

Supplementary information

S.1 dv/v location benchmarking

This section presents dv/v location benchmarking supporting the method described in the main text. We conducted a systematic evaluation of the iterative multiscale inversion method using synthetic data to assess its robustness across varying conditions.

All synthetic tests presented in figure S.1 were conducted using the following standardized parameters like initial grid resolution at 0.3° , minimum cell size at 0.05° , the number of inversion iterations is 4, regularization parameter (α) is 0.05, and coda wave kernels with 20-second lapse time.

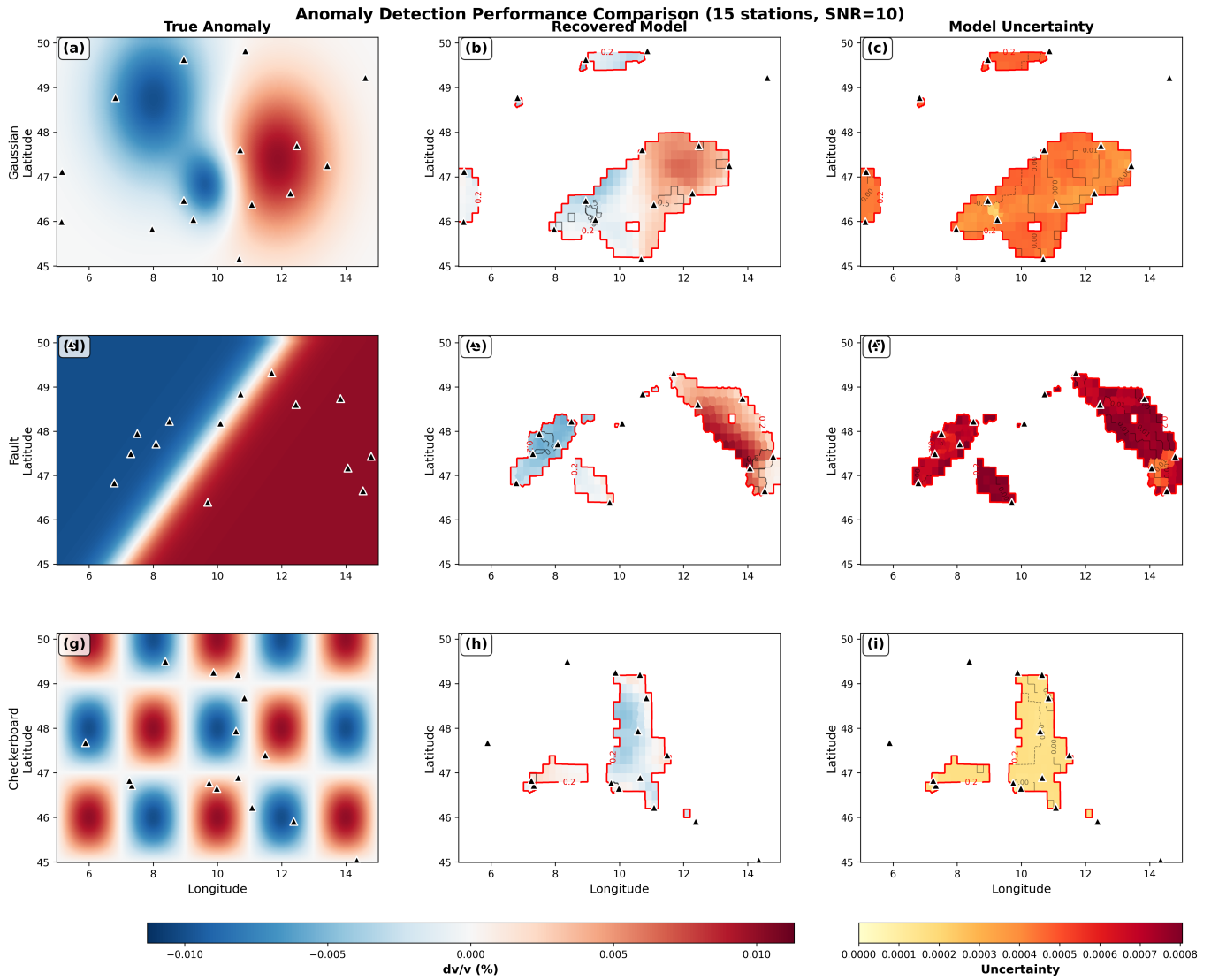


Figure S.1 – Synthetic test validation of the iterative multiscale inversion method with. (a) Gaussian, (d) fault, and (g) checkerboard true synthetic velocity anomaly with perturbations ($\pm 1\%$ dv/v) embedded in a uniform background medium. Black triangles indicate seismic station locations. (b) Gaussian, (e) fault, and (h) checkerboard recovered velocity model from the iterative multiscale inversion using synthetic travel-time measurements with SNR=10. Black contour lines show resolution values (0.2, 0.5, 0.8), with the red contour marking the minimum resolution threshold (0.2) below which results are masked. (c) Gaussian, (f) fault, and (i) checkerboard model uncertainty estimates derived from the resolution matrix analysis. Black contour lines show recovered velocity values for reference. White areas indicating regions below the resolution threshold.

For the presented examples, the performance improvement from 7 to 15 stations varied by anomaly by 15%, 28%, and 33% correlation improvement for the Gaussian, fault, and checkerboard anomalies, respectively. At SNR = 10, the

method maintained high correlation coefficients. For the gaussian recovery $r = 0.91 \pm 0.02$; fault recovery: $r = 0.89 \pm 0.03$; checkerboard recovery: $r = 0.58 \pm 0.04$. These values are representative of the figures shown, not of the full benchmarking tests with multiple random networks and noise conditions, as described in section 3.5 (codes available on <https://doi.org/10.5281/zenodo.17105840>).

The resolution of the method is limited by station geometry. Poorly resolved regions (resolution < 0.2) are masked in the final results to prevent overinterpretation. Our method offers an adaptive resolution that reduces computational cost while maintaining accuracy in well-constrained regions. It also provides edge-preserving regularization, which better preserves sharp boundaries compared to uniform smoothing, and uncertainty quantification to assess model reliability.

S.2 Spectral width results

This section provides additional spectral width analyses supporting the findings presented in the main text. The figures show detailed time-frequency representations of seismic data, illustrating temporal variations in spectral characteristics across two different station groups (Figures S.2A, S.2B, and S.2C).

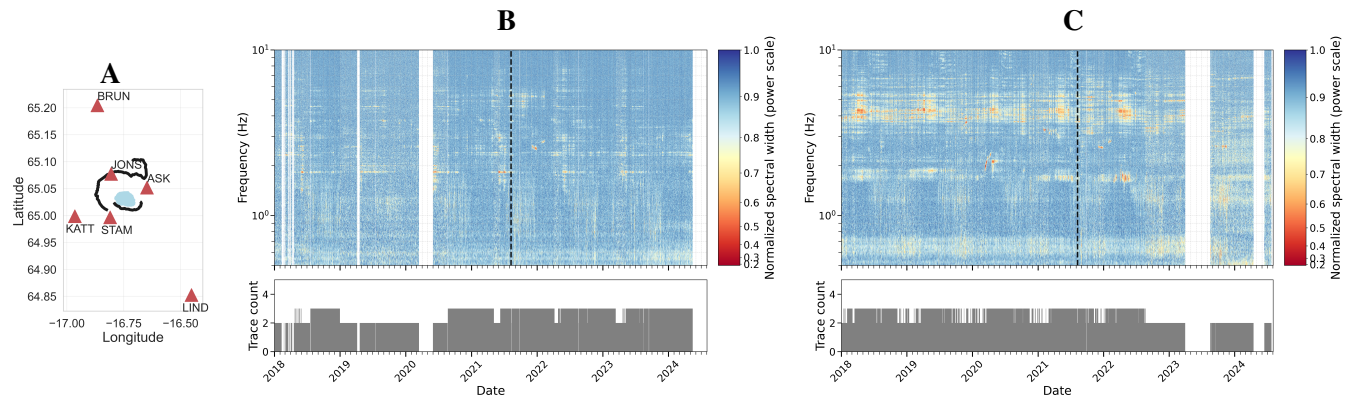


Figure S.2 – A. Map showing the Northwest group JONS, KATT, and BRUN, and the Southeast group with ASK, LIND, and STAM stations. B. Spectral width from 0.5 to 10 Hz for the period 2018–2024, computed using 100-second windows with 100-window averaging with JONS, KATT, and BRUN stations. C. Spectral width from 0.5 to 10 Hz for the period 2018–2024, computed using 100-second windows with 100-window averaging with ASK, LIND, and STAM. A low spectral width indicates coherent signals at the network scale, whereas a high spectral width is associated with incoherent noise. 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. The dashed black line marks the start of inflation on August 8, 2021.

S.3 Cross-correlations results

The following figures show detailed cross-correlation analyses for some station pairs, illustrating the temporal stability and quality of seismic correlations used in the velocity change computations discussed in the main text (Figure S.3).

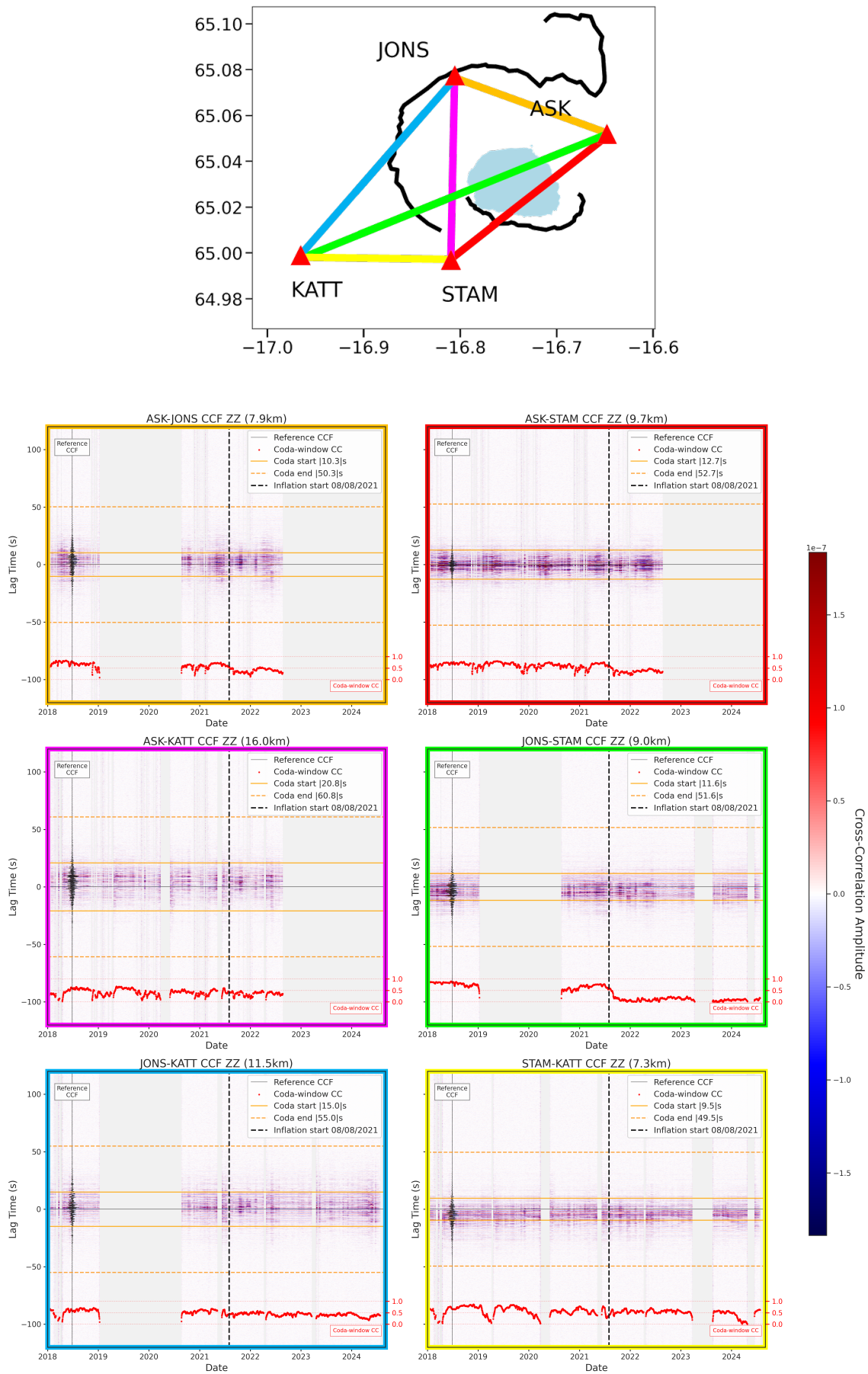


Figure S.3 – Cross-correlation results showing temporal evolution of seismic correlation quality within the 0.5–5 Hz frequency band. The figure displays correlation coefficients for station pairs across the network (see map), illustrating overall stability throughout the observation period.

S.4 Sensivity kernel

Figure S.4 illustrates the depth sensitivity kernels that support our interpretation of shallow crustal changes at Askja volcano. The frequency-dependent penetration depths shown here are used to attribute the dv/v variations to processes within the upper 3 km of the crust.

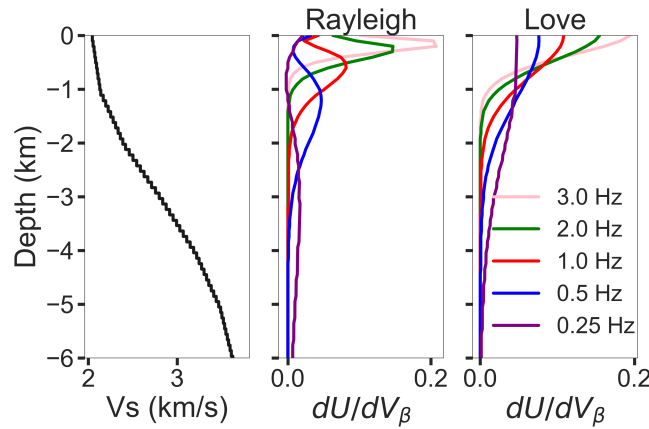


Figure S.4 – 1D sensitivity kernel for Rayleigh and Love waves from 0 to 6 km depth at Askja volcano. The velocity model is based on the results from Han et al. [2024]. Positive values show constructive sensitivity with local maxima indicating regions of highest sensitivity per wave frequency.

S.5 Weather influence on the geophysical measurements

Meteorological and geophysical parameter time series analysis from 2018 to 2024 shows the influences of seasonal variations and ground inflation on other geophysical measurements (Figure S.5).

Temperature measurements (Panel A) exhibit consistent seasonal cycles with summer maxima in July–August and winter minima, maintaining similar amplitudes across all years, with the largest annual temperature variations in 2023 ($\Delta T = 33^\circ\text{C}$). Precipitation patterns (Panel B) show high inter-annual variability, with 2020 displaying a large April peak at 15 mm/day that exceeded all other years. Air pressure measurements (Panel C) demonstrate less pronounced seasonality but exhibit considerable annual variability with still cyclical patterns. Snow mass data (Panel D) display expected seasonal accumulation and melt cycles, with peak values typically occurring in April (March in 2023 and May in 2024) before rapid summer decline with no snow mass from July to October.

Minimum spectral width values (Panel E) show a gradual seasonal increase from February to October, with post-2021 years generally exhibiting higher values than pre-inflation years. Spectral widths' number of trace counts (Panel F) show seasonal variations for the years 2021, 2022, 2023, but not throughout the entire period. Specifically, more stations are used in summer than in winter, most likely due to greatly reduced sunlight hours and snow-covered solar panels. DSAR values (Panel G) are consistent for the pre-inflation years in the ratio value between 1.8 and 2. From 2021, the value reached a maximum at 2.2 then dropped to consistent values under 1.8 in 2022. The dv/v measurements (Panel H) initially show correspondence with seasonal patterns in pre-inflation years, but exhibit increasing divergence after August 2021, with several years displaying notable negative values. GNSS vertical displacement data (Panel I) shows the gradual upward trends over the observation period, with minimal seasonal modulation. Slower rate at the beginning of every year until May.

These observations indicate that while some parameters maintain consistent seasonal patterns throughout the study period, others show increased variability following the August 2021 inflation onset.

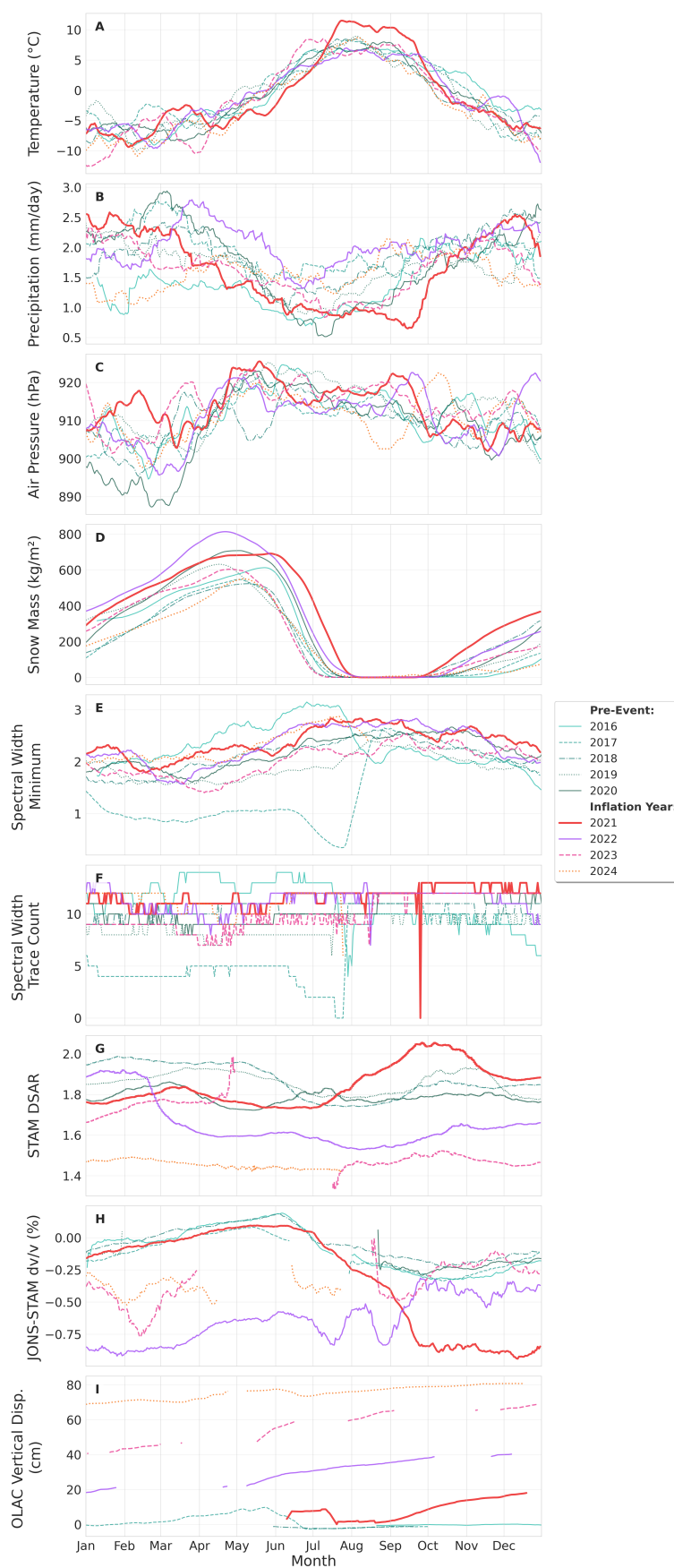


Figure S.5 – Seasonal analysis of multiple geophysical parameters (2018–2024). Multi-panel time series showing annual variations in seven key parameters. From top to bottom: A. Temperature (°C); B. Precipitation rate (mm/day); C. Air pressure (hPa); D. Snow mass (kg/m²); E. Minimum spectral width from Coveisnet measurements; F. Trace count used for the spectral width computation; G. DSAR (STAM); H. dv/v (JONS-STAM, pre-inflation reference); and I. GNSS vertical displacement (OLAC). Colors represent different years as indicated in the legend.

S.6 Iterative multiscale inversion results

To ensure seasonal processes do not bias the spatial and temporal comparison, we use a baseline spanning January 1st, 2019, to December 31st, 2020, and compare it with the period from January 1st, 2022, to December 31st, 2023 (Figure S.6). Therefore, each period covers twice the full seasonal cycle (2 years), keeping equivalent periods before and after the start of inflation, excluding the onset period itself.

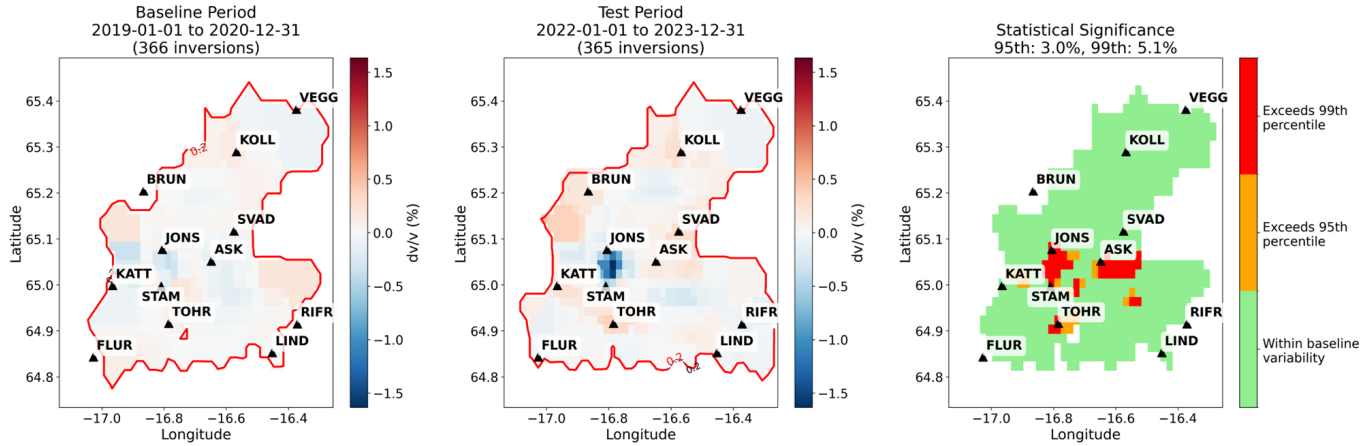


Figure S.6 – Spatial and temporal comparison of seismic velocity changes (dv/v). A. Resolution-masked dv/v maps for 2019-01-01 to 2020-12-31, before the inflation. B. Resolution-masked dv/v maps for 2022-01-01 to 2023-12-31, after the inflation. Black triangles represent seismic stations, and dashed 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.