, e.g. rainfall, barometric pressure, air and soil temperature, air and soil temperature, air and soil humidity and wind speed. To minimize these effects and avoid potential reduction of the observed flux due to water saturation of the soil, the measurements were only carried out when at least 24 hours had passed without any rain. The ground covered by the chamber was chosen to be as flat as possible to avoid changes in the inside volume of the chamber and to prevent contamination from the atmosphere; the chamber was pressed firmly against the ground during measurements.

3.2 Soil temperature and heat flux through soil

The soil temperature measurements were performed with a handheld digital thermometer that was placed 15 cm into the soil on the same grid as the CO_2 measurements. When the necessary conditions were available in Reykjanes during the winter (acceptable amount of snow and calm weather conditions), mapping of the edges of the snow cover in the geothermal area were performed using a handheld GPS unit and digital thermometer.

The heat flux through soil in the study area was estimated from soil temperature measurements using the method of Dawson (1964). The method which was calibrated by direct measurements at the Wairakei thermal field, New Zealand, is based on the correlation between measured soil temperature at 15 cm depth in °C and heat flow measurements, using a portable calorimeter (q_s in W/m^2). The relationship was resolved ending with the equation

$$Q_s = 5.19 \times 10^{-6} T_{15}^{\ 4} \tag{1}$$

which applies when T_{15} (temperature at 15 cm depth in °C) is lower than 97°C. For higher values than 97°C at 15 cm depth, the depth to the point where the soil temperature reaches 97°C (in cm) allows the estimation of the heat flow through soil using:

$$Q_D = 10^{(\log d_{97} - 3.557 / -0.894)} \tag{2}$$

where d_{97} is the depth in cm where the soil reaches 97°C temperature. Gudmundsdóttir (1988) measured soil temperature and heat flow with a calorimeter at Nesjavellir and compared her results to those of Dawson (1964). She showed that the relationship between d_{97} and the heat flow at Wairakei, determined by Dawson, applied reasonably well to her measurements at Nesjavellir, although the heat flux at the same depth of 97°C soil temperature was slightly higher at Nesjavellir.

3.3 Soil measurements and geostatistical methods

The soil measurements in the Reykjanes geothermal area were made at unevenly spaced intervals due to circumstances in the area. Geostatistical methods were used to interpolate for CO_2 flux at unmeasured locations. This was accomplished by a kriging algorithm which is focused on providing the best fit in the minimized least square sense, hence unique, without considering the resulting spatial statistics of all the estimates taken together and producing a set of estimated values whose variogram, a tool that quantifies spatial correlation, does not match with the original dataset (Salazar et al., 2001; Cardellini et al., 2003). Other limitations of the kriging algorithm are that it is incapable of detecting spatial uncertainty (Delbari et al., 2009) and it smooths out the extreme values of the dataset (large values are underestimated and small values are overestimated) (Cardellini, 2003).

More recently a stochastic simulation algorithm has been used to process gas flux measurements and other measurements in soil science, in which the spatial variability of the measured attributes has to be preserved (Goovaerts, 2001). The simulations are usually performed by using the sequential Gaussian simulation algorithm (sGs) (Cardellini et al., 2003; Friðriksson et al., 2006; Mazot et al., 2011). The sequential Gaussian simulation is a method used to interpolate or fill in the areas between measuring nodes, and is a suitable tool to model soil diffuse degassing (Frondini et al 2004). The sGs method uses the dataset to generate a great number (chosen by the user) of equiprobable representations or realizations of the spatial distribution of the CO_2 flux. It operates using a sampled attribute (e.g. CO_2 flux) and the variable is simulated at each unsampled location by random sampling of a Gaussian conditional cumulative distribution defined on the basis of the original data. The requested number of the equiprobable realizations is generated and is used to draw a map representing the average of the requested number of simulations. The advantages of using this method are that it preserves certain values of the dataset, including averages (Cardellini et al., 2003), and it allows one to evaluate the spatial uncertainty through generation of several equally probable stochastic realizations (Delbari et al. 2009).

To process the CO_2 measurement data and evaluate the total heat flow and the total CO_2 emission from the measured area, the software WinGslib has been used. For each year, 100 realizations have been calculated on a model grid with a 2 by 2 m grid spacing using the sGs algorithm of the sgsim code by Deutsch and Journel (1998) and the average value for each cell presented on maps.

3.4 Thermal infrared imaging and natural heat flow from the soil

Twice, in the last twenty years, TIR images have been obtained from an airplane at the Reykjanes geothermal area. In thermal remote sensing, radiations emitted by ground objects are measured for temperature estimation. This technology is based on the fact that all materials at temperatures over absolute zero emit energy in the form of electromagnetic waves of different wavelengths. Energy of electromagnetic waves is, according to Planck´s law, inversely proportional to its wavelength, i.e. the longer the wavelength, the lower the energy (Lillesand and Kiefer, 2000). The atmosphere between the surface and the TIR scanner does have some effects on the imagery, however, theoretical and empirical models have been applied to thermal scanner calibration in order to minimize atmospheric effects. Here, a calibration curve was constructed relating the scanned output value to a corresponding measured ground surface temperature, and this calibration relationship was used to estimate the temperature at all points in the TIR image.

4. RESULTS

4.1 CO_2 flux through soil in the Reykjanes geothermal area

The soil temperature data, collected annually since 2004, have been used to map the distribution of CO_2 flux anomalies and evaluate changes from year to year. On each annual dataset of CO_2 flux in Reykjanes, 100 sGs have been performed. The results of each 100 simulations were depicted on maps that show the mean CO_2 flux of individual cells in the model. From 2004, significant changes have appeared in the Reykjanes geothermal area. Changes have often been observed to occur from year to year, but there are still some main features that appear every year. First, in all cases there is an obvious anomaly north of the road at the Gunnuhver area, to the west of well number RN-3, in the south-eastern part of the study area. This is the area with the most intense surface activity, including steam vents. Furthermore, there is an anomaly at the western end of the study area, by the west end of the Grey lagoon where mud pits dominate the surface activity; this anomaly did not appear strongly in 2007 and 2008. Finally, there is an anomaly in the middle part that stretches south or southwest from the east tip of the Grey lagoon. Even though these anomalies have generally appeared similar from year to year, significant differences are noticeable. Most of the variations are coherent with changes seen in the soil temperature measurements and are related to the commissioning of the Reykjanes Power Plant.

When the area was first measured in 2004, three main CO_2 flux anomalies appeared: Gunnuhver anomaly, the anomaly around and east from well RN-2 and then at the mud pit area in the northwest part. In 2005, still prior to the commissioning of the Reykjanes Power Plant, a bit broader area was measured in order to have more background measurements, the distribution of CO_2 flux was rather similar even though the anomalies varied a little bit in shape (Figure 1). The amount of CO_2 gas released from the area was estimated to be almost equal for 2004 and 2005. The measurements from summer 2006 show an obvious increase in CO_2 flux compared to previous years, especially around Gunnuhver. The results from 2007 were similar to results from 2006, however in 2008, the results were different from other years (both before and after). The CO_2 flux appeared to have dropped drastically and this has not been explained thoroughly. The measurements from 2009 indicated that the CO_2 flux had reached the same level as in 2006 and 2007. The results from 2010 indicate an increase in CO_2 flux compared to 2009 in almost all parts of the geothermal area.

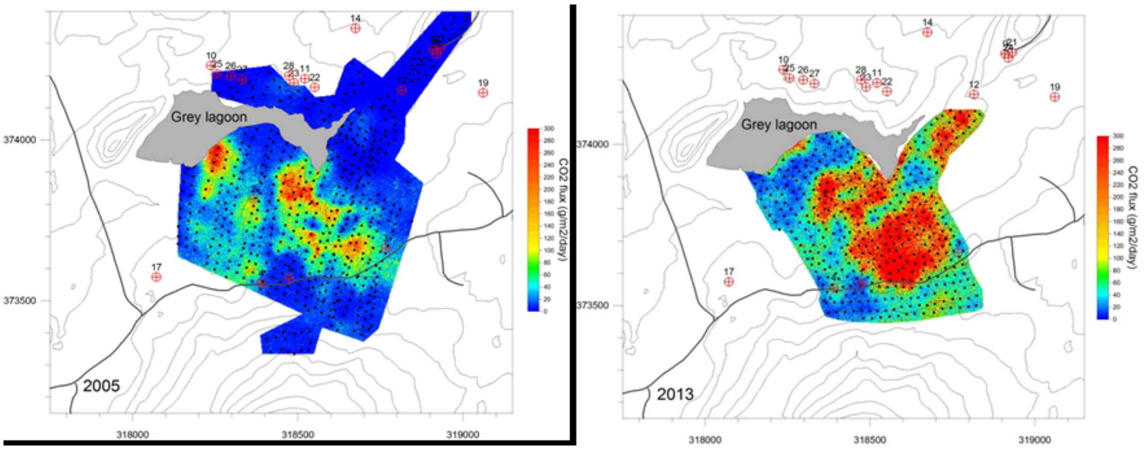

Figure 2: CO_2 flux through soil in the Reykjanes geothermal area in 2005 (left) and 2013 (right)

In summer 2011, the measurements were carried out as in previous years, however in this year, the area was measured twice – first normally in 25x25 m grid covering about 0.42 km^2 and then the same area was measured again, locating the 25x25 m grid in between the first dataset. This allowed geostatistical comparison of the two datasets and also to put them together in a tight dataset with approximately 17 m between points for more details. Óladóttir (2012) concluded that this tight dataset did not give different results when visually compared even though more details were seen in the map made from the tight dataset. Hence, a dataset with 25 m grid spacing was proved to fulfil the requirements for the monitoring in the Reykjanes geothermal area. In 2011, areas with strong CO_2 flux anomalies were bigger than previous years, especially in the middle part of the area. In 2012 and in 2013, the CO_2 flux has a very similar distribution as in 2011, however the CO_2 flux in the middle part had increased significantly along with the area along the east end of the Grey lagoon, which appears much stronger in 2013 (Figure 1).

4.2 Soil temperature measurements in the Reykjanes geothermal area

The soil temperature measurements have been performed in each node of the same sampling grid as the CO_2 measurements. The data have been used to map the distribution of the thermal anomalies and evaluate changes from year to year. Surfer software has been used to create the maps, using the kriging interpolation to interpolate between the measured points. In 2004, the temperature anomalies showed a dominant area around Gunnuhver and stretching northwest towards the Grey lagoon. Between 2004 and 2005 little changes occurred in soil temperature and the distribution was nearly the same, apart from a slight decrease within the hottest part of the area (Figure 3). In 2006, the surface activity and steam flow was significantly higher than before. The area with warm soil extended to the south and southeast and the temperature readings were in most cases higher than the previous year.

Between 2006 and 2007, the area extended even more to the south and southeast, as well as to the northeast, and the whole area appeared to be warmer. Measurements from 2008 are in agreement with the CO_2 flux measurements from that year and show lower soil temperature than 2007. In 2009, the size of the area where geothermal signature is observed was bigger than in 2007 and since then, the elevated soil temperature have appeared to be higher but the distribution is rather similar, especially between 2012 and 2013. The greatest difference is observed in the middle part of the study area, from around RN-02 and towards the Gunnuhver part where the soil temperature has appeared to be much warmer than in recent years (Figure 3).

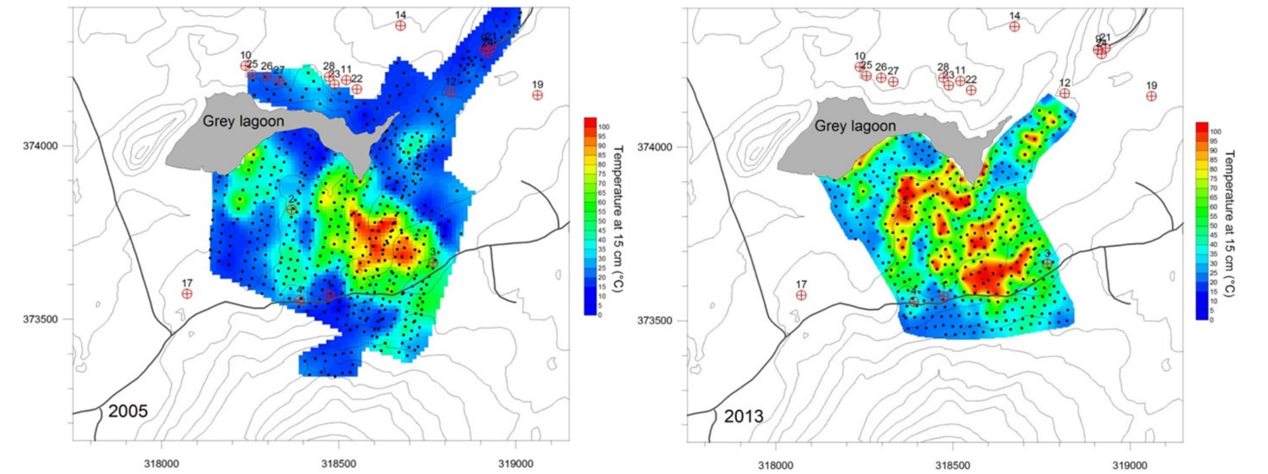

Figure 3: Soil temperature at 15 cm depth in the Reykjanes geothermal area in 2005 (left) and 2013 (right)

4.3 Thermal infrared images from the Reykjanes geothermal area

A TIR image from the Reykjanes geothermal area was obtained in April 2004 and thoroughly described by Margrétardóttir (2005). A similar TIR imager was obtained in 2011. Both image collections were done from an aircraft specially customized for aerial photography, using a TIR scanner owned by the Engineering Research Institute of Iceland (described in Margrétardóttir, 2005). Both data were corrected to get an orthographical TIR image of the surface temperature using the ArcGIS software. The images were geo-referenced and a raster image of uniform resolution of 0.63 by 0.63 meters per pixel (Figures 4 and 5) was produced. The TIR image from 2011 covers the entire peninsula's tip and is around 24 km^2 in total, while the TIR image from 2004 shows much smaller area but covers the greatest part of the geothermal area.

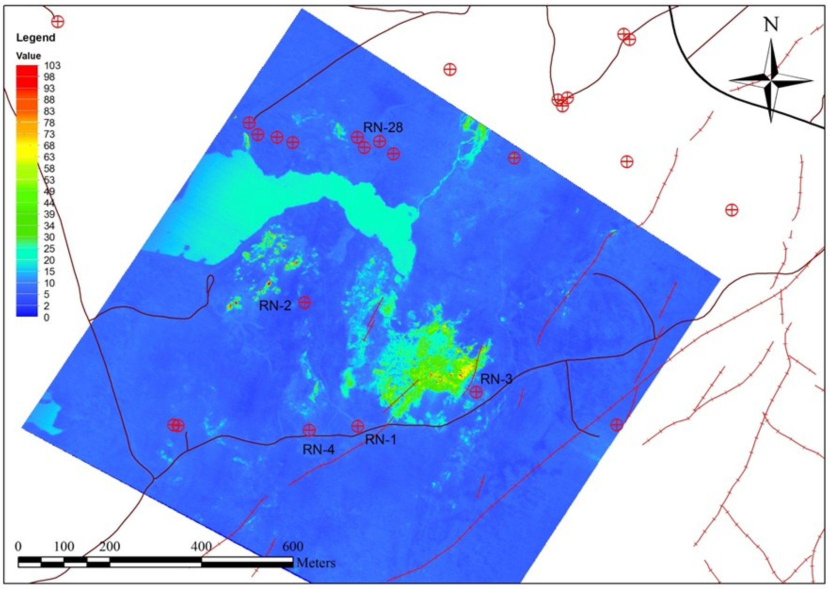

Figure 4: TIR image from April 2004 covering the area with the most significant surface activity in the Reykjanes geothermal area

Both images clearly show the temperature anomalies in the geothermal area. Visual comparison reveals that areas of elevated surface temperature have expanded, especially in the middle part of the study area where the 2011 image shows much higher temperatures than the 2004 image. The area with the highest temperature around the Gunnuhver area appears strongly in both images and so does the area furthest northwest, closest to the Grey lagoon. The area north of the lagoon does not appear warm at all in 2004 but in 2011 it clearly shows elevated temperature values. In 2005, this part of the Reykjanes geothermal area was included in the soil measurements, but since then no soil measurements have been done in this part.

In March 2011, mapping of the edges of the snow cover was done. It resulted in a snowmelt track where the soil temperature at 15 cm depth on the border of the snow reached on average 36°C. On figure 5 the snowmelt track is overlain on the TIR image from 2011. The figure shows that the snowmelt track is in excellent agreement with the outline of the thermal anomaly as detected by the TIR image. The greatest discrepancy appears in the eastern part of the area where the snowmelt track extends more towards east than is seen in the TIR image. This might be caused by a westerly wind blowing the geothermal steam towards the east and melting the snow.

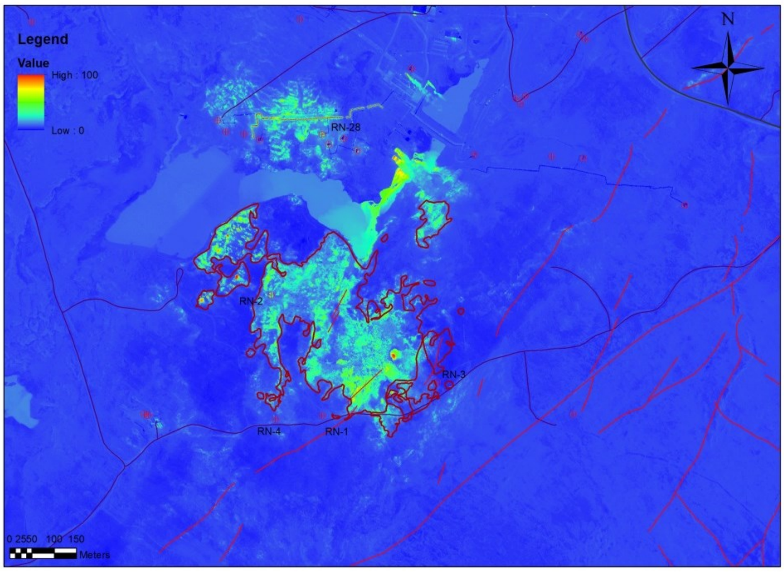

Figure 5: Calibrated TIR image from May 2011 of the geothermal area in Reykjanes. The pink line is the snowmelt tracks overlying the 2011 TIR image.

4.4 The total CO_2 flux and heat flow through soil

The datasets from each year have been used to determine the total CO_2 flux and the total heat flow. To be able to determine the total CO_2 flux, 100 equiprobable realizations using the sGs algorithm have been performed on each annual dataset and the uncertainty with 95% confidence level was evaluated using the realizations. The CO_2 flux was determined for each year's grid coverage but for comparison, a comparison area was defined in 2012 (Óladóttir, 2012) since the measured area has not been the same through the years due to changes that have appeared in areas stretching in one direction or another. To be able to compare areas where measurements were not performed during some years, a background value of 4.1 g m^{-2} day^{-1} was used to represent the CO_2 flux from areas with no geothermal effects, estimated for Reykjanes by Friðriksson et al. (2006). Except for 2008, the total CO_2 flux from Reykjanes has increased constantly since 2004 and in 2013 it was estimated 51.4 ± 8.9 tons day^{-1}, which is more than three times greater than the value in 2004 which was estimated at 13.5 ± 1.7 tons day^{-1} (Table 1 and Figure 6). This has to be considered as an underestimation since the area north of the Grey lagoon appears to have warmed up significantly during this period, as was seen from the TIR images, however this part has not yet been included in the soil measurements.

Table 1 Total heat flow and CO_2 flux through soil. In 2005 and 2006 the data were insufficient for evaluation on heat flux. Note that the data from 2004, a) is from Fridriksson et al. 2006.

Year	Heat flow in MW according to 100 sGs from the comparison area	CO_2 in tons day^{-1} according to 100 sGs from the comparison area
2004	16.9[a)] ± 1.4	13.5[a)] ± 1.7
2005		14.3 ± 3.0
2006		16.9 ± 2.8
2007	40.1 ± 10.8	18.7 ± 2.2
2008	20.6 ± 2.7	8.2 ± 0.6
2009	34.8 ± 6.8	21.6 ± 2.3
2010	29.0 ± 4.2	34.4 ± 4.8
2011	36.1 ± 2.5	36.6 ± 3.9
2012	51.9 ± 9.6	46.2 ± 6.5
2013	47.4 ± 5.9	51.4 ± 8.9

The total heat flow through soil was calculated from the soil temperature measurements (except for 2005 and 2006) using equations (1) and (2). Then the same procedure as for the CO_2 flux data was followed. The heat flow computed from the measured soil temperature has almost tripled between 2004 and 2013, but the increase has been absolutely nonlinear. A reduction in heat flow has been seen between some years, e.g. between 2007 and 2008, between 2009 and 2010 and again between 2012 and 2013 and for almost every year, the uncertainty value is very high. The values almost tripled between 2004 and 2012, but between 2012 and 2013, the heat flow did not increase and the measurements in the years to come will reveal if a peak in heat flow has been reached. Still, even when all uncertainty values are considered, there is an undoubted increase in heat flux between 2010 and 2012/2013, and the values since 2007 (except for 2008) are all twofold or more the value of 2004, prior to the commission of the power plant.

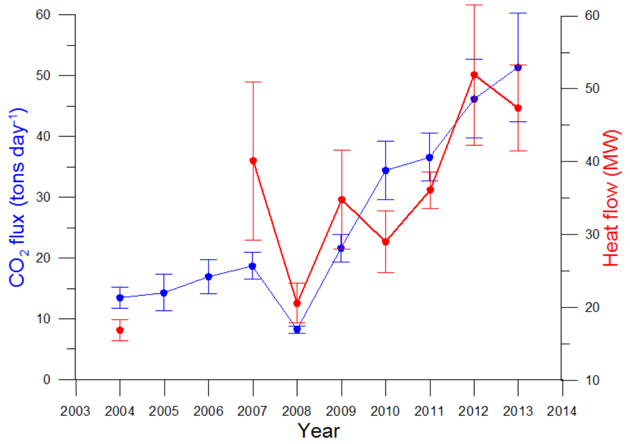

Figure 6: Evaluation of the total CO_2 flux through soil (blue line) and the heat flow (red line) derived from soil temperature measurements.

5 DISCUSSION

It is known that changes in the behavior of geothermal systems and their surface activity can occur as a result of utilization. The exploitation of a geothermal system involves withdrawal of large volumes of geothermal fluid and a pressure drawdown. A major consequence of the mass loss is a formation or rapid growth of steam-water zone in the upper part of the reservoir. Hence, the flow of steam, lateral or upwards, increases, resulting in an increased heat loss from areas of steaming ground. As the production continues, this zone increases in size while pressures in and below decreases causing increased boiling and degassing of the system (e.g. Goff and Goff, 1997; Hunt, 2001; Kristmannsdóttir and Ármannsson, 2003; Scott et al, 2005). One of the consequences at the surface is that when the pressure declines, so does the amount of geothermal liquid reaching the surface resulting in a decline in the activity of geothermal manifestations such as geysers, hot springs and mud pools, e.g. in Wairakei and Ohaaki, New Zealand, Larderello, Italy and at The Geysers, USA (Hunt 2001).

Generally, pressure changes in geothermal systems and hence in surface activity occur most abruptly immediately after the commissioning of a power plant. The pressure drawdown and heat flow from geothermal systems is expected to level off and approach a steady state condition in response to the utilization. It has been concluded that the visible changes in surface activity, and distinct increase in CO_2 flux and heat flow seen in 2006 in the Reykjanes geothermal area was related to the commissioning of the power plant (Friðriksson et al. 2010). The total CO_2 flux and the heat flow have more than tripled in Reykjanes since pre-production. A decline or disappearance of surface manifestations such as fumaroles and mud pools has not occurred in Reykjanes geothermal area after the commissioning of the power plant in 2006. On the other hand, an increased surface activity in the area has been obvious to visitors, as new mud pits split the road south of Gunnuhver and the changes have called for the rebuilding of tourist paths. However, the Reykjanes geothermal area has been known for its great variations in surface activity over the last 150 years, and three periods of remarkable sea-water geysers are known from there. At least two of these geyser periods started after seismic events, in 1926 and again in 1967 (Friðriksson et al. 2010). Such seismic events occur at a few decades' intervals on the Reykjanes tip, but due to the production in the area and its effects, it is unlikely that new geysers will appear when the next seismic event takes place.

The results from the measurements in Reykjanes cannot easily be compared to other utilized geothermal areas due to lack of data from other areas, especially on CO_2 flux. One utilized geothermal area has a record of observations on surface activity. The Wairakei geothermal system is a geothermal area in New Zealand where utilization has taken place for almost six decades and the history of the geothermal activity has been documented. Changes in surface activity have occurred in Wairakei due to the utilization, and in the Karapiti part, there has been a spectacular increase in thermal activity with the appearance of large fumaroles, steaming craters and an extensive area of steaming ground (Allis, 1981). The total heat flow from the Karapiti area has been estimated approximately every five years, and includes areal heat losses from hot ground and pools, heat flow from specific intense thermal features, and the heat content of hot water outflows. The total heat flow from Karapiti increased from 40 ± 20 MW prior to the production to a maximum of about 420 ± 20 MW in 1964 (about 380±40 MW in 1969) , before decreasing to its present level of about 200 MW (Glover and Mroczek, 2009). This heat flow value of 200 MW was first reached in 1979, about twenty years after the commissioning of the power plant, and has remained more or less constant until present. The increase in heat flow in Reykjanes is estimated to be much less than in Wairakei, however the estimate of total heat flow in Reykjanes does only include heat losses from hot ground.

As can be seen on Figure 6, the evolution of total heat flow and total CO_2 flux are rather different. No information has been found on CO_2 flux studies related to utilization with longer time series worldwide. One could expect by analogy with the observed heat flow in Wairakei that CO_2 flux would reach a peak and subsequently decline by time. This has not yet been seen in Reykjanes as longer time series is needed. There is a possibility that the CO_2 flux will not decline simultaneously with the heat flow because the CO_2 has its origin not only in steam but also in calcite. If conditions in the geothermal system turn out to be such that the calcite becomes unstable it might lead to high values of CO_2 flux even though steam would decline.

The uneven increase in heat flow through the surface experienced at Reykjanes cannot easily be explained. The heat flow in 2007 was higher than the next four years to come, but now it is clear that the heat flow had not reached its peak in 2007 since the measurements from both 2012 and 2013 give higher values. The decrease in heat flow between 2009 and 2010 and again between

2012 and 2013 does not appear in the total CO_2 flux, on the other hand, CO_2 flux appeared to have increased constantly (except in 2008) since 2004. There is one continuous series of steam samples from Reykjanes where samples have been collected annually since 2001 to detect any changes in gas composition. This series is from fumarole *Halla* (formally H-10991) on the northern slopes of Kísilhóll in the Reykjanes geothermal area. The concentration of CO_2 has been fairly constant since 2009 (Óladóttir and Óskarsson, 2013) indicating that the persistent increase in CO_2 flux could not be explained by higher CO_2 concentration in the steam.

It has been argued that gas discharge and heat flow from geothermal areas could be correlated because gas species are transported to the surface by steam and advective steam flow is a very efficient heat transport mechanism (Brombach et al. 2001; Chiodini et al. 2001). The studies have demonstrated that CO_2 flux estimated from measured heat flow from geothermal systems agrees reasonably well with measured CO_2 discharge. Accordingly, Arnórsson (1991) argued that measured or estimated heat loss could be used to estimate total steam discharge from particular areas, and thereby gas discharge, if gas concentration in the steam were known. Óladóttir (2012) used the complete dataset of soil measurements from 2004 until 2011 to explore the relationship between total CO_2 flux and total heat flow in the Reykjanes geothermal area. The point measurements revealed very poor correlation but when both parameters were filtered with 200 x 200 m mean filter to reveal the relationship on a regional scale, the parameters showed some correlation. The correlation indicated that small scale temperature changes at low temperature values (< 30°C) did not affect the CO_2 flux greatly but little increase in temperature at higher values, especially between 30°C and 60°C could increase CO_2 flux greatly. The heat flow estimate, on the other hand, is very sensitive for very high temperature values. Therefore, a slight decrease in the highest temperature values could result in lower total heat flow value, but there could still be an increase in temperature in some areas at lower values (between 30°C and 60°C) that could increase the total CO_2 flux.

Since the heat flow estimate is derived from soil temperature, Óladóttir (2012) used temperature data loggers to obtain information about fluctuations of soil temperatures at 15 cm depth in the Reykjanes geothermal area on a short term scale (hours-days). The loggers were programmed to measure temperature (in °C) and pressure (in kPa) regularly at 5 minute intervals for weeks in 2011 and 2012. They were always located in clayish soil with no overlying vegetation or water. Data on air temperature and precipitation from a weather station, located about 600 meters away was used to correlate weather parameters with the data from the loggers. It was concluded that the range of temperature values in one location increased with higher soil temperature and loggers with high temperature (> 70°C) could show sudden temperature drops of up to 30–40°C. Most of the variations could be related to precipitation, which can affect the soil temperature for few days; this emphasizes the importance of choosing the driest weather conditions possible, despite the fact that some variations cannot be completely explained by precipitation.

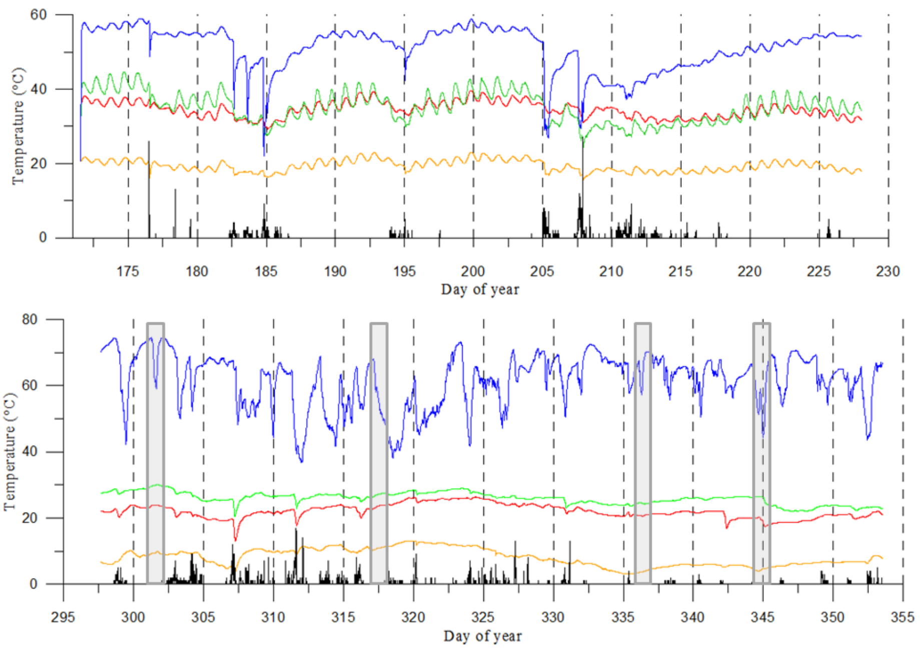

Figure 7: Soil temperature measurements from data loggers. The coloured lines show the temperature measured in four different data loggers on four different locations. The black lines show precipitation (multiplied by ten). The graph above is from June 20th to August 16th and the graph below is from October 24th to December 20th 2011.

In Figure 7, soil temperature measurements from the four data loggers are shown for two periods. The loggers were located in four different spots within the geothermal area placed 15 cm deep down in a clayish soil. During the period from October 24th to December 20th (the lower graph), it is possible to see a sudden drop in temperature that cannot be related to precipitation or any other known parameter (air temperature, air pressure), marked with grey boxes. In the equation used to calculate the heat flow, the estimated heat flow depends on the temperature value to the fourth power which means that the calculations are very sensitive to high temperature values. Since it is known that high temperature values in the soil in Reykjanes can vary greatly on short time scale and even small changes in high temperature values does affect the heat flow estimate, it is concluded that the total heat flow estimate is not a very precise indicator for the surface changes in Reykjanes. Still, the broad evolution of the heat flow is unfailing and very important and can be compared to the studies from Wairakei. The heat flow is also very important for the comparison with the total CO_2 flux that generates a fundamental knowledge of the changes in geothermal areas associated with utilization. The soil temperature measurements and mapping of the temperature anomalies show changes in soil temperature and are reliable to visually compare changes from year to year.

6 CONCLUSION

The ten years of annual measurements of soil temperature and CO_2 flux in the Reykjanes geothermal area have shown an increased activity both in heat flow and in CO_2 flux. The CO_2 flux has increased from 13.5 ± 1.7 tons per day in 2004 to 51.4 ± 8.9 tons per day in 2013 according to the results of the soil measurements and there are no clear signs of stabilization in the CO_2 flux in Reykjanes yet. The distribution of CO_2 flux anomalies has changed greatly since 2004 but appear to be very similar in 2011, 2012 and 2013. The temperature anomalies do also appear to have changed greatly since 2004 and to be rather stable in the last few years. The heat flow estimate indicates an almost tripled increase in heat flow between 2004 and 2012, despite a decline between some years, as well as a possible decrease in heat flow between 2012 and 2013. The heat flow is derived from the soil temperature and the equation used is very sensitive for high temperature values. It is now known that temperature at high values in the soil in Reykjanes does vary, therefore reducing the value of the total heat flow estimate as a very precise indicator for changes in the surface activity in Reykjanes geothermal area. The changes in surface activity are expected to approach a steady state and the measurements in future years are essential as a part of the understanding of the geothermal system. The heat flow is very important for the comparison with other utilized areas and its relationship with the changes in total CO_2 flux. It generates a fundamental knowledge of the changes in geothermal areas associated with utilization.

The thermal infrared image which was obtained in May 2011 from the Reykjanes geothermal area shows a detailed picture of the surface temperature distribution. This image provides excellent data to compare with a TIR image from April 2004, also obtained from Reykjanes. The comparison of these two images shows without any doubt that surface temperature has increased in large parts of the Reykjanes geothermal area. A warm area lying north of the Gráa lónið lagoon has not been included in the soil measurements in previous years so that these images are the only concrete data showing the increase in this area. Snowmelt tracks were recorded in March 2011 to map the distribution of surface temperature and these tracks appear to fit very well with the TIR image from 2011. The changes in surface activity in the Reykjanes geothermal area have been observed by soil measurements, snowmelt tracking and TIR imagery for the last ten years, and the data has shown a great increase in surface activity. This data and continuing measurements in the years to come are essential to the understanding of changes of the geothermal systems and their response to utilization.

REFERENCES

Allis, R.G., (1981). Changes in heat flow associated with exploitation of the Wairakei geothermal field, New Zealand. *NZ Journal of Geology & Geophysics*, 24, 1-19.

Arnórsson, S., (1991). Estimate of natural CO2 and H2S flow from Icelandic high-temperature geothermal areas, *Conference on Geology and Environmental Matters*, Programme and Abstracts, pp. 18–19 (in Icelandic).

Björnsson, S., Ólafsdóttir, B., Tómasson, J., Jónsson, J., Arnórsson, S. and Sigurmundsson, S.G. 1971: Reykjanes – Heildarskýrsla um rannsókn jarðhitasvæðisins. *Orkustofnun - Jarðhitadeild*, 54 pages.

Brombach, T., Hunziker, J.C., Chiodini, G., Cardellini, C., Marini, L., (2001). Soil diffuse degassing and thermal energy fluxes from the southern Lakki plain, Nisyros (Greece). Geophys Res. Lett. 28:69–72.

Cardellini, C., Chiodini, G., Frondini, F. (2003). Application of stochastic simulation to CO2 flux from soil: mapping and quantification of gas release. J Geophys Res 108:2425. doi:10.1029/ 2002JB002165.

Chiodini, G., Cioni, R., Guidi, M., Marini, L., Raco, B. (1998). Soil CO2 measurements in volcanic and geothermal areas. Appl Geochem 13:543–552.

Chiodini, G., Frondini, F., Cardellini, C., Granieri, D., Marini, L., Ventura, G. (2001). CO2 degassing and energy release at Solfatara Volcano, Campi Flegrei, Italy. J Geophys Res 106:16213–16221.

Chiodini, G., Granieri, D., Avino, R., Caliro, S., Costa, A., Minopoli, C., Vilardo, G. (2010). Non-volcanic CO2 Earth degassing: Case of Mefite d'Ansanto (southern Apennines), Italy. Geophysical Research Letters, vol. 37, L11303.

Chiodini, G., Todesco, M., Caliro, S., Del Gaudio, C., Macedonio, G., Russo, M. (2003). Magma degassing as a trigger of bradyseismic events: the case of Phlegrean Fields (Italy). Geophys Res Lett 30:1434. doi:10.1029/2002GL016790.

Dawson, G.B. 1964: The Nature and Assessment of Heat Flow from Hydrothermal Areas. *New Zealand Journal of Geology and Geophysics* 7, New Zealand, 155-171.

Delbari, M., Afrasiab, P., Loiskandl, W. (2009). Using sequential Gaussian simulation to assess the field-scale spatial uncertainty of soil water content. Catena 79; 163-169.

Deutsch, C.V., Journel, A.G., (1998). GSLIB: Geostatistical software library and users guide. Oxford University Press, New York, p. 1-369.

Elmarsdóttir, Á., Ingimarsdóttir, M.,. Hansen, I., Ólafsson, J.S. and Magnússon, S.H. 2003: *Gróður og smádýr á sex háhitasvæðum*. Náttúrufræðistofnun Íslands og Líffræðistofnun Háskólans, Reykjavík, 73 pages (in Icelandic).

Fridriksson, Th., Kristjánsson, B.R., Ármannsson, H., Margrétardóttir, E., Ólafsdóttir, S., and Chiodini, G. (2006). CO2 emissions and heat flow through soil, fumaroles and steam heated mud pools at the Reykjanes geothermal area, SW Iceland. Applied Geochemistry, v.21, p.1551-1569.

Fridriksson, Th., Sæmundsson, K., Óladóttir, A.A., Einarsson, G.M., Kristinsson, S.G., Ármannsson, H., Eyjólfsdóttir, E. (2010). Umhverfiseftirlit á jarðhitasvæðinu á Reykjanesi. ÍSOR-2010/100, 80 p. (in Icelandic).

Frondini, F., Chiodini, G., Caliro, S., Cardellini, C., Granieri, D., Ventura, G. (2004). Diffuse CO2 degassing at Vesuvio, Italy. Bull Volcanol 66:642–651. doi:10.1007/s00445-004-0346-x.

Giammanco, S., Bellotti, F., Groppelli, G., Pinton, A. (2010). Statistical analysis reveals spatial and temporal anomalies of soil CO2 efflux on Mount Etna volcano (Italy). Journal of Volcanology and Geothermal Research 194; 1-14.

Giroud, N. and Arnórsson, S. (2005) Estimation of long-term CO2 and H2S release during operation of geothermal power plants. World Geothermal Congress 2005, Antalya, Turkey, 24-29 April, 2995, paper 0233.

Glover, R.B., Mroczek, E.K. (2009). Chemical changes in natural features and well discharges in response to production at Wairakei, New Zealand. Geothermics 38; 117-133.

Goff, S. and Goff, F. (1997). Environmental impacts during geothermal development: some examples from central America. Proceedings of the NEDO International Geothermal Symposium, Sendai, pp.242-250.

Goovaerts, P. (2001). Geostatistical modelling of uncertainty in soil science. Geoderma 103:3-26.

Granieri, D., Chiodini, G., Marzocchi, W., Avino, R. (2003). Continuous monitoring of CO2 soil diffuse degassing at Phlegraean Fields (Italy): influence of environmental and volcanic parameters. Earth Planet Sci Lett 212:167–179.

Gudmundsdóttir, A.L. 1988: Náttúrulegt varmastreymi til yfirborðs á jarðhitasvæðum í landi Nesjavalla. Háskóli Íslands [4. árs verkefni], 37 pages.

Harris, A.J.L. and Stevenson, D.S. 1996: Thermal observations of degassing open conduits and fumaroles at Stromboli and Vulcano using remotely sensed data. Journal of Volcanology and Geothermal Research 76, 175-198.

Hunt, T.M., (2001). Five lectures on environmental effects of geothermal utilization. United Nations University. Geothermal Training Programme 2000, Report 1, p. 109.

Inguaggiato, S., Vita, F., Rouwet, D., Bubrowski, N., Morici, S., Sollami, A. (2011). Geochemical evidence of the renewal of volcanic activity inferred from CO2 soil and SO2 plume fluxes: the 2007 Stromboli eruption (Italy). Bull. Volcanol. 73:443-456.

Johnsson, G.L. and Jakobsson, S.P., 1985: Structure and petrology of the Reykjanes Ridge between 62°55'N and 63°48'N, Journal of Geophysical Research v.90, p. 10073-10083.

Kristmannsdóttir, H. and Ármannsson, H. (2003). Environmental aspects of geothermal energy utilization. Geothermics 32: 451-461.

Lewicki, J.L., Bergfeld, D., Cardellini. C., Chiodini, G., Granieri, D., Varley, N., Werner, C. (2005). Comparative soil CO2 flux measurements and geostatistical estimation methods on Masaya volcano, Nicaragua. Bull. Volcanol. 68: 76-90.

Lillesand, T.M. and Kiefer, W.R. 2000: *Remote sensing and image interpretation* [Fourth edition]. John Wiley & Sons, Inc., United States of America, 724 pages.

Margrétardóttir, E. (2005). The application of thermal infrared images to estimate natural heat loss and gas discharge from the Reykjanes geothermal area, SW Iceland. M.Sc. thesis, University of Iceland.

Mazot, A., Rouwet, D., Taran, Y., Inguaggiato, S., Varley, N., (2011). CO2 and He degassing at El Chichón volcano, Chiapas, Mexico: gas flux, origin and relationship with local and regional tectonics. Bull. Volcanol. 73; 423-441.

Mörner, N.A., Etiope, G. (2002). Carbon degassing from the lithosphere. Global and Planetary Change, Volume 33, Issues 1–2, June 2002, Pages 185-203, ISSN 0921-8181, 10.1016/S0921-8181(02)00070-X.

Óladóttir, A. A (2012) Application of soil measurements and remote sensing for monitoring changes in geothermal surface activity in the Reykjanes field, Iceland. *MS-thesis*, Department of Earth Science, University of Iceland, 110 p.

Óladóttir, A. A., Óskarsson, F., (2013). Reykjanes Geothermal Field: Effects of Earthquakes on Surface Activity in October 2013. *Iceland GeoSurvey, ÍSOR-13073*.

Pálmason, G. (2005). Jarðhitabók. Hið íslenska bókmenntafélag, Reykjavík. Iceland, pp.298.

Pálmason, G., Johnsen, G.V., Torfason, H., Sæmundsson, K, Ragnars, K, Haraldsson, G.I., Halldórsson, G.K., (1985). Assessment of Geothermal Energy in Iceland. Orkustofnun OS-85076/JHD-10, 134 pp. (in Icelandic).

Salazar, J.M.L., Hernandez, P.A., Perez, N.M., Melian, G., Alvarez, J., Notsu, K. (2001). Diffuse emission of carbon dioxide from Cerro Negro volcano, Nicaragua, Central America. Geophys Res Lett 28:4275–4278.

Scott, B.J., Gordon, D.A., Cody, A.D. (2005). Recovery of Rotorua geothermal field, New Zealand: Progress, issues and consequences. Geothermics 34: 161-185.

Sheppard, D., Mroczek, E., (2004). Greenhouse gas emissions from the exploitation geothermal systems. IGA Quarterly No. 55, 11–13.

Sigurgeirsson, M.Á. (1995). The younger Stampar eruption at Reykjanes. Náttúrufræðingurinn 64, 211-230 (in Icelandic).

Sigurgeirsson, M.Á. (2004). A chapter in the eruption history of Reykjanes: eruption episode two thousand years ago. Náttúrufræðingurinn 72, 21-28 (in Icelandic).

Sorey, M.L. and Colvard, E.M. 1994: Measurements of heat and mass flow from thermal areas in Lassen volcanic National Park, Californina, 1984-93. U.S. Geoological Survey, California, 35 pages.