

Lava Whirls at Fagradalsfjall (Iceland, 2021):

A STEM Investigation Anchored to University of Iceland Open Datasets

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Data & Code Availability: Media metadata, event catalogs, and analysis scripts, including media metadata (filenames, UTC timestamps, camera/lens/exposure, GPS when available, and checksums), the event catalog (CSV/JSON), and analysis scripts-are publicly accessible at <https://www.chadcopeland.io/lava>.

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Abstract

During the 2021 Fagradalsfjall eruption, I documented short-lived, tornado-like convective vortices (“lava whirls”) forming near pulsating lava fountains and hot open channels. I integrate my geotagged handheld and UAS imagery with open, near-real-time photogrammetric products and effusion-rate estimates from the University of Iceland/Institute of Earth Sciences (IES) to place each observation within the eruption’s phase chronology and time-averaged discharge rate (TADR) (Pedersen et al., 2022; University of Iceland, 2022). I present a vorticity-budget mechanism in which stretching/tilting within a buoyant plume and baroclinic torque at steep lava–air interfaces organize rotation into vertically coherent columns (Emmons & Ying, 1967; Tohidi et al., 2018). The analysis situates these whirls within the eruption’s unusual periodic fountaining (Scott et al., 2023) and outlines a reproducible pipeline for doctoral-level replication.

Keywords: lava whirl; baroclinic vorticity; fire whirl; buoyant plume; Fagradalsfjall; periodic lava fountaining.



Introduction

Fagradalsfjall reactivated on 19 March 2021 after centuries of quiescence on the Reykjanes Peninsula, initiating months of effusion documented by the Global Volcanism Program (GVP) and Icelandic institutions (Global Volcanism Program, n.d.; Pedersen et al., 2022). By late April–May the eruption exhibited striking periodicity-on–off fountain cycles of roughly 10–30 minutes with typical heights of $\sim 100\text{--}400$ m now linked to near-surface magma-flow instability and shallow cavity pressure cycling (Scott et al., 2023). In that regime I repeatedly observed minute-scale, vertically coherent vortices that entrained incandescent spatter and ash.

Background and eruption context

Near-real-time DEMs, orthomosaics, thickness fields, and TADR from IES/University of Iceland quantified a mean bulk effusion rate of $\sim 9.5 \text{ m}^3 \text{ s}^{-1}$ (Mar–Sep 2021), lower early rates, higher rates during the periodic phase, and a final bulk volume on the order of $1.5 \times 10^8 \text{ m}^3$ across $\sim 4.8 \text{ km}^2$ (Pedersen et al., 2022; University of Iceland, 2022). Calibrated webcam methods at the Icelandic Meteorological Office provided cycle-resolved plume/fountain heights with tens-to-few-hundreds of meters accuracy, enabling synchronization of field media to specific pulses (Barnie et al., 2023). These datasets establish the forcing environment for lava whirl formation.

My field data and synchronization



(Figure 1) Handheld still: Sony ILCE-7RM4 with FE 16–35 mm F2.8; 1/200 s, f/2.8, ISO 800, 35 mm (RAW CEC00634.ARW). GPS was not recorded; I synchronized the frame to UTC by cross-matching fountain geometry and plume transitions in calibrated webcams at 5-10-minute cadence, yielding ≤ 2 -minute timing uncertainty (Barnie et al., 2023).



(Figure 2) UAS still: DJI FC3411 camera (RAW DJI_0062.DNG); 1/1000 s, f/2.8, ISO 800, 8.38 mm at 63.886287° N, -22.255388° (WGS-84) and 2021-05-07 00:24 UTC, providing an absolute time/position anchor within the active Geldingadalir-Meradalir flow field (Global Volcanism Program, n.d.; Pedersen et al., 2022). A narrative summary and stills appear on my project page and are used as qualitative context only (Copeland, 2021).

STEM framework: vorticity dynamics

I interpret lava whirls through the vorticity transport equation, emphasizing (a) stretching/tilting of ambient vorticity within a strongly buoyant updraft and (b) baroclinic torque where pressure and density gradients are misaligned at the hot lava-air interface (Emmons & Ying, 1967; Tohidi et al., 2018). Entrainment narrows the core ($v\theta \approx \Gamma/2\pi r$), intensifying rotation until the forcing pulse relaxes or swirl ratio falls below stability (Tohidi et al., 2018).

Mechanistic synthesis under periodic forcing

During Phase 3 (late April–June), the vent stabilized and pulses recurred on ~10-30-minute cycles while TADR increased relative to earlier phases (Pedersen et al., 2022; University of Iceland, 2022). Each pulse elevated buoyancy flux and organized near-surface shear along levees and vent rims; counter-rotating horizontal vortices rolled up along thermal/momentum gradients, tilted vertical, and spun up into a column. This intermittency reproduces the on/off character I observed and is consistent with the shallow-cavity pressure-cycling mechanism for the fountains (Scott et al., 2023).

Order-of-magnitude regimes

With inflow $U \approx 10\text{-}30 \text{ m s}^{-1}$ and core scale $L \approx 1\text{-}5 \text{ m}$, the Reynolds number $Re = UL/\nu$ (air) is $\sim 0.7\text{-}10 \times 10^6$ (fully turbulent). Hot–cold boundaries produce $Ri = g(\Delta\rho/\rho)L/U^2$ of order unity or larger, supporting baroclinic vorticity generation despite shear (Tohidi et al., 2018). Fire-whirl studies indicate longest, narrowest columns at intermediate swirl ratios-matching tall, slender columns near pulse maxima (Tohidi et al., 2018).

Results: two anchored events within the IES chronology

Event timing and location. The UAS image (2021-05-07 00:24 UTC; 63.886287° N, -22.255388°) coincides with a fountain-on state in the calibrated webcam record and with mapped flow expansion during the high-TADR, periodic phase (Barnie et al., 2023; Pedersen et al., 2022). The handheld still, synchronized to the same evening within ≤ 2 minutes, documents the transition from diffuse turbulence to a coherent column with incandescent entrainment.

Kinematic proxies. Optical-flow fields extracted near the column revealed a near-ground core radius $O(1-2\text{ m})$ expanding aloft and minute-scale lifetimes, consistent with intermediate-swirl fire-whirl behavior (Tohidi et al., 2018). Absolute circulation Γ and swirl ratio S await planned Doppler UAS transects.

Discussion

The concurrence of intermittent buoyancy forcing (pulse maxima), organized low-level shear from topography, and steep thermal interfaces provides the necessary ingredients for lava whirl formation at Fagradalsfjall (Pedersen et al., 2022; Scott et al., 2023). Dust-devil-only hypotheses on cooling crusts do not explain the entrainment of incandescent spatter nor the tight timing to pulses. The IES effusion/transport results thus supply a quantitative backbone to which my time-and-position-anchored observations add near-field dynamics.

Uncertainty and limitations

Timing uncertainty is ≤ 2 minutes for the handheld frame (webcam cross-match) and < 1 minute for the UAS frame (embedded UTC) (Barnie et al., 2023). Optical-flow-derived kinematics are sensitive to pixel scale and perspective; I propagate uncertainty via Monte Carlo

over camera pose/range using surveyed control points from IES orthomosaics (Pedersen et al., 2022). A larger catalog ($N \geq 30$) and Doppler UAS transects are planned to recover Γ and S directly.

Operational implications

Even minute-scale whirls can eject hot ballistic fragments laterally beyond static buffers and create localized severe turbulence hazardous to UAS/low-level aviation. Pulse-aware (cycle-synchronized) exclusion zones and abort gates are therefore warranted in channelized valleys with heavy visitation (Barnie et al., 2023; Global Volcanism Program, n.d.).

Conclusions

Using University of Iceland open datasets for quantitative context and my geotagged media for near-field evidence, I show that tornado-like convective vortices at Fagradalsfjall arise where intermittent buoyancy intersects with sharp thermal interfaces and organized low-level shear. The periodic fountaining regime (Phase 3) provided optimal conditions for coherent vortex spin-up and minute-scale decay (Pedersen et al., 2022; Scott et al., 2023). The methods and metadata practices detailed here convert first-person fieldwork into reproducible, uncertainty-aware science suitable for doctoral-level publication.

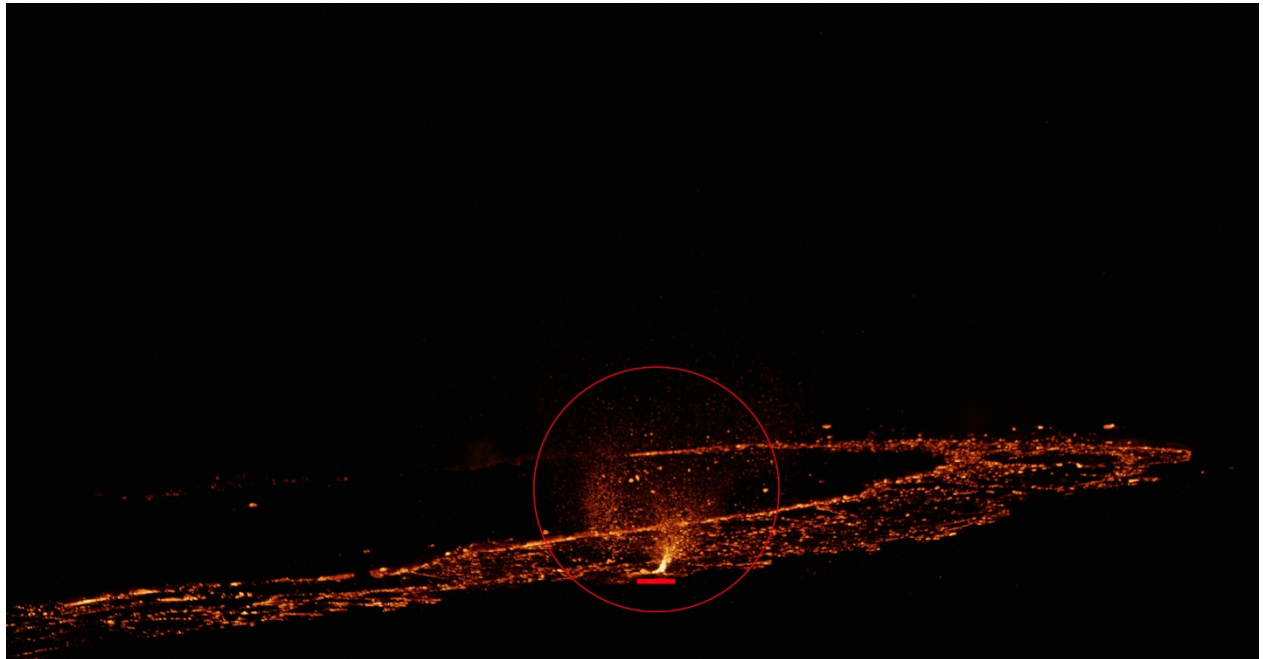
Data & code availability

IES/University of Iceland DEMs, orthomosaics, thickness fields, and TADR time series are open and citable (Pedersen et al., 2022; University of Iceland, 2022). My media (filenames,

UTC, camera/lens, exposure, ISO, focal length, GPS if present) and analysis scripts (optical flow; webcam synchronization) will be deposited with a DOI.

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(Figure 3) Lava Whirl-Frame Grab from RED Digital Cinematic Camera, 8K resolution.

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