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CO₂ emissions during the 2023 eruption in Reykjanes, Iceland: $\delta^{13}\text{C}$ tracks magma degassing

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Abstract

We report CO₂ emission rates and plume $\delta^{13}\text{C}$ during the July 2023 eruption at Litli Hrótur in the Fagradalsfjall region of the Reykjanes Peninsula. The CO₂ emission rates were measured by UAV utilizing a new method of data extrapolation that enables obtaining rapid flux results of dynamic eruption plumes. The $\delta^{13}\text{C}$ values are consistent with extensive magma degassing fractionation during and after the eruption. Our results show that rapid, real-time CO₂ flux measurements coupled with isotopic values of samples collected at the same time provide key insights into the dynamics of volcanic eruptions and have the potential of forecasting the onset and termination of activity.

Keywords

Reykjanes eruptions, CO₂ emissions, carbon isotopes, magma degassing, UAV

Introduction

A fissure opened on July 10, 2023 at Litli Hrótur in the Fagradalsfjall region of the Reykjanes Peninsula, about 30 km from Reykjavík, Iceland's capital city producing the third eruption in the region in the past three years (Kornei, 2023). We report here the first CO₂ flux from this eruption that was directly measured, rather than calculated from SO₂ flux and CO₂/SO₂ ratios. Our data were collected on July 16, 2023, less than a week after the eruption started at Litli Hrótur and deployed a new method for measuring plume CO₂ fluxes directly by utilizing UAV based sensing systems coupled with novel extrapolation approaches. We compare this method of CO₂ flux determination with the conventional method of combining remotely sensed SO₂ flux measurements with in-plume C/S ratios to obtain volcanic CO₂ fluxes. While this method has initially been tested at the 2021 eruption of Tajogaite on La Palma Island, Spain (Ericksen et al., in review), the 2023 eruption at Litli Hrótur provided an ideal laboratory to further refine the method and compare the results with conventional measurements made during the same period of time. We also report $\delta^{13}\text{C}$ values of CO₂ gas samples collected by UAV in the eruption plume and analyzed by IR Isotope Ratio Spectroscopy at the University of Iceland utilizing University of New Mexico's Delta Ray instrument following the approach of Fischer and Lopez (2016). We compare the data with gas samples collected from vents and lavas at the 2021 eruption site at Fagradalsfjall.

Rapid measurements of volcanic CO₂ emissions prior to and during an eruption are an important forecasting tool (Aiuppa et al., 2010) because of CO₂'s low solubility in silicic magmas (Holloway,

1976; Holloway and Blank, 1994) resulting in early release of CO₂ from ascending melts. CO₂ is a greenhouse gas (Arrhenius, 1896) and constraining its emissions from volcanoes during quiescence and eruptions is central to reconstructing the preindustrial geological carbon cycle (Berner, 2004) and assessing its role in climate modulations over geologic time (Sleep and Zahnle, 2001). Due to seemingly insurmountable challenges of measuring CO₂ emitted from volcanoes utilizing currently available satellite-based remote sensing approaches, such remote measurements remain exceedingly rare (Schwandner et al., 2017) and not practical for routine, high-rate measurements during eruptions. This leaves ground-based remote sensing (Burton et al., 2013) or methods utilizing Uncrewed Aerial Vehicles (UAV) equipped with sensors (Liu et al., 2020) for volcanic plume CO₂ flux determinations. As a result of these issues, almost all CO₂ flux data from volcanic plumes reported to date are from non-erupting volcanoes and based on measurements of SO₂ flux using satellite- or ground-based methods combined with CO₂/SO₂ that has been measured in the plume at some point in time and generally not during the same time as the SO₂ flux measurements (Fischer and Aiuppa, 2020; Fischer et al., 2019; Werner et al., 2019). CO₂ flux determinations during eruptions depend on eruptive CO₂/SO₂ ratios but due to obvious challenges these are extremely scarce and out of 89 eruptions in the period from 2005 – 2017 only 26 have this ratio measured just before the eruption (Fischer et al., 2019). FTIR-based methods alleviate this issue by enabling measurements during eruptions (Burton et al., 2007; Oppenheimer et al., 2014; Oppenheimer et al., 2018) but require favorable geometries and a strongly emitting IR source such as a lava lake or fountaining limiting applicability to a broad range of volcanoes. Combined approaches (FTIR+drone-based Multi-GAS) are especially useful, but unfortunately still rare (Burton et al., 2023; Halldórsson et al., 2022).

The Reykjanes peninsula, in southwest Iceland, is a subaerial trans-tensional oblique rift which comprises five volcanic complexes (Fig. 1a). Volcanic activity started in March 2021 near Fagradalsfjall mountain in Geldingadalir valley (Fig. 1b), after a year of tectonic unrest within Svartsengi and Fagradalsfjall complexes. The magma sources, evolution and transport have been studied throughout the six-month eruption, with detailed geophysical, petrologic and geochemical studies (e.g. Halldórsson et al., 2022; Pedersen et al., 2022; Scott et al., 2023). Another eruption started on 3 August 2022 in Meradalir valley, which lasted three weeks. The eruption within the Fagradalsfjall complex started on 10 July 2023 near Litli-Hrútur mountain and continued for almost a month.

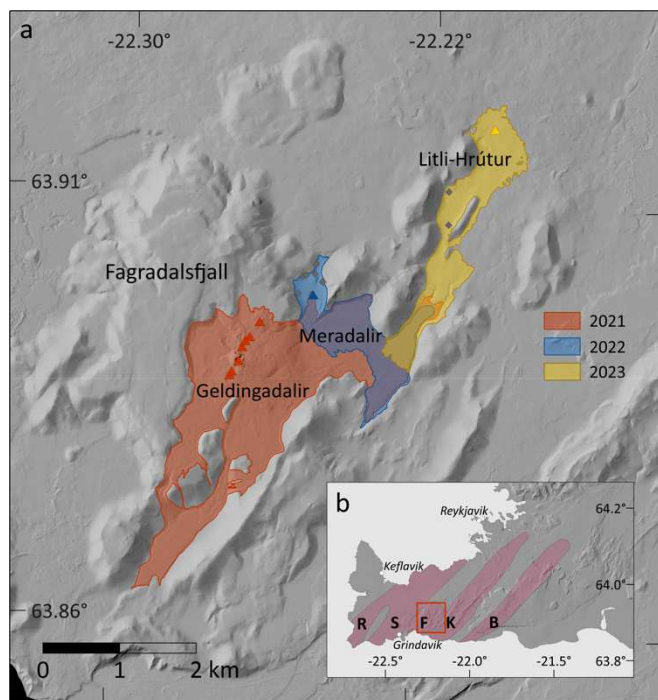


Fig. 1: Fagradalsfjall complex in the Reykjanes peninsula. b) Map of the Reykjanes peninsula and its volcanic complexes: R, Reykjanes; S, Svartsengi; F, Fagradalsfjall; K, Krýsuvík; B, Brennisteinsfjöll (Sæmundsson et al., 2010). The red square indicates the area displayed in a). a) Map showing the vents (triangles) and outlines of lava fields from the 2021, 2022 and 2023 eruptions of the Fagradalsfjall complex. The gray diamonds are the sampling locations for $\delta^{13}\text{C}$ measurements.

Materials and Methods

We present here a novel approach that is similar to the ‘ladder’ technique used by the USGS with LI-COR CO_2 sensors mounted on fixed-wing aircraft or helicopters (Gerlach et al., 1997; Werner et al., 2013). However, we use a PP Systems SBA-5, a much a lower-cost and smaller sensor mounted on a UAV (Ericksen et al., in review; Ericksen et al., 2022). In our approach we fly one UAV equipped with a multi-GAS (same unit as used in Halldorsson and al. (2022), Liu et al. (2020) and Burton et al. (2023) in a vertical profile up through the visually estimated center of the plume to locate the highest concentration of CO_2 in the vertical, and then fly a UAV with an SBA-5 sensor in a horizontal transect through the plume at the altitude of the highest concentration. Because the UAV measurements are made much closer to the source than aircraft-borne measurements, the plume has had less time to mix with the surrounding air, is more turbulent, and more heterogeneous (Sparks et al., 1997; Wang and Law, 2002). The closer to source, the less wide a plume will be, and faster to measure across. In our approach, the transect flights are automated with the CO_2 data and UAV location transmitted in real-time to the pilot who can take over the flight if needed. In the ideal case, multiple transects are flown through the plume to make a CO_2 concentration map as is done during the traditional ‘ladder’ approach, but this is often challenging for highly variable or rapidly evolving, distant or wide plumes.

For this experiment, we flew multiple consecutive horizontal transects and found the plume to be highly dynamic over short periods of time, indicating that the ‘ladder method’ (Gerlach et al., 1997; Werner et al., 2013) in which multiple transects are used to characterize the cross section of the

plume is not well suited for the Litli Hrótur plume during this phase of the eruption. To still obtain CO₂ emission rate estimates, we use individual 1-dimensional transects to describe the plume over a short period of time by assuming a normally distributed plume concentration and fit a 2-dimensional Gaussian curve to the CO₂ concentration profile. This Gaussian distribution is integrated to calculate a cross sectional concentration of a symmetrically distributed plume in the width and height dimensions. We then multiply the integrated Gaussian transect distribution by the measured wind speed to yield the CO₂ flux (Gerlach, et al, 1997; Werner et al., 2013; Ericksen et al., in review). This method is shown in detail with all data presented in the publicly accessible Jupyter Notebook linked here.

<https://github.com/BCLab-UNM/iceland-2023-expedition/tree/ATM2023>

Our approach should provide the most accurate results if the plume is transected through its highest vertical concentration point and it approaches a Gaussian shape of concentration. Considering the observed highly dynamic nature of the plume, this approach should result in a self-consistent estimate of flux. In order to test the accuracy of our rapid measurements, we compare the results to CO₂ fluxes obtained by making vehicle-based traverses under the plume using a miniDOAS SO₂ sensor (Galle et al., 2002) and in plume UAV-Multi-GAS collected CO₂/SO₂ ratios (Liu et al., 2020).

While the source of the degassing CO₂ during the eruption is clearly magmatic, we utilize carbon isotopes to constrain the extent of magma degassing. To achieve this, we use the UAV to collect gas samples of the volcanic plume during the eruption. This approach has been pioneered by Chiodini et al. (2011) using aircraft-based plume sampling. Our UAV-based sampling system has previously been used at Manam volcano in Papua New Guinea for passively degassing plumes (Galle et al., 2021; Liu et al., 2020) and at Tajogaite volcano, La Palma, Spain during an eruption (Ericksen et al., in rev.). At Litli Hrótur, we mounted the sampling system on a DJI Phantom 3 or Phantom 4. The sample was collected by pumping about 500 ml of gas into a Tedlar Bag. The pump was triggered with a timer that was set based on previous flights which allowed us to locate the densest part of the plume. Generally, two samples were collected during each flight. After collection the samples were analyzed by IR Isotope Ratio Spectroscopy on an instrument that we had temporarily installed at the University of Iceland. We obtained the $\delta^{13}\text{C}$ values and the CO₂ concentrations of the samples using analytical techniques identical to those reported previously (Fischer and Lopez, 2016; Galle et al., 2021; Liu et al., 2020). The error on the $\delta^{13}\text{C}$ analyses is < 0.1 ‰ and for CO₂ concentrations < 10 ppm. During 2022 we also collected gas samples from vents and fissures on the lava field produced by the 2022 eruption of Fagradalsfjall (Figure 1). The samples were collected by pumping gas into a Tedlar bag using a syringe and analyzed in the same way as the samples collected by UAV.

Results

Figure 2 shows the experimental observations made July 14 and July 16, 2023 at the vent of Litli Hrótur also shown in Figure 1. We launched the Dragonfly UAV from a location about 450 m from the active vent to perform several transects through the plume. Prior to launch of the Dragonfly we measured the CO₂ concentration of the vertical plume profile using a commercial UAV equipped with the Multi-GAS sensor system from the University of Palermo. We performed a vertical transect at a distance of 375 m from the vent and the highest CO₂ concentration of 1472

ppm was detected at a height of 60 m above launch site at 16:45 hours local time. We measured CO₂/SO₂ ratios using University of Palermo's UAV mounted Multi-GAS system on July 16 at 18:30 local time, and averaged in-plume concentrations to obtain a single value. We collected a Tedlar bag sample of the plume using our DJI Phantom 4 at a distance of 125 m from the vent that was analyzed by Delta Ray infrared isotope ratio spectrometer and contained 650 ppm CO₂, or about 230 ppm above ambient. On July 14, at a distance of 7.5 km downwind from the vent we performed two driving traverses using UNM's miniDOAS system mounted on a vehicle. The spectra were collected using the freely-available MobileDOAS software. The first transect was 4.5, the second 1.7 km long. Both transects captured the entire width of the plume. The data collected is summarized in Table 1.

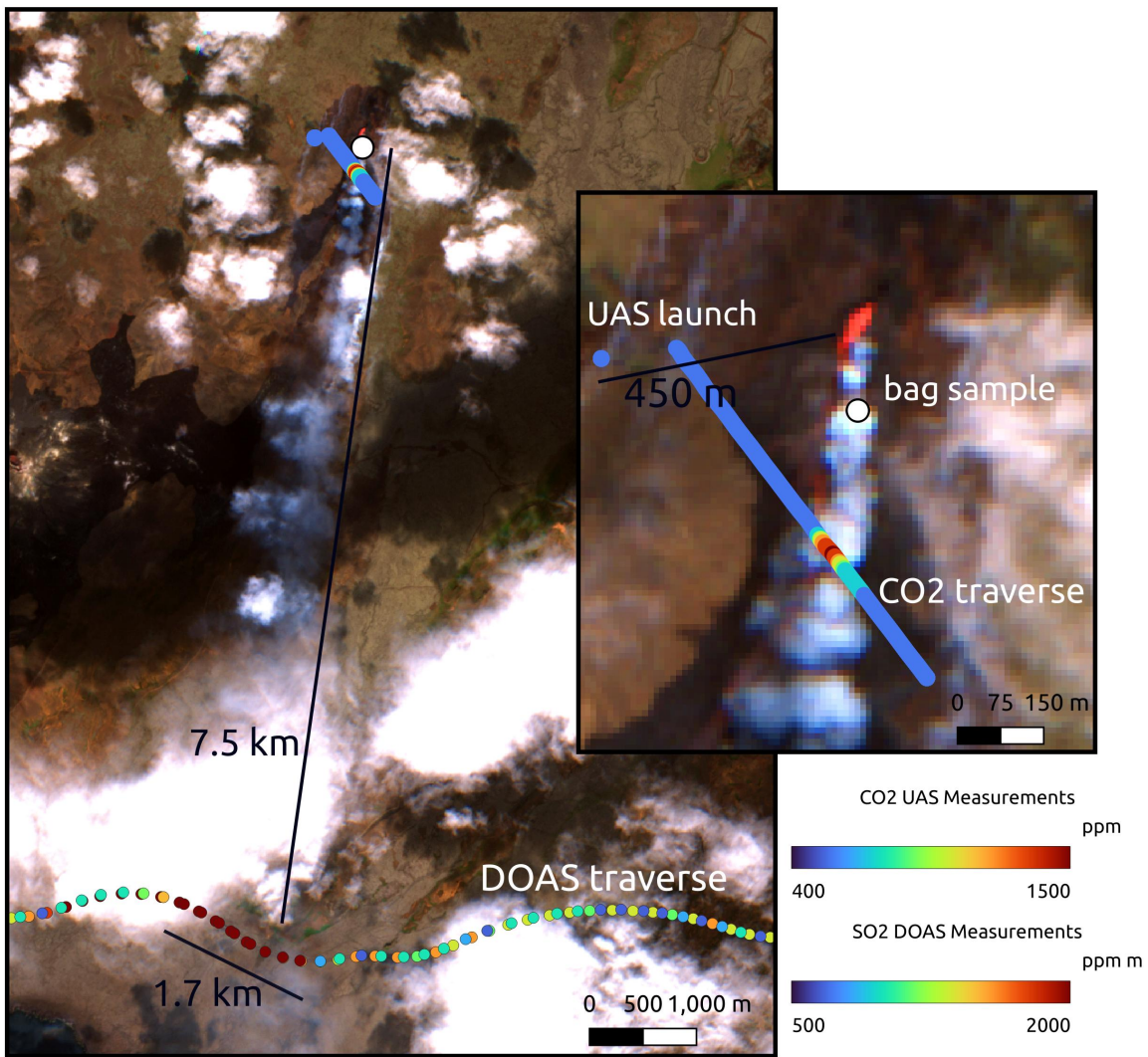


Figure 2: Map of observations and eruptive conditions overlain on Sentinel 2 visible image. DOAS traverse was collected by vehicle-mounted telescope along the paved road 7.5 km from the eruption and CO₂ traverse occurred using the UNM Dragonfly drone. Sentinel image was acquired on July 13 during which the wind direction was nearly identical to conditions on July 16, 2023.

The CO₂ flux computed using our SO₂ flux measurements of 73 – 80 kg/s (wind speed of 17 m/s) and the CO₂/SO₂ molar ratio of 3 results in a CO₂ flux of 150 – 160 kg/s. The CO₂ flux computed directly using the dragonfly VolCAN method with wind speed of 10 m/s from NNE results in a CO₂ flux of 20 and 50 kg/sec for two passes during the same out and back flight, occurring between 17:20 and 17:23 hours local time. The decrease in flux between the SO₂ ratio method measured on July 14 and direct CO₂ method measured on July 16 is consistent with the visual observations of decreasing overall emissions and CO₂ flux values until the eruption ended on August 5, 2023.

Table 1: Results of gas flux measurements on July 14 to August 2, 2023.

Method	Date	time local	max CO ₂ ppm vertical	max CO ₂ ppm horizontal	molar CO ₂ /SO ₂	plume width (m) DOAS transect	wind speed (m/s)	SO ₂ flux kg/sec	CO ₂ flux kg/sec *
miniDOAS	14-Jul	19:30				4515	17	80	
miniDOAS	14-Jul	19:15				1753	17	73	
Matrice + Palermo MG	16-Jul	16:45	1400						
Matrice + Palermo MG	16-Jul	18:30	1220		2.97				
Phanom + Bag	16-Jul	16:00	650						
Phantom + UNM MG	27-Jul	15:50, 16:50	1777		5.4				
Phantom + UNM MG	2-Aug	14:00 - 16:00	1721		5.7				
CO₂ fluxes combined techniques:									
DOAS & MG	14 & 16 Jul				2.97	1752 - 4515	17	73 - 80	150 - 160
Dragonfly + SBA-5	16-Jul	16:30	1400	1472			10		20 - 50

Note: CO₂ flux measured by DOAS and multiGAS utilizes the CO₂/SO₂ ratio of 2.97 measured by Matrice +Palermo MG

The results of the δ¹³C analyses of samples collected from the 2023 Litli Hrótur eruption and following this eruption are shown in Table 2. The results of samples collected from degassing fissures and lava flows at the 2022 eruption site are shown in Supplementary Table S1.

Table 2: Carbon isotope data collected for this study. Errors on δ¹³C values are < 0.1‰ and on CO₂ concentrations < 10 ppm. Also indicated are methods of sampling and person who sampled.

Date	Sample	δ ¹³ C+CO ₂	CO ₂ (ppm)	Notes
<u>2023 Eruption</u>				
7/10/23	eruption ground	-8.82	478	ground/Melissa
7/10/23	eruption ground	-8.37	470	ground/Melissa
7/16/23	80m	-13.53	1291	Dragonfly/John
7/16/23	140m	-7.14	650	Phantom/Scott
7/19/23	35m	-9.40	520	Phantom/Tobias
7/19/23	Air RKJ	-7.32	432	ground/Tobias

7/23/23	Air RKJ	-7.45	428	ground/Tobias
7/23/23	Air Vogar	-7.43	434	ground/Tobias
7/22/23	L.Hrutur #2	-10.13	578	Phantom/Tobias
7/22/23	L.Hrutur#3	-8.19	466	Phantom/Tobias
7/24/23	L.Hrutur#1	-9.91	1145	Phantom/Tobias
7/24/23	L.Hrutur#2	-7.15	563	Phantom/Tobias
7/24/23	L.Hrutur#3	-6.18	1045	Phantom/Tobias
7/24/23	L.Hrutur#4	-5.90	1054	Phantom/Tobias
7/24/23	L.Hrutur#4	-6.81	579	Phantom/Tobias
7/24/23	L. Hrutur fire	-14.10	1304	ground/Tobias
7/24/23	Air RKJ	-8.13	465	ground/Tobias
7/26/23	Air RKJ	-7.67	438	ground/Tobias
7/29/23	Air RKJ	-7.88	443	ground/Tobias
7/25/23	L.Hrutur #1	-7.59	547	Phantom/Felipe
7/25/23	L.Hrutur #2	-7.30	540	Phantom/Felipe
7/25/23	L.Hrutur #3	-6.45	790	Phantom/Felipe
7/27/23	L.Hrutur #1	-7.19	758	Phantom/Felipe
7/27/23	L.Hrutur #2	-7.83	630	Phantom/Felipe
<u>Post-eruption</u>				
12/2/23	L.Hrutur #1	-13.91	2473	vent 1/Celine
12/2/23	L.Hrutur #2	-12.70	1644	vent 1/Celine
12/2/23	L.Hrutur #3	-11.41	954	vent 1/Celine
12/2/23	L.Hrutur #4	-8.92	559	vent 2/Celine
12/2/23	L.Hrutur #5	-9.10	549.3	vent 2/Celine

Discussion

The two methods for obtaining CO₂ emissions compared here are fundamentally different in their observations, but it is important to state that neither method collects a complete instantaneous cross section of CO₂. Both methods are highly dependent upon the wind speed used to determine the CO₂ flux, but the SO₂ ratio method is further dependent upon the derived SO₂/CO₂ ratio determined from an averaged set of separate observations. We know that CO₂ and SO₂ should not be considered to be emitting from the same vents or traveling down-wind in consistent relative concentrations based on observations at Kīlauea (Gerlach et al., 2002) for instance. Our measurements made with UAV-mounted Multi-GAS are variable and the applied ratio is an average of that variance. Rarely is there any spatial knowledge of the plume dynamics when collecting Multi-GAS data and we do not know how CO₂ and SO₂ align spatially in the plume at the fine scale. The direct CO₂ Dragonfly method does not measure a column integrated profile of the CO₂ plume, but the flight path is a 2-dimensional sample through a plume rather than a full cross section of the CO₂.

Given the highly variable nature of the emitted plumes (see the puffy undulating plume shape in the visible Sentinel Imagery in Figure 2) there is likely to be a high degree of variability between successive observations even when taken only minutes apart. Future work should address these issues by making a high number of vertical and horizontal transects through the plume with the CO₂ Dragonfly method, collect mini-DOAS SO₂ emission data and Multi-GAS data combined with vent FTIR data. This would require an ‘ideal’ eruption that allows such measurements to be made at the same time – a highly challenging objective.

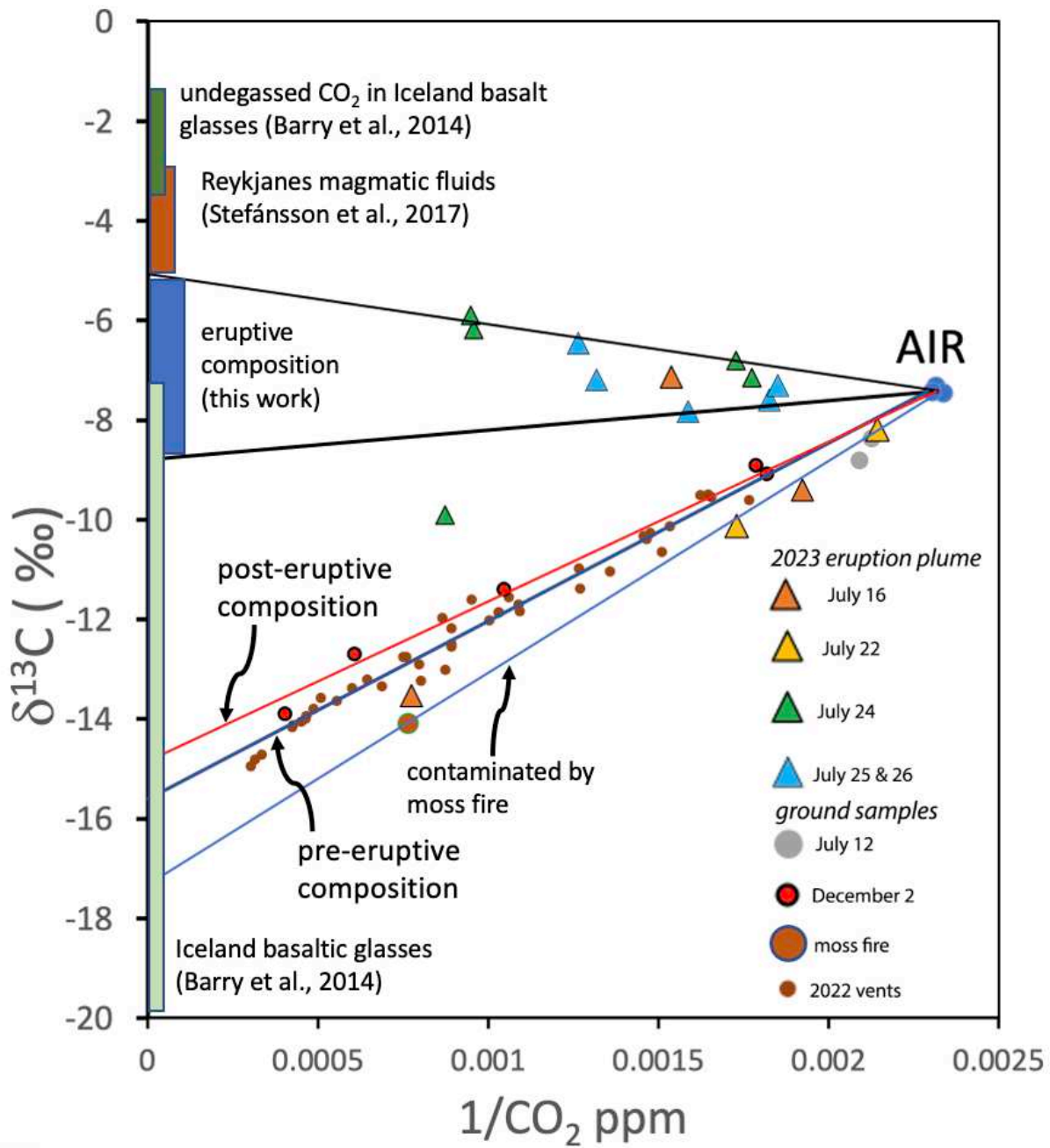


Figure 3 Shows the carbon isotope data collected using bag sampling and Isotope Ratio Infrared Spectroscopy analyses. Also shown are data from Barry et al., 2014, including degassed glasses, modeled undegassed magma and fluids from the Reykjanes Peninsula (Stefánsson et al., 2017).

Figure 3 shows $\delta^{13}\text{C}$ and $1/\text{CO}_2$ concentration values of all samples collected during the 2022 – 2023 period at Fagradalsfjall and Litli Hrófur. Using the Keeling-plot approach (Keeling, 1958), our $\delta^{13}\text{C}$ and CO_2 abundance data show mixing between ambient air and pure CO_2 . Our data are extrapolated to pure CO_2 and show light $\delta^{13}\text{C}$ values ($\sim -16\text{‰}$) following the 2022 eruption, while during the 2023 eruption values between -5 and -9‰ are observed approaching the range of the Icelandic mid-oceanic ridge (MOR) mantle in the region as sampled by hydrothermal fluids ($-3.6 \pm 0.6 \text{‰}$ Stefánsson et al., 2017). Samples collected at the eruption site in December 2023, about 3 months after the eruption ended, again show light $\delta^{13}\text{C}$ values. The samples collected from the 2022 Fagradalsfjall eruption site during the time from September 2022 to June 2023 extrapolate to light $\delta^{13}\text{C}$ values of approximately -16‰ . These values are consistent with $\delta^{13}\text{C}$ values of Western Rift Zone glasses that represent degassed MOR magmas as measured in subglacial erupted glasses (-7.6 to -20.1‰ , Barry et al., 2014). The first samples from the 2023 Litli Hrófur eruption were collected on July 12, 2023 at ground level hundreds of meters from the site. Due to the large distance from the source, the plume gases were significantly diluted by air and show light values that extrapolate to -17.5‰ . Plume samples collected by UAV on July 16 and 22 2023 align also with the sample collected directly from the moss fire and extrapolate to -17.5‰ . These light values are clearly distinct from the other Fagradalsfjall 2022 and 2023 samples. Most likely, these lightest samples are contaminated by organic carbon derived from either the lava flowing over vegetation at the start of the eruption in the case of the ground-based sample collected on July 12, and by smoke mixing with plume gases in the case of the July 16 and 22 2023 UAV-collected samples. In fact, a sample of the smoke released by a moss fire plots exactly on this extrapolation line.

Notably, samples collected by UAV during July 16 (one sample) and during July 22-26 2023 (9 samples) extrapolate to $\delta^{13}\text{C}$ values (-5 to -9‰) that are slightly lower than observed in hydrothermal gases at Reykjanes (-4.96 to -2.99‰ (Stefánsson et al., 2017) and for undegassed basaltic melts beneath Iceland ($-2.5 \pm 1.0 \text{‰}$, Barry et al., 2014). Although we were not able to collect uncontaminated samples right at the start of the eruption on July 10, 2023, our data show that by July 16, the erupting lava had a $\delta^{13}\text{C}$ signature that represented fresh and undegassed melts feeding the eruption. Samples collected at the eruption site in December 2023, three months after the eruption stopped show light values extrapolated to -15‰ . Magma degassing results in fractionation of carbon isotopes to progressively lighter values in the gas and remaining melt (Holloway and Blank, 1994) and the light values of December 2023 indicate that the magma had extensively degassed three months after the eruption had stopped.

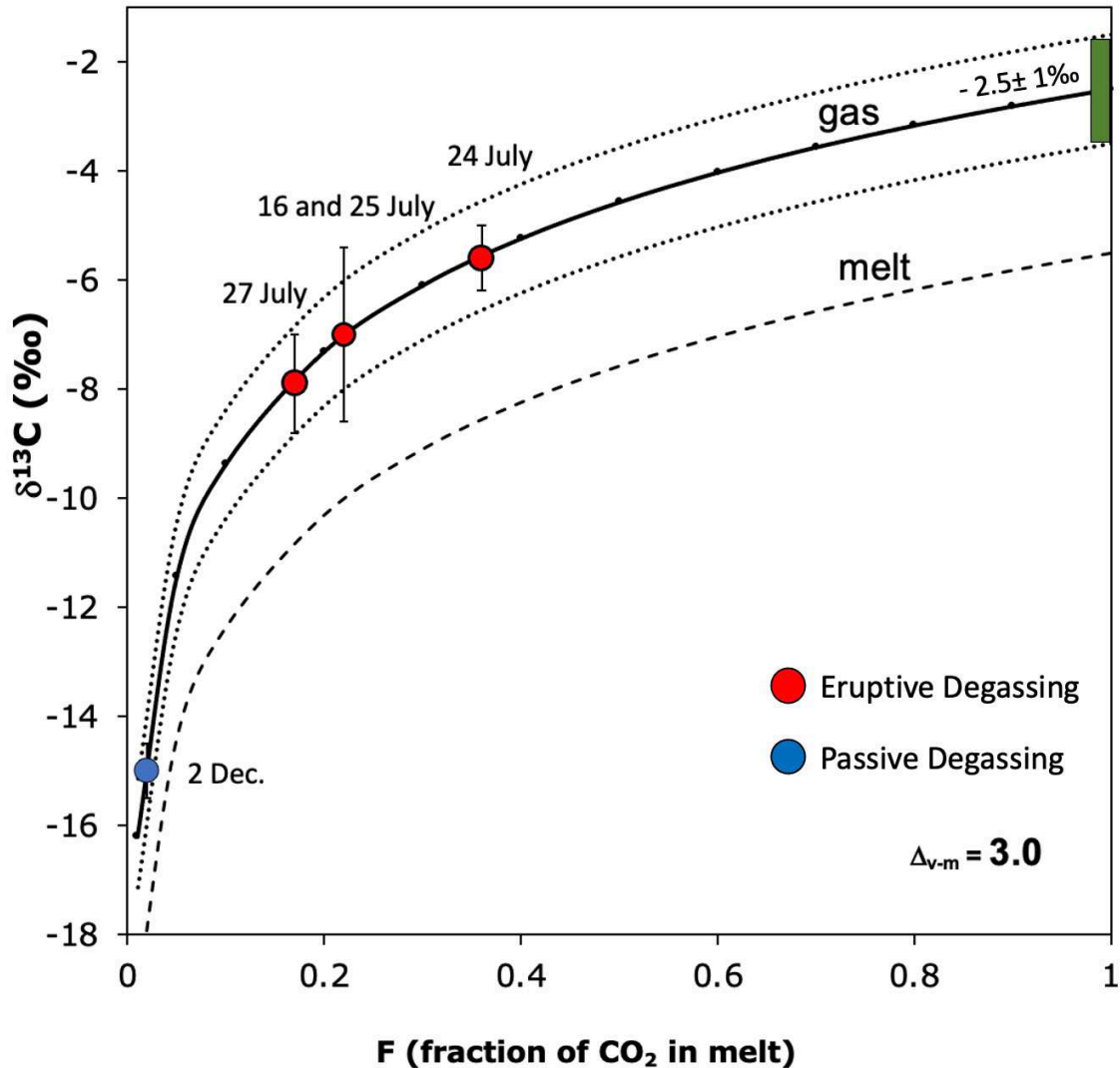


Figure 4. Degassing fractionation modeled using the approach of Holloway and Blank, 1994. Gas-melt fractionation factor is from Javoy et al., 1978 and Matthey, 1991. We use undegassed mantle beneath Iceland (-2.5 ± 1 from Barry et al., 2014) as starting composition. We plot the extrapolated $\delta^{13}\text{C}$ values collected during and shortly after the eruption in 2023 from Figure 3.

This magma degassing process can be further assessed and visualized by plotting the extrapolated $\delta^{13}\text{C}$ values against the degassing fraction (Figure 4). The fractionation of C can be computed based on a simple open-system degassing model, assuming experimentally determined isotope fractionation factors for basaltic melts (Holloway and Blank, 1994; Rayleigh, 1896). We choose an intermediate vapor-melt distribution coefficient of 3 ‰ for basaltic melts (Javoy et al., 1978; Matthey, 1991) to illustrate the tracking of the melt degassing process by our $\delta^{13}\text{C}$ values collected during and following the eruption. We use as the initial composition the values published by (Barry et al., 2014) to represent the undegassed melt composition underlying the Reykjanes peninsula (-2.5 ± 1 ‰) which is also broadly similar to DMM-values of -5 ± 1 ‰ sampled by MORB (Marty and

Zimmermann, 1999). While our data show some variability, the results indicate continuous degassing of the magma that erupted at the surface from July 16 to July 27, 2023. Based on our data we infer that the magma was about 80% degassed ($F = 0.2$) by July 27, our last sample. The eruption ended on August 6, only 10 days after. By December 2023, the magma had lost about 98% ($F=0.02$) of its CO_2 . Degassing processes can be significantly more complex than the case of open-system degassing illustrated here. Closed-system degassing (Brown et al., 1985) or hybrid models discussed in Aubaud (2022) have been documented by analyzing CO_2 in calcite or crushed vesicles of rocks. During closed system degassing the maximum isotopic shift in the gas is limited to the magnitude of the fractionation factor, in our case 3‰ and would not be able to explain our data. For application to volcanic gases, knowledge of F (fraction of gas remaining in the melt) is generally not available and $\delta^{13}\text{C}$ values of volcanic gas samples are plotted against assumed (not measured) wt% of dissolved CO_2 (Gerlach and Taylor, 1990). In our case, assuming a simple open-system degassing process enables a relative estimate of how much CO_2 has degassed. Future work should increase the rate and temporal extent of plume $\delta^{13}\text{C}$ measurements from eruption start to end to better constrain the shape of the degassing fractionation curve.

Conclusions

The data collected following the 2022 Fagradalsfjall eruption and during the 2023 Litli Hrutur eruption show that the Litli Hrutur eruption emitted significant quantities of CO_2 during its initial stages from a largely undegassed melt. Our UAV-based approach to directly obtain the CO_2 flux during eruptions is a valid alternative to more complex or involved methods that rely on several types of measurements or extensive traverses through plumes. The source of eruptive CO_2 was from fresh, undegassed magma and quite distinct from the magma that was left at depth after the end of the 2022 eruption. Our observations are consistent with the idea of volatile-charged magma injections into deep crustal levels that drive the eruptive episodes on the Reykjanes Peninsula (Halldórsson et al., 2022). Once this injected magma is degassed, the eruption stops until new volatile-rich magma is again injected.

Samples collected prior to, during and following an eruption like the ones that have occurred in 2022 and 2023 on the Reykjanes peninsula, and rapidly analyzed for $\delta^{13}\text{C}$ values provide critical insights into the dynamics of the eruption and can in theory enable the forecasting of the end of such an eruption. However, while our data shows a general decrease in $\delta^{13}\text{C}$ consistent with continuous magma degassing, better quantification of the extent of CO_2 remaining in the melt requires even more frequent sampling. Ideally, gas samples collected just before an eruption, above the injecting dike, could provide key information about the initial isotopic composition of the CO_2 released from the injecting melt and inform hazard evaluations of such eruptions.

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Reference

- Aiuppa, A., Burton, M., Caltabiano, R., Guidice, G., Guerrieri, S., Liuzzo, M., Muré, F. and Salerno, G., 2010. Unusually large magmatic CO₂ gas emissions prior to a basaltic paroxysm. *GEOPHYSICAL RESEARCH LETTERS*, , 37, L17303 doi:10.1029/2010GL043837.
- Arrhenius, S., 1896. On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. *Philosophical Magazine and Journal of Science, Series 5, Volume 41*, : 237-276.
- Aubaud, C., 2022. Carbon stable isotope constraints on CO₂ degassing models of ridge, hotspot and arc magmas. *Chemical Geology*, 605: 120962.
- Barry, P.H., Hilton, D.R., Füre, E. and Halldórsson, S.A., 2014. Carbon isotope and abundance systematics of Icelandic geothermal gases, fluids and subglacial basalts with implications for mantle plume-related CO₂ fluxes. *Geochimica et Cosmochimica Acta* 134: 74–99.
- Berner, R.A., 2004. *The Phanerozoic Carbon Cycle*. Oxford University Press, New York, 150 pp.
- Brown, P.E., Bowman, K.W. and Kelly, W.C., 1985. Petrologic and stable isotopic constraints on the source and evolution of skarn-forming fluids at Pine Creek, California. *Econ. Geol.*, 80: 72-92.
- Burton, M., Allard, P., Muré, F. and La Spina, A., 2007. Magmatic gas composition reveals the source depth of slug-driven Strombolian explosive activity. *Science*, 317: 227-230.
- Burton, M.R., Sawyer, G.M. and Granieri, D., 2013. Deep carbon emissions from volcanoes. *Reviews in Mineralogy and Geochemistry: Carbon in Earth*, 75: 323-355.
- Burton, M., Aiuppa, A., Allard, P., Asensio-Ramos, M., Cofrades, A.P., La Spina, A., Nicholson, E.J., Zanon, V., Barrancos, J., Bitetto, M., Hartley, M., Romero, J.E., Waters, E., Stewart, A., Hernández, P.A., Lages, J.P., Padrón, E., Wood, K., Esse, B., Hayer, C., Cyrzan, K., Rose-Koga, E.F., Schiavi, F., D’Auria, L. and Pérez, N.M., 2023. Exceptional eruptive CO₂ emissions from intra-plate alkaline magmatism in the Canary volcanic archipelago. *Communications Earth & Environment*, 4(1): 467.
- Chiodini, G., Caliro, S., Aiuppa, A., Avino, R., Granieri, D., Moretti, R. and Parello, F., 2011. First ¹³C/¹²C isotopic characterisation of volcanic plume CO₂. *Bulletin of Volcanology*, 73(5) 531-542.
- Ericksen, J., Fischer, T.P., Fricke, G.M., Nowicki, S., Perez, N.M., Hernandez Perez, P., Padron Gonzalez, E., Fierro, R. and Moses, M.E., in review. Drone CO₂ Measurements During the Tajogaite Volcanic Eruption. *Science Advances*.
- Ericksen, J., Fricke, G.M., Nowicki, S., Fischer, T.P., Hayes, J.C., Rosenberger, K., Wolf, S.R., Fierro, R. and Moses, M.E., 2022. Aerial survey robotics in extreme environments: Mapping volcanic CO₂ with flocking UAVs. *Frontiers in Control Engineering* 3:836720. doi: 10.3389/fcteg.2022.836720.
- Fischer, T.P. and Aiuppa, A., 2020. AGU Centennial Grand Challenge: Volcanoes and Deep Carbon Global CO₂ emissions from subaerial volcanism: recent progress and future challenges. *G-cubed* 21(3 e2019GC008690).
- Fischer, T.P., Arellano, S., Carn, S., Aiuppa, A., Allard, P., Lopez, T., Shinohara, H., Kelly, P.J., Werner, C., Cardellini, C. and Chiodini, G., 2019. The emissions of CO₂ and other volatiles from the world’s subaerial volcanoes. *Scientific Reports*, 9:18716 <https://doi.org/10.1038/s41598-41019-54682-41591>.
- Fischer, T.P. and Lopez, T.M., 2016. First airborne samples of a volcanic plume for δ¹³C of CO₂ determinations. *Geophys Res. Lett.*, 43.

- Galle, B., Arellano, S., Bobrowski, N., Conde, V., Fischer, T.P., Gerdes, G., Gutmann, A., Hoffmann, T., Itikarai, I., Krejci, T., Liu, E.J., Mulina, K., Nowicki, S., Richardson, T., Rüdiger, J., Wood, K. and Xu, J., 2021. A multi-purpose, multi-rotor drone system for long range and high-altitude volcanic gas plume measurements. . *Atmospheric Measurement Techniques Discussions* . , P. 1-33.
- Galle, B., Oppenheimer, C., Geyer, A., McGonigle, A.J.S., Edmonds, M. and Horrocks, L., 2002. A miniaturised ultraviolet spectrometer for remote sensing of SO₂ fluxes; a new tool for volcano surveillance. *J. Volcanol. Geotherm. Res.*, 119: 241-254.
- Gerlach, T., Delgado G., H., McGee, K., Doukas, M., Venegas, J.J. and Cárdenas, L., 1997. Application of the LI-COR CO₂ analyzer to volcanic plumes: A case study, volcán Popocatepetl, Mexico, June 7 and 10, 1995. *J. Geophys. Res.*, 102(B4): 8005-8019.
- Gerlach, T.M. and Taylor, B.E., 1990. Carbon isotope constrains on degassing of carbon dioxide from Kilauea Volcano. *Geochimica et Cosmochimica Acta*, 54: 2051-2058.
- Gerlach, T.M., McGee, K.A., Elias, T., Sutton, A.J. and Doukas, M.P., 2002. Carbon dioxide emission rate of Kīlauea Volcano: Implications for primary magma and the summit reservoir. *Journal of Geophysical Research: Solid Earth*, 107(B9): ECV 3-1-ECV 3-15.
- Halldórsson, S.A., Marshall, E.W., Caracciolo, A., Matthews, S., Bali, E., Rasmussen, M.B., Ranta, E., Robin, J.G., Guðfinnsson, G.H., Sigmarsson, O., MacLennan, J., Jackson, M.G., Whitehouse, M.J., Jeon, H., van der Meer, Q.H.A., Mibei, G.K., Kalliokoski, M.H., Repczynska, M.M., Rúnarsdóttir, R.H., Sigurðsson, G., Pfeffer, M.A., Scott, S.W., Kjartansdóttir, R., Kleine, B.I., Oppenheimer, C., Aiuppa, A., Ilyinskaya, E., Bitetto, M., Giudice, G. and Stefánsson, A., 2022. Rapid shifting of a deep magmatic source at Fagradalsfjall volcano, Iceland. *Nature*, 609(7927): 529-534.
- Holloway, J.R., 1976. Fluids in the evolution of granitic magmas: Consequences of finite CO₂ solubility. *Geol. Soc. America Bulletin*, 87: 1513-1518.
- Holloway, J.R. and Blank, J., 1994. Experimental results applied to C-O-H in natural melts. In: M.R.C.J.R. Holloway (Editor), *Volatiles in Magmas. Reviews in Mineralogy. Mineralogical Society of America, Fredericksburg, VA*, pp. 187-230.
- Javoy, M., Pineau, F. and Iiyama, I., 1978. Experimental determination of the isotopic fractionation between gaseous CO₂ and carbon dissolved in tholeiitic magma. *Contributions Mineralogy Petrology*, 67: 35-39.
- Keeling, C.D., 1958. The concentration and isotopic abundances of atmospheric carbon dioxide in rural areas, . *Geochim Cosmochim Acta*, 13: 322– 334.
- Kornei, K., 2023. Third time's the charm for Iceland's Fagradalsfjall, . *Eos, Transactions, American Geophysical Union*, 104, <https://doi.org/10.1029/2023EO230267>. Published on 19 July 2023.
- Liu, E., Aiuppa, A., Alan, A., Arellano, S., Bitetto, M., Bobrowski, N., Carn, S., Clarke, R., Corrales, E., de Moor, J.M., Diaz, J.A., Edmonds, M., Fischer, T.P., Freer, J., Fricke, G.M., Galle, B., Gerdes, G., Giudice, G., Gutmann, A., Hayer, C., Itikarai, I., Jones, J., Mason, E., McCormick Kilbride, B.T., Mulina, K., Nowicki, S., Rahilly, K., Richardson, T., Rüdiger, J., Schipper, C.L., Watson, I.M. and Wood, K., 2020. Aerial strategies advance volcanic gas measurements at inaccessible, strongly degassing volcanoes: Manam, Papua New Guinea. *Science Advances*, 6, (no. 44,): eabb9103.
- Marty, B. and Zimmermann, L., 1999. Volatiles (He, C, N, Ar) in mid-ocean ridge basalts: assessment of shallow-level fractionation and characterization of source composition. *Geochim. Cosmochim. Acta*, 63: 3619-3633.

- Mattey, D.P., 1991. Carbon dioxide solubility and carbon isotope fractionation in basaltic melt. *Geochim. Cosmochim. Acta*, 55: 3467-3473.
- Oppenheimer, C., Fischer, T.P. and Scaillet, B., 2014. Volcanic degassing: processes and impact. *Treatise on Geochemistry (second edition)*, 4, the crust p.111 – 179 <http://dx.doi.org/110.1016/B1978-1010-1008-095975-095977.000304-095971>.
- Oppenheimer, C., Scaillet, B., Woods, A., Sutton, A.J., Elias, T. and Moussallam, Y., 2018. Influence of eruptive style on volcanic gas emission chemistry and temperature. *Nat. Geoscience*, <https://doi.org/10.1038/s41561-018-0194-5>.
- Pedersen, G.B.M., Belart, J.M.C., Óskarsson, B.V., Gudmundsson, M.T., Gies, N.H., T. and al., e., 2022. Volume, effusion rate, and lava transport during the 2021 Fagradalsfjall eruption: Results from near real-time photogrammetric monitoring. *Geophysical Research Letters*, 49, e2021GL097125.
- Rayleigh, J.W.S., 1896. Theoretical considerations respecting the separation of gases by diffusion or similar processes. *Philosophical Magazine*, 42: 493.
- Sæmundsson, K., Jóhannesson, H., Hjartarson, Á., Kristinsson, S.G. and Sigurgeirsson, M.A., 2010. Geological Map of Southwest Iceland, 1: 100000. Iceland geosurvey.
- Schwandner, F.M., Gunson, M.R., Miller, C.E., Carn, S.A., Eldering, A., Krings, T., Verhulst, K.R., Chmel, D.S., Nguyen, H.M., Crisp, D., O'Dell, C.W., Osterman, G.B., Iraci, L.T. and Podolske, J.R., 2017. Spaceborne detection of localized carbon dioxide sources. *science*, 358: eaam5782.
- Scott, S., Pfeffer, M.A., Oppenheimer, C., Bali, E., Lamb, O.D., Barnie, T., Woods, A.W., Kjartansdóttir, R. and Stefánsson, A., 2023. Near-surface magma flow instability drives cyclic lava fountaining at Fagradalsfjall, Iceland. *Nature Communications*, 14.
- Sleep, N.H. and Zahnle, K., 2001. Carbon dioxide cycling and implications for climate on ancient earth. *J. Geophys. Res.*, 106: 1373–1399
- Sparks, R.S.J., Bursik, M., Carey, S., Gilbert, J., Glaze, L., Sigurdsson, H. and Woods, A., 1997. *Volcanic plumes*. Wiley.
- Stefánsson, A., Hilton, D.R., Sveinbjörnsdóttir, ÁE., Torssander, P., Heinemeier, J., Barnes, J.D., Ono, S., Halldórsson, S.A., Fiebig, J., Arnórsson, S., 2017. Isotope systematics of Icelandic thermal fluids. *J. Volc. Geotherm. Res.*, 337: 146-64.
- Wang, H. and Law, A.W.-k., 2002. Second-order integral model for a round turbulent buoyant jet. *Journal of Fluid Mechanics*, 459: 397-428.
- Werner, C., Fischer, T.P., Aiuppa, A., Edmonds, M., Cardellini, C., Carn, S., Chiodini, G., Cottrell, E., Burton, M., Shinohara, H. and Allard, P., 2019. Carbon Dioxide Emissions from Subaerial Volcanic Regions. IN *Deep Carbon: Past to Present*. Edited by Beth N. Orcutt, Isabelle Daniel, Rajdeep Dasgupta. Cambridge University Press.
- Werner, C., Kelly, P., Doukas, M., Lopez, T., Pfeffer, M., McGimsey, G. and Neal, C., 2013. Degassing associated with the 2009 eruption of Redoubt Volcano, Alaska. *Journal of Volcanology and Geothermal Research*, 259: 270-284.

Figure Captions

Fig. 1: Fagradalsfjall complex in the Reykjanes peninsula. b) Map of the Reykjanes peninsula and its volcanic complexes: R, Reykjanes; S, Svartsengi; F, Fagradalsfjall; K, Krýsuvík; B, Brennisteinsfjöll (Sæmundsson et al., 2010). The red square indicates the area displayed in a). a) Map

showing the vents (triangles) and outlines of lava fields from the 2021, 2022 and 2023 eruptions of the Fagradalsfjall complex. The gray diamonds are the sampling locations for $\delta^{13}\text{C}$ measurements.

Figure 2: Map of observations and eruptive conditions overlain on Sentinel 2 visible image. DOAS traverse was collected by vehicle-mounted telescope along the paved road 7.5 km from the eruption and CO_2 traverse occurred using the UNM Dragonfly drone. Sentinel image was acquired on July 13 during which the wind direction was nearly identical to conditions on July 16, 2023.

Figure 3 Shows the carbon isotope data collected using bag sampling and Isotope Ratio Infrared Spectroscopy analyses. Also shown are data from Barry et al., 2014, including degassed glasses, modeled undegassed magma and fluids from the Reykjanes Peninsula (Stefánsson et al., 2017).

Figure 4. Degassing fractionation modeled using the approach of Holloway and Blank, 1994. Gas-melt fractionation factor is from Javoy et al., 1978 and Matthey, 1991. We use undegassed mantle beneath Iceland (-2.5 ± 1 from Barry et al., 2014) as starting composition. We plot the extrapolated $\delta^{13}\text{C}$ values collected during and shortly after the eruption in 2023 from Figure 3.

S1: Supplemental Table 1 with data collected on the 2022 Fagradalsfjall eruption site after eruption stopped

Sample	Date sampling	Lat	Long	δ VPDB [‰]	^{13}C [‰]	CO ₂ [ppm]	1/CO ₂
Lava Lake #1	3 Sep 2022	63.902188	-22.249481	-13.81		2046	0.000489
Lava Lake #2	3 Sep 2022	63.902188	-22.249481	-13.21		1550	0.000645
Lava Lake #3	3 Sep 2022	63.902188	-22.249481	-13.38		1662	0.000602
Lava Lake #4	3 Sep 2022	63.902188	-22.249481	-14.13		2337	0.000428
S Vent #1	3 Sep 2022	63.902033	-22.249556	-12.91		1254	0.000798
S Vent #1	3 Sep 2022	63.902033	-22.249556	-11.84		914	0.001094
S Vent #1	3 Sep 2022	63.902033	-22.249556	-13.35		1450	0.000689
Fissure opening#1	3 Sep 2022	63.900134	-22.24759	-13.64		1797	0.000557
Fissure opening#1	3 Sep 2022	63.900134	-22.24759	-14.06		2211	0.000452
Fissure opening#1	3 Sep 2022	63.900134	-22.24759	-14.00		2155	0.000464
Fissure #1	23 Sep 2022	63.900134	-22.24759	-13.24		1244	0.000804
Fissure #2	23 Sep 2022	63.900134	-22.24759	-12.55		1120	0.000893
Fissure #3	23 Sep 2022	63.900134	-22.24759	-12.50		1119	0.000893
Lava Lake #1	23 Sep 2022	63.902188	-22.249481	-11.39		787	0.001270
Lava Lake #2	23 Sep 2022	63.902188	-22.249481	-11.05		736	0.001359
Lava Lake #3	23 Sep 2022	63.902188	-22.249481	-9.61		566	0.001768
Lava Lake #4	23 Sep 2022	63.902188	-22.249481	-10.65		662	0.001511
new vent 1	1 Nov 2022	63.900705	-22.252995	-13.58		1961	0.000510
new vent 2	1 Nov 2022	63.900705	-22.252995	-13.02		1143	0.000875
fissure 2-1	1 Nov 2022	63.900134	-22.24759	-12.76		1330	0.000752
fissure 2-2	1 Nov 2022	63.900134	-22.24759	-12.75		1316	0.000760
Fissure#1	1 Nov 2022	63.900134	-22.24759	-11.87		969	0.001032
Fissure#2	1 Nov 2022	63.900134	-22.24759	-11.70		918	0.001089
Fissure#4	1 Nov 2022	63.900134	-22.24759	-11.87		970	0.001031
Fissure#3b	1 Nov 2022	63.900134	-22.24759	-12.02		997	0.001003
vent middle #2	6 Dec 2022	63.901006	-22.249687	-9.51		616	0.001623
vent middle #3	6 Dec 2022	63.901006	-22.249687	-10.14		651	0.001535
fissure #1	6 Dec 2022	63.900134	-22.24759	-11.98		1155	0.000866
fissure #2	6 Dec 2022	63.900134	-22.24759	-11.61		1051	0.000951
fissure #1	9 Mar 2023	63.900134	-22.24759	-10.39		682	0.001467
fissure #2	9 Mar 2023	63.900134	-22.24759	-10.27		677	0.001477
fissure #3	9 Mar 2023	63.900134	-22.24759	-10.33		686	0.001457
fissure #4	9 Mar 2023	63.900134	-22.24759	-9.51		607	0.001647
fissure #5	9 Mar 2023	63.900134	-22.24759	-9.55		604	0.001656
site 1 - a	6 Jun 2023	63.90083	-22.25212	-11.56		942	0.001061
site 1 - b	6 Jun 2023	63.90083	-22.25212	-10.98		789	0.001268
site 1 - c	6 Jun 2023	63.90083	-22.25212	-12.18		1119	0.000894
site 2 - 1a	6 Jun 2023	63.89867	-22.254	-14.95		3305	0.000303
site 2 - 1b	6 Jun 2023	63.89867	-22.254	-14.72		2981	0.000335

site 2 - 1c	6 Jun 2023	63.89867	-22.254	-14.82	3163	0.000316
site 2 - 2a	6 Jun 2023	63.89867	-22.254	-14.17	2349	0.000426
site 2 - 2b	6 Jun 2023	63.89867	-22.254	-13.94	2143	0.000467

Supplementary Files

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