This manuscript has been submitted for publication to Geochemical Perspectives Letters on November 16th, 2023. Please note that this manuscript has not undergone peer review, nor has it been formally accepted for publication. Subsequent versions of this manuscript may have slightly different content. Feel free to reach out the corresponding author. We welcome constructive feedback.

Reykjanes Peninsula's historical eruptions: SO_2 emissions and future hazard implications

A. Caracciolo[1], E. Bali[1], E. Ranta[2], S. A. Halldórsson[1] , G. H. Guðfinnsson[1]

(1) NordVulk, Institute of Earth Sciences, University of Iceland, 102, Reykjavík, Iceland.

(2) Department of Geosciences and Geography, University of Helsinki, Finland

Corresponding author: Alberto Caracciolo (alberto@hi.is)

Abstract

Exposure to volcanic SO_2 can have adverse effects on human health, with severe respiratory disorders documented on the short- and long-term timescale. Here, we use melt inclusion (MI) and groundmass glass data to calculate syn-eruptive SO_2 emission potentials across the Reykjanes peninsula (RP), the most populated area of Iceland that has recently undergone magmatic reactivation with the 2021, 2022, 2023 AD Fagradalsfjall eruptions. We target 16 individual eruptions from the previous volcanic episode at the RP, the 800-1240 AD Fires. Geochemical modelling indicates that pre-eruptive variability in sulfur contents can be explained by fractional crystallization and mixing of geochemically diverse mantle-derived melts. We calculate SO_2 emission potential across the RP to be in the range 0.004-7.4 Mt. These estimates correspond to daily SO_2 emissions in the range 600-53000 tons/day, higher than the mean SO_2 field measurements of 5240 ± 2700 tons/day during the 2021 AD Fagradalsfjall eruption. By using maximum and minimum sulfur values preserved in undegassed MIs, we develop an empirical approach to calculate best- and worst-case SO_2 emission potential scenarios of any past or ongoing RP eruption of known effusion rate. We conclude that the potential sulfur emissions across the RP can be significantly higher than observed during the 2021 AD Fagradalsfjall eruption, mainly because of the more evolved nature and higher sulfur contents of magmas erupted during the 800-1240 AD Fires. Based on dominant wind directions on the RP, eruptions in Brennisteinsfjöll pose the greatest health hazard to the capital area. Our findings enable assessing of SO_2 emission scenarios of future eruptions across the RP and can be used together with gas dispersal models to forecast SO_2 pollution at ground level and its impact on human health.

Introduction

The release of volcanic gases and aerosols during volcanic eruptions can significantly impact the air quality and climate (e.g. Ilyinskaya *et al.*, 2017; Milford *et al.*, 2023), as well as the biodiversity (e.g., Weiser *et al.*, 2022). Among volcanic gases, sulfur species (SO_2, H_2S) and associated aerosols (SO_4, H_2SO_4) are the most critical aerial hazard for human health, with short and long-term impacts that have been recorded at variable distances from eruptive vents (e.g.,Ilyinskaya et al., 2017; Schmidt et al., 2015). For example, several studies have associated cardiorespiratory heath issues with volcanic sulfur emissions (e.g., Carlsen *et al.*, 2021; Heaviside *et al.*, 2021). Hence, a detailed knowledge of sulfur release potential of active volcanoes located in densely populated areas is critical to understand air quality hazards of future volcanic eruptions. This is the case of the Reykjanes peninsula (RP) in southwest Iceland, an active spreading area segmented into five volcanic systems that hosts ~70% of the Icelandic population. The latest magmatic period in the RP occurred ~800 years ago (Sæmundsson et al., 2020) but knowledge about sulfur outputs during those eruptions has been lacking thus far. Each volcanic systems on the RP tend to activate during individual magmatic periods (Sæmundsson et al., 2020) and the recent 2021, 2022 and 2023 AD Fagradalsfjall eruptions (Barsotti et al., 2023; Einarsson et al., 2023) suggest the potential initiation of a new magmatic period. Consequently, there is an increased societal need for a deeper understanding of sulfur emissions across the RP. This is crucial for a comprehensive assessment of sulfur's impact during future eruptions across the RP and its potential consequences for human health.

In this study, we calculate syn-eruptive sulfur release and sulfur emission potential of 16 geologically and petrochemically well characterized magmatic units erupted in the volcanic systems of Reykjanes, Svartsengi, Krýsuvík and Brennisteinsfjöll during the 800-1240 AD Fires (Caracciolo et al., 2023; Halldórsson et al., 2022; Peate et al., 2009) and compare those with sulfur emissions from 2021 AD Fagradalsfjall eruption (Barsotti et al., 2023; Halldórsson et al., 2022). Also, we estimate daily SO_2 emissions for the 800-1240 AD Fires and develop an empirical approach to calculate worst- and best-case sulfur emission potentials for any eruption of a given volume emplaced in the RP.

Samples and methods

Samples consist of scoria collected from multiple vents within individual eruptive units erupted during the 800-1240 AD Fires (Caracciolo et al., 2023). Here, we present new S data for the same groundmass glass (n=889) and plagioclase-, olivine- and clinopyroxene-hosted melt inclusions (MIs) (n=416) dataset published in Caracciolo et al. (2023). Sulfur was analysed by electron microprobe analyser (EMPA) at the University of Iceland using the same analytical settings as in Caracciolo *et al.* (2020) and MI compositions have been corrected for post-entrapment processes (PEP) (Caracciolo et al. 2023).

In this work we make use of the 'petrological method' (Devine et al., 1984) to calculate eruptive sulfur emissions by comparing the difference of S concentrations in mineral-hosted MIs with S concentrations measured in groundmass glass. The idea behind this reconstruction method is that melt inclusions preserve volatile concentrations at the time of trapping, namely the pre-eruptive volatile content, whereas quenched groundmass glasses provide an estimate of the post-eruptive volatile content. For the different magmatic units, the highest S concentration measured in PEC-corrected MIs (S_{MI}) is selected as the pre-eruptive S concentration, whereas the lowest measurement in groundmass glasses (S_{glass}) is chosen as post-eruptive S concentration. By combining the volume of erupted magmas with ΔS_{pre} [ΔS_{pre} (ppm)= S_{MI} - S_{glass}], we can assess the syn-eruptive SO_2 emission (ΔS_{syn}, Mt) of individual eruptions (e.g., Bali *et al.*, 2018; Hartley *et al.*, 2018). Furthermore, we calculate the SO_2 emission potential (ΔS_{pot}, Mt), which refers to complete degassing of all pre-eruptive sulfur and reflects the maximum amount of SO_2 that a specific eruption could potentially have released. This reconstruction method has been showed to have matched field-based volatile measurements exceptionally well during the 2014-15 Holuhraun eruption (Bali et al., 2018; Pfeffer et al., 2018) and the 2021 AD Fagradalsfjall eruption (this work, Table 1).

Sulfur concentrations in MI and groundmass glass

Sulfur concentrations in MIs are in the range 200-1900 ppm, with a relatively large variability of S at a given MI Mg#. Particularly, the most primitive MIs (Mg#>65), exclusively preserved in Reykjanes and Krýsuvík, record S contents in the range 580-1070 ppm (Fig. 1). Sulfur concentration in PEP-corrected MI compositions increases with decreasing MI Mg#, as expected for melt compositions controlled by fractional crystallization. Groundmass glasses with Mg# similar to the most evolved MIs have mean S contents varying between 150-450 ppm (Table 1). Groundmass glasses from Brennisteinsfjöll have mean S contents in the range 150-280 ppm, lower than mean S contents measured in glasses from the other volcanic systems (280-450 ppm) (Fig. 1a-d, Table 1). Sulfide globules were not observed in the erupted samples, neither within MIs nor as a stand-alone phase in the groundmass glass. For comparison, MIs from the 2021 AD Fagradalsfjall eruption contain maximum S concentrations of 1200 ppm, whereas the groundmass glasses contain 20-200 ppm S, significantly less than S concentrations preserved in MIs and groundmass glasses from the 800-1240 AD Fires (Fig. 1a-d).

Assessing sulfur variability and degassing during the 800-1240 AD Fires

Considering that historical eruptions on the Reykjanes Peninsula are likely sourced from mantle-derived melts of highly diverse compositions (Caracciolo et al., 2023; Harðardóttir et al., 2022; Halldórsson et al., 2022; Peate et al., 2009), including melts with variable sulfur contents (Ranta *et al.*, 2022), we use our MI record to estimate S contents of the local enriched and depleted end-member melt components. We distinguish between these components from the K_2O/TiO_2 variability, which has been proved to be a robust tracer of mantle heterogeneities in Iceland and on the RP (Halldórsson et al., 2022; Harðardóttir et al., 2022) (see supplementary information). Starting from estimated end-member melt compositions and considering that sulfur behaves as an incompatible element in basaltic magmas, most of the MI sulfur variability in our dataset can be explained by fractional crystallization (FC) and mixing of at least two end-member melt compositions (Fig. 1a-d).

In order to evaluate S saturation during magma ascent and fractional crystallization through the crust, we calculate sulfur content at sulfide saturation (SCSS) along a FC path, which reflects the amount of S^{2-} present in a melt in equilibrium with a sulfide phase (Smythe et al., 2017) (see supplementary information). Our modelling suggests that melts are sulfide undersaturated during most of magmatic fractionation across the RP (Fig. 1). Only magmas from Svartsengi and Brennisteinsfjöll have a high likelihood to be sulfide saturated prior to eruptions (Fig. 1). Furthermore, sulfide saturation is reached earlier during magmatic differentiation of enriched mantle-derived melts than depleted melts. That is, magmatic differentiation of the depleted and enriched end-member melts leads to sulfide saturation at Mg#<50 and ~55-60, respectively.

Modelling of sulfur degassing with Sulfur_X (Ding et al. 2023) suggest that basaltic melts erupted during the 800-1240 AD Reykjanes Fires are unlikely to degas significant amounts of sulfur at known pre-eruptive magma storage depths (Caracciolo et al. 2023) and that S degassing only takes place during magma ascent in the last 0.2 kbar (<700 m) (Fig. S1).

Sulfur emissions across the RP

Sulfur release ranges between 1000-1800 ppm across the RP, a typical range for Icelandic rift basalts (Ranta et al. 2022), with the largest ΔS found in lava flows from Svartsengi (SÖ lavas) and Hvammahraun (h128, Brennisteinsfjöll) (Table 1). ΔS values can be scaled by the mass of erupted material to estimate ΔS_{syn} of individual eruptions, using published volumes of individual eruptive units emplaced during the 800-1240 AD Fires (Table 1). In this case, lava flow volumes range between 0.02 km^3 to 0.72 km^3 (Einarsson et al., 1991; Jónsson, 1978; Sigurgeirsson, 2004). Using a melt density of 2700 kg/m^3 estimated with densityX program (Iacovino and Till, 2019), we calculate ΔS_{syn} between 0.004-7 Mt (Fig. 2a). The voluminous Arnarseturshraun (SÖ-A, 0.55 km^3) and Eldvarpahraun lava flows (SÖ-E, 0.28 km^3) in Svartsengi and Hvammahraun (h128, 0.72 km^3) and Tvíbollahraun (TV, 0.37 km^2) lava flows in Brennisteinsfjöll released the highest amount of SO_2 into the atmosphere during the 800-1240 AD Fires. The syn-eruptive SO_2 released by these latter voluminous lavas is approximately 2 to 7 times larger than syn-eruptive SO_2 emissions during the 2021 AD Fagradalsfjall eruption, for which we estimated ΔS_{syn} = 0.93 Mt ($\Delta S_{measured}$ =0.97±0.5, Barsotti et al. 2023). These are roughly between 20 to 70 % of the syn-eruptive SO_2 emissions estimated for the 2014-15 Holuhraun eruption (ΔS_{syn} = 10.5 Mt, Bali et al. 2018).

Similarly, we have calculated ΔS_{pot}, the maximum amount of SO_2 that could potentially have been released during the 800-1240 AD Fires, assuming complete degassing of S_{MI}. ΔS_{pot} ranges between 0.004-7.4 Mt and is only slightly higher than ΔS_{syn}, as most of the sulfur is released into the atmosphere during eruptions on the RP rather than staying dissolved in the lava (Table 1).

Evaluating end-member scenarios of sulfur emissions and hazard potential for future eruptions across the RP.

Based on the MI record of the 2021 AD Fagradalsfjall eruption (Halldórsson et al., 2022) and the 800-1240 AD Fires (this work), we constrain maximum (1900 ppm) and minimum (1200 ppm) SO_2 emission potentials and use these to evaluate SO_2 emissions of future eruptions in the RP. With these constraints, we developed an empirical approach to assess ΔS_{pot} for a given eruption of known lava volume, with important applications for forecasting the worst- and best-case scenarios of ΔS_{pot} of future eruptive events (Fig. 2b). For example, based on our approach, an eruption with an eruptive volume of 0.4 km^3, has the potential to release a maximum and minimum of 4.1 Mt and 2.9 Mt SO_2, respectively. This method also has an application when it comes evaluating the long-term SO_2 impact of ongoing eruptions in the RP. If the mean magma effusion rate is known and fixed, one can roughly estimate the volume of the lava flow and calculate ΔS_{pot} at any given moment from the onset of the eruption. During an ongoing event, this can be a valuable tool to evaluate best- and worst-case scenarios for S pollution.

Eruptive S emission calculations are strongly dependent on lava flow volumes. Hence, when it comes to comparing the 800-1240 AD Fires with 2021 AD Fagradalsfjall eruption, a more relevant parameter is the mean daily SO_2 emissions, which also is an important parameter from a hazard perspective. First, we have estimated eruption durations for the 800-1240 AD Fires starting from published erupted volumes and using mean magma output rates (MOR) calculated by Oskarsson et al. (under review), in the range 1-66 m^3/s (Table 1). This yields eruption durations in the range 6 to 177 days. Secondly, we make use of inferred eruption durations to calculate daily SO_2 emissions and speculate about potential daily S releases during future eruptive scenarios. Daily SO_2 emissions during the 800-1240 AD Fires likely ranged between 600 ton/day to 53000 ton/day (Fig. 2c). In comparison, during the 2021 AD Fagradalsfjall eruption, if we assume a total amount of SO_2 equal to 0.97 ± 0.5 Mt (Barsotti et al., 2023), we calculate average daily SO_2 emissions of 5240 ± 2700 ton/day. This estimate is in agreement with the majority of measured daily SO_2 emissions throughout the 2021 AD Fagradalsfjall eruption, in the range 1000-7600 ton/day (Esse et al., 2023). Hence, future eruptions in the RP have the potential to release significantly more SO_2 on a daily basis than the 2021 AD Fagradalsfjall eruption.

SO_2 emissions during the 800-1240 AD Fires and 2021 AD Fagradalsfjall are small compared to those during the recent basaltic eruption of Holuhraun (9.2 Mt SO_2, Pfeffer *et al.*, 2018). However, volcanic eruptions from the RP are potentially considered to be more hazardous due to their proximity to inhabited areas, to the international airport and to the large number of visitors expected at eruption sites (Fig. 3) (Barsotti et al. 2023). To assess the health hazard for potential future eruptions, we built seasonal wind roses, for the period 2012-2022, reflecting dominant wind speeds and directions in the

RP. We find that most of the time the winds blow in a direction spanning from the NW to the NE, suggesting different SO_2 health hazards potential associated with eruptions within different volcanic systems. Eruptions in Brennisteinsfjöll are the most hazardous, especially in spring and autumn seasons, as SO_2 is likely to be blown towards the capital area. Eruptions in Reykjanes pose minimal hazard as winds tend to blow away from inhabited areas. During assessment of possible eruptive scenarios in the RP, our estimates can be key input parameters to model the release and dispersion of volcanic SO_2 into the atmosphere. Our results can be used to inform SO_2 pollution hazard assessments for potential eruptive scenarios and prompt action and mitigation plans during ongoing volcanic crises in the RP.

Acknowledgement

This research was financially support by a NordVulk fellowship awarded to AC and by the Icelandic Research Fund, grant number 228933-052. We acknowledge support from the Gosvá project, a national collaborative research programme on the assessment of volcanic hazard risks in Iceland led by the Icelandic Meteorological Office (IMO) https://en.vedur.is/about-imo/news/nr/2280.

Table 1. *Eruptive units studied in this work and summary of main results. S_{MI}= pre-eruptive S concentration. S_{glass} = post-eruptive S concentration. ΔS = sulfur emissions emitted at the vent. ΔS_{syn} = Syn-eruptive SO_2 emissions. ΔS_{pot} = SO_2 emission potential. Eruption durations and daily SO_2 emissions are calculated assuming a bulk effusion rate of 9.5 m^3/s, as observed during the 2021 Fagradalsfjall eruption (Pedersen et al. 2022). [a] Calculations for the 2021 AD Fagradalsfjall eruption are from this work and based on MI and glass data from Halldórsson et al. 2022. Estimated ΔS_{syn} of 0.93 Mt from this work is in agreement with measured total SO_2 emissions of 0.97± 0.5 Mt (Barsotti et al. 2023). [b] To our knowledge, volumes for Hrútafellshraun (HRF), Svartihryggur (h142), Húsfellsbruni (Hú1 & Hú2) and Kristnitökuhraun (KRT) lava flows are not available in the literature. We estimated the volumes of those lava flows by multiplying their area by an average thickness of 5 m, consistent with average thicknesses of lava flows of known volumes with a similar aerial extent. [c] MOR data are from Óskarsson et al. (under review). MOR for the 2021 Fagradalsfjall eruption is from Pedersen et al. (2022).*

Fig. 1. *(a-d) Variation of S contents in groundmass glasses (filled circles) and PEC-corrected MIs (filled triangles) as a function of Mg# [Mg# = 100·Mg/(Mg+Fe^{2+}), Fe^{2+}/Fe^{tot} = 0.9] in samples from the 800-1240 AD Fires. Data from the 2021 AD Fagradalsfjall eruption are from Halldórsson et al. (2022). Red and blue solid lines indicate fractional crystallization paths calculated for a geochemically enriched and depleted initial melt compositions, respectively (see supplementary text). The black dotted curve indicates SCSS along an empirical fractional crystallization path calculated after Smythe et al., (2017). Data are grouped in different panels according to the volcanic system and coloured according to the lava unit. (e-h) Measured MI S contents vs calculated SCSS, coloured after MgO content. SCSS was*

calculated assuming Fe^{3+}/Fe_{tot} = 0.1, P = 2 kbar, T=1220 °C and sulfide Fe/(Fe+Ni+Cu) = 0.65, after the method of Smythe et al., (2017) (cf. Fig. S3). All SCSS models were implemented in PySulfSat code (Wieser and Gleeson, 2022).

Fig. 2. *(a) West to east variation of ΔS_{syn} calculated for the different eruptive units. (b) ΔS_{pot} as a function of eruption volume for the 800-1240 AD Fires and 2021 Fagradalsfjall eruption. At a given volume, straight lines allow to calculate ΔS_{pot} corresponding to maximum (1900 ppm) and minimum (1200 ppm) S_{MI} values measured across the RP. Inset plot show most common ΔS_{pot} across the RP, in the range 0-2 Mt and for lava volumes between 0-0.3 km^3 (c) Maximum and minimum daily SO_2 emissions calculated for each volcanic system during the 800-1240 AD Fires and for the 2021 AD Fagradalsfjall (see text for calculation details). Blue kernel density estimate curve indicate measured SO_2 emission rates during the 2021 AD Fagradalsfjall eruption (Esse et al., 2023). Labels indicate acronyms used for the different eruptive units (c.f. Table 1).*

Fig. 3. *Simplified geological map of the Reykjanes Peninsula and lava flows emplaced during the 800 – 1240 AD Fires. The map also illustrates the aerial extent of the 2021 (Pedersen et al., 2022), 2022 (Gunnarson et al., 2023) and 2023 AD (Belart et al. 2023) Fagradalsfjall lavas. The lava flows are colored according to calculated syn-eruptive SO_2 emissions, ranging from 0.1 to 7 Mt. Filled, white circles indicate the location of main urban areas in the Reykjanes Peninsula. Geological data are from Iceland GeoSurvey (ÍSOR) (Sæmundsson et al., 2016). Seasonal wind roses reflect data at 900 mPa (~1000 m a.s.l), which is the most common SO_2 injection altitude throughout the 2021 Fagradalsfjall eruption (Esse et al. 2023). Spokes indicate the direction the wind is blowing from, and the length of each spoke shows the frequency. Wind data were extracted from ERA5 (Hersbach et al. 2023).*

References

Bali, E., Hartley, M.E., Halldórsson, S.A., Gudfinnsson, G.H., Jakobsson, S., 2018. Melt inclusion constraints on volatile systematics and degassing history of the 2014–2015 Holuhraun eruption, Iceland. Contributions to Mineralogy and Petrology 173, 9. https://doi.org/10.1007/s00410-017-1435-0

Barsotti, S., Parks, M.M., Pfeffer, M.A., Óladóttir, B.A., Barnie, T., Titos, M.M., Jónsdóttir, K., Pedersen, G.B.M., Hjartardóttir, R., Stefansdóttir, G., Johannsson, T., Arason, Gudmundsson, M.T., Oddsson, B., Þrastarson, R.H., Ófeigsson, B.G., Vogfjörd, K., Geirsson, H., Hjörvar, T., von Löwis, S., Petersen, G.N., Sigurðsson, E.M., 2023. The eruption in Fagradalsfjall (2021, Iceland): how the operational monitoring and the volcanic hazard assessment contributed to its safe access. Natural Hazards. https://doi.org/10.1007/s11069-022-05798-7

Belart, J.M.C., Pinel, V., Reynolds, H.I., Berthier, E., Gunnarson, S.R., 2023. Digital Elevation Models (DEMs) and lava outlines from the 2023 Litla-Hrútur eruption, Iceland, from Pléiades satellite stereoimages. https://doi.org/10.5281/zenodo.10133203

Caracciolo, A., Bali, E., Guðfinnsson, G.H., Kahl, M., Halldórsson, S.A., Hartley, M.E., Gunnarsson, H., 2020. Temporal evolution of magma and crystal mush storage conditions in the Bárðarbunga-

Veiðivötn volcanic system, Iceland. Lithos 352–353. https://doi.org/10.1016/j.lithos.2019.105234

Caracciolo, A., Bali, E., Halldórsson, S.A., Gudfinnsson, G.H., Kahl, M., Þórðardóttir, I., Pálmadóttir, G.L., Silvestri, V., 2023. Magma plumbing systems and timescale of magmatic processes during historical magmatism on Reykjanes Peninsula. Earth and Planetary Science Letters 621, 118378. https://doi.org/10.1016/j.epsl.2023.118378

Carlsen, H.K., Valdimarsdóttir, U., Briem, H., Dominici, F., Finnbjornsdottir, R.G., Jóhannsson, T., Aspelund, T., Gislason, T., Gudnason, T., 2021. Severe volcanic SO2 exposure and respiratory morbidity in the Icelandic population – a register study. Environmental Health: A Global Access Science Source 20, 1–12. https://doi.org/10.1186/s12940-021-00698-y

Devine, D., Sigurdsson, H., Davis, A.N., 1984. Estimates of sulfur and chlorine yield to the atmosphere from volcanic eruptions and potential climatic effects. Journal of Geophysical Research 89, 6309–6325.

Ding, S., Plank, T., Wallace, P.J., Rasmussen, D.J., 2023. Sulfur_X: A Model of Sulfur Degassing During Magma Ascent. Geochemistry, Geophysics, Geosystems 24. https://doi.org/10.1029/2022GC010552

Einarsson, P., Eyjólfsson, V., Rut, Á., 2023. Tectonic framework and fault structures in the Fagradalsfjall segment of the Reykjanes Peninsula Oblique Rift , Iceland. Bulletin of Volcanology 1–17. https://doi.org/10.1007/s00445-022-01624-x

Einarsson, S., Johannesson, H., Sveinbjörnsdóttir, A.E., 1991. Krísuvíkureldar II. Kapelluhraun og gátan um aldur Hellnahrauns. Jokull 41.

Esse, B., Burton, M., Hayer, C., Pfeffer, M.A., Barsotti, S., Theys, N., Barnie, T., Titos, M., 2023. Satellite derived SO2 emissions from the relatively low-intensity, effusive 2021 eruption of Fagradalsfjall, Iceland. Earth and Planetary Science Letters 619, 118325. https://doi.org/10.1016/j.epsl.2023.118325

Fortin, M.A., Riddle, J., Desjardins-Langlais, Y., Baker, D.R., 2015. The effect of water on the sulfur concentration at sulfide saturation (SCSS) in natural melts. Geochimica et Cosmochimica Acta 160, 100–116. https://doi.org/10.1016/j.gca.2015.03.022

Gunnarson, S.R., Belart, J.M.C., Óskarsson, B. V., Gudmundsson, M.T., Högnadóttir, T., Pedersen, G.B.M., Dürig, T., Pinel, V., 2023. Automated processing of aerial imagery for geohazards monitoring: Results from Fagradalsfjall eruption, SW Iceland, August 2022 [WWW Document]. Zenodo. https://doi.org/10.5281/ZENODO.7871187

Halldórsson, S.A., Marshall, E.W., Caracciolo, A., Matthews, S., Bali, E., Rasmussen, M.B., Ranta, E., Robin, J.G., Gudfinnsson, 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., Barbara, K., Kleine, B.I., Oppenheimer, C., Aiuppa, A., Ilyinskaya, E., Bitetto, M., Giudice, G., Stefánsson, A., 2022. Rapid shifting of a deep magmatic source at Fagradalsfjall volcano, Iceland. Nature 609. https://doi.org/10.1038/s41586-022-04981-x

Harðardóttir, S., Matthews, S., Halldórsson, S.A., Jackson, M.G., 2022. Spatial distribution and geochemical characterization of Icelandic mantle end-members: Implications for plume geometry and melting processes. Chemical Geology 604. https://doi.org/10.1016/j.chemgeo.2022.120930

Hartley, M.E., Bali, E., Maclennan, J., Neave, D.A., Halldórsson, S.A., 2018. Melt inclusion constraints on petrogenesis of the 2014–2015 Holuhraun eruption, Iceland. Contributions to Mineralogy and Petrology 173, 1–23. https://doi.org/10.1007/s00410-017-1435-0

Heaviside, C., Witham, C., Vardoulakis, S., 2021. Potential health impacts from sulphur dioxide and sulphate exposure in the UK resulting from an Icelandic effusive volcanic eruption. Science of the Total Environment 774, 145549. https://doi.org/10.1016/j.scitotenv.2021.145549

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. (2023): ERA5 hourly data on pressure levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS), DOI: 10.24381/cds.bd0915c6 (Accessed on 26-10-2023)

Iacovino, K., Till, C.B., 2019. DensityX: A program for calculating the densities of magmatic liquids up to 1,627 °C and 30 kbar. VOLCANICA 1–10.

Ilyinskaya, E., Schmidt, A., Mather, T.A., Pope, F.D., Witham, C., Baxter, P., Jóhannsson, T., Pfeffer, M., Barsotti, S., Singh, A., Sanderson, P., Bergsson, B., McCormick Kilbride, B., Donovan, A., Peters, N., Oppenheimer, C., Edmonds, M., 2017. Understanding the environmental impacts of large fissure eruptions: Aerosol and gas emissions from the 2014–2015 Holuhraun eruption (Iceland). Earth and Planetary Science Letters 472, 309–322. https://doi.org/10.1016/j.epsl.2017.05.025

Jónsson, J., 1978. Jarðfræðikort af Reykjanesskaga : 1. Skýringar við jarðfræðikort 2. Jarðfræðikort. Orkustofnun.

Milford, C., Torres, C., Vilches, J., Gossman, A.-K., Weis, F., Suárez-Molina, D., García, O.E., Prats, N., Barreto, A., García, R.D., Bustos, J.J., Marrero, C.L., Ramos, R., Chinea, N., Boulesteix, T., Taquet, N., Rodríguez, S., López-Darias, J., Sicard, M., Córdoba-Jabonero, C., Cuevas, E., 2023. Impact of the 2021 La Palma volcanic eruption on air quality: Insights from a multidisciplinary approach. Science of The Total Environment 869, 161652.

https://doi.org/10.1016/j.scitotenv.2023.161652

Óskarsson, B. V. , Askew, R. A., Guðmundsson, H. (under review) The eruption capacity of effusive volcanism on the Reykjanes peninsula. Bullettin of volcanology

Peate, D.W., Baker, J.A., Jakobsson, S.P., Waight, T.E., Kent, A.J.R., Grassineau, N. V., Skovgaard, A.C., 2009. Historic magmatism on the Reykjanes Peninsula, Iceland: A snap-shot of melt generation at a ridge segment. Contributions to Mineralogy and Petrology 157, 359–382. https://doi.org/10.1007/s00410-008-0339-4

Pedersen, G.B.M., Belart, J.M.C., Óskarsson, B.V., Gudmundsson, M.T., Gies, N., Högnadóttir, T., Hjartardóttir, Á.R., Pinel, V., Berthier, E., Dürig, T., Reynolds, H.I., Hamilton, C.W., Valsson, G., Einarsson, P., Ben-Yehosua, D., Gunnarsson, A., Oddsson, B., 2022. Volume, Effusion Rate, and Lava Transport During the 2021 Fagradalsfjall Eruption: Results From Near Real-Time Photogrammetric Monitoring. Geophysical Research Letters 49, 1–11. https://doi.org/10.1029/2021GL097125

Pfeffer, M.A., Bergsson, B., Barsotti, S., Stefánsdóttir, G., Galle, B., Arellano, S., Conde, V., Donovan, A., Ilyinskaya, E., Burton, M., Aiuppa, A., Whitty, R.C.W., Simmons, I.C., Arason, Þ., Jónasdóttir, E.B., Keller, N.S., Yeo, R.F., Arngrímsson, H., Jóhannsson, Þ., Butwin, M.K., Askew, R.A., Dumont, S., Von Löwis, S., Ingvarsson, Þ., La Spina, A., Thomas, H., Prata, F., Grassa, F., Giudice, G., Stefánsson, A., Marzano, F., Montopoli, M., Mereu, L., 2018. Ground-Based measurements of the 2014-2015 holuhraun volcanic cloud (Iceland). Geosciences (Switzerland) 8, 1–25. https://doi.org/10.3390/geosciences8010029

Ranta, E., Gunnarsson-Robin, J., Halldórsson, S.A., Ono, S., Izon, G., Jackson, M.G., Reekie, C.D.J., Jenner, F.E., Guðfinnsson, G.H., Jónsson, Ó.P., Stefánsson, A., 2022. Ancient and recycled sulfur sampled by the Iceland mantle plume. Earth and Planetary Science Letters 584, 117452. https://doi.org/10.1016/j.epsl.2022.117452

Sæmundsson, K., Sigurgeirsson, M., Friðleifsson, G.Ó., 2020. Geology and structure of the Reykjanes volcanic system, Iceland. Journal of Volcanology and Geothermal Research 391, 106501. https://doi.org/10.1016/j.jvolgeores.2018.11.022

Sæmundsson, K., Sigurgeirsson, M.A., Hjartarson, Á., Kaldal, I., Kristinsson, S.G., 2016. Geological Map of Southwest Iceland, 1: 100 000 (2nd ed.). Reykjavik: Iceland GeoSurvey.

Schmidt, A., Leadbetter, S., Theys, N., Carboni, E., Witham, C.S., Stevenson, J.A., Birch, C.E., Thordarson, T., Turnock, S., Barsotti, S., Delaney, L., Feng, W., Grainger, R.G., Hort, M.C., Höskuldsson, Á., Ialongo, I., Ilyinskaya, E., Jóhannsson, T., Kenny, P., Mather, T.A., Richards, N.A.D., Shepherd, and J., 2015. Satellite detection, long-range transport, and air quality impacts of volcanic sulfur dioxide from the 2014–2015 flood lava eruption at Bárðarbunga

(Iceland). Journal of Geophysical Research: a 120, 1–17. https://doi.org/10.1002/2014JC010485.Received

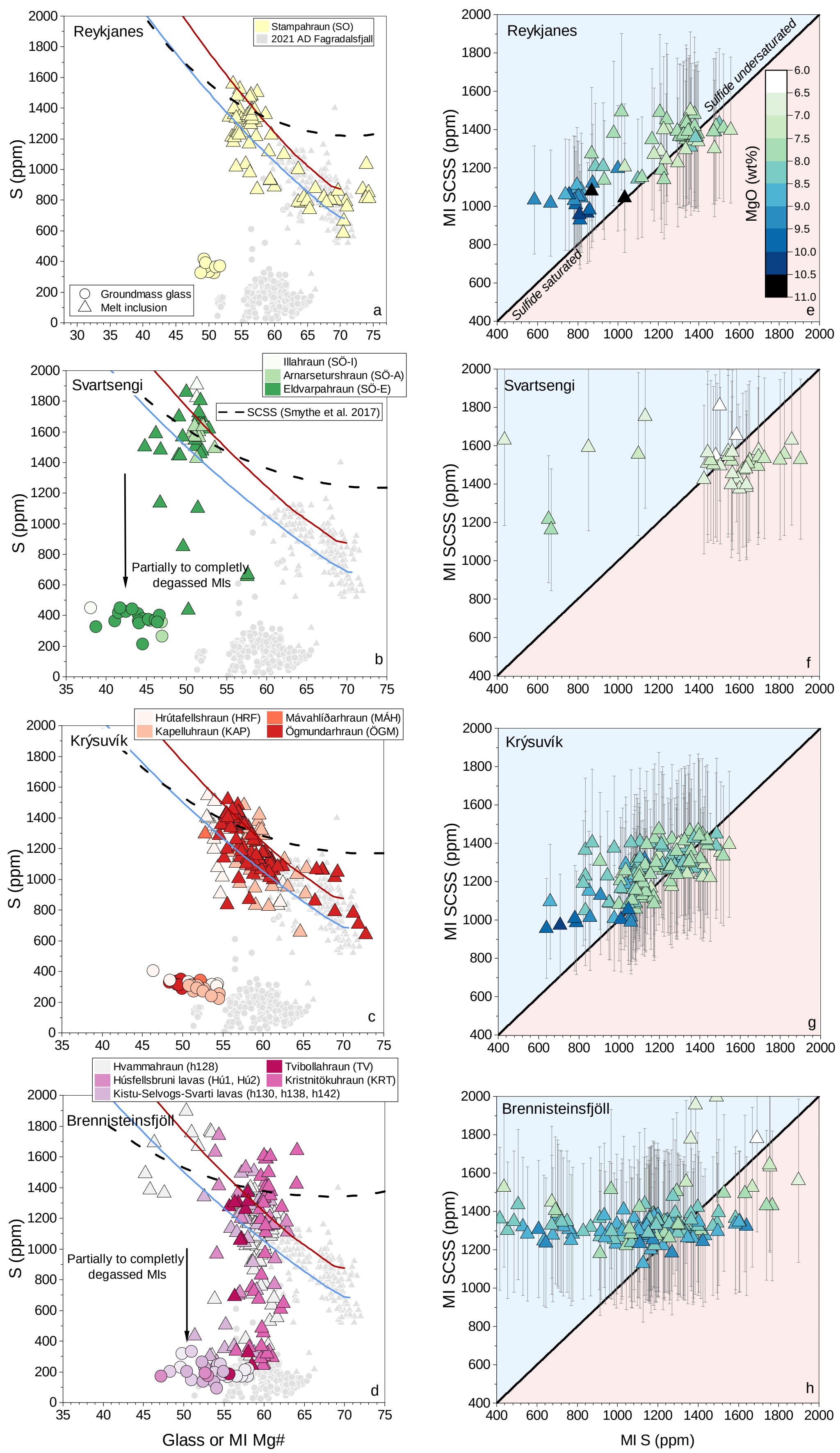
Sigurgeirsson, M.A., 2004. Þáttur úr gossögu Reykjaness. Náttúrufræðingurinn 72, 21–28.

Smythe, D.J., Wood, B.J., Kiseeva, E.S., 2017. The S content of silicate melts at sulfide saturation: New experiments and a model incorporating the effects of sulfide composition. American Mineralogist 102, 795–803. https://doi.org/10.2138/am-2017-5800CCBY

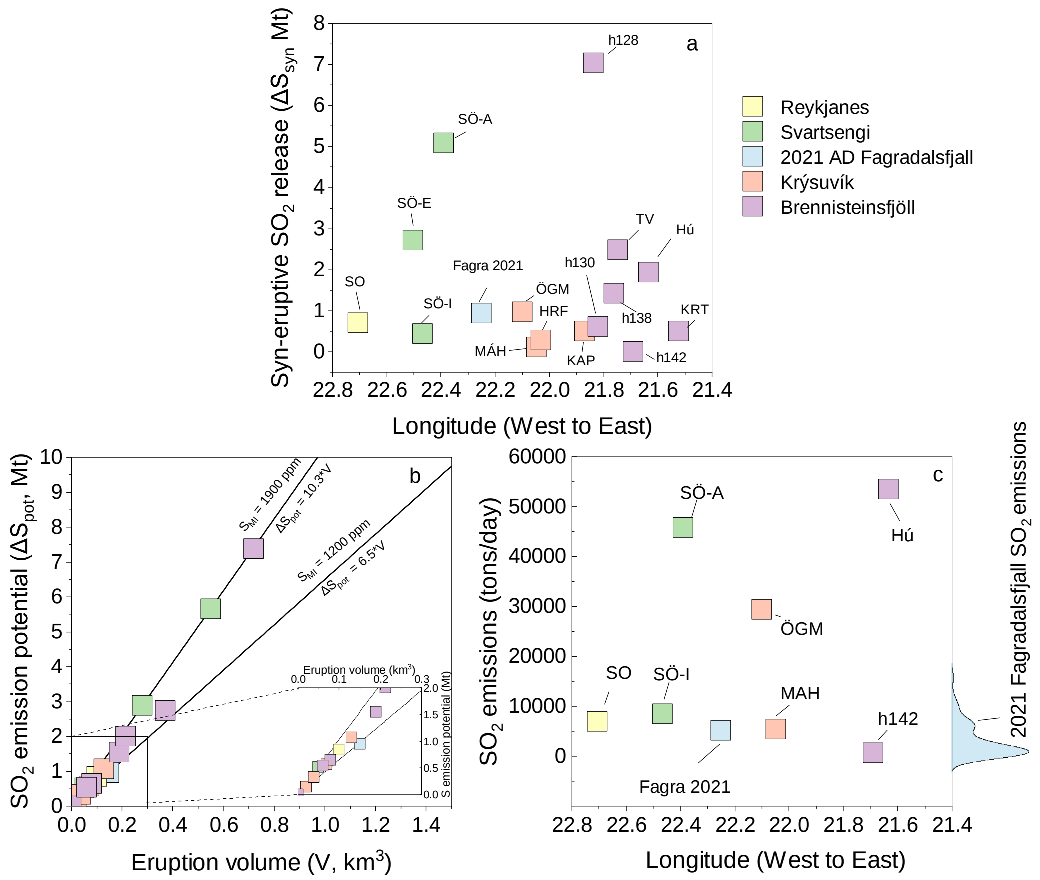
Weiser, F., Baumann, E., Jentsch, A., Medina, F.M., Lu, M., Nogales, M., Beierkuhnlein, C., 2022. Impact of Volcanic Sulfur Emissions on the Pine Forest of La Palma, Spain. Forests 13. https://doi.org/10.3390/f13020299

Wieser, P.E., Gleeson, M., 2022. PySulfSat: An Open-Source Python3 Tool for modelling sulfide and sulfate saturation.

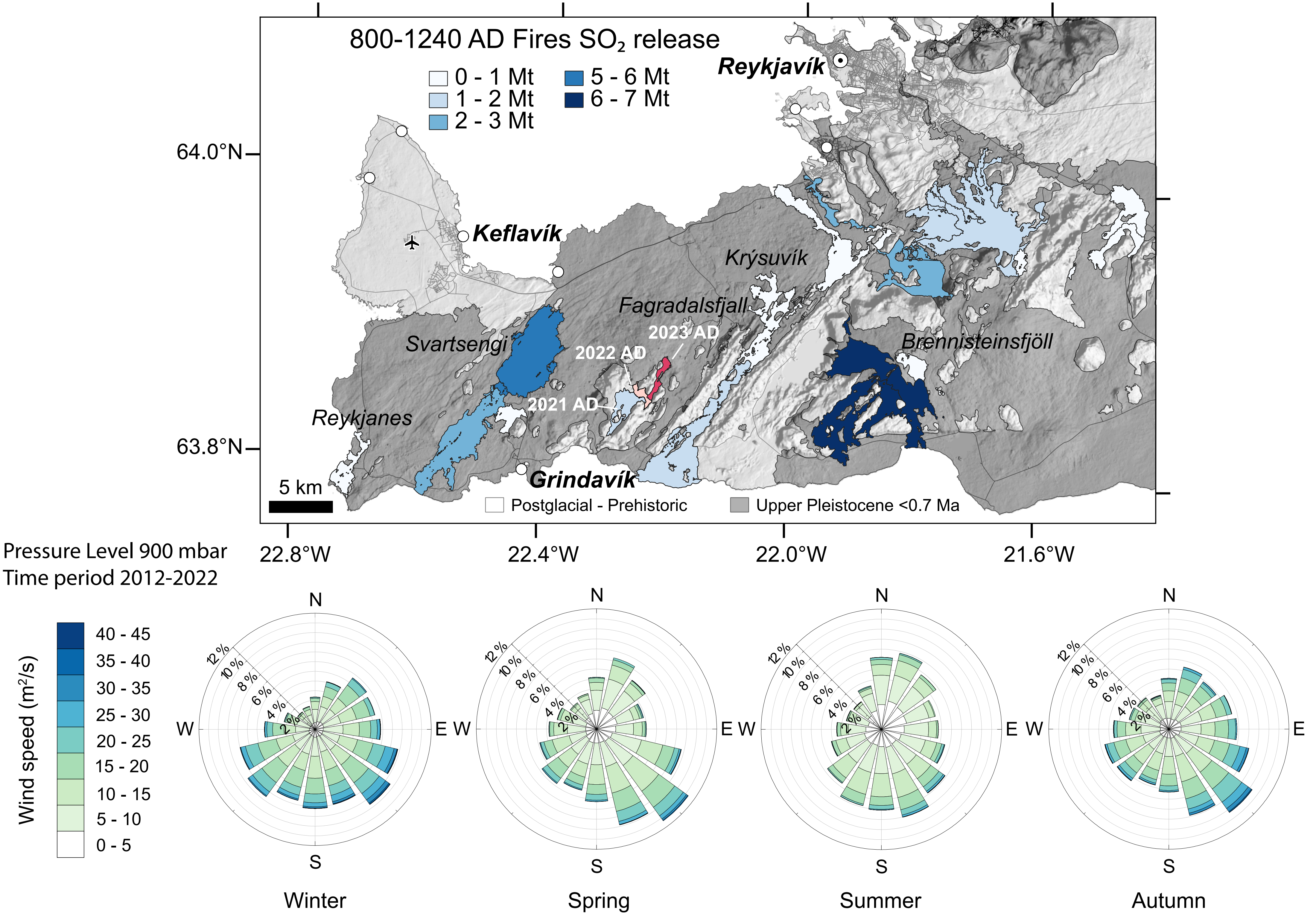
Eruptive unit	**Acronym**	**Volcanic system**	**Longitude**	**Glass S**		**S_{MI}**	**S_{glass}**	**ΔS**	**Volume**	**Mass**	**$ΔS_{syn}$**	**$ΔS_{pot}$**	**MOR[c]**	**Eruption duration**	**Daily SO_2**
				Mean ppm	±1σ ppm	ppm	ppm	ppm	km^3	Kg	Mt	Mt	m^3/s	days	tons/day
Stampahraun 4	SO	Reykjanes	22.70	360	50	1559	258	1301	0.1	2.7E+11	0.70	0.84	6.5	177	4745
Arnarseturshraun	SÖ-A	Svartsengi	22.39	300	68	1907	196	1711	0.55	1.5E+12	5.08	5.66	51.5	124	45778
Eldvarpahraun	SÖ-E	Svartsengi	22.50	390	60	1907	112	1795	0.28	7.6E+11	2.71	2.88	33.8	96	30045
Illahraun	SÖ-I	Svartsengi	22.47	450	155	1907	312	1595	0.05	1.4E+11	0.43	0.51	6.2	93	5529
Fagradalsfjall 2021	Fagra 2021	Fagradalsfjall	22.25	190	100	1170	20	1150	0.15	4.1E+11	0.93[a]	0.95[a]	9.5	185	5120
Ögmundarhraun	ÖGM	Krýsuvík	22.10	290	50	1517	138	1379	0.13	3.5E+11	0.97	1.06	41.5	36	29345
Kapelluhraun	KAP	Krýsuvík	21.87	280	42	1482	183	1299	0.07	1.9E+11	0.49	0.56	31.0	26	21415
Mávahlíðarhraun	MÁH	Krýsuvík	22.05	340	30	1297	280	1017	0.02	5.4E+10	0.11	0.14	8.9	26	5362
Hrútafellshraun[b]	HRF	Krýsuvík	22.03	330	50	1546	252	1294	0.04[b]	1.1E+11	0.27	0.33	17.5	26	12611
Hvammahraun	h128	Brennisteinsfjöll	21.84	190	70	1900	90	1810	0.72	1.9E+12	7.03	7.38	49.1	170	43485
Kistuhraun	h130	Brennisteinsfjöll	21.82	210	60	1494	94	1400	0.08	2.2E+11	0.60	0.64	7.9	117	5501
Selvogshraun	h138	Brennisteinsfjöll	21.76	180	40	1504	126	1378	0.19	5.1E+11	1.41	1.54	14.4	153	10095
Tvibollahraun	tv	Brennisteinsfjöll	21.75	180	30	1367	129	1238	0.37	1.0E+12	2.47	2.73	36.9	116	23480
Svartihryggur[b]	h142	Brennisteinsfjöll	21.69	280	150	1341	147	1194	0.0005[b]	1.5E+09	0.004	0.00	1.0	6	613
Húsfellsbruni[b]	Hú1 & Hú2	Brennisteinsfjöll	21.63	180	55	1739	55	1684	0.2[b]	5.8E+11	1.94	2.00	65.9	25	53442
Kristnitökuhraun[b]	KRT	Brennisteinsfjöll	21.52	180	40	1640	118	1522	0.06[b]	1.6E+11	0.50	0.54	18.4	38	14066



Reykjanes
Stampahraun (SO)
2021 AD Fagradalsfjall
Groundmass glass
Melt inclusion
S (ppm)
a
Reykjanes
Sulfide undersaturated
Sulfide saturated
MgO (wt%)
MI SCSS (ppm)
e
Svartsengi
Illahraun (SÖ-I)
Arnarseturshraun (SÖ-A)
Eldvarpahraun (SÖ-E)
SCSS (Smythe et al. 2017)
Partially to completly degassed MIs
b
Svartsengi
f
Krýsuvík
Hrútafellshraun (HRF)
Kapelluhraun (KAP)
Mávahlíðarhraun (MÁH)
Ögmundarhraun (ÖGM)
c
Krýsuvík
g
Brennisteinsfjöll
Hvammahraun (h128)
Húsfellsbruni lavas (Hú1, Hú2)
Kistu-Selvogs-Svarti lavas (h130, h138, h142)
Tvibollahraun (TV)
Kristnitökuhraun (KRT)
Partially to completly degassed MIs
d
Brennisteinsfjöll
h
Glass or MI Mg#
MI S (ppm)



a
Syn-eruptive SO2 release (ΔSsyn Mt)
Longitude (West to East)
h128
SÖ-A
SÖ-E
TV
Hú
h130
Fagra 2021
SO
ÖGM
SÖ-I
HRF
h138
KRT
MÁH
KAP
h142
Reykjanes
Svartsengi
2021 AD Fagradalsfjall
Krýsuvík
Brennisteinsfjöll
b
SO2 emission potential (ΔSpot, Mt)
Eruption volume (V, km3)
SMI = 1900 ppm
ΔSpot = 10.3*V
SMI = 1200 ppm
ΔSpot = 6.5*V
Eruption volume (km3)
S emission potential (Mt)
c
SO2 emissions (tons/day)
Longitude (West to East)
SÖ-A
Hú
ÖGM
SO
SÖ-I
MAH
h142
Fagra 2021
2021 Fagradalsfjall SO2 emissions


800-1240 AD Fires SO_2 release
0 - 1 Mt
1 - 2 Mt
2 - 3 Mt
5 - 6 Mt
6 - 7 Mt
Reykjavík
Keflavík
Krýsuvík
Fagradalsfjall
2023 AD
2022 AD
2021 AD
Svartsengi
Brennisteinsfjöll
Reykjanes
Grindavík
5 km
Postglacial - Prehistoric
Upper Pleistocene <0.7 Ma
64.0°N
63.8°N
22.8°W
22.4°W
22.0°W
21.6°W
Pressure Level 900 mbar
Time period 2012-2022
Wind speed (m²/s)
40 - 45
35 - 40
30 - 35
25 - 30
20 - 25
15 - 20
10 - 15
5 - 10
0 - 5
N
S
E
W
12 %
10 %
8 %
6 %
4 %
2 %
Winter
Spring
Summer
Autumn