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## Key Points:

- Subsurface deformation associated with the 2023–2024 eruption sequence on the Reykjanes Peninsula produces a pronounced  $dv/v$  signal
- The observed  $dv/v$  signal is inverted for a model of dike-opening which agrees with surface fissure locations
- This result demonstrates that inversion of stress-induced  $dv/v$  signals is viable

## Supporting Information:

Supporting Information may be found in the online version of this article.

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# Constraining Dike Opening Models With Seismic Velocity Changes Associated With the 2023–2024 Eruption Sequence on the Reykjanes Peninsula

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**Abstract** The stress field perturbation caused by magmatic intrusions within volcanic systems induces strain in the surrounding region. This effect results in the opening and closing of microcracks in the vicinity of the intrusion, which can affect regional seismic velocities. In late November 2023, we deployed a distributed acoustic sensing interrogator to convert an existing 100-km telecommunication fiber-optic cable along the coast of Iceland's Reykjanes peninsula into a dense seismic array, which has run continuously. Measuring changes in surface wave moveout with ambient noise cross-correlation, we observe up to 2% changes in Rayleigh wave phase velocity ( $dv/v$ ) following eruptions in the peninsula's 2023–2024 sequence that are likely associated with magmatic intrusions into the eruption-feeding dike. We apply a Bayesian inversion to compute the posterior distribution of potential dike opening models for each eruption by considering  $dv/v$  measurements for varying channel pairs and frequency bands, and assuming this velocity change is tied to volumetric strain associated with dike-opening. Our results are in agreement with those based on geodetic measurement and provide independent constraints on the depth of the dike, demonstrating the viability of this novel inversion and new volcano monitoring directions through fiber sensing.

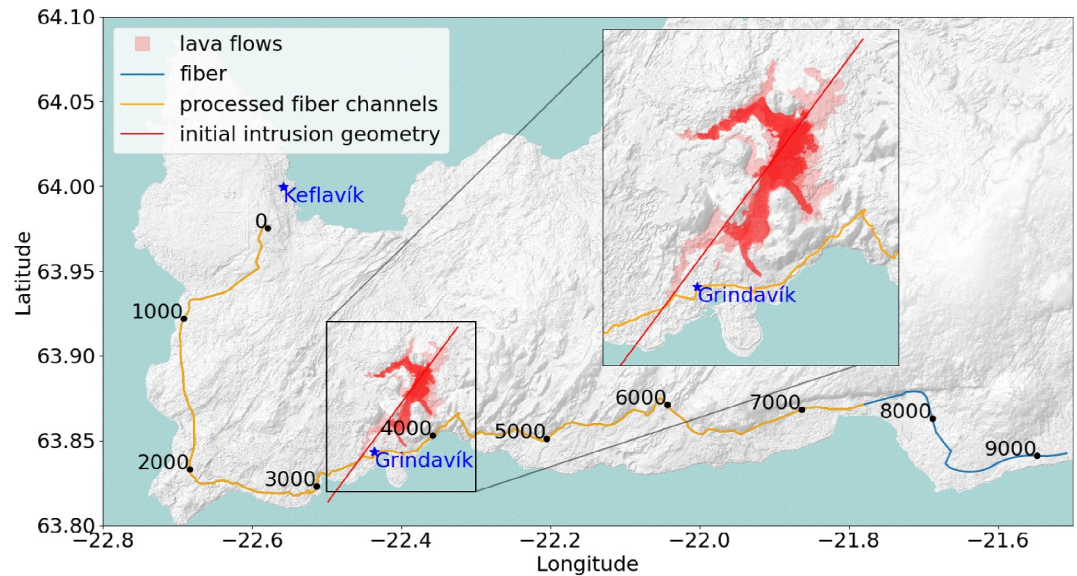
**Plain Language Summary** In volcanic regions, pressure from intruding magma can cause nearby rocks to deform. The speed of seismic waves through said rocks then increases or decreases, as the medium stretches and compresses. Prior to the 2023–2024 eruption sequence on the Reykjanes peninsula, we deployed an interferometric instrument which converted an existing optical fiber into an array of ground-motion sensors. With our array, we see a significant change in seismic velocities following eruptions, as the magma feeding the eruption moves through the subsurface. Through observation of the seismic velocity change in each eruption, we can better understand the subsurface structure of the volcanic system. We constrain the location, azimuth, length, and depth of the intruding dike using only these changes in the seismic velocity. Our constraints may be considered in tandem with those derived geodetically to better understand the dike structure.

## 1. Introduction

Located at the intersection of a mantle hotspot and the mid-atlantic ridge, Iceland is a vigorously volcanic region. In recent years, Iceland's Reykjanes peninsula (Figure 1) entered a period of activity, with its most recent eruptive series beginning in late 2023 and continuing to present (Parks et al., 2024). On 10 November 2023, a dike formed in the subsurface of the Reykjanes peninsula, striking approximately northeast (Sigmundsson et al., 2024). The intrusion was followed by a series of volcanic eruptions, the first of which occurred from December 18–21, 2023. This work studies the behavior of the volcanic system through observed changes in seismic velocities on the peninsula during the first three eruptions in the sequence.

Temporal variations in seismic velocities ( $dv/v$ ) may be indicative of myriad earth processes. Changes in the water saturation of a rock can affect its seismic velocities, so  $dv/v$  can act as an indirect measure of groundwater levels and the broad hydrological state of the subsurface (Clements & Denolle, 2018; Rodríguez Tribaldos & Ajo-Franklin, 2021; Sens-Schönfelder & Wegler, 2006; Shen et al., 2024). Changes in the microcrack density in a material can likewise impact velocities, so a velocity change may indicate volumetric strain in certain contexts. This effect makes  $dv/v$  a powerful metric in studies of the coseismic and postseismic stress and strain fields

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**Figure 1.** Map of the Reykjanes Peninsula, with fiber channels and lava flow outlines plotted (LMI, 2024). Lava flows are darker in locations where lava flows from multiple eruptions overlap. Channel numbers are listed at 1000 channel intervals after removal of bad channels. The geometry of the initial intrusion from Sigmundsson et al. (2024) is plotted in red.

associated with large earthquakes (Wegler & Sens-Schönfelder, 2007; Çubuk-Sabuncu et al., 2024). Similarly,  $dv/v$  signals can provide insights into the magmatic structures feeding volcanic systems, which will strain surrounding bodies of rock (Brenquiere et al., 2008; Donaldson et al., 2017; Mordret et al., 2010; Sens-Schönfelder et al., 2014). While such volcanic signals may produce significant velocity changes, competing environmental signals may complicate interpretations (e.g., Donaldson et al. (2019)). Generally, studies of  $dv/v$  in volcanic regions consider how surface wave phase velocity perturbations in one or more frequency bands respond to observed volcanic events, sometimes comparing these perturbations with volumetric strains estimated through geodetic measurements or modeled with point sources (Donaldson et al., 2019; Kiyoo, 1958; Maass et al., 2024; Mordret et al., 2010).

Many studies calculate  $dv/v$  signals on the basis of ambient noise cross-correlation, a method wherein continuous data from two seismic sensors are cross-correlated over a sufficiently long time window, yielding an approximation to the Green's function between the two sensors (Campillo & Paul, 2003). Relying on ambient noise, one can produce continuous estimates of the seismic velocity, a benefit over estimates of velocity changes which rely on repetitive sources (Sens-Schönfelder & Wegler, 2006). However, results are highly sensitive to changes in the noise source over time, with past results near our study site indicating sensitivity of low-frequency  $dv/v$  to ocean dynamics (Zhan et al., 2013; Çubuk-Sabuncu et al., 2024).

The core data set in this study is derived from a fiber-optic seismic array (Zhan, 2020). Fiber-optic seismic arrays consist of an interrogator unit (IU), attached to an optical fiber. The IU transmits a laser signal into the fiber and records backscattered light from impurities in the fiber. As the fiber strains, the delay between subsequent backscattered arrivals at the interrogator will change. Applying interferometric techniques to this changing backscatter signal, one can extract the strain of the fiber over time at meter-scale intervals. Fiber-optic seismology is an efficient method of densely instrumenting a large region with seismic sensors, as researchers can interrogate unused fibers in existing telecommunication networks. Fiber-optic seismology has been successfully utilized in wide-ranging geophysical fields including seismic imaging (e.g., Ajo-Franklin et al., 2019; Atterholt et al., 2024; Cheng et al., 2023; Ma et al., 2023; Martuganova et al., 2022; Yang et al., 2022), seismicity (e.g., Ajo-Franklin et al., 2019; J. Li et al., 2023), hydrology (e.g., Rodríguez Tribaldos & Ajo-Franklin, 2021; Shen et al., 2024), and physical oceanography (e.g., Lindsey et al., 2019; Mata Flores et al., 2023; Sladen et al., 2019; Williams et al., 2019, 2023). In the field of volcanology, numerous studies have leveraged the spatial density of fiber-optic arrays in characterizing the structure and dynamics of volcanic systems (Biondi et al., 2023; Caudron et al., 2024; Jousset et al., 2022; Klaasen et al., 2023). One recent study of volcanic  $dv/v$  employed data from a fiber-optic

array, demonstrating improved correlations when data were spatially averaged over the dense array (Maass et al., 2024).

## 2. Data

On 20 November 2023, we deployed an Optasense QuantX Interrogator Unit at a fiber node in Keflavík, Iceland, converting a 102 km fiber to a dense set of strainmeters. The fiber runs south from Keflavík to the southwest corner of the Reykjanes peninsula, and continues eastward along the coast, passing through Grindavík. Data are recorded at a sampling rate of 160 Hz with a gauge length of 100 and 10 m channel spacing. The deployment concluded in November 2024.

We determine the location of fiber channels as in Biondi et al. (2022). This procedure first distinguishes bad channels and fiber loops, sections of cable which are largely uncoupled with the surrounding earth structure and provide little useful geophysical data. Based on recordings of local seismic events, we identify 986 of the initial 10,200 fiber channels as bad channels. To localize the remaining channels, we drive across the array in a GPS-equipped vehicle. Station numbers (after removal of bad channels) are plotted at 1,000 channel (10 km) intervals in Figure 1.

The data are processed to produce ambient noise cross-correlation empirical Green's functions (EGFs), calculated for each day of the study period. To produce these EGFs, we filter data between 0.05 and 10 Hz, downsample to 20 Hz, perform temporal normalization, and spectrally whiten between 0.05 and 10 Hz, as in Yang et al. (2022).

## 3. Analysis

### 3.1. Extracting $dv/v$ Estimates

We extract  $dv/v$  estimates from our data using the stretching method (an established method which is detailed in Text S1 in Supporting Information S1). To implement this approach, we must choose a time window of the EGF to stretch over. We intend to capture the change in direct arrival time for a given channel pair. Thus, we predict a direct arrival time  $t_{\text{arr}}$  from the velocity model described in Málek et al. (2019) and select a window around the predicted arrival spanning  $(t_{\text{min}}, t_{\text{max}})$ , where  $t_{\text{min}} = \frac{2}{3}t_{\text{arr}}$  and  $t_{\text{max}} = \max(2t_{\text{arr}}, t_{\text{min}} + 8)$ . We require a minimum length of 8 s for each window to ensure a stable solution. While our relatively long time windows will cover a portion of the EGF coda, a high amplitude direct arrival will generally dominate the result.

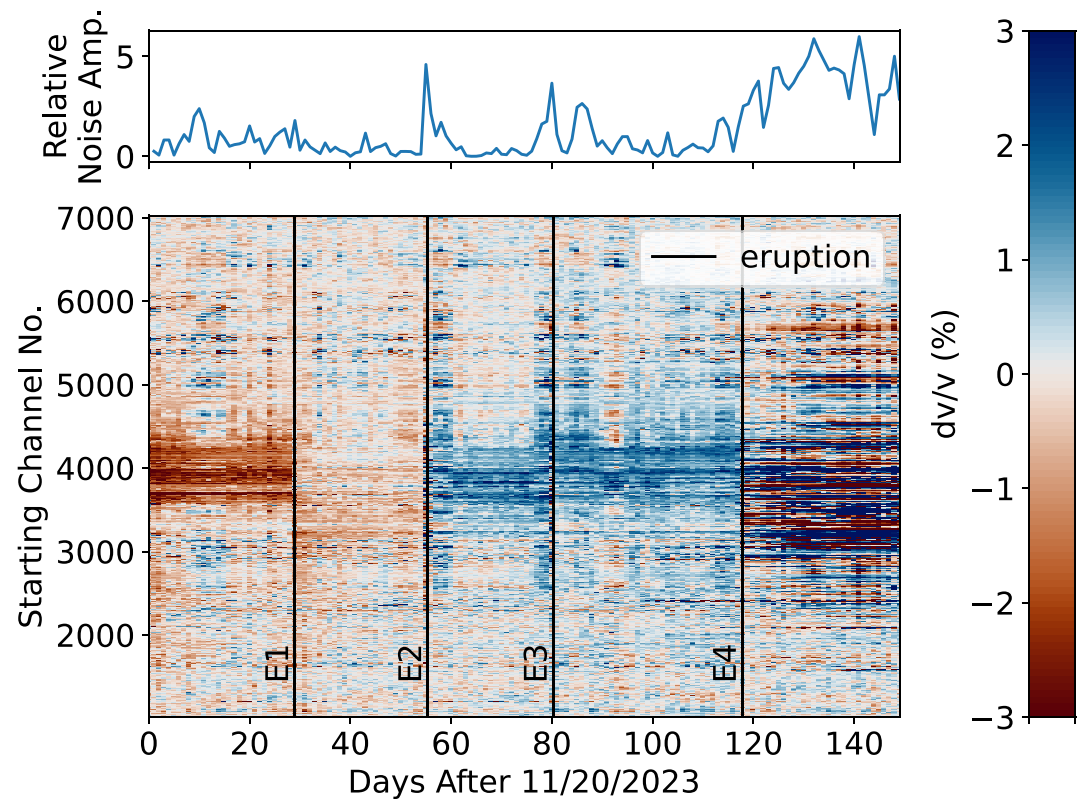
We first perform an approximate constant offset  $dv/v$  analysis, considering daily cross-correlations of channel pairs separated by 500 channels (approximately 5 km), band-passed near 1.0 s. These estimates of  $dv/v$  are calculated relative to a stacked EGF over the first 100 days of the study. We find that the data set is dominated by a change in seismic velocity following each eruption (Figure 2). Thus, the core analysis of this work considers only  $dv/v$  signals associated with the eruptions, with cross-correlations summed over the full inter-eruption periods to produce the differential measurement. We only consider the first three eruptions, as the following eruptions see intense volcanic noise biasing our results. Text S2 and Figure S1 in Supporting Information S1 detail the data quality control employed in producing our  $dv/v$  estimates.

Our inversion is based on pairwise  $dt/t$  estimates for periods  $T$  of 0.5, 1.0, and 2.0 s, for starting channels  $p_{\text{init}}$  ranging from 0 to 6,000 at 10 channel intervals, and for ending channels  $q_{\text{init}}$  from  $p_{\text{init}} + 200$  to  $p_{\text{init}} + 1300$  at 10 channel intervals. This choice limits inter-channel offsets to at most  $\approx 13$  km, as our  $dv/v$  estimates become significantly noisier at increased displacements, especially in the higher frequency bands.

We smooth and downsample our data for each eruption, arriving at data points,  $\left(\frac{dt}{t}\right)_{pqT}$ , where:

$$\left(\frac{dt}{t}\right)_{pqT} = \frac{1}{25} \sum_{r=0}^4 \sum_{s=0}^4 \left(\frac{dt}{t}\right)_{(p_{\text{init}}+p+(10r))(q_{\text{init}}+q+(10s))T}, \quad (1)$$

where  $p \in \{0, 100, \dots, 5800, 5900\}$ ,  $q \in \{p + 200, p + 350, \dots, p + 1100, p + 1250\}$ , and  $T \in \{0.5, 1.0, 2.0\}$ . Taking the standard deviation across these channel pairs, rather than the mean, we can also produce an uncertainty estimate for each of our smoothed data points. Data and uncertainty for all eruptions and frequency bands discussed are plotted in Supplementary Figures S2–S4 in Supporting Information S1.



**Figure 2.** The colormap shows  $dv/v$  across the first 150 days of our deployment, calculated at 1.0 Hz with channel pairs separated by 500 channels (approximately 5 km). The dates of the eruptions are denoted by vertical black lines and labeled (e.g., Eruption 1 is labeled as E1). Daily estimates of volcanic noise are plotted above the colormap. Where volcanic noise is high, the calculated  $dv/v$  signal appears to become noisy. The mean cross-correlation empirical Green's function across the first 100 days is used as a template in calculating the  $dv/v$ . We do not include the final 50 days in our average, due to the high levels of volcanic noise. As we are calculating  $dv/v$  relative to an averaged signal over the first hundred days, spans of fiber which consistently increased in velocity over the period will show a negative  $dv/v$  for earlier days, and positive  $dv/v$  for later days.

### 3.2. Forward Modeling

We assume that to first-order, the observed  $dv/v$  signal is the result of volumetric strain associated with an opening dike, a reasonable choice given the dominance of dike opening over other volcanic processes in other studies of this volcanic intrusion and in analogous  $dv/v$ -based studies (Donaldson et al., 2019; Sigmundsson et al., 2024). Our study will invert for models of dike-opening, as opposed to inverting for the change in S velocity at varying location and depth and inferring dike geometries from that result. This choice allows us to more directly access parameters of interest, such as the depth and length of the dike, and in taking a Bayesian approach we may infer uncertainties on these quantities. Performing time-lapse tomography would also be relatively computationally expensive, in comparison, especially if we attempted to quantify uncertainties.

We forward model the expected  $dv/v$  from dike opening models defined by the center of the dike in map-view, at  $[x_{cen}, y_{cen}]$ , the azimuth of the dike  $\theta$ , the depth extent of the dike,  $d_0$  to  $d_1$ , the length of the dike laterally,  $d_l$ , and the opening of the dike in meters  $A$ .

In general, rather than directly modeling  $dv/v$ , our analysis is placed in the framework of a change in arrival time ( $dt/t$ ). In some instances, we discuss  $dt/t$  at points in space, in which case we are referring to a fractional change in traveltime along infinitesimal segments at said points (also equal to the fractional change in slowness).

We may convert between  $dv/v$  and  $dt/t$  through the relation:

$$\frac{dt}{t} = \left( 1 / \left( \frac{dv}{v} + 1 \right) \right) - 1 \quad (2)$$

Note that for  $dt/t \ll 1$ ,  $dt/t \approx -dv/v$ .

Our inversion relies on forward modeling the expected  $dt/t$  signals between channel pairs for a chosen dike opening model. For said dike opening model, we consider an Okada model of dike opening (NIED, 2012; Okada, 1985), and predict the resulting volumetric strain in three-dimensional Cartesian space  $\epsilon(x, y, z)$ . At each point  $(x, y, z)$ , this strain may be mapped to a change in shear velocity  $dV_s/V_s$  through the empirical constant  $\eta$ :

$$\frac{dV_s}{V_s}(x, y, z) = -\eta \Delta\sigma(x, y, z) = -\eta K \epsilon(x, y, z), \quad (3)$$

where  $K$  is the bulk modulus (which we set to 50 GPa) and  $\Delta\sigma$  is the stress perturbation associated with the dike opening. This is a widely used scaling, regularly employed in the literature (e.g., Donaldson et al., 2019; Niu et al., 2008; Sheng et al., 2022; Yamamura et al., 2003).

The value of  $\eta$  is expected to decay with increasing confining pressure,  $P$  (Daley et al., 2006). We assume that  $\eta$  takes the form of a power law:

$$\log_{10} \eta = -a \log_{10} P - b, \quad (4)$$

for  $P$  in MPa and  $\eta$  in  $\text{Pa}^{-1}$ , and constrain  $a$  and  $b$  through the results of laboratory experiments for consolidated rocks compiled by L. Li et al. (2023).

The value of  $a$  is reasonably consistent between experiments ( $1 \pm 0.3$ ), while  $b$  tends to vary heavily ( $7 \pm 1.9$ ) (L. Li et al., 2023). In our forward models, we use the mean values of  $a$  and  $b$  (1 and 7). The only model parameter affected by the high variability in  $b$  is the amplitude of dike opening—if  $\eta$  is underestimated by a factor of two, our inversion will overestimate dike opening by a factor of two—and we do not expect  $\eta$  to change between eruptions. Thus, we assume that all estimates of the log-amplitude of dike opening are biased by the same factor  $\mathcal{E}(\eta_b)$ , which is equal to the difference between the value of  $b$  used in our inversion and the true value of  $b$ .

From our  $dV_s/V_s$  estimates, we predict the change in Rayleigh wave slowness,  $dt/t \approx -dv/v$ , in a pointwise sense at varying period (i.e., at points in  $(x, y, T)$  space). The pointwise  $dt/t$  estimate is used to predict the change in arrival time for a source-receiver pair. Our approach to forward modeling is discussed in more depth in Text S3–S5 in Supporting Information S1, with a particular focus on the transitioning from  $dV_s/V_s$  to inter-channel  $dt/t$ .

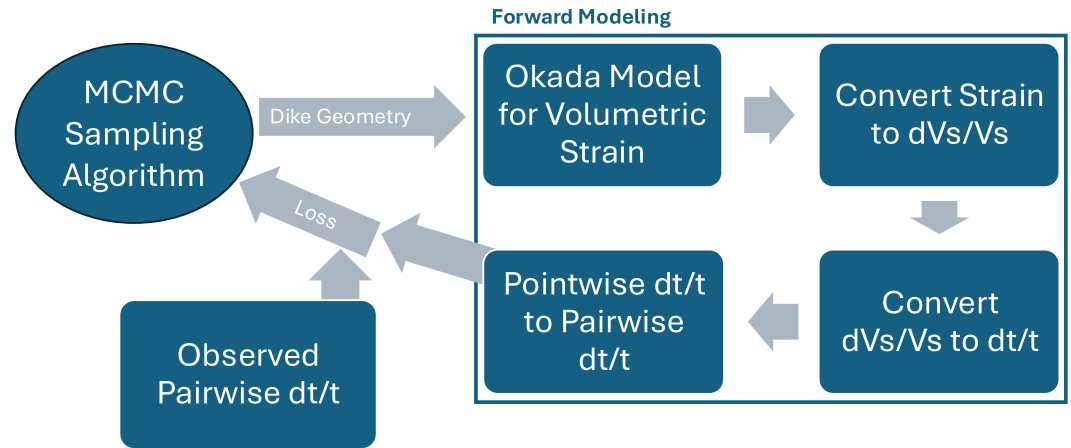
### 3.3. Inversion

Using our estimates of pointwise  $dt/t$  and their uncertainty, we fit dike parameters through a Markov Chain Monte Carlo (MCMC) approach, implemented using the package emcee (Foreman-Mackey et al., 2012). Assuming uniform opening along a vertical, rectangular dike, we invert for the location, azimuth, and vertical extent of the structure.

We define an uncertainty structure for use in this inversion of the form:

$$\mathbf{C}_D = \mathbf{C}_d + \mathbf{C}_t \quad (5)$$

$\mathbf{C}_d$  is a diagonal matrix imparting the uncertainty of our  $dt/t$  measurements.  $\mathbf{C}_t$  is a diagonal matrix associated with changes in the velocity which are not captured by our forward model (e.g., from atmospheric pressure, soil moisture, noise source variations, or volcanically driven stress changes which cannot be captured by our idealized dike) (Tarantola, 2005). We assume these variations are on the order of 0.5% (a similar variability to what is seen in e.g., Çubuk-Sabuncu et al. (2024) or Maass et al. (2024), both of which are located on the Reykjanes peninsula), resulting in a matrix of the form  $\mathbf{C}_t = (0.005)^2 \mathbf{I}$ . We choose to use a diagonal uncertainty structure, down-sampling our data to reduce the effects of error covariance, as discussed above. Using a full covariance structure



**Figure 3.** Flowchart summarizing forward modeling and inversion.

would be prohibitively time-consuming in our case, but might be possible in other contexts (e.g., given a more informative model prior which allows for faster convergence).

The probability of an individual model is then:

$$q(\mathbf{m}|\mathbf{d}) \propto e^{-\frac{1}{2}(\mathbf{G}(\mathbf{m})-\mathbf{d})^T \mathbf{C}_D (\mathbf{G}(\mathbf{m})-\mathbf{d})}, \quad (6)$$

where  $\mathbf{d}$  is the observed data,  $\mathbf{m}$  is a given dike-opening model, and  $\mathbf{G}$  maps said model to a data prediction. Here, we are assuming a uniform prior (i.e.,  $p(\mathbf{m}) \propto 1$ ). Our approach to analyzing  $dv/v$  signals is summarized in Figure 3.

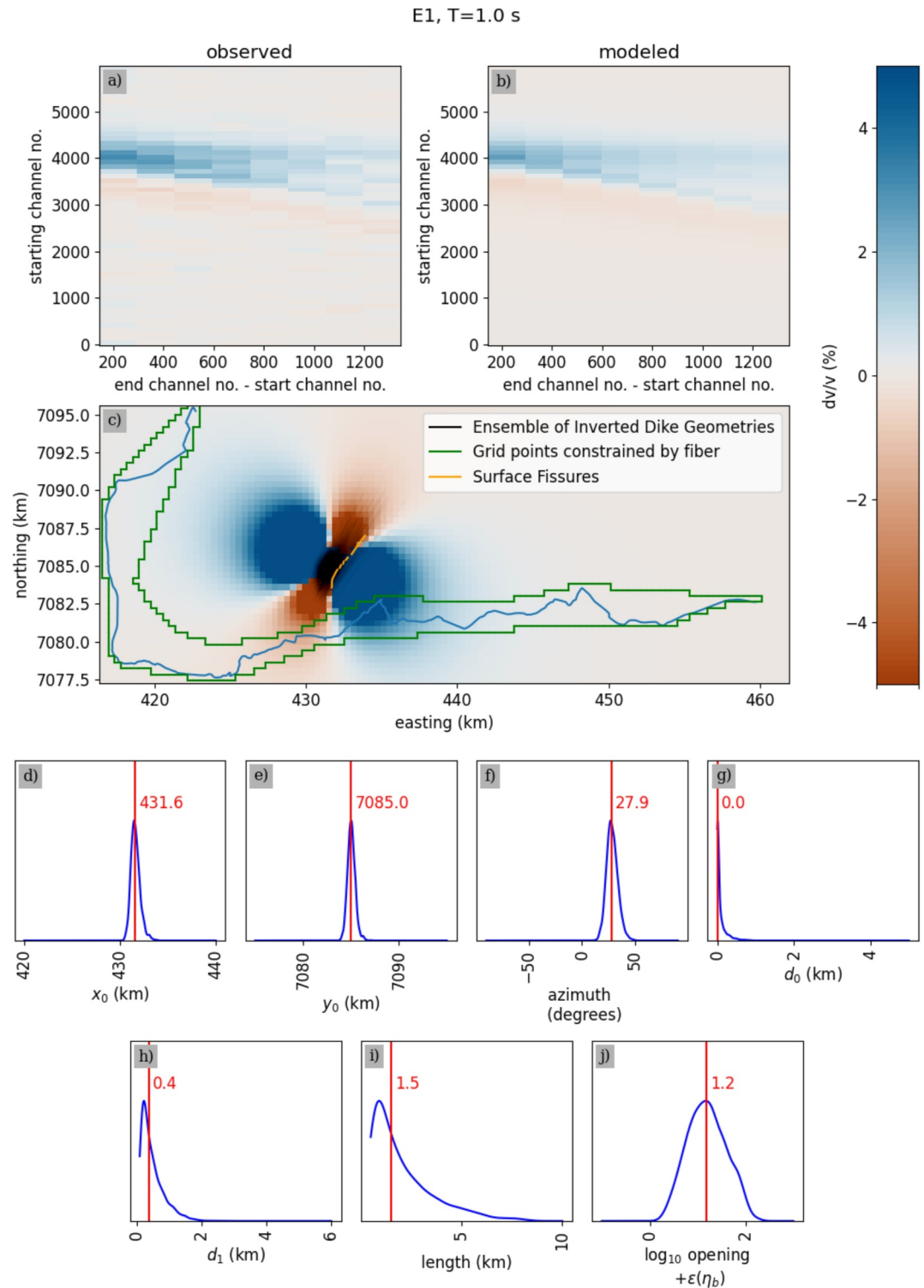
#### 4. Results

We plot the output distributions of dike opening models for eruption 1 (Figure 4, Figures S5–S7 in Supporting Information S1), eruption 2 (Figures S8–S11 in Supporting Information S1) and eruption 3 (Figure 5, Figures S12–S14 in Supporting Information S1). Alongside our distributions of dike opening models, we plot surface fissures associated with each eruption (LMI, 2024).

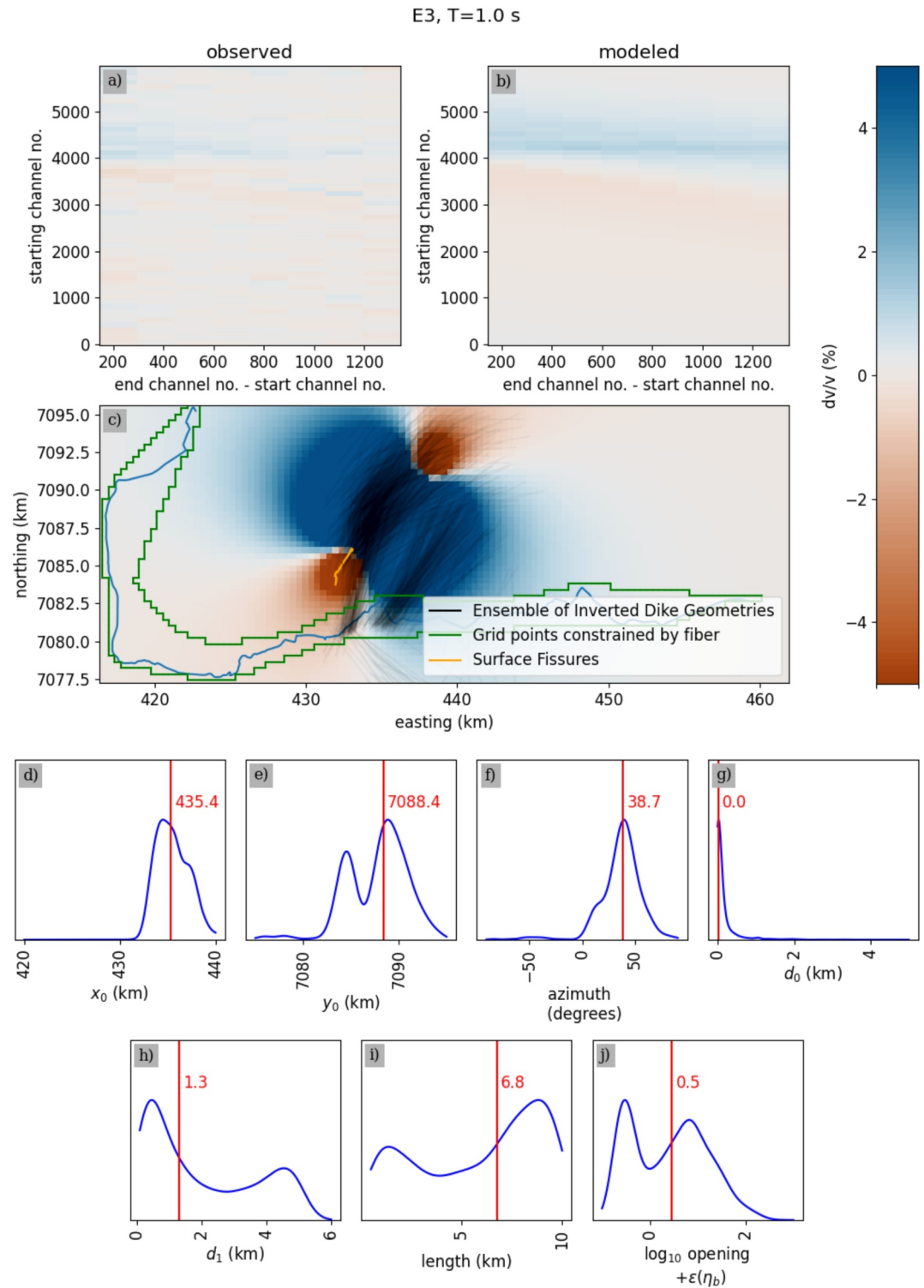
We find that our posterior distributions for eruptions 1 and 3 (E1 and E3) appear to impart real information regarding dike location, with a particularly excellent fit for E1. When plotted in map view, as in Figure 4, there is overlap between the posterior distribution and surface fissures associated with the eruption, suggesting that the location and azimuth of the dike are reasonably accurate (LMI, 2024). In both cases, the posterior distribution correctly indicates a dike which breaches the surface, and prefers dike-opening which is primarily located at shallow depths (less than 1 km). Our inversion of data from E1 predicts that  $\log_{10} \text{opening} + \mathcal{E}(\eta_b) \approx 1$  (corresponding to 10 m), while the maximum dike opening in E1 predicted through geodetic measurements is approximately 4 m (Sigmundsson et al., 2024). This suggests  $\mathcal{E}(\eta_b) \approx 0.5$  and  $\log_{10} \eta \approx -\log_{10} P - 6.5$ .

The third eruption is much less tightly constrained than the first eruption, likely due to a lower amplitude  $dv/v$  signal, which falls below noise along more of the array. The solution has two primary modes, with the likely location of the dike, as constrained by surface fissures, sitting on a the tail of the northwestern mode. The inversion of E3 also fails to provide a meaningful constraint on the length of the dike, a limitation which would likely be addressed if our array passed near both ends of the dike.

The inversion of data from eruption 2 arrives at a posterior distribution which is displaced from the volcanic fissures (LMI, 2024). Further, the preferred structure of E2 diverges from E1 and E3, with a greatly decreased dike opening over a dike with a much deeper extent, a result unsupported by Sigmundsson et al. (2024). The poor fit may be due in part to the fact that lava flows associated with this eruption extend much closer to the fiber than in the other eruptions. As such, our assumption that the dominant  $dv/v$  signal associated with the eruption is one of dike-opening may break down. Further, this dike appears to have propagated much closer to the fiber than the



**Figure 4.** (a) Observed and (b) predicted  $dv/v$  signal during eruption 1 at a period of  $T = 1$  s. Signals are smoothed on a 500 m lengthscale. The prediction is associated with the median solution from our MCMC inversion. (c) Map view of the predicted  $dv/v$  signal at a period of  $T = 1$  s for the median output of our MCMC inversion. Inverted fiber channels are plotted in blue, with the green border outlining the grid points for which the  $dv/v$  signal is constrained for our data. Black lines are ensemble members from our inversion, signifying the location of dike opening, while orange lines denote observed surface fissures (LMI, 2024). (d)–(j) Posterior distributions for each dike opening parameter. Vertical axes of subplots show probability density normalized to the maximum probability for any given variable. Median values are marked in red.



**Figure 5.** (a) Observed and (b) predicted  $dv/v$  signal during eruption 3 at a period of  $T = 1$  s. Signals are smoothed on a 500 m lengthscale. The prediction is associated with the median solution from our MCMC inversion. (c) Map view of the predicted  $dv/v$  signal at a period of  $T = 1$  s for the median output of our MCMC inversion. Inverted fiber channels are plotted in blue, with the green border outlining the grid points for which the  $dv/v$  signal is constrained for our data. Black lines are ensemble members from our inversion, signifying the location of dike opening, while orange lines denote observed surface fissures (LMI, 2024). (d)–(j) Posterior distributions for each dike opening parameter. Vertical axes of subplots show probability density normalized to the maximum probability for any given variable. Median values are marked in red.

others, potentially making our assumption of uniform deformation along a rectangular patch more problematic, as the local dike geometry may have dominated the  $dv/v$  signal along a span of the fiber.

## 5. Discussion

We have presented a new method of  $dv/v$ -based inference, inverting for an Okada model of dike-opening based solely on  $dv/v$  observation. Studies of volcanic  $dv/v$  initially focused on explaining changes in velocity structures over time through known changes in a volcanic system (or environmental signals), but with increasingly dense, high-quality data the field can move toward inferring volcanic dynamics, an exciting change in emphasis. Our approach is similar to that described in Sheng et al. (2022) which infers an Okada model associated with a slow-slip event on the basis of velocity changes, although we take an additional step in performing an inversion for our Okada model, aided by laboratory measurement of  $\eta$ . Likewise, a similar inversion to that presented in our study could naturally be applied to point sources in different volcanic contexts (Kiyoo, 1958).

The value of this kind of  $dv/v$ -based inversion is multi-fold. In some regions (e.g., in certain ocean-bottom contexts), seismic coverage might exceed what is available geodetically. Additionally,  $dv/v$  signals have been observed in the absence of geodetic signals (e.g., Mordret et al. (2010)). In such cases, the application of a  $dv/v$ -based inversion could illuminate volcanic structures which are otherwise inaccessible. Many common geodetic techniques also have drawbacks, some of which a  $dv/v$ -based seismic approach may avoid. For example, interferometric synthetic-aperture radar (InSAR) generally has low temporal resolution and may observe low coherence in areas of high vegetation (Fernández et al., 2017). Similarly, to achieve high spatial resolution in GNSS data one must average data over long timescales (Fernández et al., 2017).

Further,  $dv/v$  could be a powerful tool when used jointly with geodetic data. As surface waves of differing frequency have variable depth sensitivity,  $dv/v$ -based methods will sample deformation in a different way than approaches such as InSAR or global navigation satellite systems (GNSS), which describe surface deformation (Fernández et al., 2017). Comprehensively considering  $dv/v$  signals in different frequency bands may provide us with stronger constraints on volcanic features. Our study, in particular, provides a distribution of potential dike depth extents, which may be considered in concert with geometries derived geodetically to better capture the shape of the feature. In localizing a velocity change within a range of depths, we generally require that data at multiple frequency bands have sensitivity in that depth range. In our case, sensitivity kernels indicate that we will likely fail to localize the depth of any velocity changes deeper than 3 km.

Appreciating the great potential of increasingly quantitative applications of  $dv/v$ , it is also critical that we recognize the simplifications which may limit the broad applicability of the inversion we have presented. Okada models assume elastic deformation to a homogeneous half-space, a simplification to the composition and deformation of the study region. Further, our Okada model assumes uniform dike opening along a single rectangular section. This parameterization is an idealization of the true dike geometry, intended to provide first-order information about its depth and location relative to the fiber, but its simplicity may result in some of the misfit between prediction and observation. For example, dikes often observe increased opening closer to the free surface and see variable opening along-strike, and thus a uniform opening in depth is expected to be non-physical (Geshi et al., 2020; Sigmundsson et al., 2015). The effect of this simplification can be clearly observed when our results are compared with other observations. The median lateral length of the first dike-opening event from our posterior distribution is 1.5 km, while surface fissures extend closer to 5 km, likely due to variable degrees opening along the fissures (LMI, 2024). Likewise, the results of Sigmundsson et al. (2024) suggest that dike-opening during the first eruption extended deeper and further laterally than our observation. However, the study suggested that the maximum opening occurred in a patch with a length of  $\approx 1$  km and depth of  $\approx 0.5$  km, which agrees well with our inversion.

Additionally, while we are able to forward model volumetric strain to  $dV_s/V_s$  through laboratory measurements, the scaling between these quantities,  $\eta$ , can vary greatly depending on material (L. Li et al., 2023). While outside the scope of this study, future inversions could calibrate the relationship between these quantities based on known strain signals at the site (e.g., those observed geodetically). In certain contexts, no ground-truth deformation signal is available, so our choice to fit models without calibration of  $\eta$  allows for a more general understanding of the power of  $dv/v$ -based inversions.

We also assume a constant velocity model (and thus make a straight-ray approximation). In reality, lateral heterogeneities in the starting velocity model will impact how the stress from dike opening is propagated to a  $dv/v$  between channel pairs, as the forward propagation of depth-dependent  $dV_s/V_s$  to  $dv/v$  is tied to the starting Versus model. Further, when integrating pointwise  $dt/t$  to get  $dt/t$  along a raypath, the weight of any given point will scale with its absolute Rayleigh velocity. In the case of extreme velocity gradients, the raypaths may experience non-negligible bending, a further complication to the forward problem.

Finally, we treat all  $dv/v$  signals unrelated to dike opening as noise. Future work could instead forward model  $dv/v$  associated with known environmental factors, such as temperature and rainfall, and use the result as a correction. This could be of particular value in accounting for  $dv/v$  from other reservoirs in the volcanic system, such as dike-feeding magma chambers, co-eruptive faulting, tremor-related noise source variations, or lava flows at the surface, as these signals are likely to have significant covariance with that of an opening dike.

## 6. Conclusion

As we move toward an age of increased, dense seismic instrumentation, studies of temporal seismic velocity change are increasingly well-constrained. We observed changes in Rayleigh wave phase velocity on the order of 2% associated with the 2023–2024 eruptions on the Reykjanes peninsula. We explain some of these signals through simple models of uniform dike opening along a vertical, rectangular patch. Said models of dike opening are consistent with the location of surface fissures.

Our result has implications both for the study of volcanic systems and generally for the use of  $dv/v$  as a measure of stress change. Moving forward, we hope to build on the methodology employed here and apply it in varied settings throughout the Earth system.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

Data are available on CaltechDATA (Bird & Zhan, 2024).

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