

# Integrated seismic monitoring reveals subsurface evolution during volcanic inflation at Askja volcano, Iceland

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**Abstract** Identifying volcanic transitions from quiescence to unrest and tracking subsurface evolution remains critically challenging. We analyzed continuous seismic records from Askja volcano (Iceland) from 2008–2024 using coda wave interferometry to track relative seismic velocity variations ( $dv/v$ ) as a proxy for subsurface changes during renewed volcanic intrusion. This analysis is complemented with three additional methods: network covariance matrix analysis, Displacement Seismic Amplitude Ratio (DSAR) single-station analysis, and sensitivity kernel analysis, alongside GNSS, earthquake catalog, and meteorological datasets. Since August 2021,  $dv/v$  measurements revealed an abrupt transition from regular seasonal oscillations ( $\pm 0.2\%$ ) to predominantly negative values reaching  $-0.7\%$  near the inflation center, coinciding with 76cm GNSS-detected ground uplift by August 2024. DSAR indicated higher seismic attenuation near the inflation source, suggesting volatile accumulation in the shallow subsurface through June 2022, followed by marked decreases associated with depressurization. Sensitivity kernel analysis demonstrated wave sensitivity reaches down to 3km depth, encompassing the shallow reservoir levels. Integrated seismic observations revealed magma-induced seismic velocity drops, followed by system reorganization with frequency-dependent recovery, and finally establishment of a new state with hydrothermal circulation maintaining altered seismic properties. This approach demonstrates the effectiveness of continuous seismic monitoring for detecting volcanic unrest transitions and tracking evolving subsurface processes.

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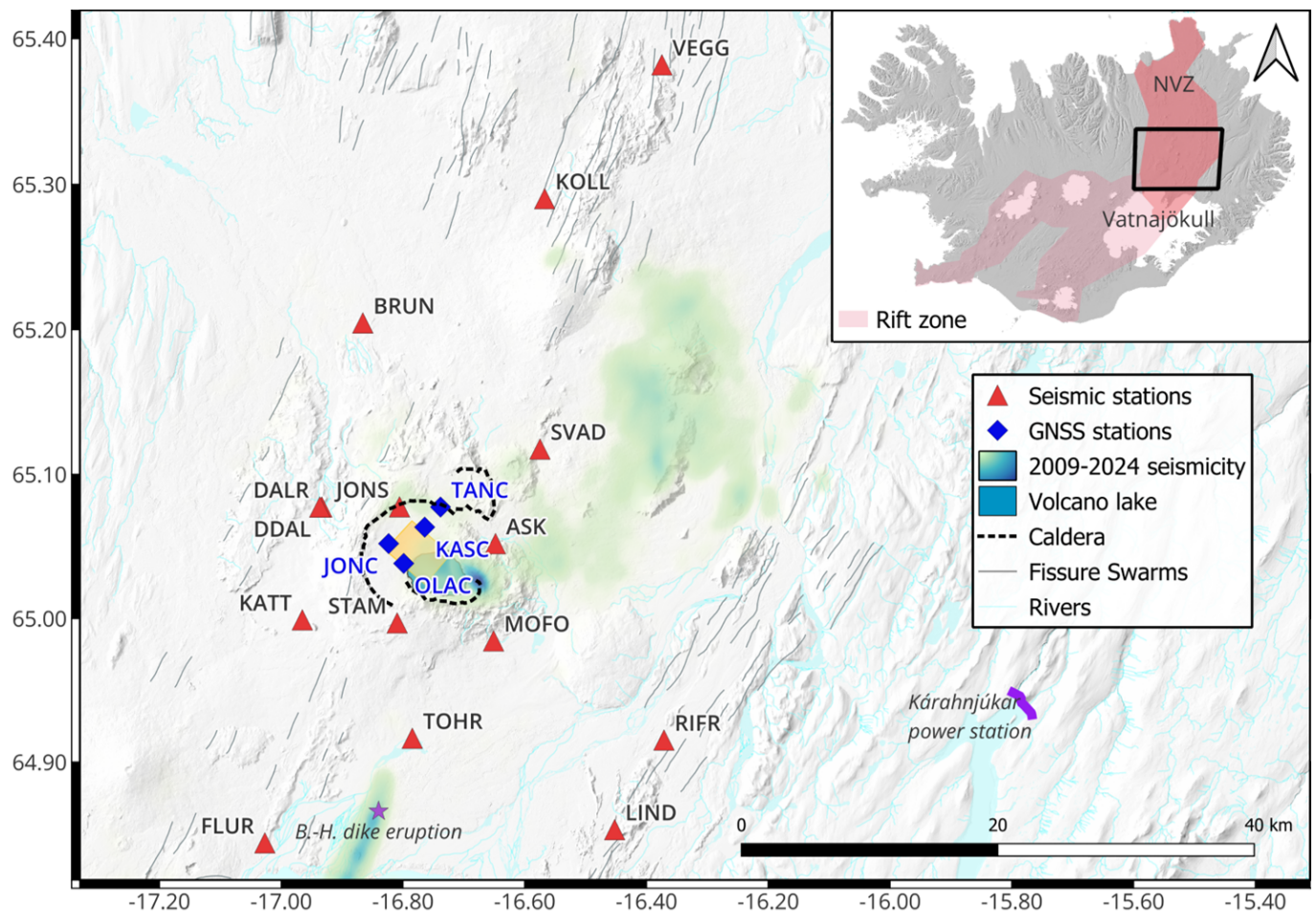
## 1 Introduction

Located within Iceland's Northern Volcanic Zone (Figure 1), the Askja volcanic system experienced a rapid inflation of  $76.5 \pm 0.6$  cm from August 2021 to August 2024, measured by a Global Navigation Satellite Systems (GNSS) station named OLAC, with continued inflation beyond the study period (Veðurstofa Íslands, 2023d; Sturkell et al., 2023; Parks et al., 2024) (Figure 2). Recent studies proposed several mechanisms for this deformation: (1) elastic deformation from active magmatic fluid migration (Parks et al., 2024; Han et al., 2024), (2) delayed poro-viscoelastic response of the shallow crust to fluid migration (Koymans et al., 2023; Parks et al., 2024), and (3) hydrothermal processes (Petrosino et al., 2023; Koymans et al., 2023). Distinguishing between magmatic fluid migration and poroviscoelastic responses remains challenging, particularly when considering potential hydrothermal influences.

These mechanisms can be further assessed by using coda wave interferometry. This is a widely used seismic

imaging technique that utilizes multiply-scattered seismic waves to estimate their Green's function and measure weak changes in seismic velocities (e.g., Snieder, 2006). This imaging technique can be applied actively, using repetitive sources throughout a limited period (e.g., Ratdomopurbo and Poupinet, 1995; Wegler and Sens-Schönfelder, 2007), or passively, using seismic noise cross-correlation (e.g., Campillo and Paul, 2003; Shapiro et al., 2005; Brenguier et al., 2008). Passive coda wave interferometry has been applied to multiple volcanoes worldwide, revealing diverse patterns of pre-eruptive and co-eruptive velocity changes. For example, at Merapi (Indonesia), seasonal velocity variations were observed and attributed to hydrological effects from groundwater level changes (Sens-Schönfelder and Wegler, 2006). Piton de la Fournaise (La Reunion, France) showed velocity decreases of 0.05% several weeks before eruptions, suggesting pre-eruptive inflation due to increased magma pressure (Brenguier et al., 2008), while Mount Ruapehu (New Zealand) showed a 0.8% velocity decrease starting two days before the 2006 eruption, attributed to fracture opening from a magma

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**Figure 1** Monitoring network used around Askja volcano, Iceland. The map shows the seismic stations (red triangles) and GNSS stations (blue diamonds) locations. The inflating sill from 20 September 2021 to 10 September 2023, modeled by Parks et al. (2024) is in orange. The density of seismic events located by Veðurstofa Íslands (2023a) since 2009 is heat-mapped from green (low) to blue (high). The main caldera is outlined with a dashed line, with Öskjuvatn lake in the center. North and East of the main caldera, there are concentrated fissure swarm areas (gray lines). The purple star is the eruption location of the Bárðarbunga-Holuhraun dike in 2014. The purple line is the Kárahnjúkar dam location. The inset map (top right) shows the location of the volcanic systems in Iceland within the NVZ and rift zone. Map data are from Náttúrufræðistofnun Íslands (Icelandic Institute of Natural History) (2025) and Graham et al. (2025).

pocket pressurization (Mordret et al., 2010). At White Island (New Zealand), velocity increases were identified during volcanic activity in 2012–2013 and preceding a 2016 phreatic eruption, with the technique successfully distinguishing volcanic signals from seasonal and coseismic effects by comparing local and distant station records (Yates et al., 2019). At Kawah-Ijen (Indonesia), significant seismic velocity drops of  $>0.2\%$  were observed during two major unrest periods in 2011–2012, with these variations concurrent with monochromatic tremor activity, lake temperature increases, and mass discharge episodes. All this suggested that velocity changes were associated with shallow hydrothermal processes rather than deeper magmatic activity (Caudron et al., 2015).

In Iceland's Northern Volcanic Zone, seismic velocity variations can reflect minor crustal stress changes that are influenced by various factors, including volcanic activity, seasonal variations, and tectonic processes (e.g., Donaldson et al., 2019; Nowé et al., 2021). Specifically, Donaldson et al. (2019) demonstrated a linear correla-

tion between seismic velocity changes and volumetric strain associated with the 2014 Bárðarbunga-Holuhraun dike intrusion, showing that stations in regions of compression exhibited velocity increases while those in dilatational regions showed decreases. Complementing these findings, Nowé et al. (2021) identified three distinct seismic source types around the Vatnajökull icecap: permanent oceanic sources, seasonal glacial-related sources linked to enhanced river flow during ice melting periods, and episodic volcanic sources including the Bárðarbunga-Holuhraun eruption. Seismic velocity sensitivity to stress variations underlines their utility as a monitoring tool for detecting and understanding the dynamic processes within volcanic systems. While individual seismic analysis techniques have proven valuable in volcanic monitoring, there remains considerable potential for integrating multiple complementary seismic approaches to provide enhanced constraints on subsurface processes during volcanic unrest.

In this study, to distinguish volcanic signals from

seasonal variations, our analysis starts by encompassing the extended period from 2008 to 2024, including the 2014 Bárðarbunga-Holuhraun dike eruption. We then present seismic velocity variations at Askja volcano spanning the inflation episode that began in August 2021 using seismic noise cross-correlation. To investigate the relationship between these variations and the ground deformation characterized in recent studies (detailed in Part 2), we use three other complementary approaches: spectral width of covariance matrices to evaluate seismic sources, the Displacement Seismic Amplitude Ratio (DSAR) to estimate the seismic attenuation and surface wave sensitivity kernel analysis to locate the changes. With this multifaceted analysis of continuous seismic records, we aim to gain a better understanding of Askja's long-term dynamics, focusing on the transition to renewed activity associated with the inflation.

## 2 Volcanic setting

The central edifice of Askja contains three nested calderas (e.g., Sturkell et al., 2006b), with the youngest being filled by Öskjuvatn lake. Since the formation of this latest caldera, eight reported eruptions occurred between 1919–1938, with a maximum Volcanic Explosivity Index (VEI) of 2 (maximum historic VEI=5), and the most recent eruption in 1961 (e.g., Thorarinsson and Sigvaldason, 1962; Blasizzo et al., 2022).

A few years after the last eruption, in 1966, ad hoc measurements of Askja ground displacement began (Tryggvason, 1989). Between 1970 and 1974, the uplift rate was at  $\sim 20$  cm/yr, then the ground level subsided with a maximum rate of  $\sim 10$  cm/yr in 1983–1987 (Tryggvason, 1989). Since 1983, continuous yearly measurements began, which revealed ongoing Askja ground subsidence (Sturkell and Sigmundsson, 2000), followed by measurements of decreasing microgravity (Sturkell et al., 2006a). On July 21, 2014, at 23:24 local time, a landslide occurred on the Southeast caldera wall facilitated by the combination of caldera subsidence, geothermal alteration, and seasonal conditions (Gylfadóttir et al., 2017). In the same year, 19 km southeast of Askja central volcano a  $\sim 47$  km-long dike coming from Bárðarbunga volcano (Sigmundsson et al., 2015) extruded  $1.6 \pm 0.3$  km<sup>3</sup> of lava (Gíslason et al., 2015) within the Askja fissure swarm area (Geiger et al., 2016) (Figure 1). During this event, from August 16, 2014, to February 27, 2015, more than 30,000 earthquakes were detected up to magnitude 4. They were generated along the path of the Bárðarbunga dike with seismic activity occurring at both Bárðarbunga and Askja volcanic systems (Ágústsdóttir et al., 2016; Greenfield et al., 2020; Winder, 2022).

Following this eruptive period nearby, Askja entered a relatively quiescent phase until August 2021, when the OLAC GNSS station measured an abrupt inflation with a cumulative displacement of up to  $76.5 \pm 0.6$  cm in August 2024 (Veðurstofa Íslands, 2023d; Sturkell et al., 2023; Parks et al., 2024) (Figure 2). This inflation was further observed by coherent measurements from new GNSS stations deployed since October 2021, including KASC ( $45.4 \pm 0.5$  cm), JONC ( $31.6 \pm 0.6$  cm), and TANC

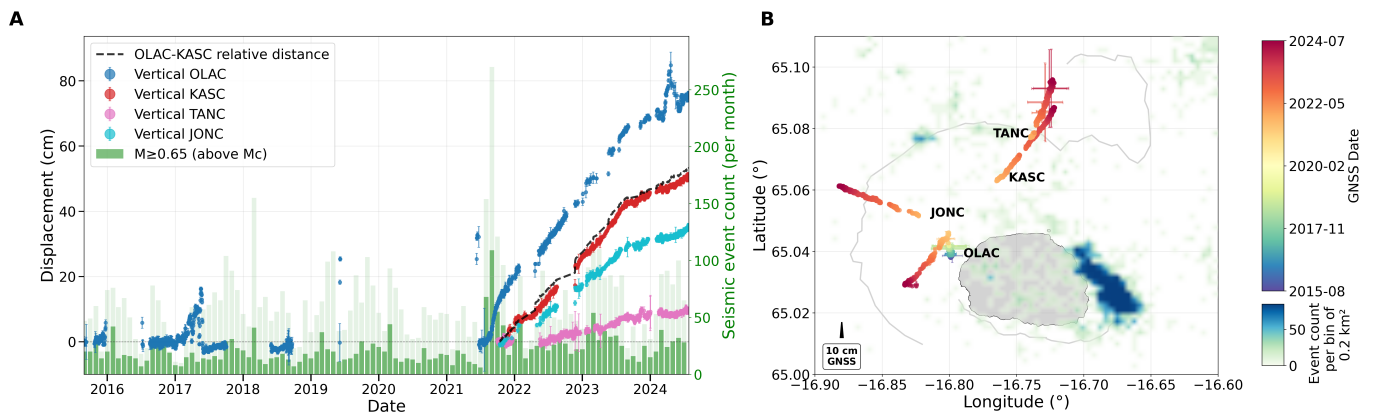
( $8.2 \pm 0.5$  cm) (Figure 1); the lower deformation amplitudes are due to their distance to the inflation source (Parks et al., 2024; Veðurstofa Íslands, 2023c,b). The inflation onset occurred on August 8, 2021, and a high rate of 70.19 cm/yr (at OLAC station) was maintained until September 20, 2021. From September 2021 to September 2023, the rate was 27.58 cm/yr at OLAC, 22.77 cm/yr at KASC, 16.15 cm/yr at JONC, and 4.03 cm/yr at TANC. Then, there was a reduced rate of inflation from September 2023 with a mean of  $9.85 \pm 2.36$  cm/yr from OLAC, KASC, and JONC stations. Additionally, the horizontal displacements of the GNSS stations showed an outward migration from the inflation source, with increasing distance between the stations OLAC and KASC (Figure 2).

From the Veðurstofa Íslands (2023a) earthquake catalog, we observed an increase in seismicity at the onset of the inflation with 68, 109, and 55 events in August, September, and October 2021, respectively, after filtering to only include events with  $M_L > 0.65$ , to account for varying magnitude of completeness (Figure 2A). On a longer timescale, the inflation was accompanied by increased seismic activity, with a pre-inflation median of 15 events per month, which increased to 26 events per month from November 2021. Winder et al. (2023) showed that the seismicity rate increase at the onset of inflation is concentrated around the Öskjuvatn ring fault, close to the inferred sill (Figure 2B). Focal mechanisms indicated consistent reverse faulting parallel to the inner-caldera rim (Winder et al., 2023; Siggers et al., 2024).

To complement the deformation data and understand the subsurface mass changes, Koymans et al. (2023) have conducted microgravity surveys. However, no microgravity measurements were made between 2017 and 2021, before the onset of the ground uplift. Within the data gap, microgravity increased in the center of the caldera. The limited data did not let Koymans et al. (2023) determine whether the increase was linear or sudden at a given time. From August 2021 to 2022, microgravity observations have not shown changes and are associated with large uncertainties. From 2022 to 2023, joint inversion of deformation and microgravity data shows a mass increase  $6.27\text{--}10.1 \times 10^{10}$  kg that is constrained through modeling to be caused by a mass intrusion with density between  $1606\text{--}3743$  kg/m<sup>3</sup>, consistent with basaltic magma (Sepúlveda-Araya et al., under review). Thus, microgravity measurements showed an increase that spanned the inflation onset and continued through 2023; though whether the initial change was sudden or gradual remains unclear. Koymans et al. (2023) identified several processes that could explain the observed uplift, including subsurface density changes and viscoelastic effects. Distinguishing between these mechanisms remains challenging given the available data.

Complementary geophysical methods provide additional constraints on the structure of the magmatic system beneath Askja. Seismic tomography surveys show at least three melt reservoirs at  $\sim 2$  km,  $\sim 5$  km (main storage), and  $\sim 9$  km below sea level (Greenfield et al., 2016; Han et al., 2024; Fone et al., 2025). Seismic activity





**Figure 2** Seismic events and GNSS displacement around Öskjuvatn caldera from 2015 to 2024. A. Temporal evolution of vertical displacement (dU, in cm) for OLAC, KASC, TANC, and JONC GNSS stations relative to 2015 and the horizontal distance between OLAC and KASC stations in black. Dark green bars show monthly seismic event counts filtered above magnitude 0.65 to account for varying magnitude of completeness and light green bars show all recorded events per month. B. Spatio-temporal horizontal displacement for the four GNSS stations, with the dots representing the trajectories colored by date, with the corresponding scale of the displacement on the bottom right. The background shows Öskjuvatn lake and caldera with seismic event ( $M \geq 0.65$ ) density per spatial bin of  $0.2 \text{ km}^2$ . Data are shown with their error bars and filtered using a 30-point lagged median filter to reduce measurement noise.

is detected in the upper 20 km, at 15 km and around 2 km depth, suggesting crustal-scale melt transport (Greenfield et al., 2016). Moreover, the 2.8 km depth also corresponds to the deformation source locations, according to a homogeneous elastic deformation model (Parks et al., 2024). Parks et al. (2024) show that between July 26 and September 20, 2021, one source is inflating at 2.8 km depth, and a second is deflating at greater depth. These sources are interpreted as reflecting an upward migration of magmatic fluids. After September 20, 2021, only one inflation source was identified at a depth of 2.7 km. This behavior suggests that the magma was recharging from depth or represents a poro-viscoelastic response to initial magma migration (Parks et al., 2024).

### 3 Data and Method

#### 3.1 Data

The main data for this study are continuous seismic records acquired at 15 stations managed by the Cambridge Volcano Seismology research group, in collaboration with the University of Iceland (stations with four-letter names) and the Icelandic Meteorological Office (IMO) (Figure 1). The stations began operating on July 1, 2007, with continuous recordings from July 2008 onward. Our analysis extends to July 27, 2024. Throughout this 17-year period, seismic monitoring was conducted through three successive networks: 4F (2007–2011), Z7 (2011–2016), and 8K (since 2016). The network consists of 11 Guralp 6TD broadband seismometers (30-second corner frequency, flat response above 0.033 Hz), and 4 3ESPCD instruments (60-second corner frequency, flat response above 0.016 Hz, ASK, FLUR, KOLL, and LIND). ASK seismic station used a Cambridge Guralp 6TD from 2007–2017, then switched to an IMO 3ESPCD. Currently, all seismometers in the network record three components: East, North, and Vertical. Several technical changes occurred throughout the monitoring period.

From July 2016, a significant temporary reduction in the Cambridge network occurred. The following year, the network was restored, and the sampling rate was switched from 100 Hz to 50 Hz at the end of July 2017. Additional technical issues included a clock error at station TOHR, identified in late 2016 before its replacement.

We also used GNSS data (Veðurstofa Íslands, 2023b) of stations OLAC, JONC, TANC, KASC to look at the ground deformation and the seismic catalog from the Icelandic Meteorological Office (Veðurstofa Íslands, 2023a) from 2009 to July 2024. From ERA5-land (Muñoz Sabater, 2019), we extracted temperature, air pressure, precipitation, and snow depth water equivalent measurements. These datasets support the analysis and interpretation of the continuous seismic data.

#### 3.2 Network-based covariance matrix analysis

The spectral width (Seydoux et al., 2016) of 5000-s-long successive covariance matrices was computed to identify coherent signals within the multiple continuous seismic data. We use the open source CovSeisNet Python package (Tong et al., 2024). The initial step was to preprocess the 24-hour data chunks if less than 5% of the data is missing. This preprocessing included downsampling to 50 Hz using Lanczos resampling (giving a Nyquist frequency at 25 Hz), synchronization, and applying temporal and spectral normalization. Time and spectral domain normalization techniques, such as one-bit and water-level normalizations, were employed to reduce the impact of earthquakes, instrumental response, and non-stationary noise sources. To reduce contamination from oceanic microseisms, we studied frequencies above 0.5 Hz (Stehly et al., 2024). Then, the cross-spectra matrices were computed on sub-windows of 100 seconds. The choice of sub-window size involved a trade-off between a robust covariance matrix estima-



tion and good time resolution. The detection of coherent signals depended on both the size of the windows and the station availability (Seydoux et al., 2016). Finally, a covariance matrix was estimated on each time window by averaging cross-spectra matrices over 100 sub-windows (Seydoux et al., 2016). From each covariance matrix, we extracted the width of its eigenvalue distribution to estimate a spectral width at a specific frequency. When the spectral width is low, it indicates the existence of a dominant source that produces coherent signals at the network scale (Anderson, 1963). The final step was concatenating daily results in the time domain to improve signal-to-noise ratio (Seydoux et al., 2016) and provide valuable insights into seismic activity. This method highlighted persistent sources, enabling continuous monitoring of the subsurface (e.g., Seydoux et al., 2016; Soubestre et al., 2018). While network-based covariance matrix analysis provides insights into coherent signals across the network through eigenvalue distributions, we also employed Displacement Seismic Amplitude Ratio to monitor temporal changes in the seismic wavefield attenuation at individual stations.

### 3.3 DSAR

We computed the Displacement Seismic Amplitude Ratio (DSAR) on the vertical components of each station following the method of Caudron et al. (2019). This metric results from the ratio of the absolute amplitude of low and high-frequency bands over 10-minute windows. The low-frequency band was defined between 6 and 9 Hz, thereby avoiding the frequency bands where persistent sources are most active (see results from section 4.1). The high-frequency band was set between 9 and 16 Hz, allowing the detection of small-scale crustal changes (Caudron et al., 2019). This has led to the identification of eruption precursors at multiple volcanoes in New Zealand (Caudron et al., 2019; Ardid et al., 2022, 2024), as well as Kawah-Ijen in Indonesia (Caudron et al., 2019) and Pavlof in Alaska, USA (Ardid et al., 2024).

### 3.4 Relative seismic velocity change

From the continuous seismic data records, we estimated temporal changes in seismic velocity within the medium (e.g., Poupinet et al., 1984; Ratdomopurbo and Poupinet, 1995; Brenguier et al., 2008) using the MSNoise package (Lecocq et al., 2014) to analyze ambient seismic noise cross-correlations.

Our data processing workflow began with the removal of the instrumental response to account for station changes over time. After aligning the signals and interpolating small gaps (<10 seconds), we resampled the data at 25 Hz and applied a bandpass from 0.1 to 10 Hz. The signals were then winsorized by three times the root-mean-square amplitude (Tukey, 1962) and spectrally whitened to an amplitude of 1 (except for auto-correlations) (Bensen et al., 2007). From these processed signals, we computed cross-correlations between two seismic stations. It allowed us to estimate Green's function of scattered waves at one station, considering the other station as the virtual source (Campillo

and Paul, 2003). The resulting cross-correlation reflects information about the medium crossed by the waves and its modifications over time between the two stations (Shapiro et al., 2005; Brenguier et al., 2016; Nakata et al., 2019; Hutapea et al., 2020). The cross-correlation was computed for each station pair on 30-minute sub-windows from 0 to  $\pm 120$  seconds lag and stacked daily. The linear stacking was extended over several days using moving windows of 10 and 30 days (for time series and mapping, respectively). We computed CCFs for individual pairs of stations on ZZ components and single stations on the cross-components (EN, EZ, and NZ). From the cross-correlation and spectral-width results, we identified a stable period from 2018 to 2019 (Supplementary Figure S3). This period showed the most consistent cross-correlation functions (Supplementary Figure S3) and therefore were assigned to the static reference cross-correlation function (Lecocq et al., 2014). This static reference CCF was compared to each "current" CCFs to determine the travel time delays of different wave arrivals within the coda window, ranging from 5 to 120 seconds lag, with a dynamic minimum lag determined from inter-station distances and wave speed (1 km/s). The maximum lag time for the coda window is determined by adding the product of the period and 20 coda cycles to the minimum lag time.

For computing these travel-time delays, we used the wavelet cross-spectrum transform (WCT) method (Mallat, 1999; Mao et al., 2020) with a dynamic time lag criterion to avoid the ballistic wave arrival for the different station pairs (Lecocq et al., 2014). The WCT method convolves the reference CCF and the "current" CCF with various scaled and translated versions of a mother wavelet. The cross-spectrum was calculated and smoothed, then normalized by the individual power spectrum to obtain phase information in the time-frequency domain. Time delays were derived from phase differences using  $dt = -\phi/(2\pi f)$ , where  $\phi$  is the phase and  $f$  the frequency. The calculated time delays yield the changes in velocity through linear regression within coda windows expressed as  $-dt/t = dv/v$ .

To obtain a better insight into the changes during the inflation and account for the potential impact on the cross-correlation at its onset, we also use a moving reference. The moving reference,  $\frac{\delta v}{v}(t)_{ref}$ , is defined as the preceding stack for each processed date  $\frac{\delta v}{v}(t)_{curr}$ , with no overlap. Thus, the measured velocity represents the change between successive stacks in this case using 10-day stacks, giving

$$\Delta \frac{\delta v}{v}(t) = \frac{\delta v}{v}(t)_{curr} - \frac{\delta v}{v}(t)_{ref}. \quad (1)$$

Thus, when there is data gap,  $\Delta \frac{\delta v}{v}(t)$  is computed with  $\frac{\delta v}{v}(t)_{ref}$  before the gap compared to the first  $\frac{\delta v}{v}(t)_{curr}$  after the gap, to account for the step change in velocities during the gap. The absolute  $dv/v$  is reconstructed by cumulative summation of each  $\Delta \frac{\delta v}{v}(t)$ ,

$$\frac{\delta v}{v}(t) = \frac{\delta v}{v}(t_0) + \sum_{k=1}^t \Delta \frac{\delta v}{v}(k), \quad (2)$$

anchored at zero at the start of the analysis period

( $\frac{\delta v}{v}(t_0) = 0$ ), making it comparable to the static reference  $dv/v$ .

To constrain the origin of the velocity changes, we analyzed the multiple time series across different frequency bands and compared them with GNSS and weather measurements.

### 3.5 $dv/v$ location

Once the relative velocity changes were measured through time, sensitivity kernels were computed to identify which areas our measured velocity changes ( $dv/v$ ) are the most sensitive to, allowing us to map these changes through iterative multiscale inversion. The sensitivity kernels are computed using the Askja velocity model from Han et al. (2024).

For this purpose, we first consider a 1D gradient velocity model derived from the horizontal average of the P and S wave velocities from a 3D local body wave tomography model of the Askja volcanic system (Han et al., 2024). The velocity model shows how the seismic velocities change according to the structures of the medium at different depths. To understand how changes in the medium's properties affect our seismic measurements, we computed sensitivity kernels of surface waves using the Disba python package (Luu, 2020), under the assumption that surface waves dominate the recorded wavefield. The sensitivity kernel quantifies how the velocities of Rayleigh and Love surface waves respond to variations in the velocity model structure, as described by the equation  $K = dU/dV_{\beta}$ , with  $U$  the phase velocity for a mode and  $V_{\beta}$  the shear wave velocity at depth. Positive values show constructive sensitivity with local maxima indicating regions of highest sensitivity, while negative values indicate destructive sensitivity. By analyzing variations in velocity based on their frequency ranges, we can estimate the depth at which the waves are most sensitive to. The waves' probing depth ( $D$ ) depends on their frequency ( $f$ )  $D = c/\pi f$ , with  $c$  the wave velocity. This relationship demonstrated that lower-frequency waves probed deeper into the crust compared to higher-frequency waves, enabling depth-dependent sensitivity analysis across the frequency ranges.

While this vertical sensitivity analysis provides crucial depth constraints, our full methodology extends to the horizontal dimension through two types of sensitivity kernels: a Fresnel-zone based approach for direct waves and a diffusion-based approach for coda waves. For coda waves, the implementation follows Obermann et al. (2013), modeling both coherent and diffusive regimes with a smooth transition based on lapse time. The code accounts for 2D velocity variations by scaling transport properties with local velocity from 1 km depth as specified by the Han et al. (2024) velocity model. The scattering properties of the medium are characterized by a frequency-dependent mean free path following the power-law relationship  $l^*(f) = l_0(f/f_0)^{-\alpha}$ , where  $l_0$  represents the reference scattering mean free path of 0.8 km (Lesage et al., 2025) at the reference frequency  $f_0$  of 1.0 Hz. The frequency scaling exponent  $\alpha$  is set to 0.8. To incorporate wave-

field anisotropy, we adopt an average scattering angle  $\langle \cos \theta \rangle = 0.6$ , yielding a transport mean free path  $l^* = l/(1 - \langle \cos \theta \rangle) = 2.5l$ . The diffusivity parameter is calculated dynamically as  $D = v_{local} \times l_{local}^*/3$  following radiative transfer theory, where both velocity and transport mean free path vary spatially based on the local velocity model.

Prior to inversion, we used the 30-day moving window  $dv/v$  time series previously acquired for each station pair to reduce measurement noise while preserving the temporal evolution patterns. Only measurements with correlation coefficients  $\geq 0.3$  between the "current" and reference stacked cross-correlations were retained. Each inversion reflects the mean seismic velocity state relative to the same 2018-2019 reference, and contributes independently to the period average, improving noise reduction while preserving the spatial structure of persistent velocity anomalies.

The spatial distribution of seismic velocity variations ( $dv/v$ ) was mapped using an iterative multiscale inversion approach with adaptive grid refinement. This method begins with a coarse, uniform grid and refines it through five iterations. Grid cells were subdivided based on weighted scores combining model velocity gradient, uncertainty, and data resolution, with up to 45% of cells refined per iteration down to a minimum resolution of  $0.2^\circ$  ( $\sim 2.2$  km). Refinement thresholds increased across iterations, ensuring computational resources focus on well-constrained areas. The regularization strategy applies stronger smoothing constraints in poorly resolved areas while allowing more detail to emerge where the data provides good constraints. The station contributes to the results only during periods in which it recorded data. Therefore, the spatial resolution can vary over time and areas with insufficient data coverage are masked based on the resolution threshold. Additionally, the method preserves sharp velocity boundaries by reducing smoothing across regions with large velocity contrasts. This prevents artificial blurring while still stabilizing the solution in areas with limited data coverage.

Our iterative multiscale inversion method demonstrated robust performance across various synthetic anomaly types, station distributions, and noise conditions (Section S1 and Supplementary Figure S1). The method performs well in recovering Gaussian and fault-type anomalies, achieving correlation coefficients up to 0.93 and 0.92, respectively, even in the presence of noise (SNR=10). Station density significantly impacted performance; a 15-station network outperformed a 7-station network by a correlation increase of 15–33%. Checkerboard patterns are the most challenging, yielding correlations up to 0.62. RMS errors remained consistently low ( $<0.007$ ) across all scenarios, with denser networks reducing errors by up to 50% compared to sparse configurations. This evaluation confirms the method's effectiveness in the presence of realistic velocity anomalies.

This methodology allowed us to track both temporal evolution and spatial distribution of seismic velocity changes in the volcanic region. The complete workflow can be found on Zenodo (see Data and code availability).

## 4 Results

### 4.1 Network-based covariance matrix analysis

Spectral width analysis was applied from 2008 to 2024 using data from up to fourteen stations. The results revealed persistent seismic sources across the network scale with frequencies that varied seasonally (Figure 3). Persistent sources concentrate in the frequency range between 3 and 7 Hz (Figure 3B). In summer (April–October), signals extend to lower frequencies of 1–3 Hz (green highlight on Figure 3B), with lower spectral width values in the 3–7 Hz range.

The distribution of minimum spectral width values over time reveals a consistent seasonal pattern (Supplementary Figure S5E). Each year, the lowest values typically occur between January and June, with a marked minimum in March. Values rise from May to July before declining again from October to January, highlighting a recurring trend across multiple years (Supplementary Figure S5).

To better characterize the source signal, we run an analysis of geographic sub-network groups based on their position relative to the caldera. In particular, there is a Northwest group with JONS, KATT, and BRUN stations and a Southeast group with ASK, LIND, and STAM stations positioned closer to the Kárahnjúkar power station dam located Southeast of Askja (Figure 1). The Northwest group showed mostly high spectral width values with a few sources with narrow frequency band (Supplementary Figure S2B). The Southeast group, closer to the Kárahnjúkar power station dam, which could be a potential source, showed a continuous signal between 3.5–5 Hz, accompanied by a weaker signal at 1.8 Hz (Supplementary Figure S2C).

Thus, during the years from 2008 to 2024, we observed a permanent tremor signal between 3 and 7 Hz with seasonal variations that can impact lower frequencies extending down to 1 Hz. This signal characteristic enabled us to define three frequency bands: one between 0.5 and 1 Hz that isolates the ambient noise from the microseisms and the tremor signals; a second that isolates the permanent tremor signal between 3 and 5 Hz; and finally, an intermediate frequency band between 1 and 3 Hz (Figure 3B).

We also observe changes in the source and frequency content during the 2014–2015 eruption of Bárðarbunga (Figure 3A) near Askja (Figure 1), as well as before the network change in 2017. The start of inflation in early August 2021 occurred without a noticeable change in the persistent tremor source.

The seasonal variations in tremor characteristics guide our selection of frequency bands to be used for the analyses in the following 4.2 and 4.3 sections. This helps us to distinguish between seismic wave property changes associated with source effects and/or seasonal variations, and those that could reflect genuine medium changes.

### 4.2 DSAR

The Displacement Seismic Amplitude Ratio analysis reveals distinct temporal patterns and station-specific behaviors from 2018 to 2024 (Figure 4). Stations closest to the Askja caldera (ASK, STAM, JONS) display median DSAR values higher than 1.4 (horizontal blue dashed lines on Figure 4) compared to more distant stations, with KATT (median = 1.05) and BRUN (median = 0.9) showing lower attenuation levels. RIFR, located within a fault swarm area, maintains relatively high values (median = 1.4).

ASK has the most pronounced seasonal variability, fluctuating between 1.1 and 2.1 with two distinct annual peaks corresponding to snowfall periods (November–December) and increased liquid precipitation (April–June) (Supplementary Figure S5). KATT maintains consistently lower baseline values (0.8–1.6) with seasonal oscillations showing larger amplitudes from 2021. Distant stations BRUN and RIFR maintain clear seasonal patterns throughout the period. However, RIFR seems to deviate from 2024 with increased values followed by a decrease.

Since the inflation onset in August 2021, DSAR at STAM shows an increase to 2.0, with this level maintained through June 2022. JONS also reaches high values following the inflation onset, but the data gap in 2019 and 2020 does not permit a clear comparison. Notably, both stations show divergence from the seasonal pattern, and the increase from the inflation onset occurs earlier, out of phase with the seasonal patterns visible before 2021 at STAM and in 2018 and 2023 at JONS. This contrasts with the concurrent seasonal decrease observed at other stations. Following June 2022, both stations exhibit values below the median, with STAM at its minimum value of approximately 1.5 by 2024. From mid-2023 onwards, divergent behavior emerges: JONS gradually returns to higher values (2.0–2.2) while STAM remains at reduced levels (1.5).

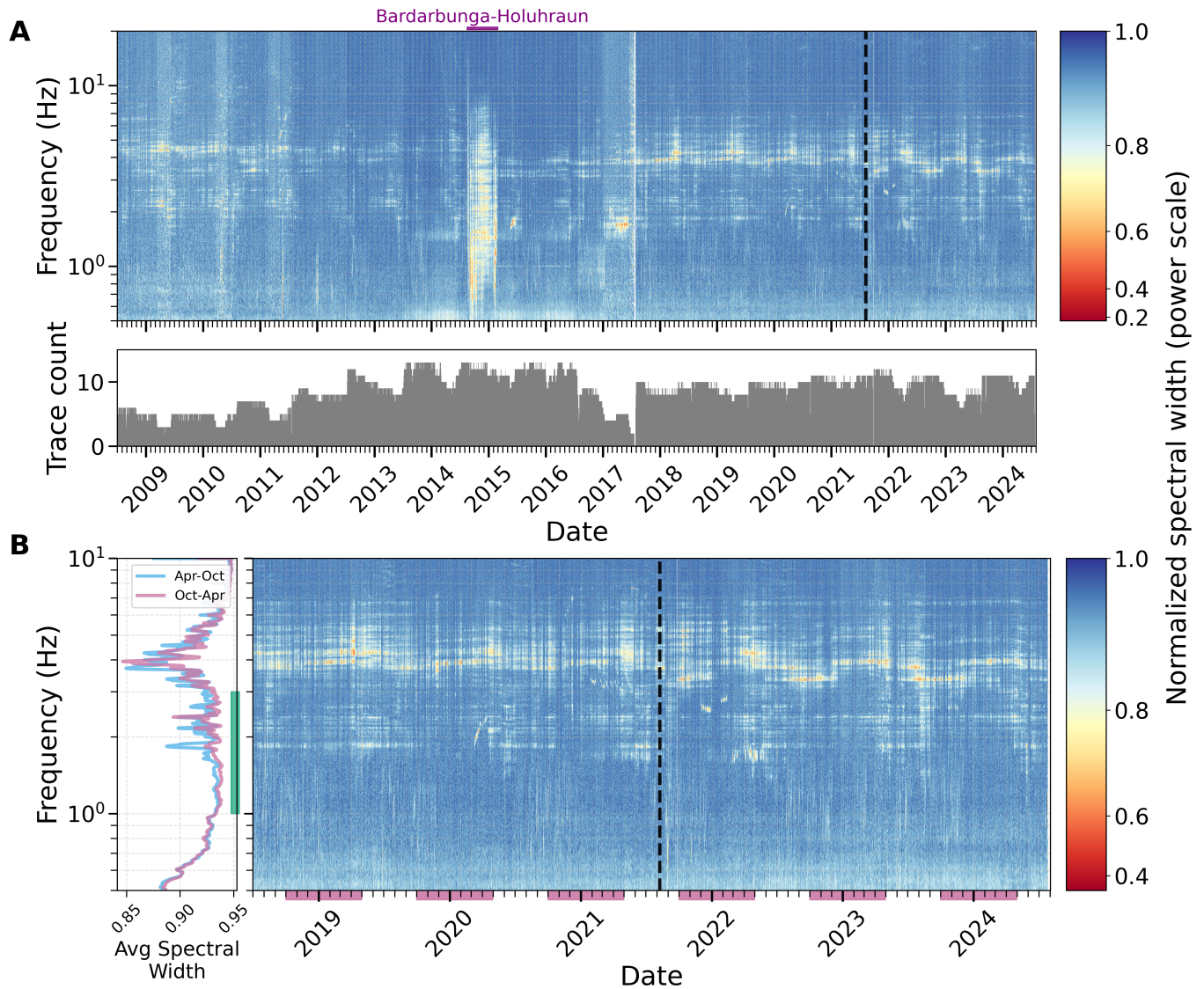
Stations ASK and KATT show minimal disruption to seasonal patterns during inflation, with a pre-inflation increase that does not persist. KATT, in particular, exhibits the highest values just before the start of the inflation.

### 4.3 Relative seismic velocity variations ( $dv/v$ )

#### 4.3.1 Cross-correlation analysis

We assessed the quality and temporal evolution of cross-correlations within the 0.5 to 5 Hz frequency range (Supplementary Figure S3). We computed cross-correlation coefficients using Pearson correlation within the dynamic coda-windows used for the  $dv/v$  computation at 0.5 Hz. For the presented station pair results, the cross-correlation coefficients range between 0 and 0.892, with a median of 0.511. The cross-correlation coefficients generally remained stable throughout the observation period. A decrease occurred in 2020 for the STAM-KATT pair and in August 2021 for the other pairs shown, including the largest drop of 60% for the JONS-STAM pair. Additionally, the correlation coefficients exhibit





**Figure 3** A. Spectral width from 0.5 to 20 Hz for the period 2008–2024, computed using 100-second windows with 100-window averaging. A low spectral width indicates coherent signals at the network scale, whereas a high spectral width is associated with incoherent noise. The dashed black line marks the start of inflation on August 8, 2021. The bottom panel shows the number of stations used for each computed day. A low number of stations can influence the visual representation of the results by artificially reducing the spectral width values. The horizontal purple bar marks the Bárðarbunga-Holuhraun activity (August 16, 2014 – February 27, 2015). B. Spectral width from 0.5 to 10 Hz for the period 2018–2024. The winter signal is flagged in pink on the time axis, while the summer frequency band is flagged in green on the frequency axis.

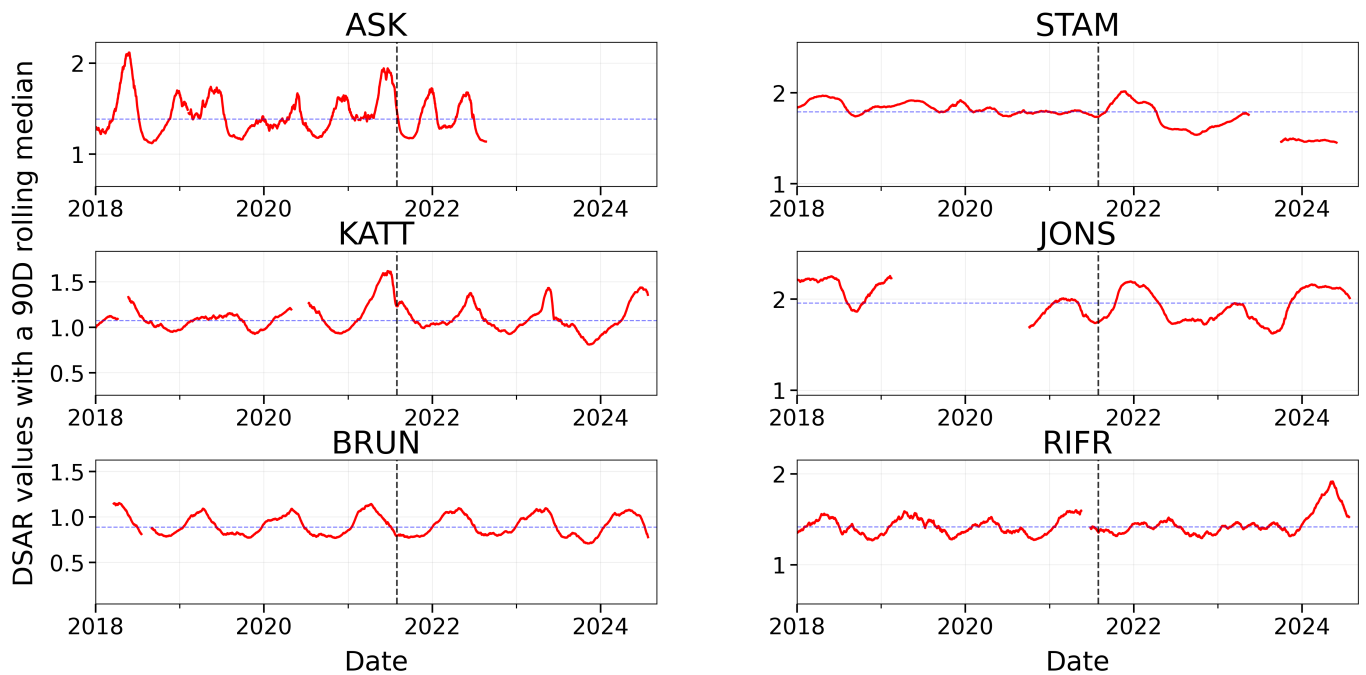
seasonal variations at the network scale, with systematically lower values observed during the winter months ( $0.464 \pm 0.199$ , while summer mean =  $0.531 \pm 0.180$ ). We selected the 2018–2019 period as the reference for  $dv/v$  computation because the cross-correlations exhibit good stability despite the seasonal variations, covering a period with minimal gaps and appropriate temporal separation from the inflation onset. All  $dv/v$  results presented here use the 2018–2019 reference, unless otherwise stated (i.e., preceding 10-day moving reference).

#### 4.3.2 Network-wide $dv/v$

Network-scale analysis of the mean  $dv/v$  values in a frequency band from 0.5–5 Hz from 2008 to 2024 with 2018–2019 static reference uses the average over 65 sta-

tion pairs. It reveals seasonal variations that produce a variability of  $0.20 \pm 0.06\%$  with higher  $dv/v$  at the beginning of each year, switching to lower values in July, then returning to positive values in December (Figure 5). The uncertainty reflects the year-to-year variability in seasonal amplitude, computed as the standard deviation of yearly maximum-minimum differences.

We also observe changes due to the 2014–2015 Bárðarbunga eruption near Askja. This volcanic activity corresponds to a notable reduction in the number of measurements used during 2014 (Figure 5), as cross-correlation coefficients are below the 0.3 threshold, indicating reduced signal quality across the network. For the two following years after 2014, the seasonal variations are impacted, with the lowest  $dv/v$  values occurring in October instead of July as in the other years, and the highest  $dv/v$  values occurring in February or



**Figure 4** DSAR 90 days causal median results for the stations ASK, STAM, KATT, JONS, BRUN, and RIFR from 2018 to 2024. Station distances to the source estimated by Parks et al. (2024) are 5.37 km, 4.62 km, 10.69 km, 5.89 km, 20.16 km, and 21.91 km, respectively. The dashed vertical black line represents the start of the inflation on August 8, 2021. The dashed horizontal blue line is the median value for the full period.

March instead of April. The dike intrusion (2 weeks) and the eruptive processes (6 months) during the event are concomitant with this  $dv/v$  variation shift, and spectral widths results also show changes in the source origin of the noise (Figure 3A). Additionally, a second data gap occurred in summer 2017 due to limited station availability, with a minimum of two stations during this period.

The  $dv/v$  yearly amplitude decreased from 0.38% (2008–2011) to 0.29% (2011–2016) to 0.27% (since 2016), coinciding with a progressive increase in the number of contributing station pairs (Figure 5, network-code change from 4F to Z7 to 8K is only administrative).

#### 4.3.3 Station pairs $dv/v$

We focused on the period from 2018 onward using the most recent network (8K) with improved data quality recording and more consistent data availability to study the inflation at Askja, which began on August 8, 2021.

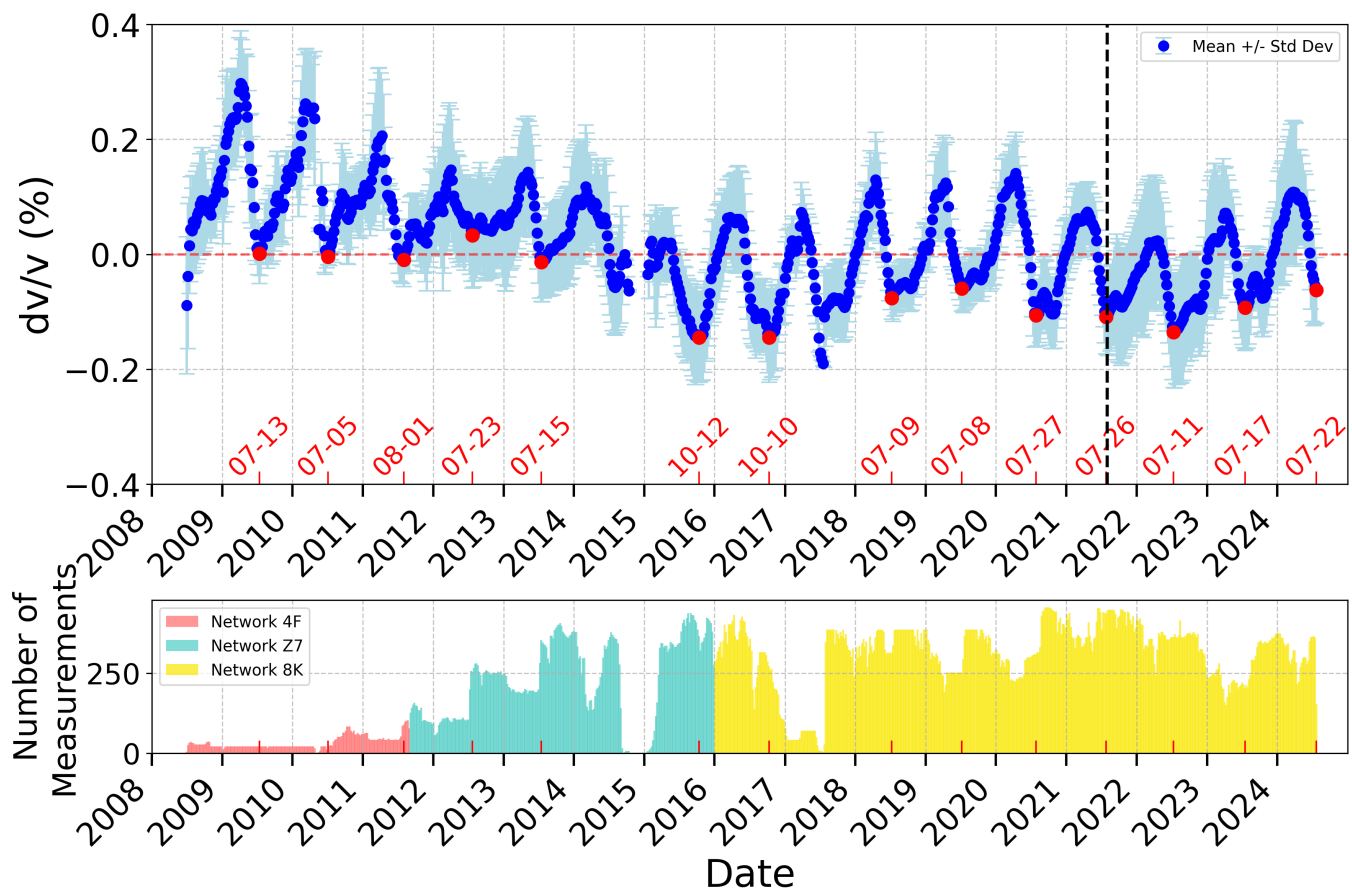
To present the  $dv/v$  results, we selected the four stations closest to the inflation source: ASK, JONS, KATT, and STAM (Figure 6). Prior to the inflation, all station pairs displayed regular seasonal oscillations from 2018 to 2021, characterized by positive  $dv/v$  values occurring in winter months (October–April) and negative values in summer months (April–October) (Figures 6 and S5). This pattern was most pronounced in the 1–5 Hz range, while frequencies below 1 Hz showed less visible seasonal variations. Additionally, the ASK-STAM station pair alternates negative and positive values with a checkerboard-like pattern from 0.8 to 1.5 Hz, and KATT-STAM and ASK-STAM pairs exhibit stronger seasonal contrast than other pairs.

The onset of inflation on August 8, 2021, marks an

abrupt transition from the pre-existing seasonal variations to predominantly negative  $dv/v$  values across all station pairs. ASK-JONS pair shifted from mixed to predominantly negative values for all frequencies. The strongest transition to negative  $dv/v$  occurs in the JONS-STAM pair. After a couple of months, ASK-KATT, ASK-STAM, KATT-STAM, and JONS-KATT are showing negative values at lower frequencies, while the higher frequencies maintained seasonal variations. The frequency limit between these two behaviors varies across the different pairs, ranging from 1 Hz (ASK-KATT) to 3 Hz (ASK-STAM, KATT-STAM). By 2024, partial recovery is apparent for JONS-KATT and STAM-KATT pairs, though values remain generally higher than pre-2021 levels. In contrast, the JONS-STAM pair maintains predominantly negative values.

The proximity and orientation of station pairs relative to the inflation source appear to influence the magnitude and pattern of the observed  $dv/v$  response, with JONS-STAM showing the most significant post-inflation changes. The network response indicates that the August 2021 inflation event represents a fundamental change, evidenced by the transition from regular seasonal variations to persistently lower  $dv/v$  values across multiple frequency bands and station pair geometries (Figure 6).

To better visualize the  $dv/v$  variations during inflation, we extracted the mean values from the wavelet result for three frequency bands (0.5–1 Hz, 1–3 Hz, and 3–5 Hz) (Figure 7). These results enable us to facilitate comparisons between frequency bands and associate the  $dv/v$  values with their cross-correlation coefficients, reflecting the reliability of the data and an indicator of structural change in the medium when it accompanies



**Figure 5** Biweekly network average  $dv/v$  values from 2008 to July 2024, with blue dots showing mean values of data that have an associated minimum correlation coefficient of 0.3. The light blue error bars indicate standard deviation over the available results of the 65 station pairs. The static reference is defined by the two years 2018 and 2019. Yearly minima are labeled in red with dates on the x-axis when there are more than 10 measurements. The dashed black line marks the start of inflation on August 8, 2021. The bottom panel shows the number of measurements used from all station pairs for each biweekly plotted value, indicating the representativeness of the network-averaged results.

$dv/v$  changes (Donaldson et al., 2019; Yates et al., 2023).

JONS-STAM pair (Figures 7 A, B, 8 and S5H) exhibits the most consistent negative response to the inflation, accompanied by a drop in the cross-correlation coefficient, especially in the 1–3 Hz  $dv/v$ . The higher frequency band 3–5 Hz, characterized by consistent lower  $dv/v$ , shows seasonal variations with a  $dv/v$  drop of 0.2 % in 2022. The 0.5–1 Hz range shows the initial drop after the inflation followed by immediate recovery before stabilizing. Then, at the end of 2022, the  $dv/v$  starts to decrease gradually for a year.

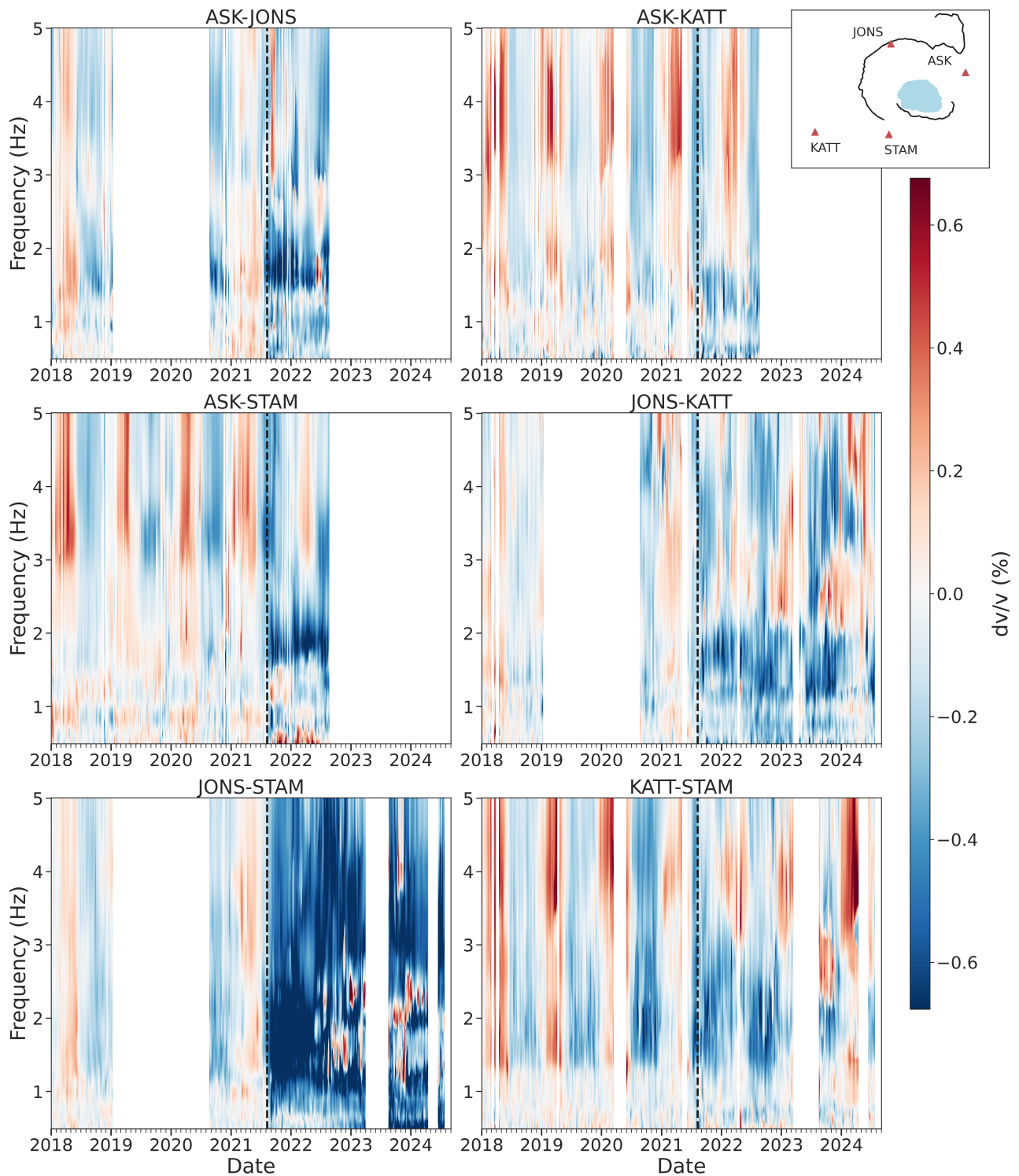
In addition to the 2018–2019 pre-inflation static reference, we use a moving reference (Figure 7B). The moving reference is computed on a 10-day moving window that ends before each 10-day stack processed date. This allows us to better examine changes in  $dv/v$  independently of the cross-correlation coefficient drop. The 0.5–1 Hz and 1–3 Hz frequency bands show the largest negative  $dv/v$  values with comparable amplitude. The 3–5 Hz band shows a weaker decrease, remaining above -0.8% throughout the inflation period. From late 2021 to mid-2022, the 1–3 Hz frequency band shows a brief and moderate increase in  $dv/v$ , while other frequency bands show less variation. From May 2022,  $dv/v$  resumes a

marked decrease across 0.5–3 Hz frequency bands, with an amplitude comparable to the initial drop at the inflation onset and a lower gradient. From 2023, higher-frequency bands (1–5 Hz)  $dv/v$  start to increase, while 0.5–1 Hz  $dv/v$  continues to decrease. From November 2023, the  $dv/v$  of all frequency bands follow an increasing trend.

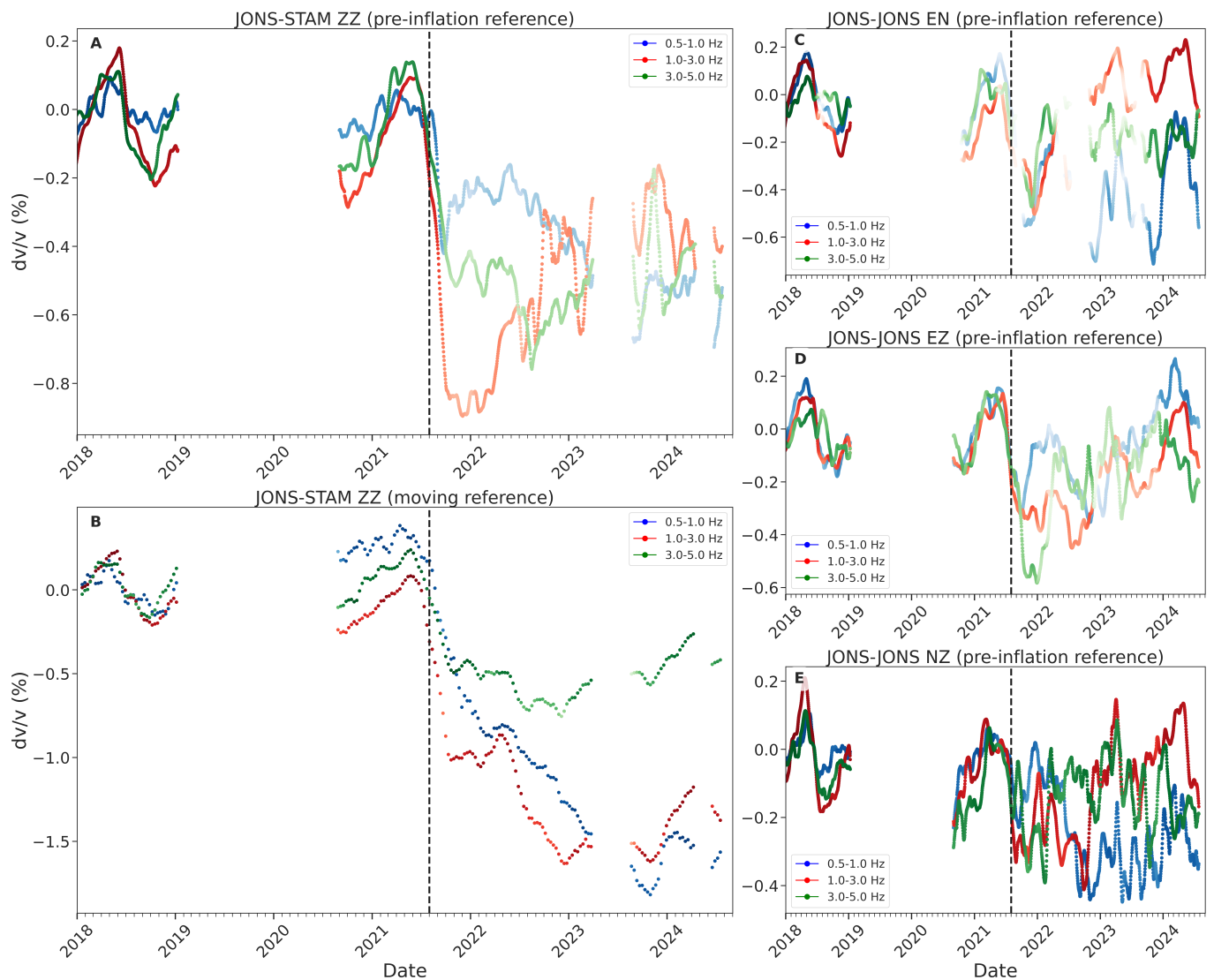
#### 4.3.4 Single stations $dv/v$

The analysis of  $dv/v$  variations (using the static 2018–2019 pre-inflation reference) across different cross-components for the ASK, JONS, and STAM single stations reveals distinct patterns between East-North (EN) and East-Up (EZ) components for each station (Figure 9 and 7 C, D, E). Prior to the August 2021 inflation, the stations exhibit seasonal patterns with positive  $dv/v$  values each year, transitioning to negative values from July onwards. Following the inflation event, all stations demonstrate sustained negative  $dv/v$  values that persist well beyond seasonal variations, with neither JONS nor STAM stations having fully returned to pre-inflation conditions by 2024 (Figure 9). All the  $dv/v$  results involving the vertical component (Z) follow the same scenario that starts with a drop





**Figure 6** Station pairs relative seismic velocity changes to the static reference from 0.1 to 5 Hz (2018–2024) using Z component. The station combinations involved ASK, JONS, KATT, and STAM. The dashed vertical black line represents the start of the inflation on August 8, 2021. Positive  $dv/v$  (in red) show increasing seismic wave velocity compared to the 2018–2019 reference period. While negative  $dv/v$  values (in blue) show decreasing wave velocity. The results are plotted using a 10-day smoothing moving window. The inset map shows station locations around Askja volcano.



**Figure 7** Relative seismic velocity curves for the three frequency bands from the wavelet results (0.5–1 Hz, 1–3 Hz, and 3–5 Hz). A. JONS-STAM station pair with pre-inflation reference. B. JONS-STAM station pair with moving reference. C. JONS EN cross-component with pre-inflation reference. D. JONS EZ cross-component with pre-inflation reference. E. JONS NZ cross-component with pre-inflation reference. The dot transparency corresponds to the cross-correlation coefficient values (0 to 1) associated with the  $dv/v$ , where darker colors indicate higher similarity to the reference state. There is a 30-day backward smoothing applied to the plotted results. The dashed vertical black line represents the start of the inflation on August 8, 2021.

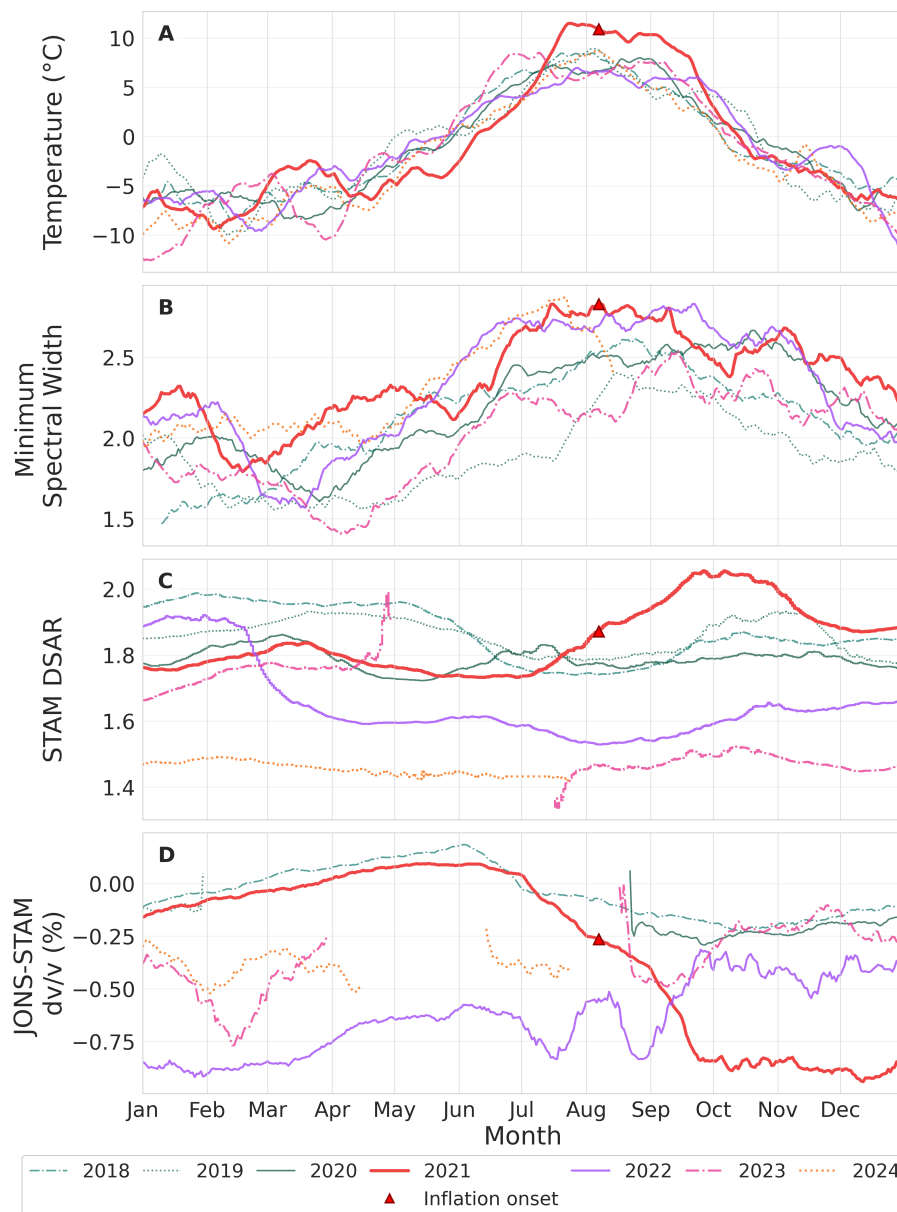
of the  $dv/v$  (August–September 2021), followed by a separation between frequency bands, each showing distinct trends (September 2021–June 2022). The 0.5–1 Hz band then shows a decreasing  $dv/v$  trend while the higher frequency bands show increasing trends (June 2022–mid 2023). Finally, the frequency bands converge toward a common trend, yet remain offset from each other and compared to pre-inflation  $dv/v$  values (Figures 9D,E, and 9).

Pattern intensity and consistency vary between cross-components for each station. ASK cross-component  $dv/v$  (Figure 9) shows different behavior at 3.5–5 Hz, EZ keeps showing partial seasonal variations (not from 3.5–4.5 Hz in 2019 and 2020) while EN shows mostly negative values with episodic negative  $dv/v$ . Following the inflation, EZ  $dv/v$  shows negative  $dv/v$  values across frequencies for a couple of months. In contrast, EN values exhibit a stronger decrease in  $dv/v$  from October to June 2022. Under 3.5 Hz, the negative  $dv/v$  values remained

below pre-inflation values even after an interval of positive  $dv/v$  values.

JONS cross-component  $dv/v$  results have a 2019–2020 data gap that prevents direct visual comparison to pre-2021 conditions. Following the start of the inflation, JONS EN cross-component  $dv/v$  results (Figures 9 and 7) show negative values persisting through 2022 except at 2–4 Hz (positive values). From 2023, positive  $dv/v$  values are getting to lower frequencies (1–3 Hz), and these values increase in 2024 (Figure 9). It seems that the different frequency bands show parallel temporal variations in  $dv/v$  but at different ranges of values (Figure 7 C).

In contrast, EZ cross-component (Figure 7 D) is showing the same evolution as the JONS-STAM (ZZ) station pair with a faster recovery of the 4–5 Hz band (Figure 9). However, this frequency range also shows anomalous positive  $dv/v$  values at the end of 2023 that deviate from seasonal patterns, while 2–4 Hz frequencies exhibit reduced  $dv/v$  amplitudes compared to pre-2021



**Figure 8** Seasonal analysis of multiple geophysical parameters (2018–2024). Multi-panel time series showing annual variations in seven key parameters. From top to bottom: A. Temperature (°C); B. Minimum spectral width from Coveisnet measurements; C. DSAR (STAM); and D.  $dv/v$  (JONS-STAM, pre-inflation reference); Colors represent different years as indicated in the legend.

levels. All the frequencies demonstrate increasing  $dv/v$  values from 2023 onward. The NZ  $dv/v$  shows the smallest drop (-0.1%) following the inflation but drastically increased variability afterward (Figure 7 E).

The STAM station demonstrates relatively similar patterns between cross-components, with clear pre-2021 seasonal variations and post-inflation negative values. However, the EN shows more negative responses at 0.5–3 Hz during 2022–2024, while EZ exhibits increased positive values from 2023 in the 1–3 Hz range.

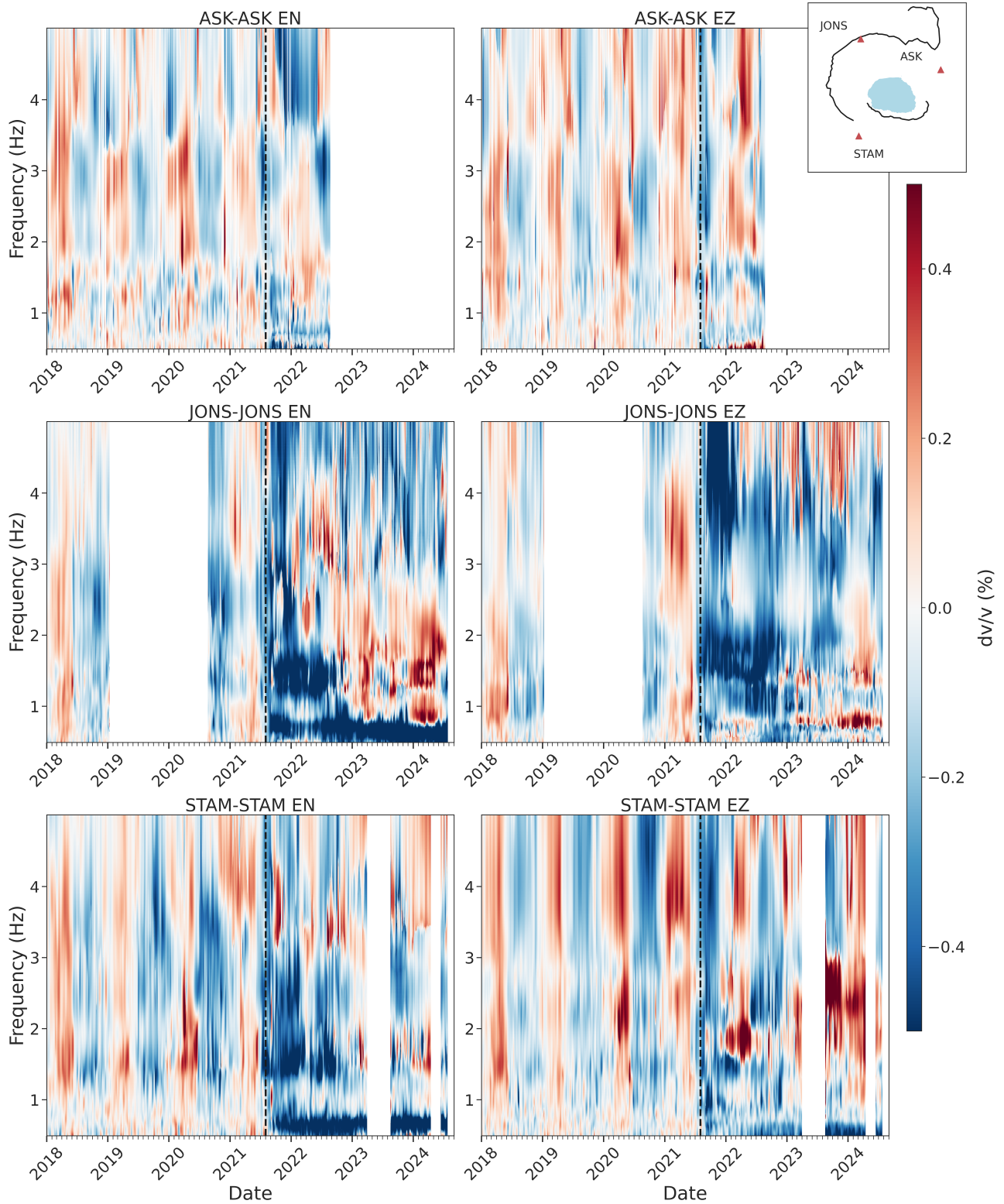
Additionally, EZ and NZ (vertical) components show localized, intense responses in specific frequency bands, while EN (horizontal) component exhibits broader, more distributed frequency responses.

## 4.4 Seismic velocity location

### 4.4.1 Sensitivity kernels

In this part, the primary focus is on determining the seismic wave sensitivity location at Askja volcano. The sensitivity kernel analysis considers frequency bands from 0.25 Hz to 3 Hz. Higher frequencies do not show significant changes in sensitivity compared to the 2 Hz behavior (Supplementary Figure S4, see 3 Hz pink curve). Lower frequencies approach the instrument limit and the microseism signals constrain our analysis. According to the velocity model of Askja volcano (Han et al., 2024), Rayleigh waves propagating at 1 and 2 Hz are sensitive to depths down to 2 km, where a significant increase in surface wave velocities is observed (Supplementary Figure S4). Thus, most variations in the  $dv/v$  results are likely associated with changes in the shallow





**Figure 9** Single stations relative seismic velocity changes to the static reference for JONS, ASK, and STAM (2018–2024) with cross-components (EN, EZ) and 10-day moving window. The dashed vertical black line represents the start of the inflation on August 8, 2021. The inset map shows station locations around Askja volcano.

crust up to 3 km depth (deepest at 0.5 Hz), including the modeled deformation source (Parks et al., 2024).

Based on the vertical sensitivity kernel results, we defined the horizontal mapping of the network sensitivity kernel by extracting the horizontal velocity distribution at 1 km depth from the velocity model, which corresponds to the depth most sampled by the coda wave frequencies. We used the  $dv/v$  from the ZZ static cross-correlations with a 30-day moving stack window to reduce measurement daily variation while preserving longer-term temporal evolution.

#### 4.4.2 Iterative multiscale inversion

The network-averaged  $dv/v$  demonstrates a consistent seasonal pattern, with annual minima during summer (July–August), in addition to longer-term variations over multi-year timescales (Figure 5). To minimize seasonal bias in the spatial analysis, we compare equivalent periods before and after the start of inflation, excluding the onset period itself (Figure 10). Baseline period spanned from January 1st, 2018 to July 31st, 2020, and we compared it to the January 1st, 2022 to July 31st, 2024. We favor this period range to maximize the amount of data for the inversion. However, to ensure seasonal processes do not bias the results, we also compare using baseline (01-01-2019 to 31-12-2020) and test periods (01-01-2022 to 31-12-2023) that span full seasonal cycles over two years (Supplementary Figure S6). In both cases, the final inversion is similar.

Spatial  $dv/v$  maps apply a data resolution threshold of 0.2 (over 1), masking poorly constrained areas outside the seismic network. Additionally, the maps have no linear interpolation to prevent bias and artificial attribution of velocity values to locations with insufficient resolution constraints. This conservative approach ensures that mapped velocity variations reflect genuine measurements rather than interpolated estimates that the network density could not constrain. There are two better-defined regions within the network; one south that comprises Askja volcano and one north sampling a fissure swarm area (see fissure swarms on Figure 1). The northern region exhibits higher  $dv/v$  values around the station KOLL, while the southern region displays lower  $dv/v$  values with spatial heterogeneity. Positive  $dv/v$  values surround negative values in a pattern consistent with Askja caldera's velocity structure in the area between stations JONS, ASK, STAM, and KATT.

Ground inflation began in August 2021 following the year's minimum network-scale  $dv/v$  measurements (26-07-2021). Comparative analysis of  $dv/v$  maps between the pre-inflation period (2018–2020, Figure 10A) and the inflation period (2022–2024, Figure 10B) reveals localized velocity reductions concentrated within Askja's caldera.

Statistical analysis (Figure 10C) reveals that negative  $dv/v$  changes within Askja caldera are part of the most significant changes, exceeding the 99th percentile compared to the baseline (2018–2020). Other changes exceeding this threshold and the 95th percentile occur around TOHR and between ASK and SVAD stations, associated with positive  $dv/v$ . This spatial pattern between

STAM and JONS stations coincides with the documented ground inflation (Parks et al., 2024) (Figure 1 inflation sill).

## 5 Discussion

We first discuss the origin of the seasonal variations and, in doing so, assess whether changes in noise sources could also explain the long-term changes observed in  $dv/v$  or DSAR. We then focus on the long-term changes associated with the August 2021 inflation onset.

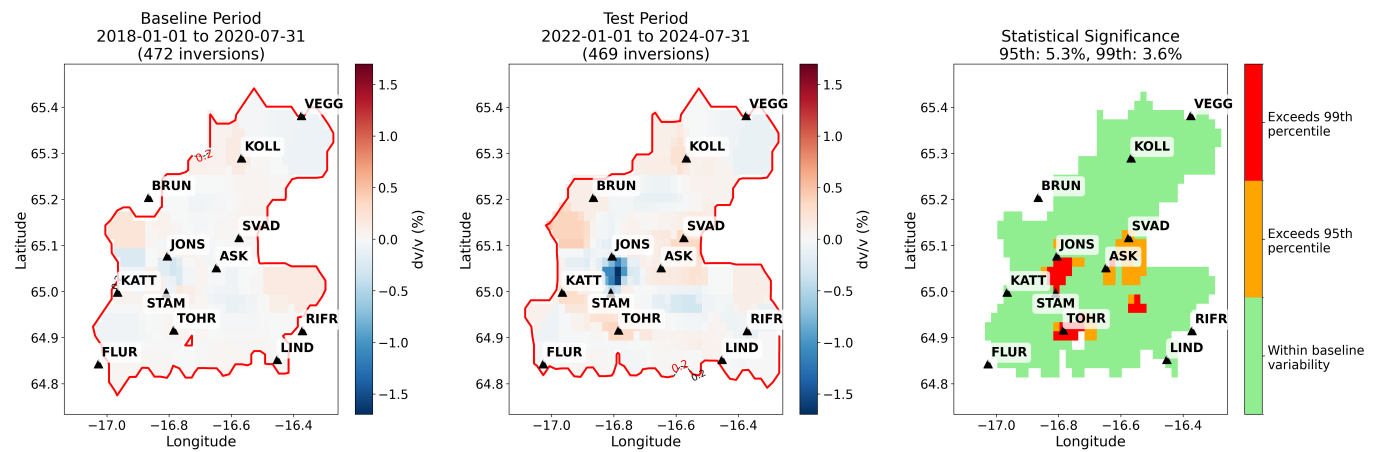
### 5.1 Seasonal variations

All stations used in this study display seasonal variations across all methods (Figure 8). One concern is whether the measured signals could reflect changes in the noise sources rather than changes in the medium's properties. The yearly variations of spectral widths (Figure 8B) follow the number of trace counts for a few specific years (2021, 2022, 2023; Supplementary Figure S5F). Specifically, more stations are available in summer than in winter, most likely due to greatly reduced sunlight hours and snow-covered solar panels. However, in the other years, the spectral widths show clear seasonal variations without corresponding changes in trace counts. We therefore do not attribute the seasonal variations in the results to changes in station availability.

We observed seasonal variations in spectral widths across the full network, but they are more pronounced at the Southeast station group (ASK, LIND, STAM), which is located closest to the Kárahnjúkar dam (Supplementary Figure S2C). The dam could contribute to the observed source in the spectral widths, as its operation varies seasonally with water levels. However, we cannot confirm this attribution with the available data and require further work.

Independent of the origin of the seasonal source variations, the spectral width results demonstrate that tremor source between 1 and 7 Hz remained consistent with the background levels throughout the inflation period, with sustained seasonal frequency variations (Figures 3B, 8B, and S5E). Additionally, the wavelet-based  $dv/v$  method has been shown to be less sensitive to changes in the seismic source (Mao et al., 2020). This stability in source characteristics at the inflation onset confirms that the long-term negative  $dv/v$  trend likely reflects genuine medium property modifications rather than artifacts from varying source properties.

Several processes could be responsible for the seasonal signal observed in the Displacement Seismic Amplitude Ratio (DSAR). Snow cover can attenuate high-frequency ground motion more than lower frequencies, potentially biasing DSAR during winter months. This effect has been explored at Mount St. Helens (Köpfler et al., 2024) and may contribute to seasonal variability observed across stations. The seasonal DSAR signal varies between stations depending on elevation, local slope, and distance to the hydrothermal system, linking differences in infiltration timing of snowmelt and ground-water dynamics rather than a regional signal (Köpfler



**Figure 10** Spatial and temporal comparison of seismic velocity changes ( $dv/v$ ). A. Resolution-masked  $dv/v$  maps for 2018-01-01 to 2020-07-31, before the inflation. B. Resolution-masked  $dv/v$  maps for 2022-01-01 to 2024-07-31, after the inflation. Black triangles represent seismic stations, and dashed lines indicate the resolution threshold of 0.5 (lower resolution than 0.5 is masked). The color scale represents  $dv/v$  values ranging from -0.16 (blue) to 0.16 (red). C. Significance map of the second period compared to variations of the first period (baseline). Dark red corresponds to significant changes that exceed the 99th percentile.

et al., 2024). Local attenuation associated with discontinuous permafrost and buried ice (Eitzelmüller et al., 2020; Shoemaker Thackston et al., 2024) may further contribute to differences between stations. Most stations show some timing differences and amplitude variations in DSAR likely related to these local effects (e.g., KATT in 2021 and RIFR in 2024, Figure 4). The dual-peak DSAR pattern observed at station ASK (Figure 4) could reflect both the combined influence of seasonal snow loading and enhanced groundwater recharge. These two processes could be enhanced at the ASK station location because of the steep slopes and drainage networks surrounding it. These topographic controls may increase subsurface fluid saturation, thereby intensifying seismic wave attenuation (Zhang et al., 2022), compared to flat-terrain stations. As seen, local seismic noise sources such as rivers (Figure 1), wind, and snow cover can radiate energy in restricted frequency bands and thus impact the amplitude ratio (Köpfler et al., 2024). Here, DSAR measurements cover the 6–16 Hz frequency band, while spectral width results show a source signal extending to 7 Hz. Therefore, the higher DSAR values in summer could be contaminated by this source signal and its seasonal variation. However, the long-term DSAR changes observed after the inflation onset, especially at STAM station (Figures 4 and 8C), and the absence of comparable changes prior to the inflation onset, suggest that these changes are unlikely to be only caused by local or meteorological factors.

As observed elsewhere, the resulting seismic velocity variations at Askja volcano reflect complex interactions between environmental loading, tectonic processes, and magmatic intrusion operating on multiple temporal and spatial scales (Donaldson et al., 2019; Winder et al., 2023; Parks et al., 2024). Network-scale seasonal  $dv/v$  variations exhibit amplitudes of  $0.20 \pm 0.06\%$ , with consistent patterns of higher velocities during winter months and lower velocities during summer, spanning the 16-year observation period from 2008 to

2024 (Figures 5 and 8D). We assume predominantly surface wave sensitivity, as surface waves typically dominate ambient seismic noise, providing an appropriate approximation for characterizing shallow crustal heterogeneity despite potential body wave contributions (Obermann et al., 2013, 2016).

Our results show annual vertical sinusoidal variations in  $dv/v$ , with the minimum in fall and the maximum in spring (Figures 8D and S5H). The persistent seasonal cycling at higher frequencies (3–5 Hz) indicates that the 3–5 Hz waves primarily sample shallower crustal levels above the inflation source. Seasonal variations are also observed with  $dv/v$  computed using the moving reference, with  $dv/v$  dropping around July (Figure 7B). Seasonal variations of  $dv/v$  are led by the highest frequency (3–5 Hz), followed by the low frequency bands. This could reflect changes that first occur at the surface, then impact deeper portions of the subsurface, and hence likely a surface-driven process. These seasonal fluctuations align with established patterns documented in Iceland's Northern Volcanic Zone, where models combining elastic and poroelastic responses to changes in snow thickness, ground frost, atmospheric pressure, and groundwater levels (e.g., Drouin et al., 2016; Donaldson et al., 2019; Hotovec-Ellis, 2024; Bruland et al., 2025). These models validate the interpretation that the observed cycles at Askja reflect elastic and poroelastic responses to surface loading effects rather than volcanic processes.

At Askja, seasonal variations (Figures 8 and S5) follow a pattern consistent with the interpretation from  $dv/v$  by Donaldson et al. (2019): from April to July,  $dv/v$  drops and attenuation increases as pore pressure increases with snow melting and water filling the crust. This hydrological loading occurs alongside runoff, while atmospheric pressure decreases at a slower rate than the snowmelt. From July to October, melting has ceased, but runoff continues, causing pore pressure to decrease through the drainage. DSAR and  $dv/v$  show delayed



recovery during this period and increase at a slower rate than groundwater level changes. From October to April, snow accumulates again, increasing the load to its maximum while groundwater remains constant. This period matches the DSAR second peak at ASK station. The 1997–2014 GPS measurements described by Drouin et al. (2016) show maximum deformation in fall and minimum in spring, which follow the changes in rates of the GNSS measured uplift, where we observe a lower rate until April every year (Supplementary Figure S5). The spatial heterogeneity in seasonal deformation patterns likely explains the observed spatial variations in DSAR and  $dv/v$  seasonal amplitudes between stations.

Therefore, to explore the impact of seasonal variations, it is critical to consider the influence of snow thickness (Wang et al., 2017; Yates et al., 2024), ground frost (Hotovec-Ellis, 2024), atmospheric pressure (Silver et al., 2007), groundwater level (Clements and Denolle, 2018), and temperature (Richter et al., 2014; Bruland et al., 2025). Snow mass shows a clear positive correlation (Pearson  $r$  ratio is 0.75 from 2016 to 2020) with  $dv/v$  (Supplementary Figure S5D), having at least twice the influence on the annual cycle amplitude change compared to atmospheric pressure (Donaldson et al., 2019). Additionally, we observe higher precipitation in 2020 (Supplementary Figure S5B), which results in pore pressure changes lowering  $dv/v$  values (Hillers et al., 2014; Feng et al., 2021; Bruland et al., 2025) (Figures 5, 6, and 9). Donaldson et al. (2019) showed that the annual decreases in  $dv/v$  occur prior to the ground warming, suggesting ground frost does not dominate the seasonal variations. Also, as the entire network is exposed to freezing temperatures (Figure 8A) and seasonal snow mass (Supplementary Figure S5D), stations above an elevation of 1 km may also be influenced by discontinuous permafrost (Etzelmüller et al., 2020; Shoemaker Thackston et al., 2024). Disentangling at each station the respective contributions of snow loading (Wang et al., 2017; Yates et al., 2024), buried ice (Shoemaker Thackston et al., 2024), and other meteorological factors remains challenging.

## 5.2 Inflation variations

### 5.2.1 Inflation onset

The onset of inflation in August 2021 triggered a transition from regular seasonal variations to predominantly negative  $dv/v$  values across a broad frequency range using both station pairs and single stations (Figures 6, 7, and 9). The inflation started while seasonal processes were already likely inducing a decrease in  $dv/v$ . It is therefore challenging to ascribe the negative  $dv/v$  before August 8th, 2021, as a definite precursor to the inflation. However, the magnitude of the inflation onset change stands out from seasonal variations ( $\pm 0.2\%$ ) and reaches maximum values of  $-0.7\%$  near the inflation center.

Nevertheless, unlike the network-wide impact observed during the 2014 Bárðarbunga eruption, the decrease in cross-correlation coefficients appears spatially localized, affecting only a subset of station pairs (Figures 5 and S3). Comparable perturbations have

been observed across other volcanic systems, with decorrelation interpreted as resulting from active unrest as the intrusion of magmatic fluids into the plumbing system, or crustal deformation that opens or fills cracks (Obermann et al., 2013; Ruiz et al., 2022; Clements and Denolle, 2023; Yates et al., 2025). At Þorbjörn-Svartsengi, Cubuk-Sabuncu et al. (2021) documented approximately 1% velocity drops during rapid inflation events and magmatic intrusion.

### 5.2.2 Spatial distribution

The spatial decay of  $dv/v$  and attenuation (DSAR) with distance from the inflation source at Askja appears consistent with the measured deformation (Figures 4 and 10). The background spatial variability between elevated  $dv/v$  values regions and lower values potentially reflects differences in crustal properties between the fissure swarm area and the main volcanic edifice (Figure 1). The  $dv/v$  values show spatial heterogeneity in the vicinity of Askja caldera, with negative values surrounded by positive values in the areas outside the caldera. This spatial pattern is consistent with the known low-velocity zone at 0.5–2 km depth (Han et al., 2024; Fone et al., 2025), which overlaps with the negative  $dv/v$  values within the caldera. The surrounding positive values align with the high-velocity consolidated intrusive rocks that encircle the caldera (Greenfield et al., 2016; Han et al., 2024). Therefore, the negative  $dv/v$  values most likely result from the magmatic intrusion at the inflation source. The surrounding positive values likely reflect crustal compaction from outward-directed deformation that increases seismic velocities. Additionally, the spatial correspondence between the initiation of ground deformation near OLAC GNSS station and the most pronounced seismic velocity variations at the JONS-STAM pair crossing the western part of the caldera (Figures 1, 2, and 10) demonstrates a direct link between ground deformation and seismic velocity variations. These multi-parameter observations collectively suggest that the ground inflation identified with the GNSS data is likely reflected in other seismic measurements, particularly in the  $dv/v$  measurements, despite the significant influence of the seasonal variations.

The depth sensitivity analysis suggests that low-frequency (0.5–1 Hz) velocity changes are most sensitive to variations occurring within the upper 2–3 km of the crust (Supplementary Figure S4). Assuming Rayleigh wave sensitivity, kernel calculations show sensitivity down to 2 km depth for 1 Hz frequencies and approximately 1 km depth for 2 Hz frequencies. This depth range encompasses both the low-velocity zone (0.5–2 km) identified through local earthquake tomography with reduced seismicity within this anomaly, suggesting the presence of molten material that inhibits both stress accumulation and brittle failure (Greenfield et al., 2016; Han et al., 2024; Fone et al., 2025). The overlap between ambient noise sensitivity and the depth of documented geological structures suggests that velocity changes reflect the deformation dominating the upper crust. Gravity increases documented by Koymans et al. (2023) sup-

port subsurface mass augmentation from melt injection, consistent with estimated melt fractions of 12–15% in the shallow anomaly (Han et al., 2024) and the 2.7 km depth source of the inflation modeled by Parks et al. (2024). The deformation would be expected to decrease  $dv/v$  due to the melt injection and the mechanical stress in the surrounding medium. As well as an increase of DSAR with the possible input of volatile, and potentially followed by a decrease with the depressurization of the inflation.

### 5.2.3 Component-dependent responses

Bacon et al. (2022) found seismic anisotropy associated with stress-aligned vertical fractures perpendicular to the plate spreading orientation with localized disruptions around Askja attributed to stress perturbations from magmatic activity. Fone et al. (2025) identified positive radial anisotropy beneath Askja at around 2 km depth, contrasting with predominantly negative values in the NVZ, which they interpreted as evidence of magma storage in a horizontal sill. In this study, component-dependent responses between horizontal (EN) and vertical (EZ) cross-correlations reveal different behavior after the inflation onset (Figures 7 and 9). Different components preferentially record different wave types, with Rayleigh waves dominating the radial-vertical components and Love waves the transverse components (Lin et al., 2008; Nayak and Thurber, 2020; Savage et al., 2013), possibly causing different sensitivities between vertical and horizontal correlations. The EZ component demonstrates more localized but strong responses in specific frequency bands, whereas the EN component exhibits broader frequency responses and recovers seasonal behavior from 2023 onward. These differences likely reflect varying contributions of vertically and horizontally polarized wavefields, as observed elsewhere (Machacca-Puma et al., 2019; Flinders et al., 2020; Hotovec-Ellis et al., 2022). They could interact differently with the anisotropic crustal structure beneath Askja, where stress-aligned fractures and radial anisotropy have been documented at comparable depths (Bacon et al., 2022; Fone et al., 2025). The origin of these component-dependent differences remains uncertain, but the consistency across stations supports the observed velocity changes associated with the 2021 inflation.

### 5.2.4 Temporal evolution

The decrease of JONS-STAM cross-correlation coefficients in August 2021 with the pre-inflation reference, which persists without recovery throughout the observation period, suggests structural modifications to the medium coincident with inflation onset (Figures 7 and S3). This motivates the use of the moving reference for the temporal analysis that follows. This reference also shows the impact of the inflation on the medium through significant  $dv/v$  decreases (Figure 7B). The temporal evolution of the  $dv/v$  reveals distinct responses across different frequency bands (Figure 7). These observations could be associated with varying responses to a single process across depth, as well as frequency-

dependent signatures involving separate processes at different depths. During the first months (August–September 2021), significant decreases were observed across all frequency bands, with low frequencies showing more significant responses (−0.7%). The change observed at 0.5–3 Hz (Figure 7B) exceeds typical seasonal variations (Figure 7A before inflation), which have less impact than at higher frequencies. The 0.5–1 Hz  $dv/v$  sample shallow depths, in addition to sampling partially both the deeper deflating source and the storage zone at 2.7 km. The larger velocity decreases at lower frequencies suggest a deeper origin relative to seasonal processes, which have a stronger influence at higher frequencies. Therefore, this response could reflect initial magma migration at 2–3 km depth (Parks et al., 2024; Fone et al., 2025). Several physical mechanisms could explain the associated decrease in velocity with magma intrusion. Magma pressurization can drive dilatation and crack opening and stress field reorganization, reducing seismic velocity (Brenguier et al., 2008; Donaldson et al., 2017). Additionally, as  $dv/v$  can indicate increased gas influx (Moune et al., 2022) and rising groundwater table (Sens-Schönfelder and Wegler, 2006), this change could also reflect the effect of magmatic or hydrothermal fluid intrusion driving the inflation and amplifying the velocity perturbation. The melt injection within the storage zone itself may also influence, though disentangling the respective contributions of each process remains challenging.

The frequency bands used for DSAR computation (> 6 Hz) are not sensitive to the depths where magma intrusion is modeled (2.7 km, Parks et al. (2024); Supplementary Figure S4), making a direct association with the magmatic intrusion itself unlikely. Still, we observed elevated DSAR values at the stations closest to the inflation source, JONS and STAM stations (Figure 4), from September 2021 through June 2022, aligning with Caudron et al. (2021)'s observations at Whakaari, where elevated DSAR values reflected increased subsurface volatile accumulation or enhanced sealing. The observed surface inflation confirms that deformation from the deeper magmatic intrusion reaches the surface. It could drive shallow processes in the upper 1 km that are observed in the DSAR changes, including crack opening, stress field reorganization, scattering property changes (Köpfl et al., 2024), and volatile redistribution (Caudron et al., 2021). The sustained and spatially heterogeneous DSAR anomalies at JONS and STAM persisting beyond the initial inflation onset indicate complex subsurface process interactions, with variable network response reflecting local effects.

The stabilization of  $dv/v$  between October 2021 to February 2022 (Figure 7B), occurs at higher frequencies (1–5 Hz, sensitive above 2 km depth) before lower frequencies (0.5–1 Hz, sensitive up to 2–3 km depth). We interpret this frequency dependent response as reflecting a perturbation persisting at deeper levels and the impact of the intrusion body. We observe a similar behavior from January to April 2023 with the 1–3 Hz  $dv/v$  showing a stabilization with increasing  $dv/v$ . Seasonal variations may contribute to these changes, since they occur around the same period of time and can cause

large  $dv/v$  fluctuations, as shown previously. However, the  $dv/v$  values differ between frequency bands and expected seasonal trends, especially at low frequencies, consistent with the inferred location of the intrusion. The sustained higher DSAR values of JONS and STAM (Figure 4) until June 2022 align with the scenario in which pressure increases at 2.7 km depth from the initial magma migration, modifying fluid circulation and gas distribution near the surface.

This could be associated with a recharge into the sill at 2.7 km depth (Parks et al., 2024; Fone et al., 2025), destabilizing the hydrothermal circulation. While stress fields between 0 and 2 km depth relax and fracture networks begin healing as hydrothermal systems re-establish circulation patterns and seasonal variation influences. DSAR measurements complement this interpretation, showing marked decreases at both JONS and STAM after June 2022, indicating depressurization reflecting reduced volatile accumulation and enhanced fluid circulation at the surface.

From September 2023, at JONS-STAM pair (Figure 7B),  $dv/v$  trends across frequency bands begin to be similar, which could indicate that the system reaches a new state with established hydrothermal and magmatic pathways at multiple depths as inflation continues with a reduced rate. Additionally, at the station level, JONS recovery and STAM persistence at low DSAR values reveal spatially heterogeneous hydrothermal responses. The lack of synchronized behavior between stations during the ongoing inflation suggests that DSAR changes reflect shallow hydrothermal processes controlled by local geological factors rather than uniform system responses, such as seasonal variations. Thus, the August 2021 inflation event triggered long-lasting subsurface structural or stress modifications that continue to influence seismic wave propagation.

## 6 Conclusion

This study demonstrates that noise-based relative seismic velocity changes can effectively measure crustal changes at Askja volcano, with sensitivity comparable to that of GNSS stations, capturing variations as seasonal fluctuations of  $\pm 0.2\%$  due to pore pressure changes and ground loading from 2008 to 2024. Moreover,  $dv/v$  changes also match the August 2021 intrusion-induced ground uplift with a drop up to  $\sim 0.7\%$ . The sensitivity kernel analysis indicates that the  $dv/v$  results are associated with depths down to 3 km, consistent with the modeled source of inflation identified in previous studies. Additionally, the onset of inflation on August 8th coincided with a progressive increase in DSAR values of 0.4 units, suggesting enhanced attenuation, possibly due to the accumulation of magmatic or hydrothermal volatiles, followed by a decrease in DSAR of 0.5 units due to the depressurization of the volcanic system. This suggests the potential activation of the hydrothermal system in response to magma transfer within the upper part of the Askja volcanic system.

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## Data and code availability

Seismic data were obtained from the Icelandic Meteorological Office (IMO) and from the University of Cambridge. Raw seismic data are publicly available through IRIS/EarthScope for networks 4F (2007–2011; [https://www.fdsn.org/networks/detail/4F\\_2007/](https://www.fdsn.org/networks/detail/4F_2007/), Robert White, 2007) and Z7 (2011–2015; [https://www.fdsn.org/networks/detail/Z7\\_2010/](https://www.fdsn.org/networks/detail/Z7_2010/), Robert White, 2010). Data for network 8K (2016–2022) are documented at Winder (2016), and are in the process of being uploaded to ORFEUS. Data from 2022–2024 are currently under embargo and will become available on the IRIS Data Management service in 2028, in the same way as the previous datasets. Data from the station ASK, operated by the IMO are available at <https://doi.org/10.5281/zenodo.17165025> from 2008 to 2011, <https://doi.org/10.5281/zenodo.17165027> from 2012 to 2016, and <https://doi.org/10.5281/zenodo.17165031> from 2017 to 2022. ASK station data have not undergone formal quality control at the IMO and may alternatively be obtained by contacting the IMO directly (<https://en.vedur.is/about-imo/contact/>).

Stacked cross-correlations generated in this study are archived in Zenodo repositories for station pairs <https://doi.org/10.5281/zenodo.17164247> and single stations <https://doi.org/10.5281/zenodo.17155964>. The velocity model is derived from Han et al. (2024), and is available at <https://doi.org/10.5281/zenodo.17105840>. GNSS data are provided by Veðurstofa Íslands (2023b). The earthquake catalog is available from the IMO at <https://skjalftalisa.vedur.is/>. Meteorological data were obtained from the IMO (<https://athuganir.vedur.is>) and ERA5 dataset (Hersbach et al., 2023). This study uses the following open-source Python software packages: CovSeisNet (Tong et al., 2024), Disba (Luu, 2020), and



MSNoise (Lecocq et al., 2014). The complete workflow and results used for this study are archived on <https://doi.org/10.5281/zenodo.17105840>.

## Competing interests

The authors have no competing interests.

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