

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

Louisa Bagot

Kyoto University: Kyoto Daigaku

Bogdan Enescu

`benescu@kugi.kyoto-u.ac.jp`

Kyoto University <https://orcid.org/0000-0003-2153-0097>

Florent Brenguier

Université Grenoble Alpes: Université Grenoble Alpes

Nicolas Paris

Université Grenoble Alpes: Université Grenoble Alpes

Quentin Higuier

Caltech: California Institute of Technology

Yusuke Kakiuchi

The University of Tokyo: Tokyo Daigaku

François Lavoué

Université Grenoble Alpes: Université Grenoble Alpes

Aurélien Mordret

Université Grenoble Alpes: Université Grenoble Alpes

Masatoshi Miyazawa

Kyoto University - Uji Campus: Kyoto Daigaku - Uji Campus

Tetsuya Takeda

NIED: Bosai Kagaku Gijutsu Kenkyujo

Research Article

Keywords: Ambient noise seismic interferometry, 2011 Tohoku-Oki earthquake, triggered earthquakes, coseismic velocity changes, seismic velocity susceptibility

Posted Date: October 7th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11004756/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Abstract

Large earthquakes can produce widespread seismic velocity changes through strong ground motion and associated perturbation of crustal stress and fluid conditions. Following the 2011 M_w 9.0 Tohoku-Oki earthquake, several large earthquakes were triggered across Japan, including the M_w 6.2 Northern Nagano earthquake and the M_w 6.0 East Shizuoka earthquake near Mount Fuji. Here, we investigate the spatial patterns of coseismic velocity changes in these two regions using ambient noise seismic interferometry. Velocity variations are estimated from noise cross-correlations using wavelet cross-spectrum analysis, with enhanced station-pair coverage in the Nagano region. Both study areas show coherent coseismic velocity decreases, with particularly large changes in volcanic regions. Comparison with peak ground acceleration indicates that stations along volcanic fronts commonly exhibit larger velocity decreases than expected from the regional shaking trend. We further estimate seismic velocity susceptibility to dynamic stress using peak ground velocity. Pronounced susceptibility anomalies are observed in volcanic regions. In Nagano, some coincide with areas of high heat flow, consistent with enhanced sensitivity of fluid-rich and/or mechanically compliant crust to dynamic stress perturbations. With improved spatial resolution in the Nagano region, we more clearly delineate the previously reported anomaly near the M_w 6.2 Northern Nagano earthquake and compare its spatial expression across frequency bands to obtain qualitative constraints on its possible origin. The volcanic front anomalies weaken at higher frequencies, whereas the localized anomaly near the Nagano earthquake becomes more pronounced and spatially confined. Because the temporal resolution prevents the separation of the Tohoku-Oki and subsequent local earthquakes, the origin of this localized anomaly cannot be uniquely determined. Nevertheless, its spatial distribution and frequency dependence are consistent with a contribution from local earthquake shaking and differ from the broader volcanic susceptibility pattern. These results show that spatial and frequency-dependent susceptibility patterns provide complementary information on the response of volcanic and tectonic regions to strong dynamic stress perturbations, while highlighting the need to account for triggered earthquakes when interpreting velocity changes following major earthquakes.

1. Introduction

Monitoring seismic wave velocity in the Earth's subsurface is a primary objective in seismology. Large earthquakes can induce seismic velocity decreases due to stress accumulation or pore pressure changes (Poupinet et al. 1984; Brenguier et al. 2008; Nakata and Snieder 2011). Such velocity changes have been attributed to dynamic stress perturbations associated with strong ground motion (Takagi et al. 2012; Sawazaki et al. 2016), static stress changes at depth (Wang et al. 2019), and pore-pressure changes associated with fluid migration, particularly in volcanic areas (Brenguier et al. 2014; Wang et al. 2021). A common method to monitor velocity variations is ambient noise seismic interferometry. By correlating continuous noise signals recorded at two stations, it is possible to retrieve an empirical estimation of the Green's function of the medium between these two stations, corresponding to the subsurface impulse response (Shapiro and Campillo 2004). Temporal seismic velocity variations can

then be estimated from these correlation functions (Sens-Schönfelder and Wegler 2006; Hobiger et al. 2012; Nimiya et al. 2017).

On March 11, 2011, the M_w 9.0 Tohoku-Oki earthquake occurred on the Japan Trench, leading to a devastating tsunami and causing extensive damage and many casualties. It also triggered widespread seismicity across Japan, with significant events occurring in areas that experienced small positive or even negative static stress changes (Terakawa et al. 2013). A possible mechanism for seismicity activation in such areas is dynamic stress perturbation associated with the passage of surface waves from the Tohoku-Oki earthquake and subsequent large events (Miyazawa 2011; Opris et al. 2018).

The M_w 6.2 Northern Nagano earthquake, which occurred 13 hours after the Tohoku-Oki megathrust event (Shimojo et al. 2014), is one of the relatively large inland earthquakes possibly triggered by the Tohoku-Oki earthquake. Shimojo et al. (2014, 2021) suggested that dynamic stress changes, possibly accompanied by aseismic processes such as fluid migration, may have contributed to seismic activation in the Nagano region prior to the M_w 6.2 event.

Significant post-Tohoku-Oki seismicity activation was predominantly observed in volcanic areas (Miyazawa 2011; Yukutake et al. 2013; Opris et al. 2018). Brenguier et al. (2014) showed that the Tohoku-Oki earthquake had a major impact on volcanic areas, where large velocity decreases were observed. These areas exhibit high seismic velocity susceptibility to dynamic stress changes, consistent with an important influence of highly pressurized fluids on the response of volcanic regions to dynamic stress perturbations. One notable event was the March 15, 2011, M_w 6.0 East Shizuoka earthquake that occurred on the southern side of Mount Fuji. Kakiuchi et al. (2024) were able to differentiate the local effect of this triggered earthquake from the impact of the Tohoku-Oki earthquake. Indeed, responses to triggered earthquakes may be obscured by the dominant Tohoku-Oki earthquake signal, complicating the estimation of the local impact of these events. It is important to analyze this local effect, as it can help to understand the different mechanisms behind large coseismic velocity changes.

This study investigates whether localized features in seismic velocity changes and susceptibility may reflect contributions from triggered earthquakes within the dominant response to the Tohoku-Oki megathrust earthquake. We investigate two regions affected by large, triggered earthquakes: the M_w 6.2 Northern Nagano and M_w 6.0 East Shizuoka events (Figs. 1a,b). Because the Northern Nagano earthquake occurred only a few hours after the Tohoku-Oki earthquake, its local impact is difficult to isolate from the broader regional response (Hobiger et al. 2016). We therefore examine the spatial distribution of coseismic velocity changes at a finer scale than Brenguier et al. (2014), using denser station-pair coverage in the Nagano region. We also analyze the Mount Fuji region using the cross-correlation data of Kakiuchi et al. (2024), providing a complementary volcanic setting for comparison.

The main advances of this study are the denser spatial coverage achieved in the Nagano region, the consistently processed comparison with the Mount Fuji region, and the characterization of seismic velocity susceptibility across multiple frequency bands. We compare the inferred velocity changes with

peak ground velocity and peak ground acceleration to characterize strong ground motion and assess susceptibility to dynamic stress perturbations. The results reveal enhanced susceptibility in volcanic regions and a localized anomaly near the Northern Nagano earthquake. The distinct frequency dependence of this anomaly provides additional constraints on its possible origin.

2. Data and methods

2.1. Data

We use three-component continuous waveforms recorded at seismic stations belonging to the high-sensitivity permanent Japanese network Hi-net (NIED 2019a). Stations have an average spacing of approximately 20 km. We selected 129 stations for the Nagano area and 53 stations for the Mount Fuji area (Figs. 1a,b). For the latter region, the data also include V-net stations (NIED 2019b) around Mount Fuji. We process data for an eight-month period, from January 1 to August 31, 2011. We retrieve velocity measurements for all station pairs separated by at most 30 km for both areas. Additionally, we include 154 station pairs beyond 30 km distance for the Nagano region: the spatial coverage is greatly improved, providing denser spatial sampling compared to previous studies. The noise cross-correlations for the Mount Fuji area were those computed by Kakiuchi et al. (2024).

Peak ground velocity (PGV) and peak ground acceleration (PGA) data of the M_w 9.0 Tohoku-Oki, M_w 6.2 Northern Nagano and M_w 6.0 East Shizuoka earthquakes from KiK-net measurements are also used (NIED 2019c). We selected the KiK-net boreholes sensors that are in the same boreholes as the Hi-net sensors used in this study. To compare our results to subsurface geological properties, we retrieved terrestrial heat flow measured in the Hi-net station boreholes by Matsumoto (2007).

For comparison with post-Tohoku-Oki seismicity, we also use hypocenter data from the Japan Meteorological Agency (JMA) (2011) unified hypocenter catalog for the period from March 11 to May 31, 2011.

2.2. Measurement of velocity changes

Hourly cross-correlations were computed in the 0.1–2.0 Hz frequency band and then stacked to obtain daily cross-correlation functions, for all nine component combinations of the Green's tensor (see Supplementary Material 1). This analysis was performed for 453 and 217 station pairs, in the Nagano and Mount Fuji regions, respectively (Figs. 2a, 3a). To enhance the measurement coherence, the correlations were averaged using a 30-day moving window (Fig. 1c). This processing reduces temporal resolution but improves convergence toward the Green's function (Takagi et al. 2012).

We perform the wavelet cross-spectrum analysis of these cross-correlation functions (Mao et al. 2020; Higuieret 2021; Paris et al. 2025). For each station pair, we first compute a reference waveform, obtained by stacking all the correlations, and calculate the cross-spectrum between each daily cross-correlation and the reference. This provides their phase difference at each frequency and lag time, from which we

derive seismic velocity changes. We apply this method to the coda of the station-pair cross-correlations. The coda contains waves scattered by heterogeneous structures, so it provides a more diffuse effective source distribution, improving convergence toward the full Green's function (Colombi et al. 2014). The wavelet cross-spectrum analysis is therefore performed on a selected time window, with a minimum lag time defined by the early coda, and the same fixed maximum lag time of 80 s for all station pairs (see Supplementary Material 2). This time window was chosen after comparing different possible maximum lag times (Figure S3). When selecting the time window, we also check the quality of the measurements by looking at the cross-coherence value from the cross-spectrum analysis. When the signal lacks coherence, the station pair is discarded (Figs. 2a,3a; Figures S1). This criterion leads to the rejection of 31 paths out of 453 for the Nagano area.

The sensitivity of scattered waves varies with frequency. We therefore compare velocity change estimates across several frequency bands. The wavelet cross-spectrum method was applied to three frequency bands: 0.1–0.9 Hz, 0.1–0.6 Hz and 0.6–1.1 Hz. Assuming a homogeneous surface wave velocity of 3 km/s, the depth sensitivity of these measurements extends from the shallow subsurface to a depth of approximately 5 km (Wang et al. 2021). The velocity change maps show broadly consistent large-scale spatial patterns across the three frequency bands, while also exhibiting band-dependent differences that are examined below (Figures S9a,c,e; S10a,c,e). To estimate the coseismic velocity changes and facilitate comparison with previous studies (Brennguier et al. 2014; Kakiuchi et al. 2024), we focus on the commonly used 0.1–0.9 Hz frequency band. We estimated the velocity change time series, denoted as dv/v , for each component combination and station pair and then averaged them over all component combinations. For each station, we subsequently averaged the time series of all station pairs that included that station, yielding a single station-based time series with improved coherence (Figure S2). We then calculated the coseismic velocity change, denoted as dv/v_{cos} , as the difference between the values of the last and first days whose 30-day moving average windows contained the mainshock (Fig. 1d; see Supplementary Material 2).

2.3. Smoothed PGV and PGA

An important control on coseismic velocity changes is the dynamic stress associated with strong ground motion. We characterize the shaking using both peak ground velocity, which is proportional to the dynamic strain and therefore enters the susceptibility calculation directly, and peak ground acceleration, which is the more common proxy for shaking intensity used in previous comparisons with velocity changes. We use PGV and PGA measurements for the M_w 9.0 Tohoku-Oki earthquake and the triggered local earthquakes. Because the 30-day velocity change estimates may contain contributions from both the Tohoku-Oki and local events, we additionally construct PGV and PGA maps based on the larger value recorded at each site during either event. These station-wise maximum values are used only as a sensitivity test to assess the influence of the local-earthquake shaking and are not interpreted as a measure of cumulative shaking.

The spatial distribution of PGA shows large values at some stations (> 800 gal at sites closer to the Tohoku-Oki earthquake epicenter; Figures S5b, S6b). To obtain spatially smoothed PGV and PGA fields,

the median value at each site is computed from measurements at stations within a 30 km radius. We then use these smoothed PGV and PGA values for each individual event (Figs. 2b, 3b, Figures S7a–d, S8a–d), or the alternative station-wise maxima across the Tohoku-Oki earthquake and the triggered event (Figures S7e,f, S8e,f).

2.4. Seismic velocity susceptibility

After retrieving coseismic velocity changes, we compute the seismic wave velocity susceptibility to dynamic stress perturbations. This analysis highlights areas that are more likely to have large velocity decreases during strong transient stress changes. Following the method of Brenguier et al. (2014), we define the dynamic stress as $\Delta \sigma = \mu v/c$, with $\mu = 30 \times 10^9$ Pa the mean crustal shear modulus, v the PGV (cm/s) and $c \approx 3$ km/s the mean Rayleigh wave phase velocity. The susceptibility can then be calculated as:

$$\frac{dv/v_{cos}}{\Delta \sigma}$$

where dv/v_{cos} is the coseismic velocity change. We used the smoothed PGV values (Figures S7, S8; see Supplementary Material 3) in these calculations. Because the 30-day velocity change estimate may include contributions from both the Tohoku-Oki and local earthquakes, we also test the influence of the PGV. The susceptibility is therefore computed for two distinct cases: one considering only the PGV of the Tohoku-Oki earthquake, and one using the larger PGV value at each station from either the Tohoku-Oki or the triggered event. The latter is treated as a sensitivity test rather than as a cumulative shaking measure. This analysis is performed for all three frequency bands to compare the frequency-dependent features.

3. Results

3.1. Coseismic velocity changes

Overall, the dv/v time series show high coherence in both study areas, with most values exceeding 0.7 (Figs. 2a and 3a). However, coherence remains low at some stations, such as HRNH and MYTH in the Nagano area; stations with a mean coherence below 0.4 were therefore excluded (Figure S4). From the resulting time series, we estimate the coseismic velocity change dv/v_{cos} associated with the earthquake sequence at each selected station. Most stations exhibit a coseismic velocity decrease (Fig. 1d), consistent with previous studies. Because the cross-correlations were averaged using a 30-day moving window, the effects of the Tohoku-Oki earthquake and the subsequently triggered local earthquakes cannot be separated in time. We therefore linearly interpolate the coseismic velocity change estimates and examine their spatial distribution for possible signatures of the local earthquakes.

For the Nagano area (Fig. 2c), the largest velocity decreases occur in the east, reaching -0.24% at KWSH, -0.25% at KMAH, and a maximum of -0.27% at TDOH. The decreases become progressively

smaller westward, with almost no velocity change observed on the Noto Peninsula (0.00% at SUZH). This pattern defines a pronounced east–west gradient that likely reflects the dominant regional impact of the Tohoku-Oki earthquake. Notably, the largest decreases in the northeast do not coincide with the highest smoothed PGA values (Fig. 2b). Relatively large decreases are also observed in the southwest (– 0.08% at TGKH and KTRH, – 0.07% at IGWH, and – 0.06% at YTOH) despite comparatively lower PGA values (Figs. 2b,c). Around the M_w 6.2 Northern Nagano earthquake, larger decreases are observed northeast of the epicenter (– 0.10% at KWNH, – 0.09% at SZWH and YNTH) than at nearby stations farther to the northeast (– 0.07% at TDMH, – 0.06% at STDH and NGOH). These stations lie within the area that experienced strong shaking during the Northern Nagano earthquake (Figure S7d).

For the Mount Fuji area, the spatial distribution differs from that observed in Nagano; the largest velocity decreases are not recorded at stations in the northeast, closest to the Tohoku-Oki earthquake (Fig. 3c). Instead, the largest decreases occur along the volcanic front, particularly around Mount Hakone (– 0.24% at MNZH and – 0.21% at ASGH) and Mount Fuji (– 0.23% at SSNH, – 0.22% at FJSV, and – 0.21% at FJ5V). Because the temporal resolution does not allow us to separate the effects of the M_w 6.0 East Shizuoka earthquake from those of the Tohoku-Oki earthquake, the estimated velocity changes may contain contributions from both events. Their spatial distribution does not closely follow the PGA pattern (Fig. 3b), suggesting that local volcanic conditions may exert an important control on the coseismic velocity changes.

3.2. Comparison with the PGA

To assess the relationship between velocity decreases and shaking intensity, the coseismic change dv/v_{cos} at each station is plotted as a function of the corresponding smoothed PGA value. For both areas, we observe a linear trend for most stations (Figs. 4a,b; see Supplementary Material 3), consistent with previous studies linking strong shaking to velocity changes. However, some stations deviate substantially from the trend and show a larger or smaller coseismic velocity change for their corresponding PGA value. We map the regression residuals to examine the spatial distribution of these deviations (Fig. 4c,d).

For the Nagano area, a few stations have a smaller velocity change than expected for their PGA value (blue dots in Fig. 4a). Stations KNAH and IWSH, for example, are located near the edge of the study area and close to discarded stations; therefore, they have poorer spatial coverage and low coherence (Figure S4). More notably, a cluster of stations above the regression trend (red dots in Fig. 4a) is located along the eastern volcanic front (Fig. 4c). This area recorded the largest coseismic decreases, even though it did not experience the largest PGA values (Fig. 2b). This observation suggests the modulation of velocity changes by volcanic structure. For the Mount Fuji area, we observe a similar result, with several stations substantially above the trend (Fig. 4b) that are also all located along the volcanic front, mostly around Mount Fuji and Mount Hakone (Fig. 4d).

3.3. Susceptibility and heat flow

The spatial distribution of seismic velocity susceptibility in the 0.1–0.9 Hz band is evaluated using alternative PGV references. Using only the Tohoku-Oki PGV, large susceptibility anomalies are observed along the volcanic fronts and near the triggered earthquake epicenters (Figs. 5a,b). As a sensitivity test, we also calculate susceptibility using the station-wise maximum PGV from the Tohoku-Oki or local triggered earthquake. This alternative normalization strongly reduces or removes the local anomaly, while leaving the broader spatial pattern largely comparable (Figure S11). Because the denominator increases where local shaking is strongest, this reduction is partly inherent to the calculation and cannot be interpreted as independent evidence for a local earthquake origin.

To better characterize the spatial features of these anomalies, we compare the results with those obtained in two narrower frequency bands: a higher-frequency band (0.6–1.1 Hz) and a lower-frequency band (0.1–0.6 Hz), considering only the Tohoku-Oki PGV. In the Nagano area, the 0.1–0.6 Hz band shows a spatial pattern similar to that of the 0.1–0.9 Hz band (Figs. 5a,c), with high susceptibilities along the eastern volcanic front and in the southwestern part of the study area. The most prominent feature is the anomaly east of the M_w 6.2 Northern Nagano earthquake epicenter, which appears less intense in the lower-frequency band (Figs. 5a,c). In the higher-frequency band (Fig. 5e), most anomalies along the eastern volcanic front weaken or disappear, whereas the anomaly near the triggered earthquake epicenter becomes more localized and pronounced. In the Mount Fuji area, the overall spatial pattern is similar across the three frequency bands. The largest susceptibility anomalies occur on the Izu Peninsula and in the southwestern part of the study area, while high susceptibility values are also observed around Mount Fuji and Mount Hakone (Figs. 5b,d,f). In the 0.6–1.1 Hz band, these anomalies appear somewhat more localized and better defined.

Because the susceptibility distribution highlights volcanic regions, we compare it with heat flow measurements reported by Matsumoto (2007) at several Hi-net stations (Figure S12). The heat flow values were interpolated to facilitate comparison with the spatial distribution of seismic-velocity susceptibility. In the Nagano area, regions of high susceptibility generally coincide with high heat flow, except near the Northern Nagano earthquake (Fig. 5g). In contrast, in the Mount Fuji area, the heat flow pattern does not closely correspond to the volcanic front or to the main susceptibility anomalies (Fig. 5h).

4. Discussion

The results show widespread coseismic velocity changes following the Tohoku-Oki earthquake in both study regions. In the Nagano area, we retrieve larger velocity decreases than those reported by Brenguier et al. (2014), particularly in the central part of the study area, where they found decreases of 0.02–0.04%, whereas we observe decreases of 0.06–0.08% (Fig. 2c). This difference may reflect both the use of a different method to estimate the velocity changes and the improved spatial coverage of our analysis, which enables a more detailed characterization of the regional pattern. The velocity decrease anomaly near the M_w 6.2 Northern Nagano earthquake was already apparent in Brenguier et al. (2014), but the denser station-pair coverage used here delineates its spatial distribution more clearly. Although the

temporal resolution does not allow us to separate the contribution of the triggered earthquake from that of the Tohoku-Oki earthquake, the spatial pattern is consistent with a local contribution from the Northern Nagano event. In the Mount Fuji area, the spatial distribution of the retrieved coseismic changes is broadly consistent with the results of Brenguier et al. (2014) and Kakiuchi et al. (2024). Kakiuchi et al. (2024) reported a larger velocity decrease south of Mount Hakone than at Mount Fuji, which is also observed in our results (-0.24% at MNZH compared with -0.21% at FJ5V). Because the M_w 6.0 East Shizuoka earthquake occurred close to Mount Fuji, its contribution cannot be spatially separated from the broader response to the Tohoku-Oki earthquake, which dominates the regional signal.

Comparison with the smoothed PGA highlights the influence of volcanic settings on the observed velocity changes. In both study regions, stations lying above the general velocity-change–PGA trend are concentrated along volcanic fronts (Fig. 4). This pattern is reinforced by the seismic velocity susceptibility results, which show large anomalies in volcanic regions (Fig. 5). In the Nagano area, the anomalies along the eastern volcanic front weaken or disappear in the higher-frequency band (Figs. 5a,c,e). Brenguier et al. (2014) showed that high seismic susceptibility to dynamic stress in volcanic regions may be associated with magmatic or highly pressurized fluids, which may help explain the distinct frequency dependence of the volcanic front anomalies. To further examine this relationship, we compare the susceptibility distribution with heat flow measurements (Fig. 5g). The two spatial patterns show some correspondence, consistent with an association between volcanic structure and coseismic velocity changes. In the Mount Fuji area, higher seismic velocity susceptibility is also observed around volcanic regions and on the Izu Peninsula. The latter may be related to the Izu collision zone, which contains numerous faults and may be characterized by relatively high crack density (Figs. 5b,d,f). In contrast to the Nagano area, the main susceptibility anomalies in the Mount Fuji region do not closely correspond to high heat flow values (Fig. 5h). One possible explanation is the relatively sparse distribution of available heat flow measurements around Mount Fuji and Mount Hakone (Figure S12). Also, Nimiya et al. (2020) found no shallow low-velocity anomaly indicative of magma storage beneath the Izu Peninsula, supporting a crack-related rather than magmatic origin for the susceptibility anomaly there.

In the higher frequency band, two prominent susceptibility anomalies are observed in the Nagano area (Fig. 5e). The larger anomaly in the southwest may be associated with faults along the Niigata–Kobe Tectonic Zone and with volcanic structure, as it broadly coincides with areas of high heat flow (Fig. 5g). Enhanced seismic activity was also observed in this region after the Tohoku-Oki earthquake (Terakawa et al. 2013; Figure S13). A second notable anomaly occurs northeast of the M_w 6.2 Northern Nagano earthquake epicenter and is also apparent in the results of Brenguier et al. (2014). Its frequency dependence differs from that of the volcanic front anomalies, which weaken in the higher-frequency band (Figs. 5c,e), suggesting that the Nagano anomaly may have a different origin. The stronger localization at higher frequency may reflect greater sensitivity to shallow, localized changes.

The sensitivity test using the station-wise maximum PGV recorded during either the Tohoku-Oki earthquake or the Northern Nagano earthquake strongly reduces or removes this local anomaly (Figures S11a,c). A similar effect is observed in the Mount Fuji region when the East Shizuoka earthquake is included in the alternative normalization (Figures S11b,d). However, this reduction is partly inherent to the calculation because the denominator increases where local earthquake shaking is strongest. The sensitivity test therefore demonstrates that the inferred susceptibility anomaly depends strongly on the choice of PGV, but it does not provide independent evidence that the anomaly was produced by the local earthquake. Additional support of a possible local contribution comes from the spatial correspondence between the susceptibility anomaly and the PGA distribution of the Northern Nagano earthquake (Figure S7d). Together, these observations are consistent with a contribution from local earthquake shaking, possibly through earthquake-induced damage or changes in crack and fluid conditions. The underlying physical mechanism, however, cannot be uniquely resolved by the present analysis.

Overall, the susceptibility patterns indicate that different processes may contribute to the observed coseismic velocity changes. The broad anomalies associated with volcanic regions are consistent with enhanced sensitivity of fluid-rich or mechanically compliant crust to dynamic stress perturbations, whereas the more localized anomaly near the Northern Nagano earthquake may partly reflect the effects of strong local shaking. Seismic velocity susceptibility may therefore provide a useful means of distinguishing regional volcanic signatures from more localized effects associated with triggered earthquakes, although the interpretation remains dependent on the temporal resolution of the velocity change measurements and on the choice of ground motion reference.

5. Conclusion

We performed ambient noise seismic interferometry in two regions of Japan that experienced large triggered earthquakes following the M_w 9.0 Tohoku-Oki earthquake: the M_w 6.2 Northern Nagano and M_w 6.0 East Shizuoka earthquakes. Using wavelet cross-spectrum analysis applied to noise cross-correlations, we retrieved time series of seismic velocity variations at selected stations. The estimated coseismic velocity changes show coherent spatial patterns, with larger decreases in volcanic regions. Comparison with PGA reveals velocity changes that deviate from the regional shaking trend, particularly along volcanic fronts in both study areas.

We then estimated seismic velocity susceptibility to dynamic stress perturbations. Its spatial distribution shows pronounced anomalies in volcanic regions, consistent with enhanced sensitivity of fluid-rich and/or mechanically compliant crust to dynamic stress. These results support a fluid-related contribution to the observed coseismic velocity response in volcanic settings.

Finally, we identify a localized susceptibility anomaly near the Northern Nagano earthquake. Although the temporal resolution does not allow us to separate its contribution from that of the Tohoku-Oki earthquake, the spatial pattern and its frequency dependence are consistent with a contribution from local earthquake shaking. This highlights the need to consider triggered earthquakes when interpreting

mainshock-centered velocity changes. More generally, seismic velocity susceptibility may help provide complementary information on broad volcanic signatures from localized effects associated with strong shaking, although its interpretation depends on the ground motion reference.

Abbreviations

M_w

Moment magnitude

PGV

Peak Ground Velocity

PGA

Peak Ground Acceleration

NIED

National Research Institute for Earth Science and Disaster Resilience

Hi

net—High Sensitivity Seismograph Network Japan (NIED)

KiK

net—Kiban Kyoshin Network (NIED)

V

net—Fundamental Volcano Observation Network (NIED)

Declarations

Ethics approval and consent to participate:

Not applicable.

Consent for publication:

Not applicable.

Competing interests:

The authors declare that they have no competing interests.

Funding:

LB is grateful for the MEXT scholarship awarded for her PhD studies. BE acknowledges support from JSPS KAKENHI Grant Number JP26K07241 and from the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, under the Third Earthquake and Volcano Hazards Observation and Research Program (Earthquake and Volcano Hazard Reduction Research).

Authors' contributions:

LB performed data processing and analysis with the contributions of NP and YK. TT, MM and BE provided data-related guidance. This study was designed by LB, BE and FB. LB, FB, NP, QH, FL and AM contributed to the methodology and interpretation of the results. The original draft was written by LB and further edited by BE. All authors read and approved the final manuscript.

Acknowledgements:

We thank Dr. Takumi Matsumoto, NIED, for providing the heat flow data. We are also grateful to Professor Shiro Ohmi, DPRI, and the participants of the Kyoto University seismology seminar for helpful discussions.

Availability of data and materials:

The continuous waveforms from Hi-net and V-net, as well as the PGV and PGA measurements from KiK-net, are publicly available from the National Research Institute for Earth Science and Disaster Resilience (NIED, <https://www.hinet.bosai.go.jp/>; <https://www.vnet.bosai.go.jp/> and <https://www.kyoshin.bosai.go.jp/ja/>). The heat flow measurements can be requested from Takumi Matsumoto. The coseismic velocity changes evaluated during the current study are available from the corresponding author on reasonable request.

References

1. Brenguier F, Campillo M, Hadziioannou C, Shapiro NM, Nadeau RM, Larose E (2008) Postseismic relaxation along the San Andreas Fault at Parkfield from continuous seismological observations. *Science* 321(5895):1478–1481. 10.1126/science.1160943
2. Brenguier F, Campillo M, Takeda T, Aoki Y, Shapiro NM, Briand X, Emoto K, Miyake H (2014) Mapping pressurized volcanic fluids from induced crustal seismic velocity drops. *Science* 345(6192):80–82. 10.1126/science.1254073
3. Colombi A, Chaput J, Brenguier F, Hillers G, Roux P, Campillo M (2014) On the temporal stability of the coda of ambient noise correlations. *Comptes Rendus Géoscience* 346(11–12):307–316. 10.1016/j.crte.2014.10.002
4. Higueret Q (2021) Qhig/cross-wavelet-transform: First release of a cross wavelet transform algorithm in Python (v1.0.0) [Software]. *Zenodo*. 10.5281/zenodo.4783514
5. Hobiger M, Wegler U, Shiomi K, Nakahara H (2012) Coseismic and postseismic elastic wave velocity variations caused by the 2008 Iwate-Miyagi Nairiku earthquake, Japan. *J Geophys Res Solid Earth* 117:B09313. 10.1029/2012JB009402

6. Hobiger M, Wegler U, Shiomi K, Nakahara H (2016) Coseismic and post-seismic velocity changes detected by Passive Image Interferometry: comparison of one great and five strong earthquakes in Japan. *Geophys J Int* 205(2):1053–1073. 10.1093/gji/ggw066
7. Japan Meteorological Agency (JMA) (2011) The Seismological Bulletin of Japan: Hypocenter data. Japan Meteorological Agency, Tokyo, Japan
8. 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. 10.1029/2023JB027978
9. Mao S, Mordret A, Campillo M, Fang H, van der Hilst RD (2020) On the measurement of seismic traveltime changes in the time–frequency domain with wavelet cross-spectrum analysis. *Geophys J Int* 221(1):550–568. 10.1093/gji/ggz495
10. Matsumoto T (2007) Terrestrial heat flow distribution in Japan area based on the temperature logging in the borehole of NIED Hi-net. Abstract T23A-1217 presented at 2007. Fall Meeting, AGU, San Francisco, CA
11. Miyazawa M (2011) Propagation of an earthquake triggering front from the 2011 Tohoku-Oki earthquake. *Geophys Res Lett* 38:L23307. 10.1029/2011GL049795
12. Nakata N, Snieder R (2011) Near-surface weakening in Japan after the 2011 Tohoku-Oki earthquake. *Geophys Res Lett* 38:L17302. 10.1029/2011GL048800
13. National Research Institute for Earth Science and Disaster Resilience (2019a) NIED Hi-net [dataset]. National Research Institute for Earth Science and Disaster Resilience. 10.17598/NIED.0003
14. National Research Institute for Earth Science and Disaster Resilience (2019b) NIED V-net [dataset]. National Research Institute for Earth Science and Disaster Resilience. 10.17598/NIED.0006
15. National Research Institute for Earth Science and Disaster Resilience (2019c) NIED K-NET, KiK-net [dataset]. National Research Institute for Earth Science and Disaster Resilience. 10.17598/NIED.0004
16. Nimiya H, Ikeda T, Tsuji T (2017) Spatial and temporal seismic velocity changes on Kyushu Island during the 2016 Kumamoto earthquake. *Sci Adv* 3:e1700813. 10.1126/sciadv.1700813
17. Nimiya H, Ikeda T, Tsuji T (2020) Three-dimensional S wave velocity structure of central Japan estimated by surface-wave tomography using ambient noise. *J Geophys Research: Solid Earth* 125. 10.1029/2019JB019043
18. Opris A, Enescu B, Yagi Y, Zhuang J (2018) Triggering and decay characteristics of dynamically activated seismicity in Southwest Japan. *Geophys J Int* 212(2):1010–1021. 10.1093/gji/ggx456
19. 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 Mw 7.5 Noto earthquake, Japan. *Earth Planet Space* 77:51. 10.1186/s40623-025-02177-x
20. Poupinet G, Ellsworth WL, Fréchet J (1984) Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras Fault, California. *J Geophys Res* 89(B7):5719–5731. 10.1029/JB089iB07p05719

21. Sawazaki K, Saito T, Ueno T, Shiomi K (2016) Estimation of seismic velocity changes at different depths associated with the 2014 Northern Nagano Prefecture earthquake, Japan (Mw 6.2) by joint interferometric analysis of NIED Hi-net and KiK-net records. *Prog Earth Planet Sci* 3:36. 10.1186/s40645-016-0112-7
22. Sens-Schönfelder C, Wegler U (2006) Passive image interferometry and seasonal variations of seismic velocities at Merapi Volcano, Indonesia. *Geophys Res Lett* 33:L21302. 10.1029/2006GL027797
23. Shapiro NM, Campillo M (2004) Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise. *Geophys Res Lett* 31:L07614. 10.1029/2004GL019491
24. Shimojo K, Enescu B, Yagi Y, Takeda T (2014) Fluid-driven seismicity activation in northern Nagano region after the 2011 M9.0 Tohoku-Oki earthquake. *Geophys Res Lett* 41:7524–7531. 10.1002/2014GL061763
25. Shimojo K, Enescu B, Yagi Y, Takeda T (2021) Nucleation process of the 2011 northern Nagano earthquake from nearby seismic observations. *Sci Rep* 11:8143. 10.1038/s41598-021-86837-4
26. Takagi R, Okada T, Nakahara H, Umino N, Hasegawa A (2012) Coseismic velocity change in and around the focal region of the 2008 Iwate-Miyagi Nairiku earthquake. *J Geophys Res Solid Earth* 117:B06315. 10.1029/2012JB009252
27. Terakawa T, Hashimoto C, Matsu'ura M (2013) Changes in seismic activity following the 2011 Tohoku-Oki earthquake: effects of pore fluid pressure. *Earth Planet Sci Lett* 365:17–24. 10.1016/j.epsl.2013.01.017
28. Wang Q-Y, Campillo M, Brenguier F, Lecointre A, Takeda T, Hashima A (2019) Evidence of changes of seismic properties in the entire crust beneath Japan after the Mw 9.0, 2011 Tohoku-Oki earthquake. *J Geophys Res Solid Earth* 124:8924–8941. 10.1029/2019JB017803
29. Wang Q-Y, Campillo M, Brenguier F, Lecointre A, Takeda T, Yoshida K (2021) Seismic evidence of fluid migration in northeastern Japan after the 2011 Tohoku-Oki earthquake. *Earth Planet Sci Lett* 563:116894. 10.1016/j.epsl.2021.116894
30. Yukutake Y, Miyazawa M, Honda R, Harada M, Ito H, Sakaue M et al (2013) Remotely triggered seismic activity in Hakone volcano during and after the passage of surface waves from the 2011 M9. 0 Tohoku-Oki earthquake. *Earth Planet Sci Lett* 373:205–216. 10.1016/j.epsl.2013.05.004

Figures

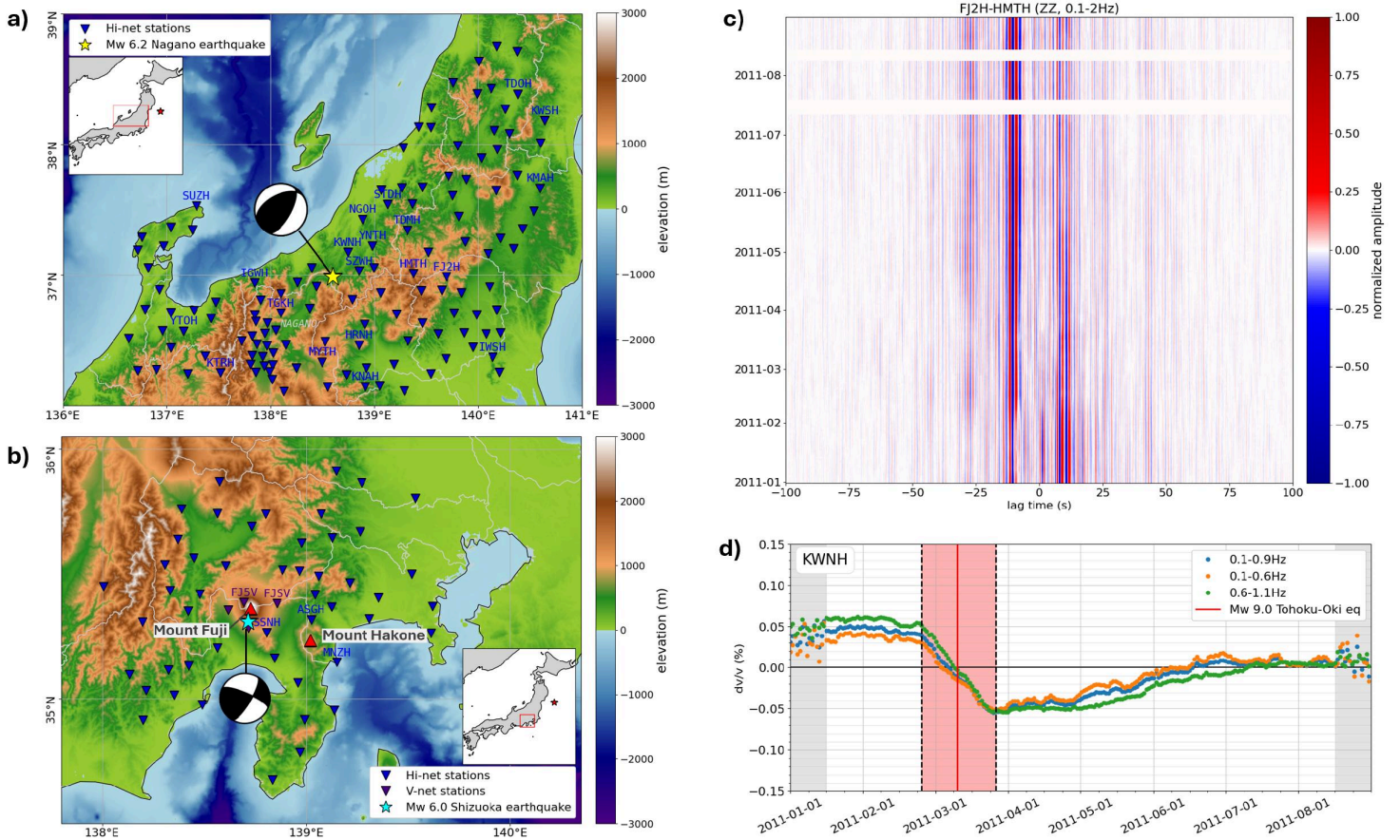


Figure 1

a) Map of the Nagano study area showing the selected Hi-net stations (blue inverted triangles), the M_w 6.2 Northern Nagano earthquake epicenter (yellow star), its focal mechanism, and elevation (color scale). The inset shows the location of the study area in Japan (red rectangle) and the M_w 9.0 Tohoku-Oki earthquake epicenter (red star). **b)** Map of the Mount Fuji study area showing the selected Hi-net stations (blue inverted triangles), V-net stations (purple inverted triangles), the M_w 6.0 East Shizuoka earthquake epicenter (blue star), its focal mechanism, and elevation (color scale). Red triangles mark Mount Fuji and Mount Hakone. The inset shows the location of the study area in Japan (red rectangle) and the M_w 9.0 Tohoku-Oki earthquake epicenter (red star). **c)** Correlograms of the ZZ-component for station pair FJ2H–HMTH in the 0.1–2 Hz band after a 30-day moving average. The color scale indicates the normalized amplitude. **d)** Seismic velocity variation time series at station KWNH for the three analyzed frequency bands. 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.

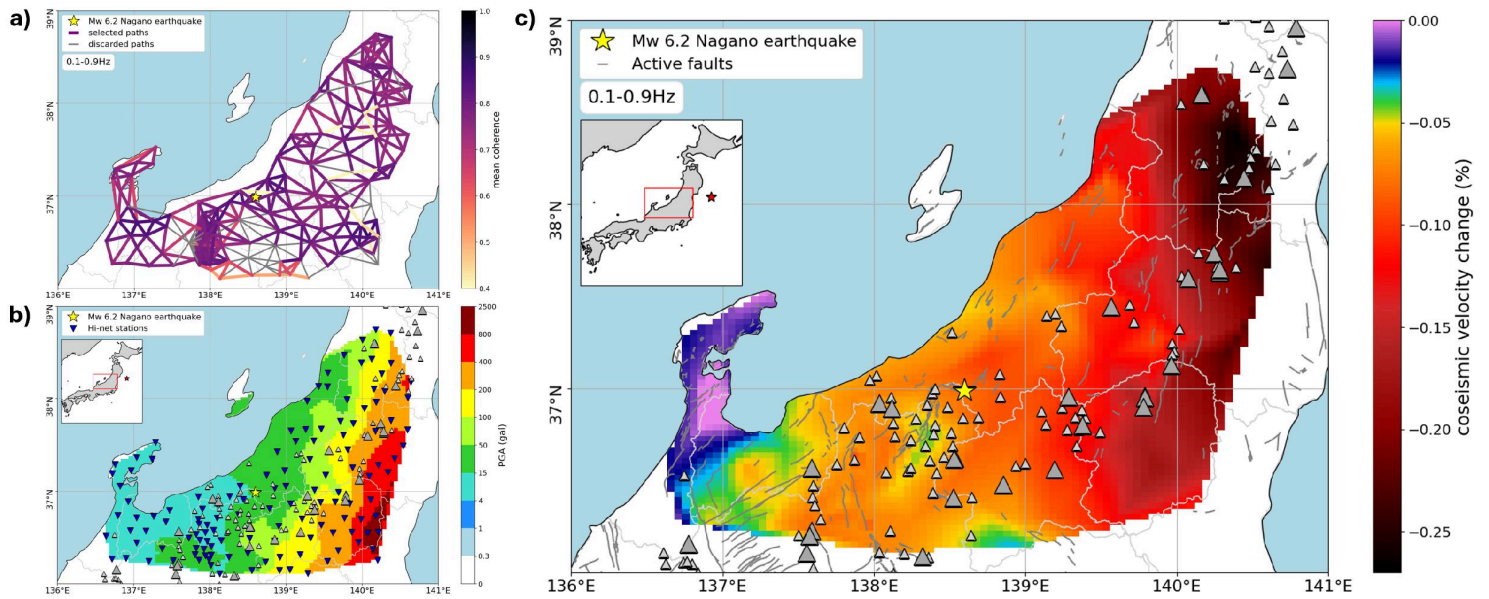


Figure 2

a) Station-pair paths used for the velocity-change analysis in the Nagano area in the 0.1–0.9 Hz band. Selected paths are colored according to their mean coherence, whereas discarded paths are shown in gray. The yellow star marks the M_w 6.2 Northern Nagano earthquake epicenter. **b)** Spatially smoothed PGA field of the M_w 9.0 Tohoku-Oki earthquake in the Nagano area. Small light-gray triangles indicate Quaternary volcanoes, larger dark-gray triangles indicate active volcanoes, and blue inverted triangles indicate Hi-net stations. The yellow star marks the M_w 6.2 Northern Nagano earthquake epicenter. The inset shows the study area in Japan (red rectangle) and the M_w 9.0 Tohoku-Oki earthquake epicenter (red star). **c)** Interpolated spatial distribution of the coseismic velocity change in the 0.1–0.9 Hz band. Symbols are as in **b)**; gray lines indicate known active faults.

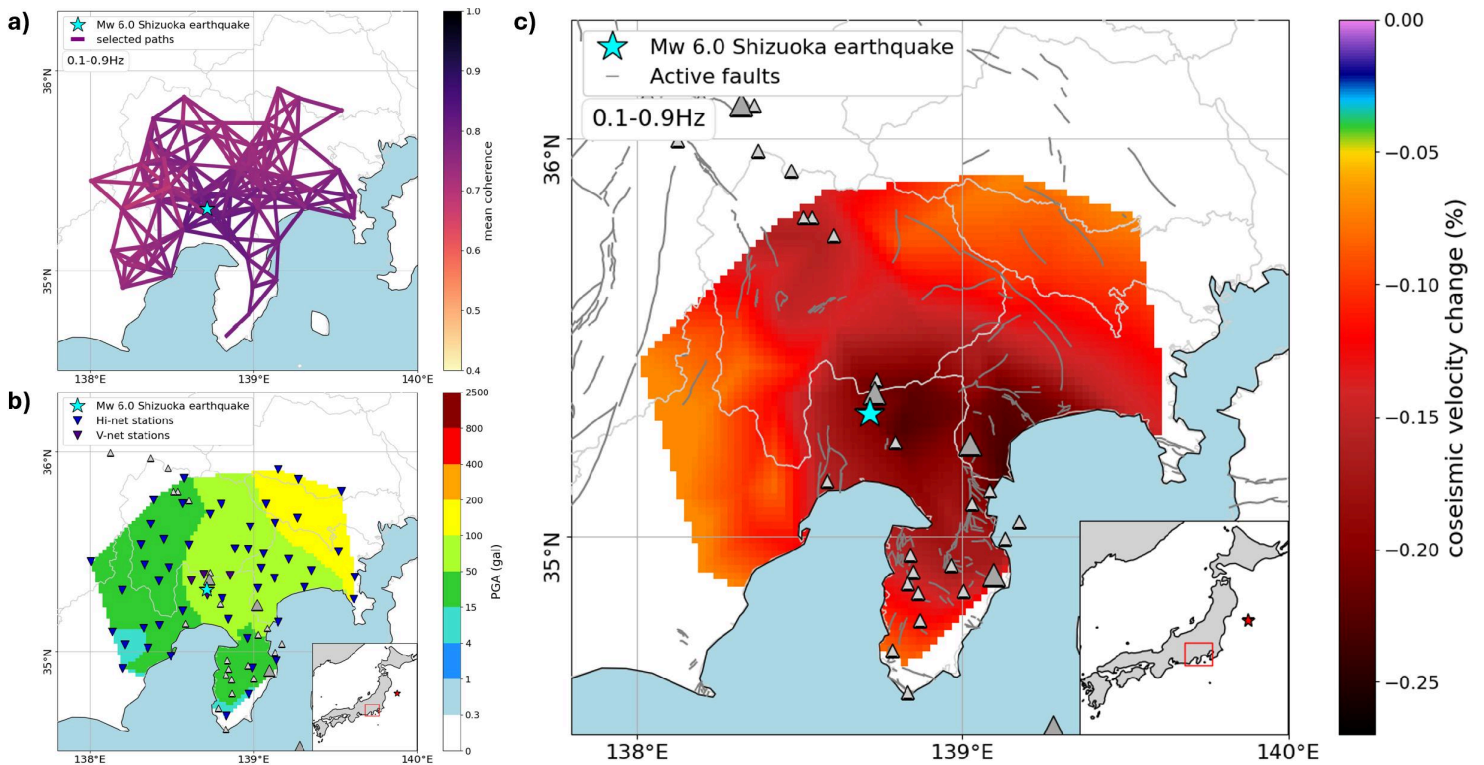


Figure 3

a) Station-pair paths used for the velocity-change analysis in the Mount Fuji area in the 0.1–0.9 Hz band. All paths passed the coherence screening and are colored according to their mean coherence. The blue star marks the M_w 6.0 East Shizuoka earthquake epicenter. **b)** Spatially smoothed PGA field of the M_w 9.0 Tohoku-Oki earthquake in the Mount Fuji area. Small light-gray triangles indicate Quaternary volcanoes, larger dark-gray triangles indicate active volcanoes, blue and purple inverted triangles indicate Hi-net and V-net stations, respectively. The blue star marks the M_w 6.0 East Shizuoka earthquake epicenter. The inset shows the study area in Japan (red rectangle) and the M_w 9.0 Tohoku-Oki earthquake epicenter (red star). **c)** Interpolated spatial distribution of the coseismic velocity change in the 0.1–0.9 Hz band. Symbols are as in **b)**; gray lines indicate known active faults.

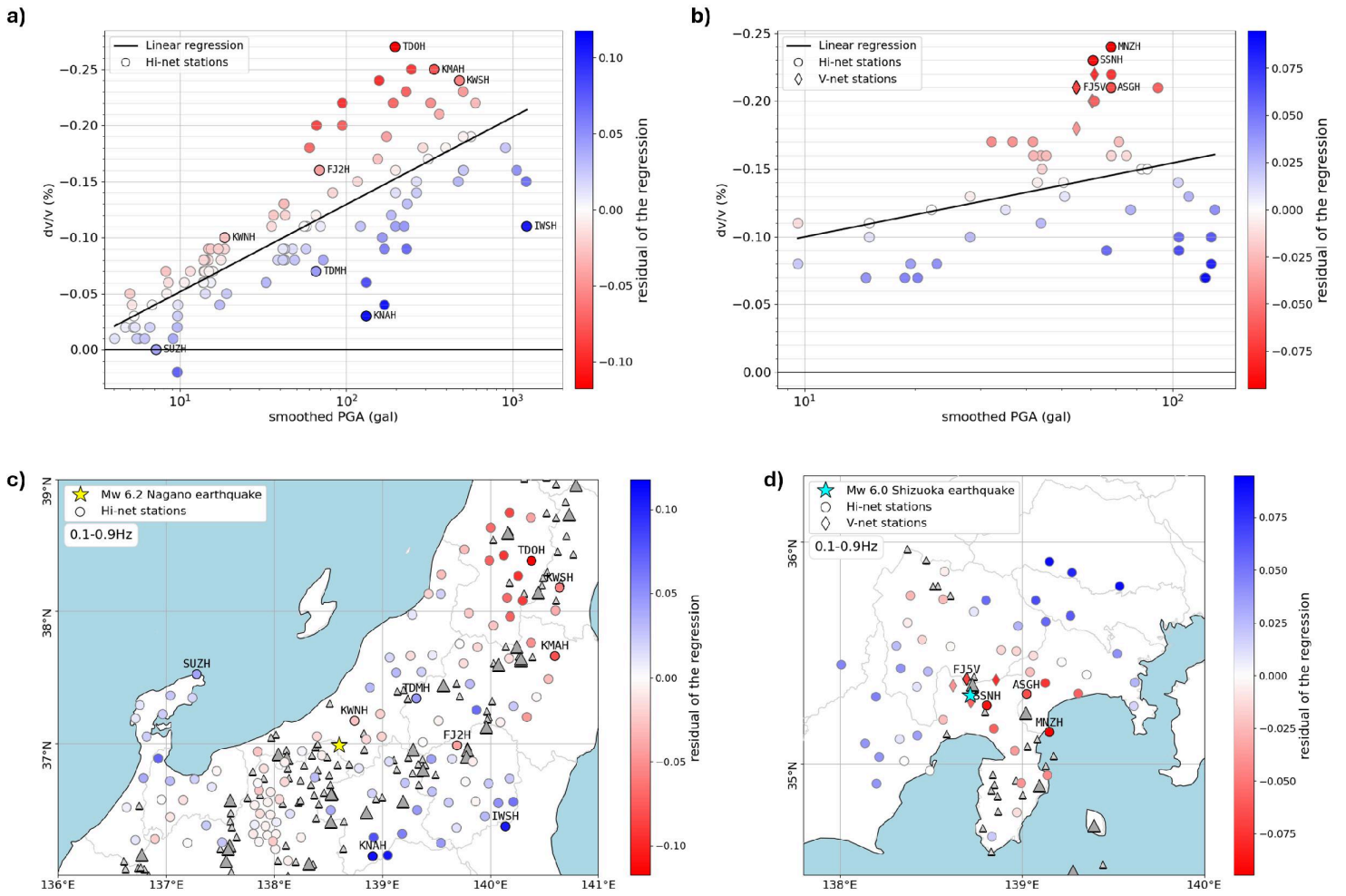


Figure 4

a) Coseismic velocity change as a function of the smoothed PGA for the Nagano area in the 0.1–0.9 Hz band. The black line shows the linear regression, and station values are colored according to the regression residual. **b)** Same as **a)** for the Mount Fuji area. **c)** Spatial distribution of the regression residuals shown in **a)** for the Nagano area. Circles indicate Hi-net stations and are colored according to the residual. Small light-gray triangles indicate Quaternary volcanoes, larger dark-gray triangles indicate active volcanoes, and gray lines indicate known active faults. The yellow star marks the M_w 6.2 Northern Nagano earthquake epicenter. **d)** Spatial distribution of the regression residuals shown in **b)** for the Mount Fuji area. Circles and diamonds indicate Hi-net and V-net stations, respectively, and are colored according to the residual. Other symbols are as in **c)**, with the blue star marking the M_w 6.0 East Shizuoka earthquake epicenter.

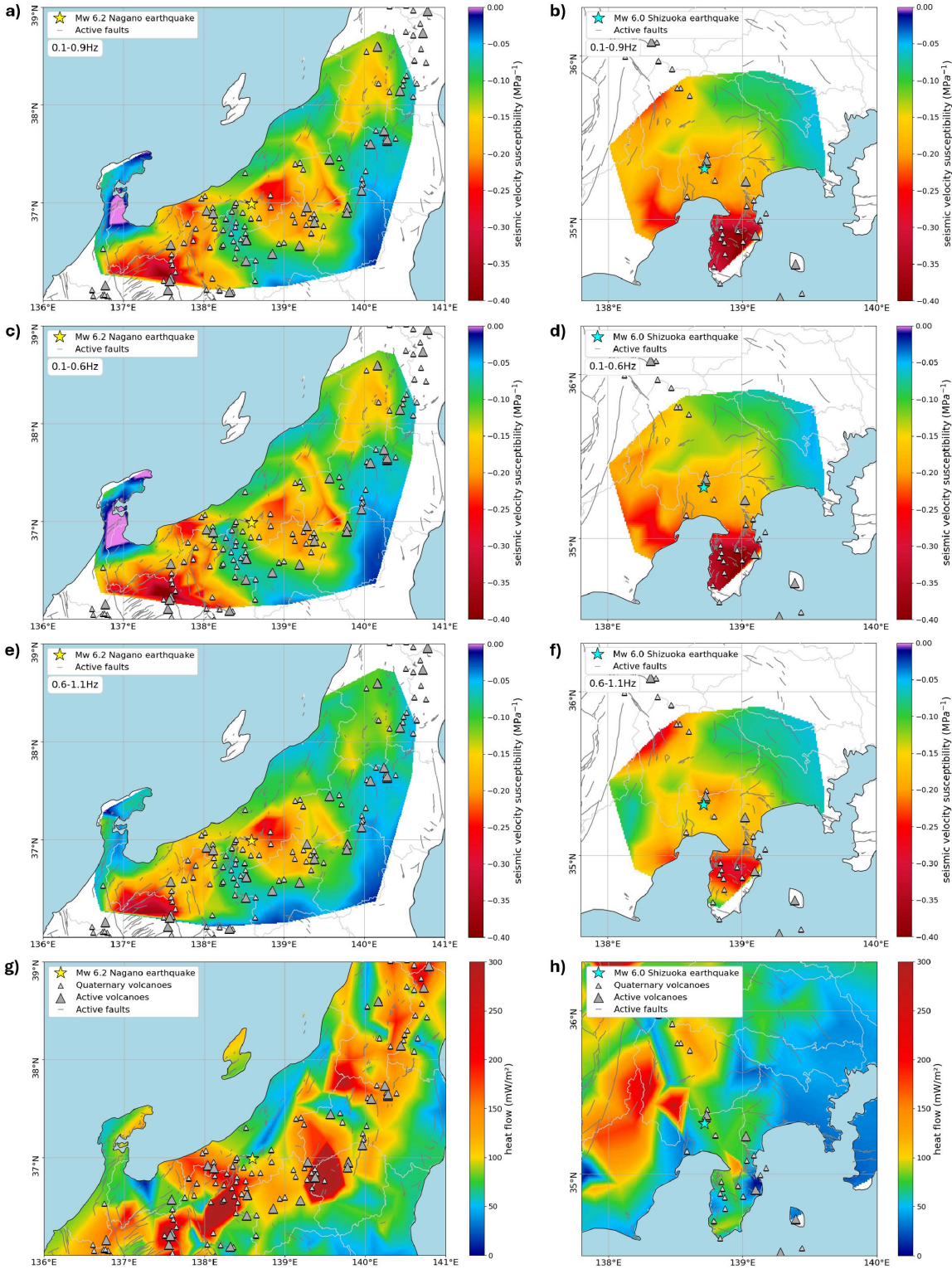


Figure 5

Spatial distribution of seismic velocity susceptibility to dynamic stress perturbations, calculated using the Tohoku-Oki PGV, for the Nagano area in the **a)** 0.1–0.9 Hz, **c)** 0.1–0.6 Hz, and **e)** 0.6–1.1 Hz bands, and for the Mount Fuji area in the **b)** 0.1–0.9 Hz, **d)** 0.1–0.6 Hz, and **f)** 0.6–1.1 Hz bands. The color scales indicate susceptibility (MPa⁻¹). Small light-gray triangles indicate Quaternary volcanoes, larger dark-gray triangles indicate active volcanoes, and gray lines indicate known active faults. The yellow star

marks the M_w 6.2 Northern Nagano earthquake epicenter in the Nagano panels, and the blue star marks the M_w 6.0 East Shizuoka earthquake epicenter in the Mount Fuji panels. **g, h**) Interpolated heat flow fields derived from the measurements reported by Matsumoto (2007) for **g**) the Nagano area and **h**) the Mount Fuji area. The color scales indicate heat flow (mW m^{-2}); map symbols are as in the corresponding susceptibility panels.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [BagotetalEPSsupplementarymaterials.pdf.pdf](#)
- [graphicalabstract.png](#)