

Supplementary Materials

for

Contrasting frequency-dependent seismic velocity responses in Northern Nagano and Mount Fuji regions after the 2011 M_w 9.0 Tohoku-Oki earthquake

Louisa Bagot (1), Bogdan Enescu (1,7), Florent Brenguier (2), Nicolas Paris (3), Quentin Higuieret (2,8), Yusuke Kakiuchi (4), François Lavoué (2), Aurélien Mordret (2,9), Masatoshi Miyazawa (5), Tetsuya Takeda (6)

1. Department of Geophysics, Graduate School of Science, Kyoto University, Kyoto, Japan
2. Université Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IRD, UGE, ISTerre, Grenoble, France
3. Université Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, Grenoble, France
4. Graduate School of Engineering, The University of Tokyo, Tokyo, Japan
5. Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
6. National Research Institute for Earth Science and Disaster Resilience (NIED), Tsukuba, Japan
7. National Institute for Earth Physics, Romania
8. Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA
9. Geophysics and Sedimentary Basins, GEUS, Copenhagen, Denmark

1. Cross-correlation computation

For the Mount Fuji region, the analysis includes cross-correlations from both Hi-net and V-net stations, as described by Kakiuchi et al. (2024). For the Nagano region, we use the three-component E, N, and Z signals recorded by Hi-net stations. The two horizontal components E and N are rotated to obtain the transverse (T) and radial (R) coordinates. We then perform the analysis for all nine possible component combinations: RR, RT, RZ, TR, TT, TZ, ZR, ZT, ZZ. The raw data is detrended, resampled to 25 Hz, and band-pass filtered between 0.1 and 2 Hz. The waveforms are separated into 10-min long windows with a 2-min overlap. Each window is temporally and spectrally normalized: we apply clipping (by 5 times the standard deviation), spectral whitening, and one-bit normalization. The cross-correlation between two signals is then computed. The windows are then stacked to obtain hourly and then daily cross-correlations for each station pair.

To improve the coherence of the resulting cross-correlations, a 30-day moving average is computed for each station pair and each component combination. The first and last days (from 2011-01-01 to 2011-01-15 and from 2011-08-16 to 2011-08-31) cannot be evaluated with a complete 30-day window and are therefore less stable.

2. Velocity changes computation

We perform the wavelet cross-spectrum analysis on the causal and anticausal parts of the waveforms separately. We use the Python implementation of the cross-wavelet transform developed by Higueret (2021), following the workflow of Paris et al. (2025). The analysis is applied to a selected time window. The time window is chosen separately for both parts of the correlations after a spectral analysis that highlights the coherence of the measurements for different frequencies and lag times (Figure S1). We are interested in the early coda, so the minimum lag time of this window is defined as 5 s after the fundamental-mode surface-wave arrival. For the maximum lag time, we define a fixed value for all station pairs. We test maximum lag times of 60, 80, and 100 s. The results are similar (Figure S3), so we select 80 s as a trade-off between longer lag times and signal coherence. Station pairs that did not show sufficient cross-coherence within the selected coda window were excluded through visual screening. This screening excluded 31 of the 453 station-pair paths in the Nagano region. No station-pair paths were excluded in the Mount Fuji region.

We obtain dv/v time series for each component combination, for the causal and anticausal parts, resulting in a total of 18 time series for each station pair. They are averaged to obtain one time series for each pair. We then apply a spatial average, where for each station, we average the time series of all the station pairs that include that station. We therefore have a single time series for each station, which greatly improves the coherence of the dv/v values (Figure S2). The number of time series used in the spatial average differs from station to station. For stations close to the edges of the study areas, there are usually fewer paths that include them, resulting in lower coherence for the final dv/v time series (Figure S4).

From each station-averaged dv/v time series, we compute the coseismic velocity change. Because of the moving average, the coseismic change appears as a smooth decrease over approximately 30 days rather than as an abrupt step. Because the available temporal resolution does not allow us to separate the triggered events from the Tohoku-Oki earthquake, the estimated coseismic change may contain contributions from both events. We nevertheless center the measurement on the Tohoku-Oki earthquake. Operationally, the coseismic change is calculated as the difference between the dv/v value of the last

day (2011-03-27) and first day (2011-02-24) containing the day of the Tohoku-Oki earthquake (2011-03-11) within the 30-day moving-average window.

3. Comparison with the smoothed PGA

The PGV and PGA measurements are smoothed to remove site effect. We computed the median value at each site from measurements at stations within a 30 km radius. We tried different radii (20 km and 40 km), to verify that the seismic velocity susceptibility anomalies were not due to smoothing artifacts. The large anomalies in the volcanic areas and close to the M_w 6.2 Northern Nagano earthquake are still visible for different PGV smoothing.

We compare the coseismic velocity changes dv/v_{cos} to the logarithm of the smoothed PGA values. A linear regression is computed, to identify a relation between the velocity changes and the shaking. For the Nagano area (Figure 4a), we obtain a trend with $R^2 = 0.63$, showing that 63% of the variations are explained by the regression. We observe a significant negative linear relationship (sample size=121, slope = -0.0338 , $p < 0.001$). For the Mount Fuji area (Figure 4b), the regression does not explain well the variations ($R^2 = 0.12$), but there is still a statistically significant negative linear relationship (sample size=53, slope = -0.0237 , $p = 0.0116$).

References:

- Higueret Q (2021) Qhig/cross-wavelet-transform: First release of a cross wavelet transform algorithm in Python (v1.0.0) [Software]. *Zenodo*. doi:10.5281/zenodo.4783514.
- Kakiuchi Y, Nimiya H, Tsuji T (2024) Spatiotemporal variations and postseismic relaxation process around Mt. Fuji, Japan, during and after the 2011 Tohoku-Oki earthquake. *J Geophys Res Solid Earth* 129:e2023JB027978. doi:10.1029/2023JB027978.
- Paris N, Itoh Y, Brenguier F, Wang Q-Y, Sheng Y, Okada T, Uchida N, Higueret Q, Takagi R, Sakai S, Hirahara S, Kimura S (2025) Coseismic crustal seismic velocity changes associated with the 2024 M_w 7.5 Noto earthquake, Japan. *Earth Planets Space* 77:51. doi:10.1186/s40623-025-02177-x.

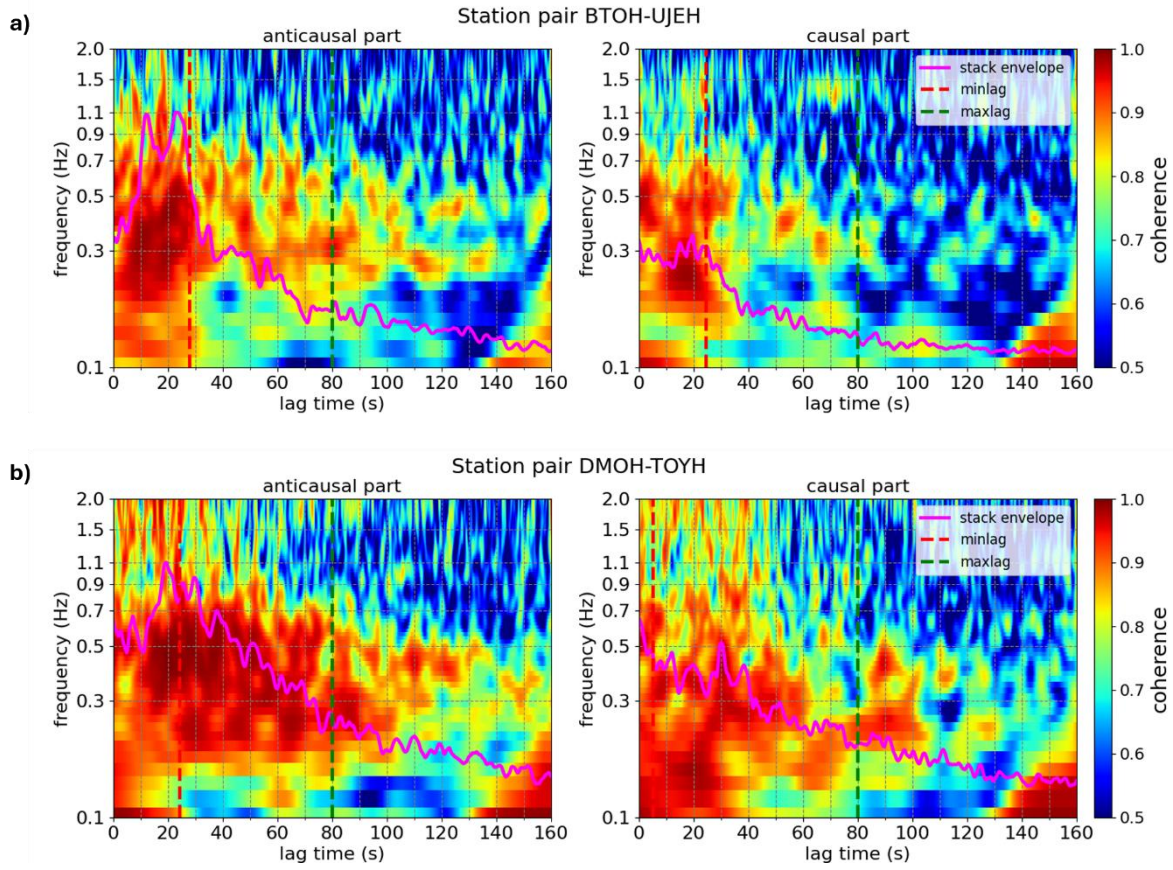


Figure S1. Cross-correlation coherence as a function of frequency and lag time, with the color indicating coherence **a)** for station pair BTOH-UJEH; **b)** for station pair DMOH-TOYH. The left panel is the anticausal part, the right panel is the causal part of the cross-correlation. The pink line is the envelope of the stack of all the component combinations, the red dotted line is the minimum lag time of the selected time window 5 s after the surface wave first arrival and the green dotted line is the maximum lag time fixed at 80 s.

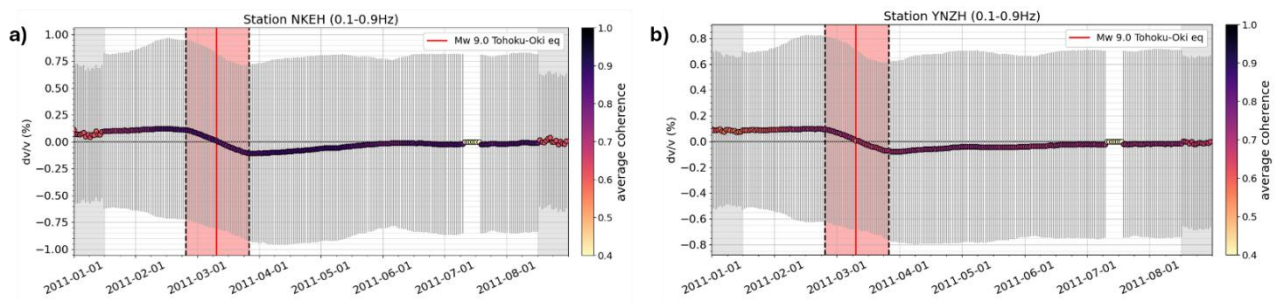


Figure S2. Seismic velocity variation time series for 0.1–0.9 Hz at station **a) NKEH** and **b) YNZH**. The red vertical line marks the M_w 9.0 Tohoku-Oki earthquake, and the two black dashed vertical lines indicate the dates used to estimate the coseismic velocity change. The red shading marks the interval between these dates. Light-gray shading at the beginning and end of the time series indicates periods for which a complete 30-day moving average cannot be calculated. The grey vertical lines show the errors estimated as the standard deviation of all time series including the station. The color indicates the average coherence.

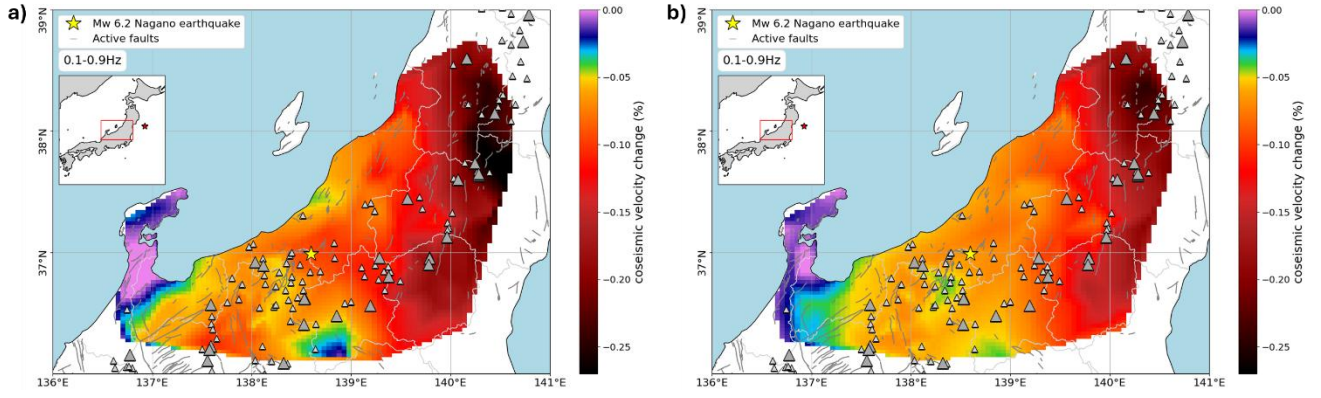


Figure S3. a) Map of the coseismic velocity changes for the Nagano area (0.1–0.9 Hz), for a selected time window with a maximum lag time of 60 s. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes, the gray lines representing known active faults. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Nagano area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter; **b)** Map of the coseismic velocity changes for the Nagano area (0.1–0.9 Hz), for a selected time window with a maximum lag time of 100 s. The legend is the same as the one shown in **a)**.

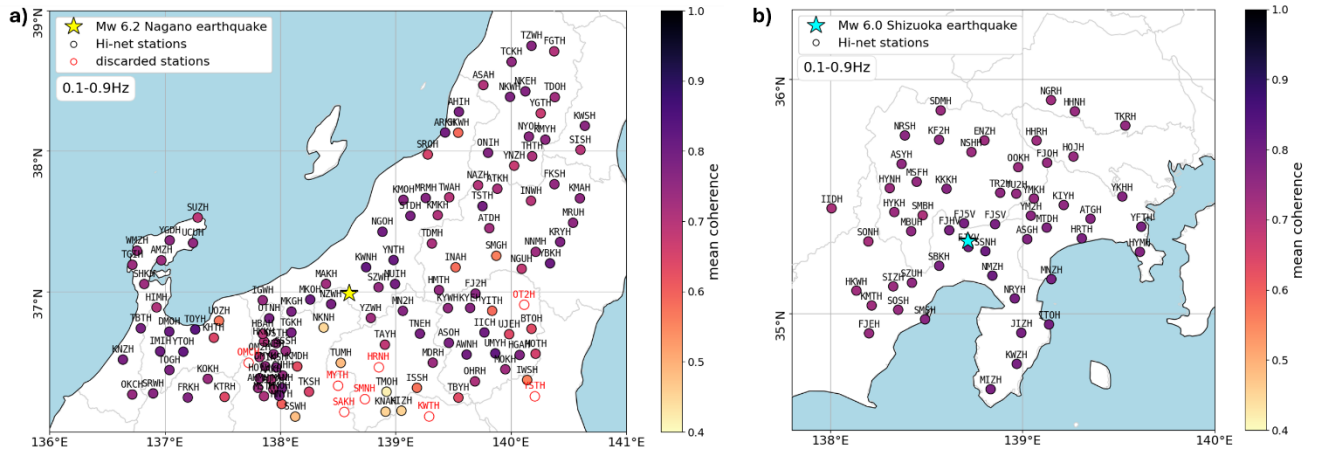


Figure S4. a) Map of the selected Hi-net stations (mean coherence > 0.4), with the color indicating the mean coherence, for the Nagano area (0.1–0.9 Hz). The red open dots are the discarded stations (mean coherence < 0.4). The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter; **b)** Map of the selected Hi-net stations (mean coherence > 0.4), with the color indicating the mean coherence, for the Mount Fuji area (0.1–0.9 Hz). No station was discarded. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter.

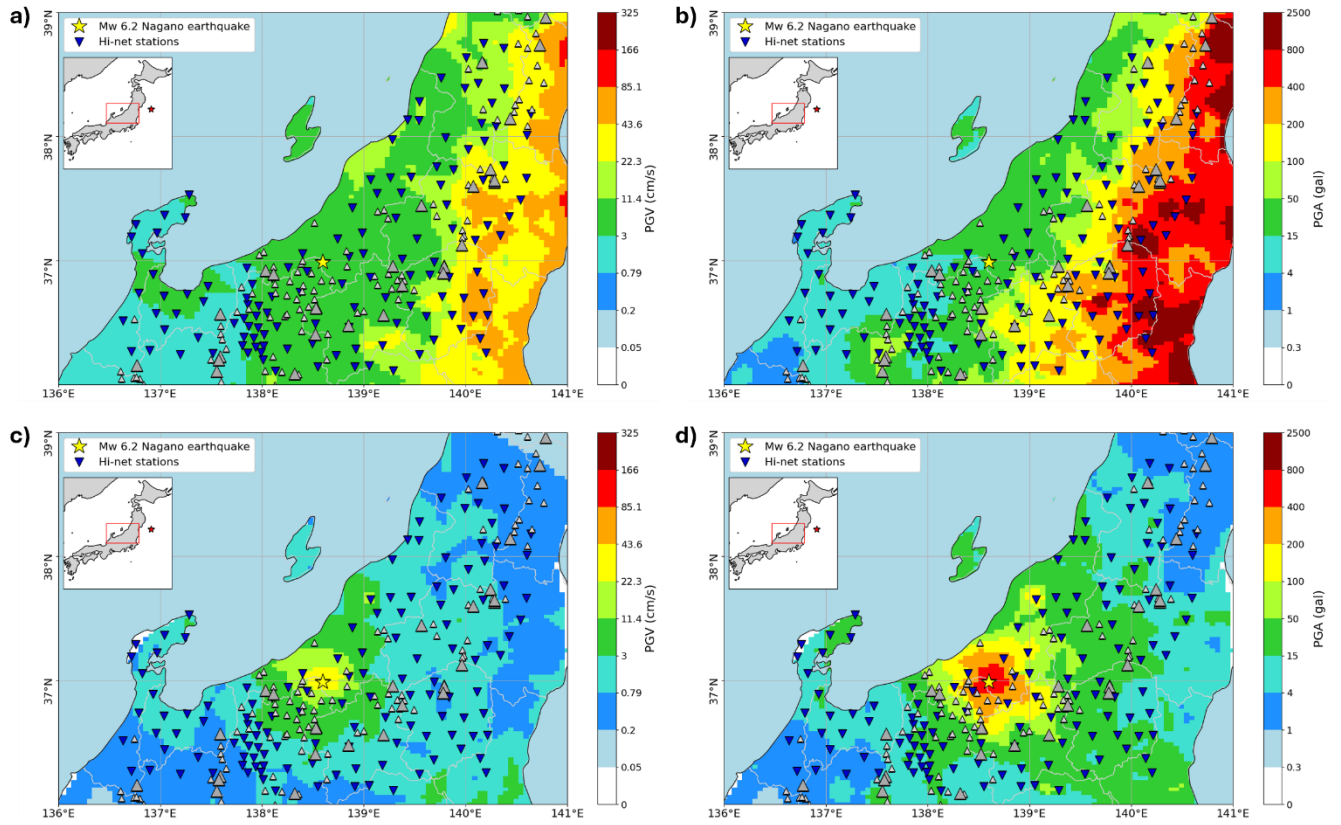


Figure S5. **a)** Map of the maximum PGV of the M_w 9.0 Tohoku-Oki earthquake in the Nagano area; **b)** Map of the maximum PGA of the M_w 9.0 Tohoku-Oki earthquake in the Nagano area; **c)** Map of the maximum PGV of the M_w 6.2 Northern Nagano earthquake in the Nagano area; **d)** Map of the maximum PGA of the M_w 6.2 Northern Nagano earthquake in the Nagano area. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes. The blue inverted triangles are the Hi-net stations. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Nagano area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter.

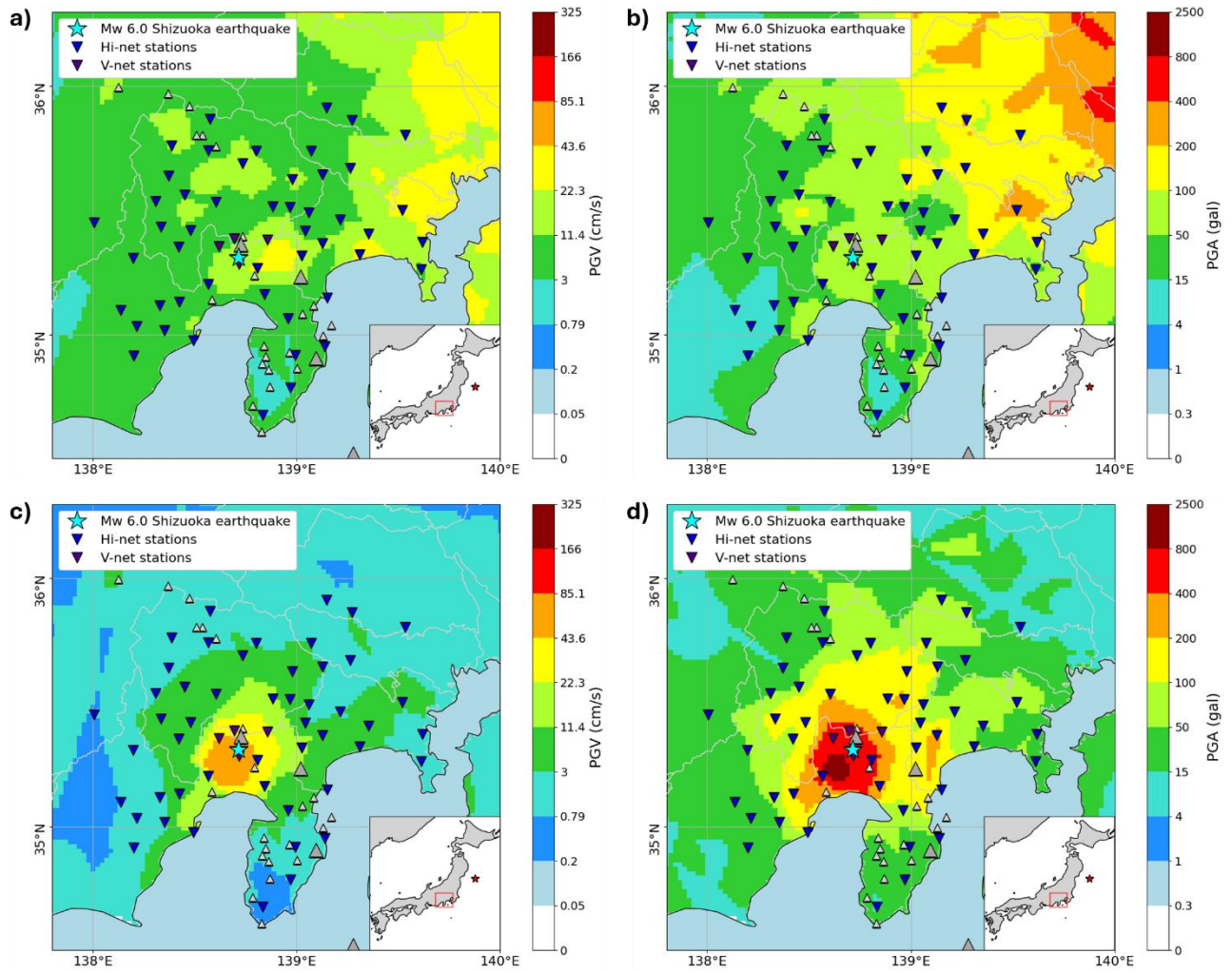


Figure S6. **a)** Map of the maximum PGV of the M_w 9.0 Tohoku-Oki earthquake in the Mount Fuji area; **b)** Map of the maximum PGA of the M_w 9.0 Tohoku-Oki earthquake in the Mount Fuji area; **c)** Map of the maximum PGV of the M_w 6.0 East Shizuoka earthquake in the Mount Fuji area; **d)** Map of the maximum PGA of the M_w 6.0 East Shizuoka earthquake in the Mount Fuji area. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes. The blue and purple inverted triangles are the Hi-net and V-net stations, respectively. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Mount Fuji area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter.

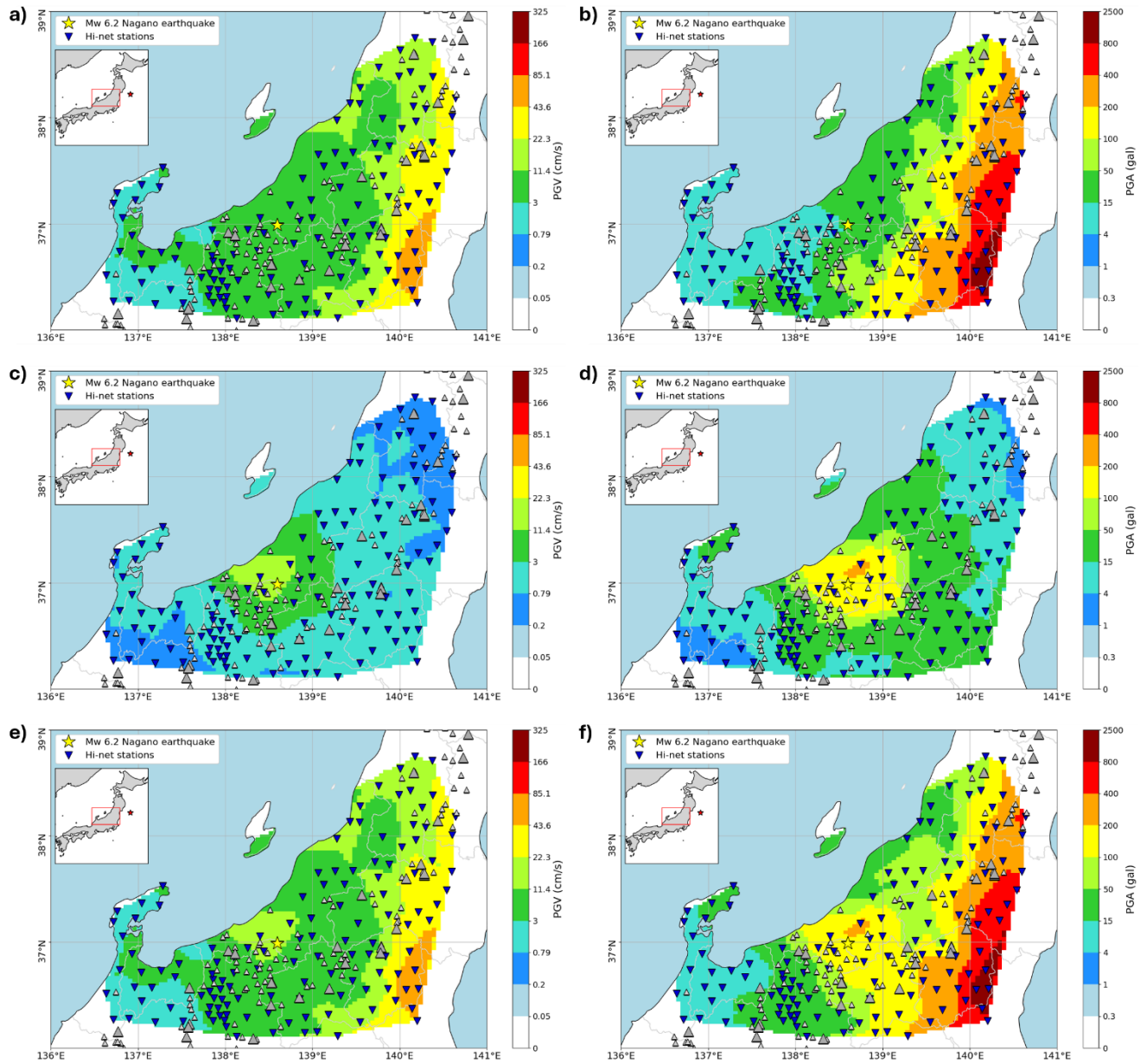


Figure S7. **a)** Map of the smoothed PGV of the M_w 9.0 Tohoku-Oki earthquake in the Nagano area; **b)** Map of the smoothed PGA of the M_w 9.0 Tohoku-Oki earthquake in the Nagano area; **c)** Map of the smoothed PGV of the M_w 6.2 Northern Nagano earthquake in the Nagano area; **d)** Map of the smoothed PGA of the M_w 6.2 Northern Nagano earthquake in the Nagano area; **e)** Map of the station-wise maximum of the smoothed PGV between the M_w 9.0 Tohoku-Oki and the M_w 6.2 Northern Nagano earthquakes in the Nagano area; **f)** Map of the station-wise maximum of the smoothed PGA between the M_w 9.0 Tohoku-Oki and the M_w 6.2 Northern Nagano earthquakes in the Nagano area. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes. The blue inverted triangles are the Hi-net stations. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Nagano area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter.

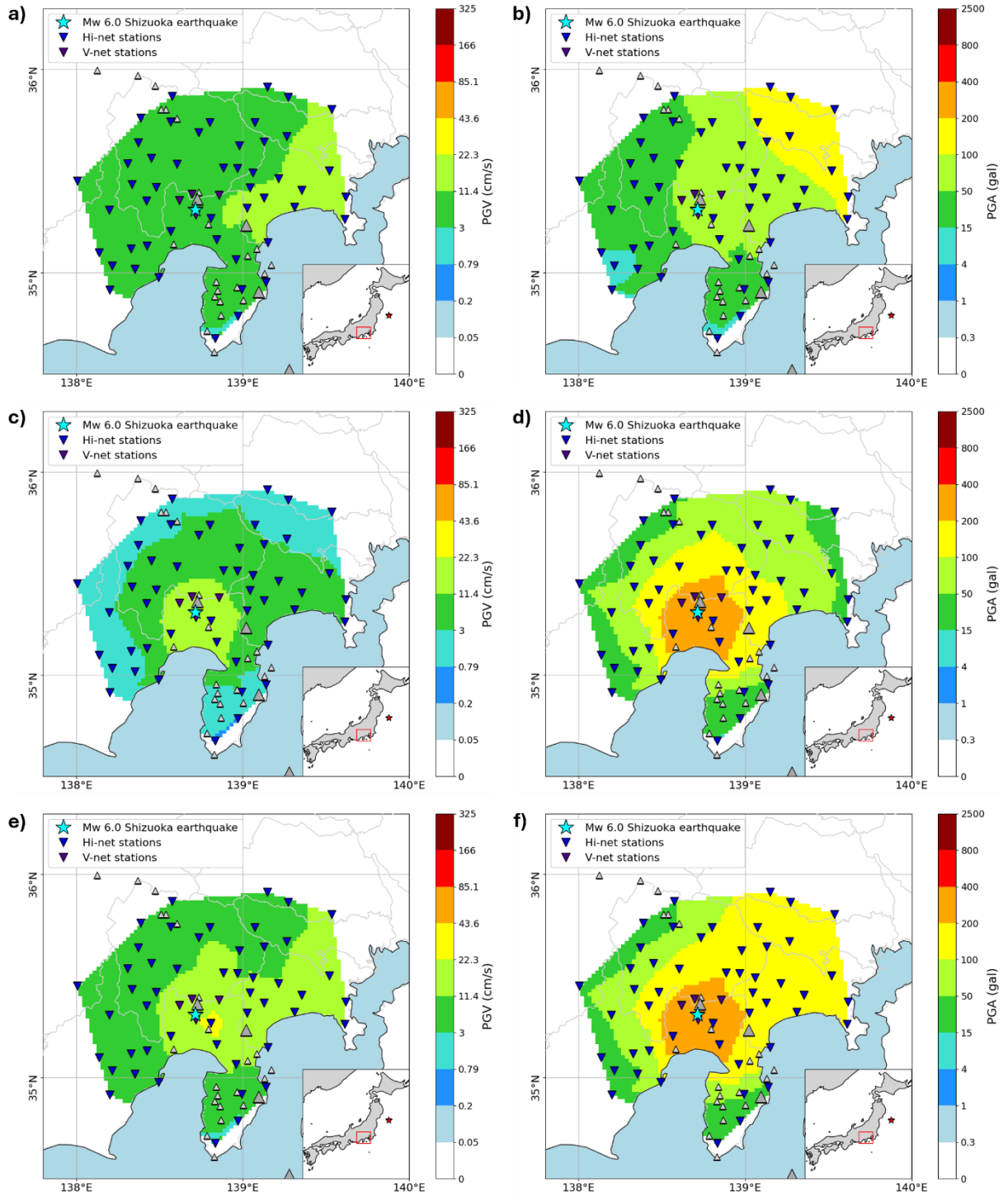


Figure S8. **a)** Map of the smoothed PGV of the M_w 9.0 Tohoku-Oki earthquake in the Mount Fuji area; **b)** Map of the smoothed PGA of the M_w 9.0 Tohoku-Oki earthquake in the Mount Fuji area; **c)** Map of the smoothed PGV of the M_w 6.0 East Shizuoka earthquake in the Mount Fuji area; **d)** Map of the smoothed PGA of the M_w 6.0 East Shizuoka earthquake in the Mount Fuji area; **e)** Map of the station-wise maximum of the smoothed PGV between the M_w 9.0 Tohoku-Oki and the M_w 6.0 East Shizuoka earthquakes in the Mount Fuji area; **f)** Map of the station-wise maximum of the smoothed PGA between the M_w 9.0 Tohoku-Oki and the M_w 6.0 East Shizuoka earthquakes in the Mount Fuji area. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes. The blue and purple inverted triangles are the Hi-net and V-net stations, respectively. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Mount Fuji area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter.

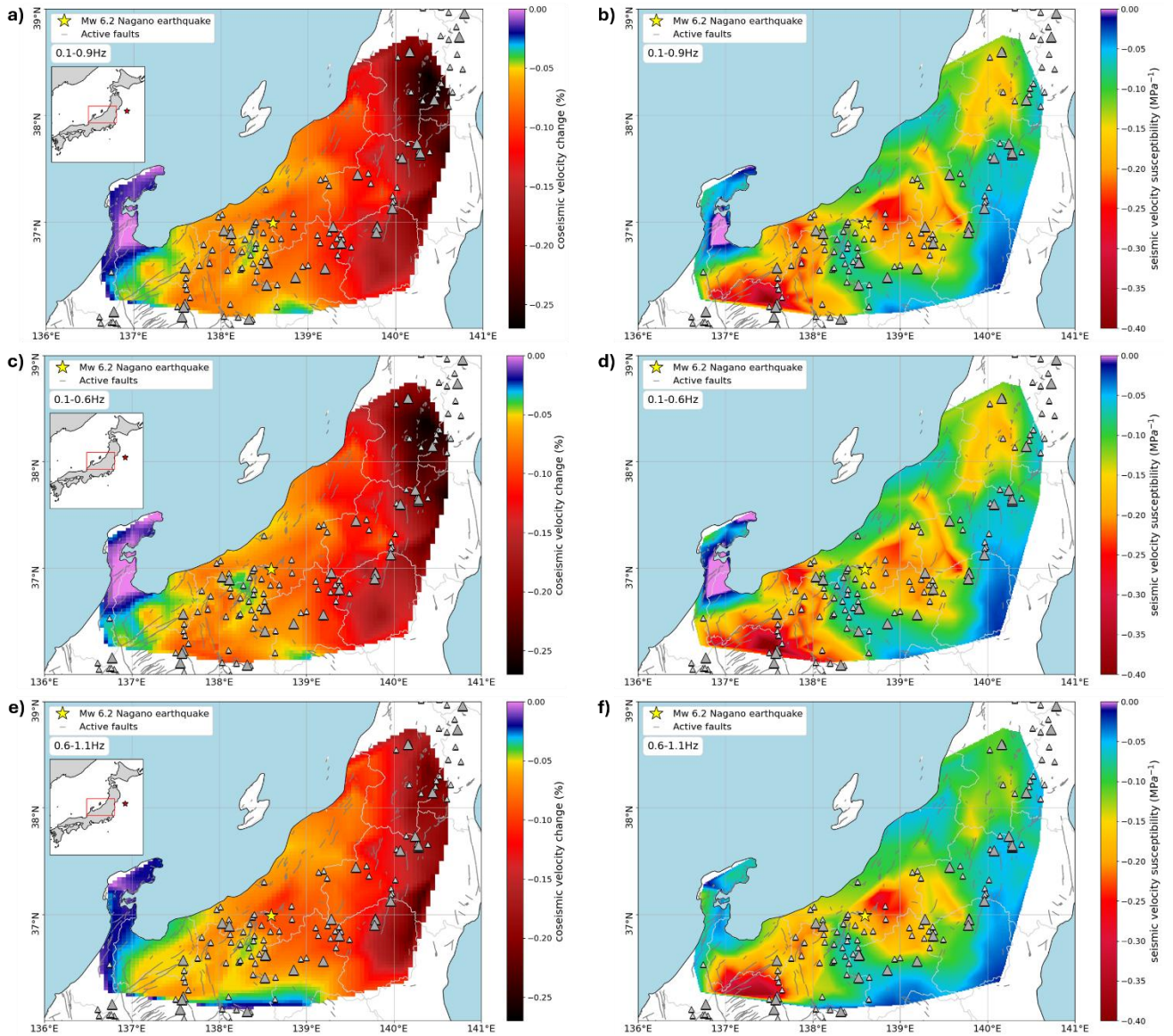


Figure S9. Map of the coseismic velocity changes for the Nagano area for **a)** 0.1–0.9 Hz; **c)** 0.1–0.6 Hz; **e)** 0.6–1.1 Hz. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes, the gray lines are the known active faults. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Nagano area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter; Map of the seismic wave velocity susceptibility to dynamic stress changes for the Nagano area for **b)** 0.1–0.9 Hz; **d)** 0.1–0.6 Hz; **f)** 0.6–1.1 Hz. The susceptibility is computed using only the Tohoku-Oki PGV. The legend is the same as the one shown in **a)**.

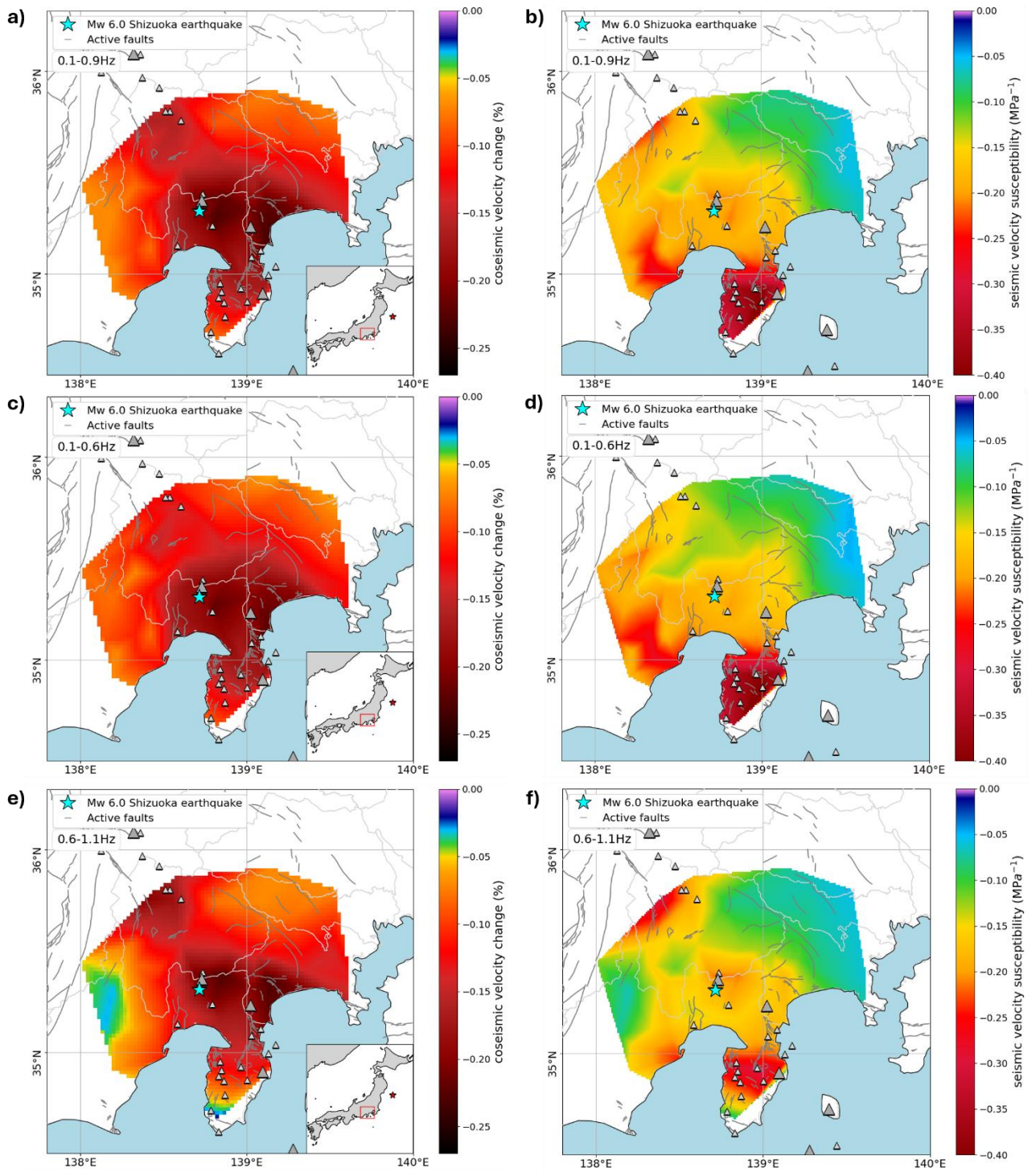


Figure S10. Map of the coseismic velocity changes for the Mount Fuji area for **a)** 0.1–0.9 Hz; **c)** 0.1–0.6 Hz; **e)** 0.6–1.1 Hz. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes, the gray lines are the known active faults. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter. The inset shows a map of Japan, the red rectangle delineates the Mount Fuji area study zone, the red star is the M_w 9.0 Tohoku-Oki earthquake epicenter; Map of the seismic wave velocity susceptibility to dynamic stress changes for the Mount Fuji area for **b)** 0.1–0.9 Hz; **d)** 0.1–0.6 Hz; **f)** 0.6–1.1 Hz. The susceptibility is computed using only the Tohoku-Oki PGV. The legend is the same as the one shown in **a)**.

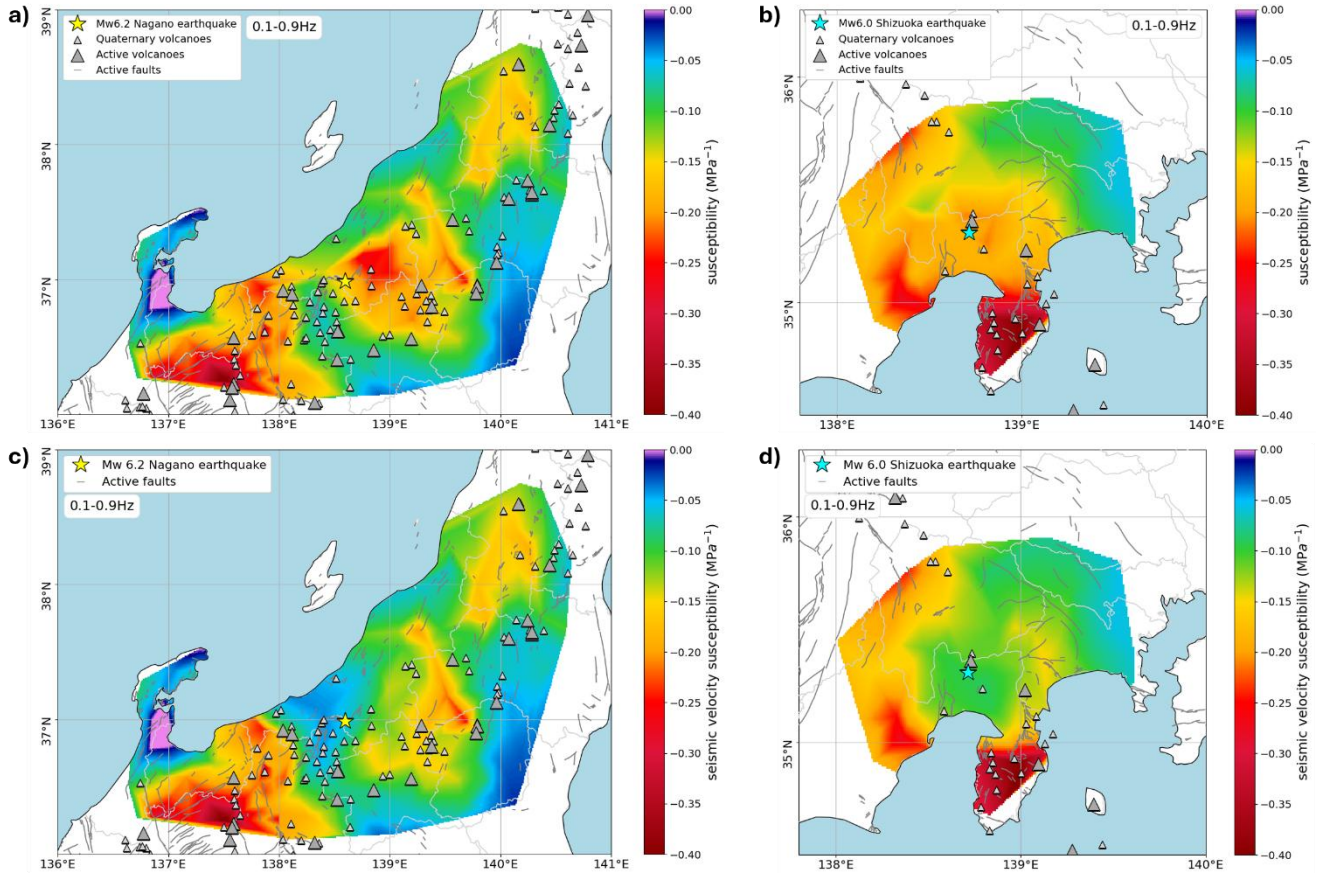


Figure S11. Map of the seismic wave velocity susceptibility to dynamic stress changes for the Nagano area (0.1–0.9 Hz) computed using **a)** only the M_w 9.0 Tohoku-Oki earthquake PGV; **c)** the station-wise maximum of the smoothed PGV values from the M_w 9.0 Tohoku-Oki and the M_w 6.2 Northern Nagano earthquakes; Map of the seismic wave velocity susceptibility to dynamic stress changes for the Mount Fuji area (0.1–0.9 Hz) computed using **b)** only the M_w 9.0 Tohoku-Oki earthquake PGV; **d)** the station-wise maximum of the smoothed PGV values from the M_w 9.0 Tohoku-Oki and the M_w 6.0 East Shizuoka earthquakes. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes, the gray lines are the known active faults. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter.

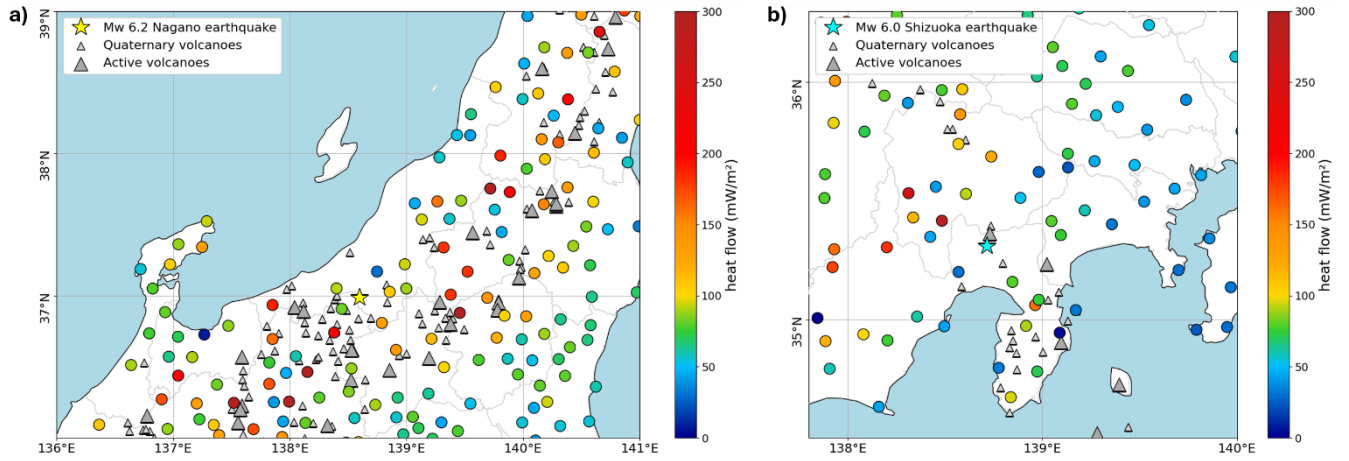


Figure S12. Map of the heat flow values measured at each Hi-net station, modified from heat-flow measurements reported by Matsumoto (2007), **a)** for the Nagano area; **b)** for the Mount Fuji area. The smaller gray triangles are the Quaternary volcanoes, the larger darker gray triangles are the active volcanoes. The yellow star is the M_w 6.2 Northern Nagano earthquake epicenter. The blue star is the M_w 6.0 East Shizuoka earthquake epicenter.

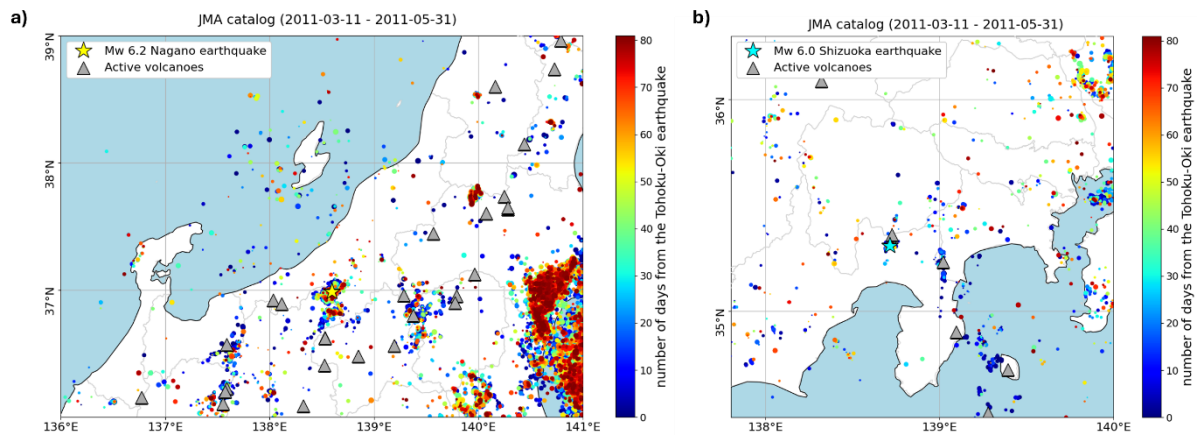


Figure S13. Spatial distribution of earthquakes from the Japan Meteorological Agency (JMA) (2011) unified hypocenter catalog between March 11 and May 31, 2011, for **a)** the Nagano area and **b)** the Mount Fuji area. Colors indicate the number of days elapsed since the M_w 9.0 Tohoku-Oki earthquake. Dark-gray triangles indicate active volcanoes. The yellow star marks the M_w 6.2 Northern Nagano earthquake epicenter, and the blue star marks the M_w 6.0 East Shizuoka earthquake epicenter.