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An overview of carbon dioxide emissions from Icelandic geothermal areas

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A R T I C L E I N F O

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A B S T R A C T

The origin of CO_2 in fluids from Icelandic high-temperature geothermal systems is predominantly magmatic. Emissions from producing areas have risen with increased production. Abnormal rises have been recorded due to magmatic activity and the onset of boiling due to increase in production. Natural flow is predominantly through soil but to a small extent via steam vents and steam heated pools. The extent of natural steam flow varies considerably between areas, apparently due to the formation of carbonate deposits (mainly calcite) in relatively cool liquid dominated aquifers at shallow depths, where these are present. The CO_2 concentration of fluids from aquifers at higher temperatures apparently decreases with temperature and is for instance very low (< 1000 ppm) in fluid from IDDP-1, Krafla where the source temperature is 450 °C.

1. Introduction

The International Geothermal Association (2002) carried out a survey of CO_2 emissions from geothermal power plants in order to demonstrate the environmental advantage of geothermal energy in mitigating global warming. The results were presented in terms of emitted CO_2 per energy unit (g kWh^{-1}) in relation to production in MW_e (Table 1). The total range for all plants was 4–740 g kWh^{-1} with a weighted average 122 g kWh^{-1}. In the report it was suggested that the natural emission rate pre-development be subtracted from that released from the geothermal operation, citing Larderello as an example of a field, where a decrease in natural release of CO_2 has been recorded, and suggested to be due to development. Italy has accordingly not presented CO_2 emissions from geothermal production as a part of emissions recorded annually in international protocols.

Geothermal systems are often located in volcanic areas or other areas of high CO_2 flux of magmatic origin, but CO_2 may also be derived from depth where it is mainly produced by metamorphism of marine carbonate rocks. There is often a large flux through soil but CO_2 dissolves in groundwater, where this is present, usually reaching saturation where the flux is sufficiently large. Processes of natural generation are independent of geothermal production. The output is very variable but usually quite substantial. Estimated output from several volcanic and geothermal areas, and a total for the world are shown in Table 2.

A thorough investigation of the proportion of CO_2 emitted through various conduits in Pantelleria Island was conducted by Favara et al. (2001), but estimates of fractions emitted through groundwater on the one hand and soil and fumaroles on the other have been made at Mammoth Mountain (Sorey et al., 1998; Evans et al., 2002; Gerlach et al., 2001) and Furnas (Cruz et al., 1999). The results for these areas are listed in Table 3, along with results for Reykjanes, Iceland, discussed below.

Thus variations in carbon dioxide concentrations in geothermal fluids may have various causes. The objective of this paper is to investigate such variations at the scale of a country, i.e. Iceland, and at the same time present a detailed overview.

2. Origin of gas in Icelandic high-temperature geothermal fluids

The gas in fourteen of the fifteen areas, in which the carbon-13 isotope ratio has been studied, is apparently magmatic in origin, whereas that in the Öxarfjörður area could originate in organic sediments (Ármannsson, 2016). Stefánsson (2017) surmised that the sources of the magmatic CO_2 and H_2S may be basalt and progressive fluid rock interaction and/or degassing of basaltic melts, either at great depth upon partial melting within the upper mantle and lower crust, or at shallower levels within the crust. Both types of source have been suggested, particularly evidenced in the case of CO_2 (e.g., Stefánsson et al., 2016), whereas H_2S is considered to originate predominantly from basalt upon rock leaching (Stefánsson et al., 2015; Gunnarsson-Robin et al., 2017).

3. Gas emissions from geothermal activity in Iceland

The CO_2 emission from Icelandic geothermal plants has been recorded since about 1970 (Fig. 2). Gas concentrations in steam in Krafla

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Table 1
CO_2 emission and total running capacity of power plants divided into 9 emission categories (International Geothermal Association, 2002).

Emission category (g/kWh)	Running capacity (MW_e)	Average (g/kWh)
> 500	197	603
400–499	81	419
300–399	207	330
250–299	782	283
200–249	346	216
150–199	176	159
100–149	658	121
50–99	1867	71
< 50	2334	24

Table 2
CO_2 output from some volcanic and geothermal areas.

Area	Megaton (10^9 g) yr^{-1}	Reference
Pantelleria Island, Italy	0.39	Favara et al. (2001)
Vulcano, Italy	0.13	Baubron et al. (1991)
Solfatara, Italy	0.048	Chiodini et al. (1998)
Ustica Island, Italy	0.26	Etiope et al. (1999)
Popocatepetl, Mexico	14.5–36.5	Delgado et al. (1998)
Yellowstone, USA	10–22[a]	Werner and Brantley (2003)
Mammoth Mountain, USA	0.055–0.2	Sorey et al. (1998), Evans et al. (2002), Gerlach et al. (2001)
White Island, New Zealand	0.95	Wardell and Kyle (1998)
Mt. Erebus, Antarctica	0.66	Wardell and Kyle (1998)
Taupo Volcanic Zone, New Zealand	0.44	Seward and Kerrick (1996)
Furnas, Azores, Portugal	0.01	Cruz et al. (1999)
Mid-Ocean Volcanic System	30–100	Gerlach (1991), Marty and Tolstikhin (1998)
Total	200–1000	Mörner and Etiope (2002), Kerrick (2001), Delgado et al. (1998), Marty and Tolstikhin (1998)

[a] Diffuse degassing only.

Table 3
Relative CO_2 emission through different conduits from four areas (Favara et al., 2001; Sorey et al., 1998; Evans et al., 2002; Gerlach et al., 2001; Fridriksson et al., 2006).

	Pantelleria Island	Furnas Volcano	Mammoth Mountain	Reykjanes
Soil %	81	49[a]	63–90[a]	97
Focussed degassing %	7			
Fumarole %	0.0004			2
Bubbles %	3			
Groundwater %	9	51	10–37	1

[a] Total flow directly to atmosphere.

were relatively high during the late seventies and eighties due to magmatic gas. These have stabilized, but the increase seen around 2000 is due to increased production. As is frequently observed the gas concentrations decreased gradually with steady production and seem to have reached stability. The gas concentrations in Svartsengi rose in the early nineties due to the formation of a steam cap and increased production from that cap. A steady value has been reached, which may be expected to decrease if production is not increased. As is expected the gas emissions from Hellisheiði have increased during the power plant‘s first years of production. A similar rise but not as drastic is observed at Reykjanes.

The emissions from Nesjavellir are low and relatively constant. A comparison between the CO_2 emissions per kWh from the major geothermal plants in Iceland shows that they can be divided into two groups, i.e. Krafla and Svartsengi on the one hand but Hellisheiði, Reykjanes and Nesjavellir on the other (Table 4). The table also shows that the emissions per kWh in Krafla and Svartsengi have decreased since the year 2000. The effect of cascaded use, i.e. simultaneous production of heat and electricity in the year 2000 in Svartsengi and Nesjavellir is also shown.

Two areas that have been interpreted as ancient high temperature areas that are cooling down may be mentioned here, i. e Leirá, Borgarfjördur where temperatures up to 170 °C have been logged at 2000 m depth, and Grímsnes (Fig. 1), where temperatures in excess of 200 °C have been logged, and it may still be considered as a high temperature area (Ármannsson, 2016). Carbon dioxide concentrations up to about 500 mg/L have been observed in the water phase from a borehole at Leirá (Ármannsson, 1981) and concentrations up to 2500 ppm in the water phase from a well at Hædarendi, Grímsnes (Sæmundsson et al., 2007). A large amount of free CO_2 is also emitted at Hædarendi, and carbon dioxide produced there is sufficient for all industrial and agricultural use in Iceland (Ármannsson, 2016).

4. Results of gas flux studies in Iceland

Reykjanes: Fridriksson et al. (2006) studied the natural gas flow from the Reykjanes geothermal area prior to the commissioning of the Reykjanes power plant, and their findings are summarized below.

Total discharge of CO_2 to the atmosphere at Reykjanes. Natural atmospheric emissions of CO_2 at Reykjanes take place via three general pathways; soil diffuse degassing, steam vent discharge and gas bubbling through steam heated pools. The combined CO_2 emission via these three pathways at Reykjanes is equal to 13.9 t d^{-1} or 5060 metric t yr^{--1}. Most of this CO_2, by far (97.4%), is emitted through soil diffuse degassing, while only 1.7 and 0.9% are emitted through steam vents and fractures, and steam heated pools, respectively. It must be noted that the CO_2 flux by soil diffuse degassing was determined directly, whereas the CO_2 emissions from steam vents and steam heated pools were determined by indirect methods. The Reykjanes volcanic system has been dormant during the last 800 years or so, whereas geologic evidence indicates that episodes of volcanic activity occur with about 1000 year intervals (Sigurgeirsson, 2004). The relatively long repose period since the last volcanic episode at Reykjanes suggests that the present rate of CO_2 degassing may be at a minimum and it may have been significantly higher immediately after volcanic episodes with associated dike intrusions.

Several researchers (Favara et al., 2001; Werner et al., 2000; Sorey et al., 1998; Evans et al., 2002; Gerlach et al., 2001), indicate that soil diffuse degassing is generally a major, if not the dominating pathway of CO_2 release from geothermal systems (See Table 3), as appears to be the case at Reykjanes. Ármannsson et al. (2005) estimated that the maximum CO_2 emissions from all Icelandic geothermal systems were 1.3 × Mt yr^{--1} based on geological observations. Earlier estimates of total CO_2 discharge from Icelandic geothermal systems range between 0.15 × Mt yr^{-1} (Ármannsson, 1991) to 1 to 2 × 10 Mt yr^{-1} (Arnórsson, 1991; Arnórsson and Gíslason, 1994; Óskarsson, 1996). The lower value (Ármannsson, 1991) refers to steam vent discharge only, whereas the higher values represent the estimated total release of CO_2 from Icelandic geothermal systems, including atmospheric emissions (via soil diffuse degassing, steam vents, and steam heated pools), as well as CO_2 discharge into groundwater.

Geologic controls of CO_2 emissions at Reykjanes. The spatial distribution of soil diffuse degassing, soil temperature and heat flow indicates a strong tectonic control of both diffuse CO_2 emissions and heat loss. Two well defined linear diffuse degassing and heat loss structures and two or possibly three smaller linear features are observed. The orientation of the diffuse degassing structures (DDSs) is in all cases between N-S and NNE-SSW (between 000° and 020°). The most active parts of the DDSs define a NW-SE trend. The orientation of the DDSs at Reykjanes geothermal area is consistent with the orientation of the right lateral strike-