

Seismic Velocity Variations Observed Prior to the La Palma Volcano Eruption on 19 September 2021, in Cumbre Vieja, Canary Islands (Spain)

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Abstract

In the recent years, coda-wave interferometry from seismic noise correlation functions has been increasingly used for volcanic eruption forecasting through velocity changes observed in the crust. Because La Palma Island in the Canary Archipelago is very well instrumented, we studied the possible velocity variations related to the last Cumbre Vieja eruption on 19 September 2021, aiming to obtain clear variations in the seismic velocity. For this purpose, we used the moving-window cross-spectral analysis technique for seismic noise within the 0.1–1.0 Hz frequency interval for determining two- and single-station cross-component correlations. During the 2018–2022 observation period, we first detected a seasonal seismic velocity variation possibly caused by annual rainfall and the induced pore pressure change. On 12 September 2021, a dramatic decrease in the velocity of -0.15% was detected, leading to the volcanic eruption at Cumbre Vieja seven days later. The results are compatible with those of models proposed for rapid magma migration from a shallow reservoir at 11 km to the surface.

Cite this article as Mezcua, J. and J. Rueda (2024). Seismic Velocity Variations Observed Prior to the La Palma Volcano Eruption on 19 September 2021, in Cumbre Vieja, Canary Islands (Spain), *The Seismic Record*. **4**(1), 11–20, doi: [10.1785/0320230048](https://doi.org/10.1785/0320230048).

Supplemental Material

Introduction

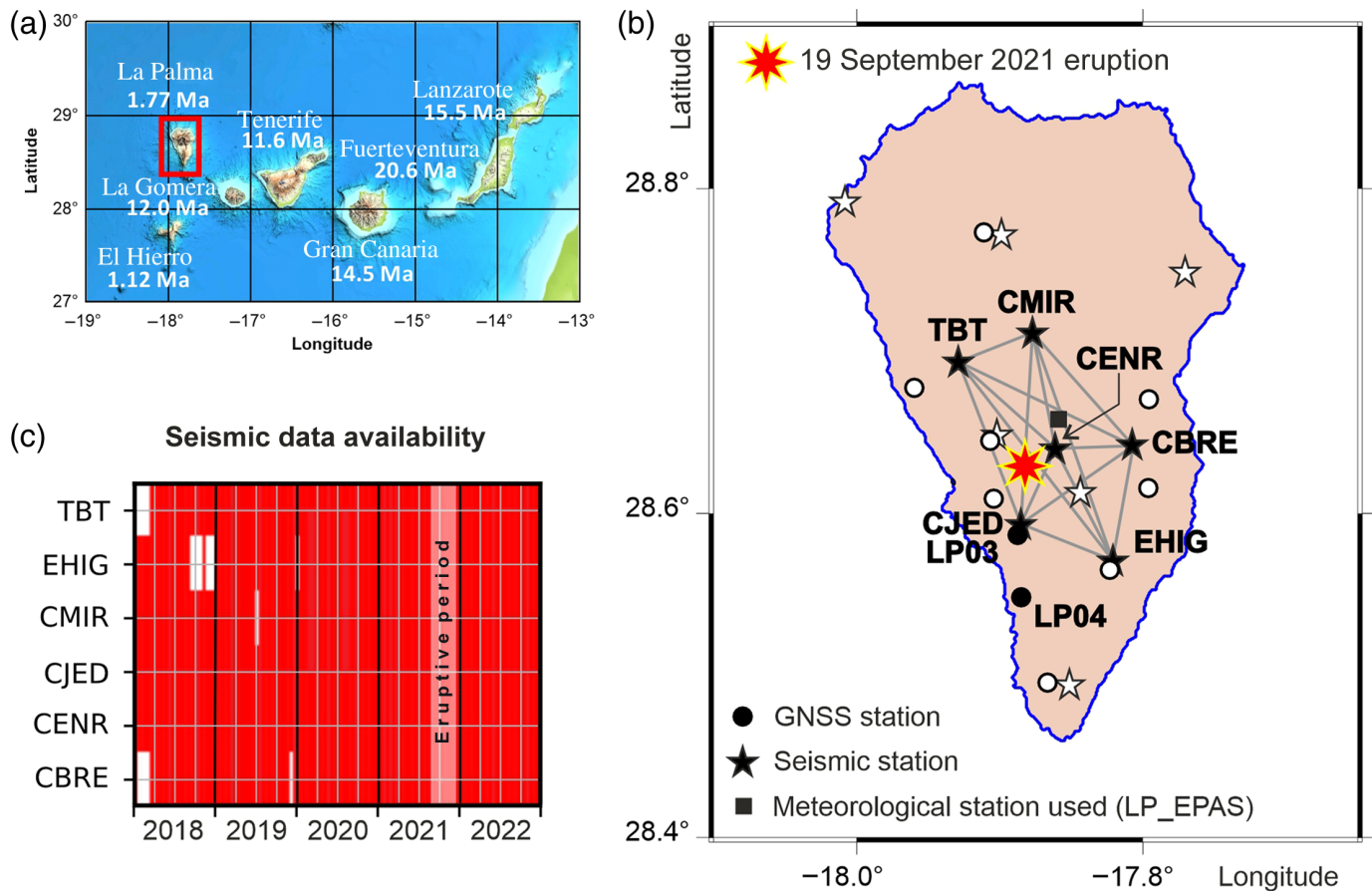
Most historical and recent volcanic eruptions on La Palma in the Canary Islands (Fig. 1a) were preceded by different manifestations, such as ground fissures, ground changes produced by subtle swelling, and notable earthquakes (Bonelli, 1950; Romero, 1991; Rueda *et al.*, 2020). These signals may be considered the result of deeper processes that usually occur prior to an imminent volcanic eruption, such as underground movement of magma (Brenguier *et al.*, 2008, 2016), presence of water or steam (Taira and Brenguier, 2016), and magma pressurization changes, which may be accompanied by associated crack dilation or compression (Obermann *et al.*, 2013; Donaldson *et al.*, 2017, 2019), thus modifying the elastic properties of media. Consequently, variations in the velocity of elastic wave propagation are expected under volcanic unrest. In particular, velocity changes were detected in inflation and deflation processes associated with volcanic eruptions by Patanè *et al.* (2003), Brenguier *et al.* (2008), and Obermann *et al.* (2013). The alternative methods for monitoring these

possible velocity changes are either temporal repeated tomography or seismic noise interferometry. Repeated tomography using a dense instrument network around the volcanic edifice may reveal the expected temporal velocity changes. However, contrary to expectations, an irregular spatial-temporal local seismicity distribution may introduce larger apparent velocity changes than those corresponding with inner structural changes (Berezhnev *et al.*, 2023). On 19 September 2021, an eruption occurred at Cumbre Vieja in La Palma in the Canary Islands after a series of swarms starting in 2017 (Torres-González *et al.*, 2020; Mezcua and Rueda, 2023). This

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Strombolian eruption was characterized by effusive lava emission through fissures in a multicrater vent complex (Carracedo *et al.*, 2022). Several signs were observed before the 2017 and 2018 swarms, such as variations in the hydrogen concentration and air-corrected helium isotopic ratio (Torres-González *et al.*, 2020). In addition, deformation of several centimeters was observed 3.5 months before the eruption started (Fernández *et al.*, 2022). This long-term preparation process of the 2021 Cumbre Vieja eruption should be reflected in changes in the elastic properties of the structure that can be observed through variations in the seismic velocity, as was detected recently by Cabrera-Pérez *et al.* (2023). For this purpose, in this work, we use ambient noise interferometry (ANI; Snieder, 2006) to observe the temporal variation in the seismic velocity with high accuracy. In this study, ANI analysis is performed using the cross correlations between the fourteen possible pairs of the six selected stations and the cross correlations between the different components of a single station. The signals retrieved from the cross-correlation functions are predominantly surface waves with the associated frequency–depth dependence, and, consequently, it is possible to maintain control of the sampled crustal depths. However, in the case of

Figure 1. (a) Location of the Canary Islands (Spain). (b) Distribution of Instituto Geográfico Nacional (IGN) broadband stations at La Palma in the Canary Islands (white stars); the six stations used in this study, with their names, are denoted by black stars. Lines connecting different stations represent the pair of stations used in this study. The Global Navigation Satellite Systems (GNSS) stations in operation during the study are denoted by white circles, and the stations considered in this analysis are LP03 and LP04 (black circles). The meteorological station used in this study LP_EPAS is represented by a black square. Topographic and bathymetric data are from the National Geographic Institute, the Oceanography Spanish Institute, and the Navy Hydrographic Institute of Spain. (c) Data availability for the seismic stations used in this work showing the eruption interval.

single-station cross correlations between the different components, we register only singly and multiply scattered waves of the media around the station.

Data and Methods

We investigated possible velocity changes dv/v using the seismic stations operated by the Instituto Geográfico Nacional of Spain since mid-2017 as part of the National Seismic Network (Fig. 1b). We selected six broadband stations around the volcanic edifice

with complete data from the beginning of 2018 and during the eruption (Fig. 1c). In this study, we considered microseismic ambient noise in the 0.1–1.0 Hz frequency band, which is sensitive to the structure at a depth of a few kilometers, where we estimated the volcanic process. The six selected stations covered the expected area of the volcanic process, delineated by the seismicity patterns recorded before and during the eruption (Mezcua and Rueda, 2023). We avoided the use of long-distance pairs for those stations located outside of the Cumbre Vieja unit (Carracedo *et al.*, 2022). In Figure 1b, we include all stations belonging to the National Seismic Network. However, the six stations considered in this study are also shown with their names. The selected stations covered the expected area defined by the seismicity recorded before and during the eruptive process, with the exception of two stations inside this area (open stars), because they covered only a few months in 2021 and not enough data were stored in this case. The data availability is shown in Figure 1c.

The data are transmitted in real time to the headquarters in Madrid, where a systematic analysis and location process is performed. The sampling frequency is 100 Hz for the three broadband components used. In the preprocessing process, we eliminate single spikes. Upon data collection, a band-pass filter between 0.01 and 8.0 Hz is applied, and the data are finally resampled to 20 Hz.

Following the guidelines proposed in MSNOISE software (Lecocq *et al.*, 2014) used in this work, for measuring the seismic velocity changes dv/v , several steps can be considered. First, the original records are demeaned, spectrally whitened and subjected to one-bit normalization processing to eliminate possible earthquakes (Bensen *et al.*, 2007). In the next step, we obtain cross-correlation functions of the registered noise at 30 min intervals, and daily averaged for the vertical component (ZZ) for each station pair is considered. We also obtain the cross correlation for the different pairs of components (EZ, NZ, and EN) of the selected stations. Third, to facilitate enhancement, stacking is performed of the two- or single-station correlations. Finally, temporal velocity variations are obtained using ANI by measuring the apparent time shift between the cross-correlation functions of the two-station (NCF) or single-station (ACF) and reference (RNCF) obtained for a period of time without interference from seismic or volcanic events. To show the data stability over time of the NCFs and ACFs, a correlogram of the EN cross correlation for station CJED is shown in Figure 2, which is only interrupted during the eruption interval. Coherence with respect to the RNCF is

also shown by comparing the different moving-window stackings of 1, 5, 10, and 15 days. The decreases in the correlation coefficient starting on 19 September 2021 correspond to the Cumbre Vieja eruption interval.

Travel-time delays are performed for different arrivals between the individual NCFs/ACFs and a previously defined cross correlation of the RNCF using moving-window cross-spectral analysis. The time delay dt detected at the center of the time t window “ dt/t ” is equivalent to “ $-dv/v$ ”—the change in the velocity for the sampled crust (Ratdomopurbo and Poupinet, 1995). The selected time-window length was 12 s with a step of 2 s for the three filters. In Figure 3a, we show the weighted mean velocity variation (ZZ) obtained for the fourteen pairs of stations for the 2018–2022 period, which includes the reference period. The data considered for the RNCF are selected for the time interval of 1 March 2018–30 June 2020, which is considered free of significant seismic or volcanic events, as corroborated by the seismic spectral-amplitude measurement (0.5–15.0 Hz) for the reference period at station CENR, close to the volcanic edifice (Fig. 3b). As expected, no velocity variations are observed during the reference period, and the observed minor velocity variations may be considered the noise level of the velocity variations. In Figure 3a, we also show the rainfall observed at meteorological station LP_EPAS (Fig. 1b) close to the volcanic edifice, indicating a probable negative correlation involving a positive time lag with the dv/v values obtained over the same period, following Andajani *et al.* (2020). In Figure 3c, we show the NCFs for the different pairs (Z component) of stations used in the 0.1–1.0 Hz interval ordered by the interstation distance (in km) over the reference period. Clear direct arrivals (mainly Rayleigh waves) are observed on both the sides (causal and acausal). The observed symmetry between the positive and negative values suggests that similar sources are present on both the sides of the island. We also include the travel times corresponding to wave propagation at 1, 2, and 3 km/s through the island.

Velocity Changes Observed Prior to the Cumbre Vieja Eruption on 19 September 2021

The calculated mean ± 2 standard deviations and the weighted mean of the velocity changes dv/v using the fourteen pairs of stations for the ZZ components are shown in Figure 4 for 1, 5, 10, and 15 days moving windows in the 0.1–1.0 Hz frequency interval. In the same figure, we include the daily seismic activity, the vertical deformation observed at Global Navigation Satellite

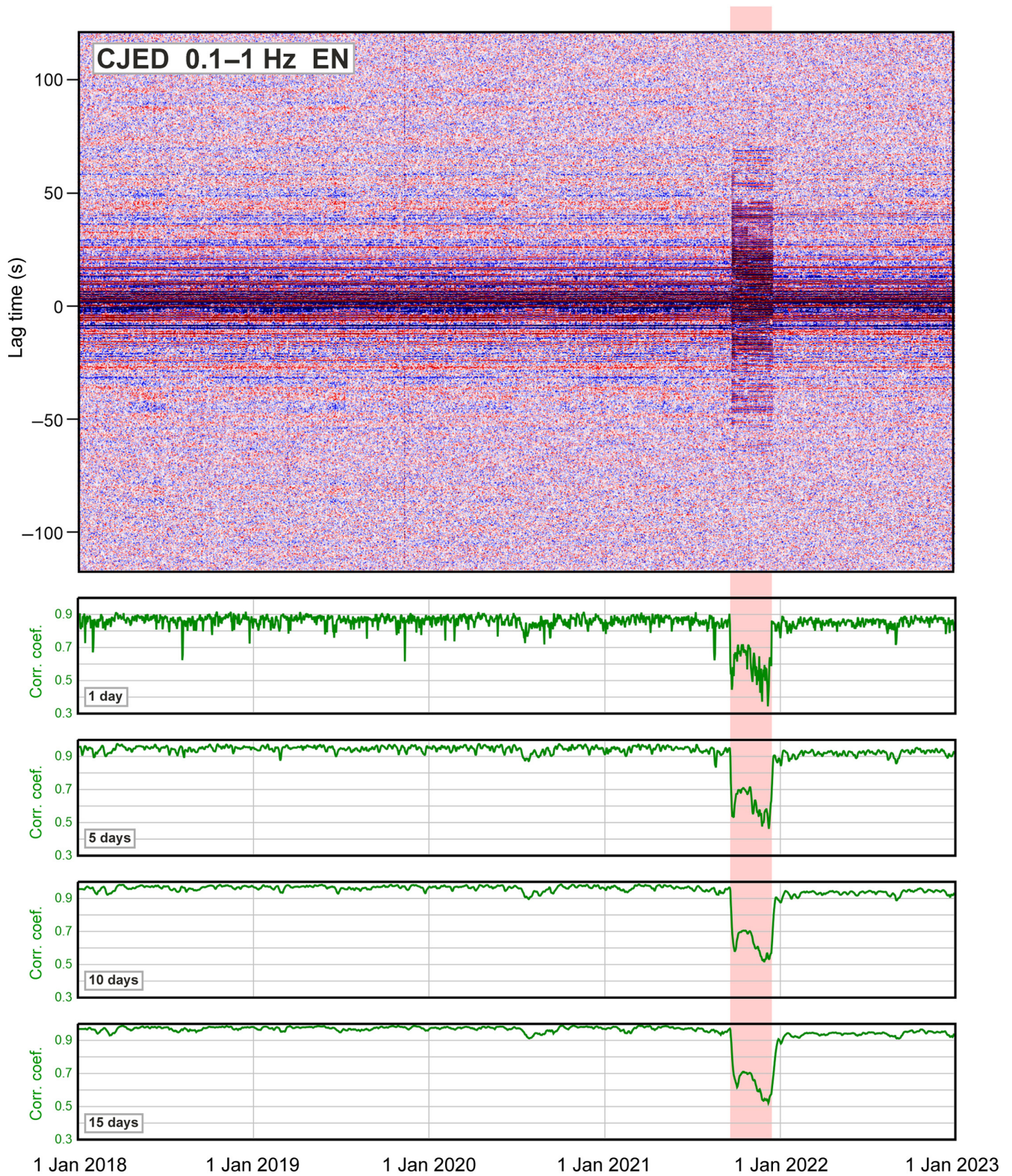


Figure 2. Cross-correlation functions (ACFs) for the EN components as a function of time for the CJED station for the period 2018–2022. Correlation coefficients with the reference (RNCF) are determined for

1-, 5-, 10-, and 15-day moving windows. The eruption period is also shown with lower correlation coefficients (pink box).

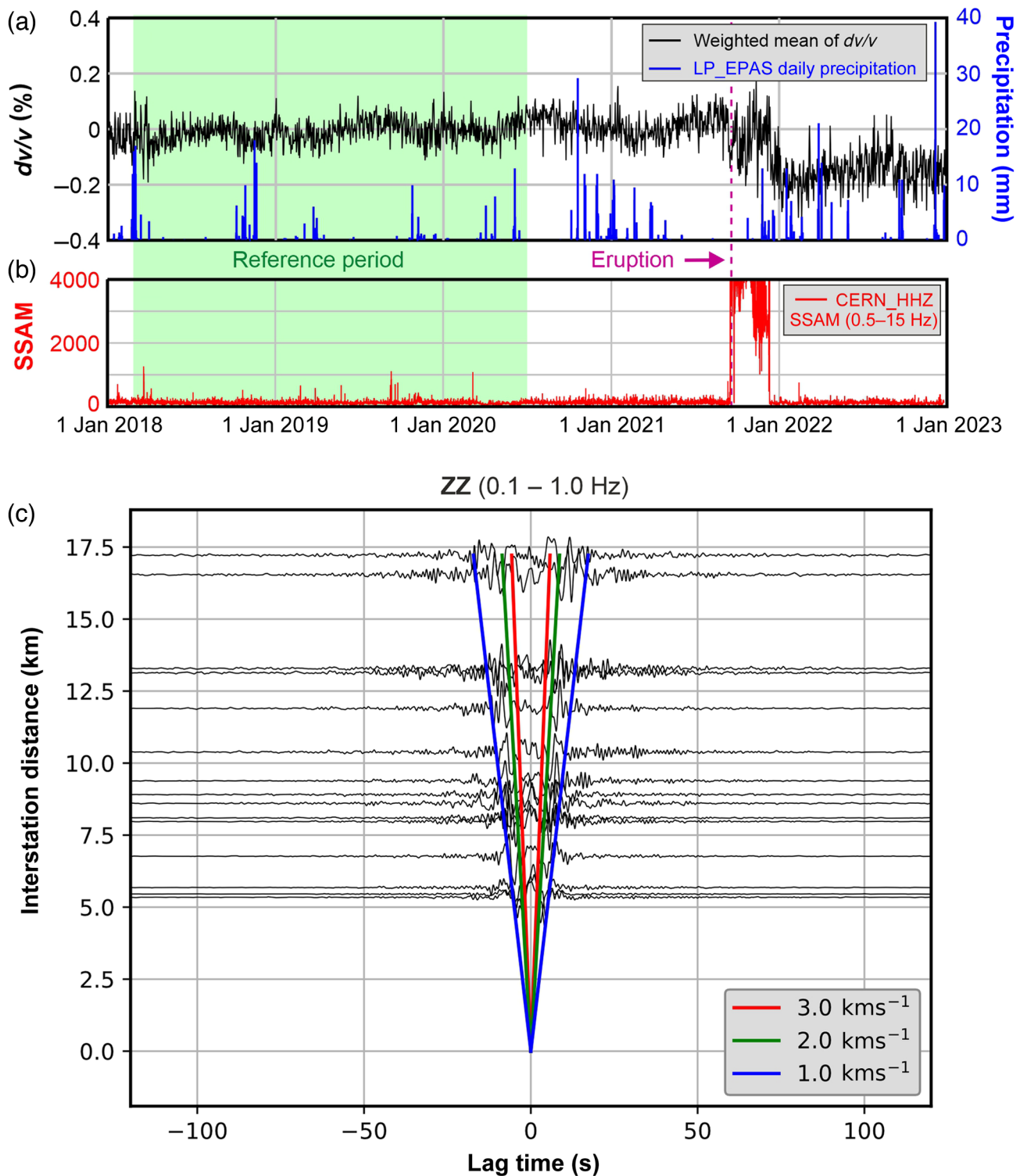


Figure 3. (a) Weighted mean of the velocity variation obtained for the fourteen pairs of stations for the 2018–2022 period and daily precipitation registered at nearby meteorological station LP_EPAS. (b) Seismic spectral amplitude measurement (SSAM) for the frequency interval of 0.5–15 Hz at station CERN for the vertical component during the same

time interval. (c) Cross-correlation functions for the vertical components obtained in the 0.10–1.0 Hz frequency band for the different pairs of stations plotted against the interstation distance for the reference period. The travel times of 1, 2, and 3 km s^{-1} correspond to the different ballistic waves arriving before the noise used in this study.

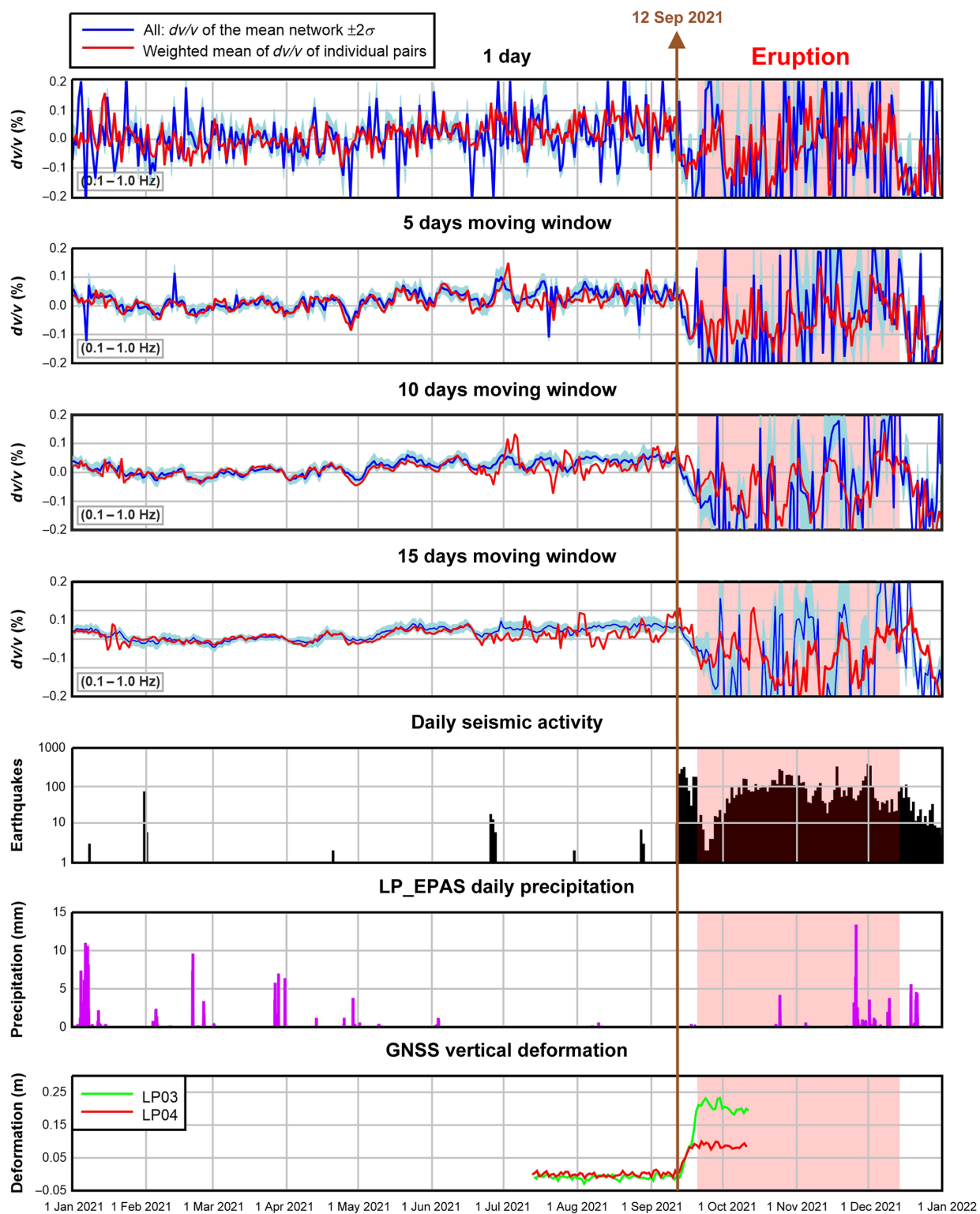


Figure 4. Mean with ± 2 standard deviation (blue) and the weighted mean of dv/v (red line) detected for 2021 at a window frequency band of 0.1–1.0 Hz for different moving windows showing the eruption time (pink box). The daily seismic activity, the vertical deformations observed at

the LP03 and LP04 GNSS stations, and the precipitation at the LP_EPAS meteorological station are also included. The date of the start of the decrease in velocity is also marked (brown bar).

Systems (GNSS) stations LP03 and LP04, and the precipitation observed at meteorological station LP_EPAS for La Palma Island. The locations of the LP03 and LP04 GNSS stations and LP_EPAS meteorological station are also shown in Figure 1b. As usually occurs, with increasing time window, the fluctuation in the observed velocity change decreases. We observe that the 10-day window provides the best coincidence for both the results, showing a clear decline in the velocity starting on 12 September 2021. This time coincides with the shooting of a shallow swarm of 366 events located at an average depth of 9.5 km (Mezcua and Rueda, 2023). The GNSS stations also indicate that vertical deformation starts on this date, indicating that this velocity variation is clearly related to magma ascent. On 18 September 2021, another swarm of 328 located events (Mezcua and Rueda, 2023) was also detected, with a shallower depth of 4 km and ending on 19 September 2021, when the eruption of Cumbre Vieja started. This date corresponds with the maximum vertical displacement at both the GNSS stations (De Luca *et al.*, 2022). We also present the precipitation at a nearby meteorological station (LP_EPAS) with no significant values since May 2021 (four months before the eruption). The maximum velocity change observed was $dv/v = -0.15\%$.

The single-station cross-component correlation permits us to expand the frequency interval and to compare the results with those previously obtained with the fourteen pairs of stations (ZZ components). Station CJED is close (5 km) to the volcanic edifice (Fig. 1b) with enough data extended back in time and is selected to study the single-station cross correlation between the three components (EN, EZ, and NZ), discarding the noisy autocorrelation ZZ. However, we also include the rest of the stations in the supplemental material, available to this article. The results are shown in Figure 5 for a moving window of 10 days and for three frequency intervals: 0.1–1.0, 0.5–1.0, and 0.1–0.5 Hz. The best results correspond to the 0.1–1.0 Hz frequency interval, in which the three possible cross correlations show a clear velocity decrease starting on 12 September 2021, with a very low standard deviation of the velocity change, reaching the minimum value of -0.3% on 19 September 2021, when the eruption started. The possible influence of moderate earthquakes in the observed velocity decrease (Flinders *et al.*, 2020) can be ruled out, because we locate only three M_L 1.0 earthquakes during the previous 73 days of velocity decrease detection. The observed change in the velocity for the EN and EZ components in 0.5–1.0 Hz frequency interval, which corresponds to the shallow part of the crust, reaches -0.3% , further decreasing to -0.45% for the NZ cross correlation.

The low values observed all stations and for all components within the 0.1–0.5 Hz frequency interval are the result of the shallower location where the velocity decrease is produced.

Results

The results presented here favored a classical interpretation given the different velocity variations observed during many volcanic eruptions (Donaldson *et al.*, 2017, 2019; Olivier *et al.*, 2019; Flinders *et al.*, 2020; Bereznev *et al.*, 2023; among others). The first result is that the seasonal velocity change over the 2018–2022 period, with the exception of the eruption period, reaches $\pm 0.1\%$ using the fourteen pairs of stations. However, the velocity variation detected on 19 September 2021 clearly exceeds -0.15% or even -0.45% for the NZ cross correlation at the CJED station, which is the nearest station to the volcanic edifice. A similar velocity change observation at the closed station is also observed in other volcanic eruptions, de Plaen *et al.* (2016, 2019). We also detect a velocity decrease from 12 to 19 September 2021 at the rest of the stations (albeit lower values), which suggests that the sources of velocity variation were spatially distributed around the volcanic edifice, with the maximum value at the nearest station. Moreover, the amplitude of the velocity variation at single stations is larger when using the Z component, which is interpreted as the consequence of the anisotropy of the velocity behavior due to the pressurization of the volcanic edifice (Machacca-Puma *et al.*, 2019).

Another important result is the correlation between the velocity variation and the short-term swarms detected from 12–19 September 2021, with decreasing average depth as we approach the eruption start time (Mezcua and Rueda, 2023). In addition, the b parameter, which is related to the stiffness of the material in which the activity is occurring, continuously decreases from 1.5 ± 0.2 to 0.9 ± 0.1 , which may be related to magma cooling as it ascends from ~ 9 km up to 4 km above sea level.

The starting time of the mean velocity decrease coincides with that of an almost linear increase in the vertical deformation at the nearby GNSS stations LP03 and LP04 (De Luca *et al.*, 2022), finishing the day of eruption for LP03 with $+0.20$ m, whereas the vertical deformation reached $+0.10$ m on 15 September 2021 for LP04. This time difference in reaching the maximum vertical displacement can be interpreted as the north–south ascending magma along the northern direction first passing LP04 and then LP03. This result shows that an increase in stresses occurred in the eruption preparation process.

CJED 10 days moving window

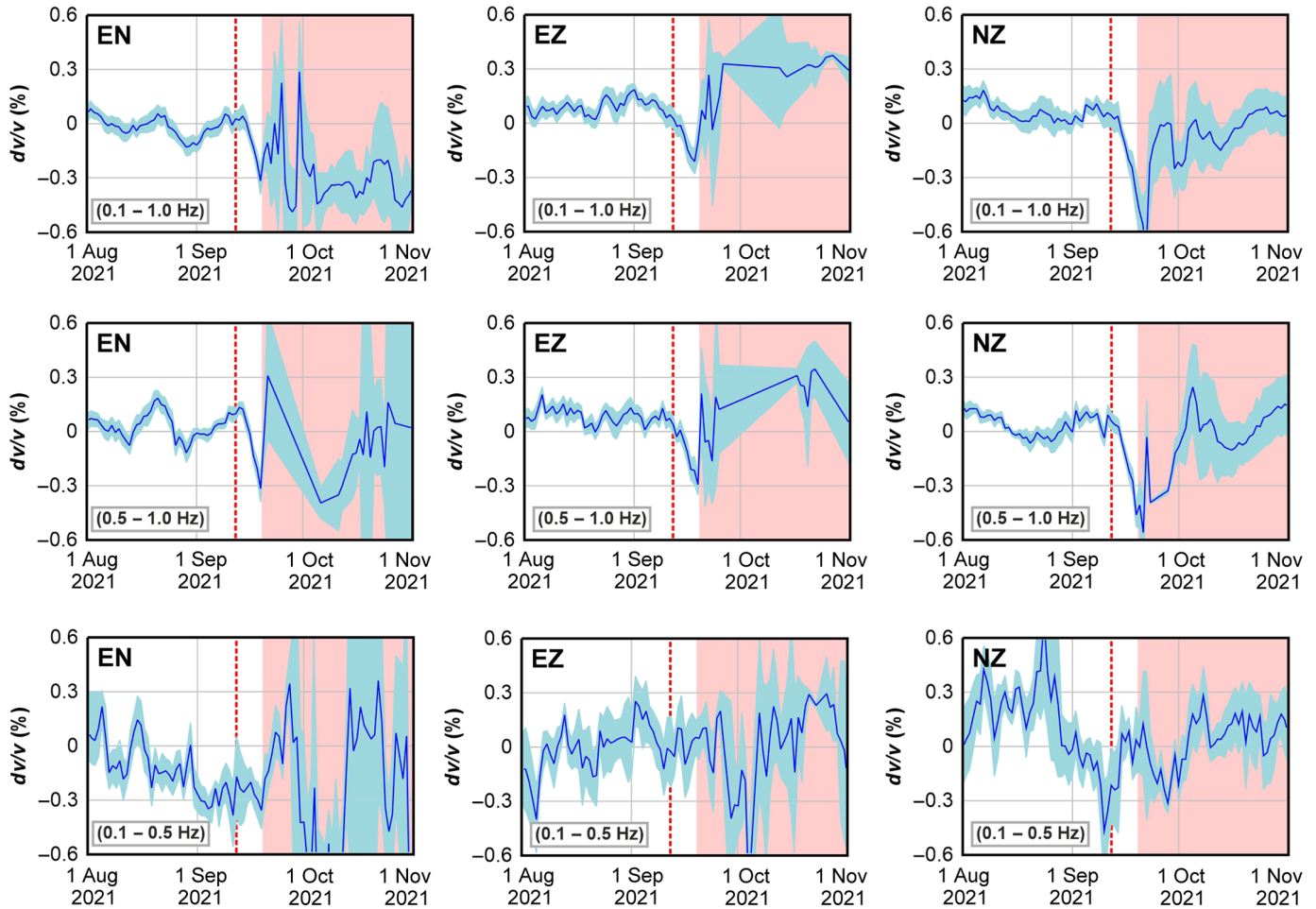


Figure 5. Mean seismic velocity variations dv/v (%) (blue line) with ± 2 standard deviation (blue band) obtained for the station CJED cross components (EN, EZ, and NZ) in the 0.1–1.0, 0.5–1.0, and 0.1–0.5 Hz frequency bands and 10-day moving window from 1 August 2021 to 1 November 2021, showing that part of the eruption process started (pink box) and the line corresponding to 12 September 2021 (red dotted line). The rest of the stations are included as the supplemental material.

Finally, another important result is the suggested seasonal variation in the velocity changes observed over the 2018–2022 period using the fourteen pairs of selected stations covering the area. It is very important to provide of long-term data for excluding possible velocity changes not related to a volcanic episode. The velocity variation with the rainfall periodicity is on the order of $\pm 0.1\%$, exhibiting a negative correlation with a positive time lag, which suggests that a decrease in the velocity (dv/v) follows several days after the maximum rainfall. This result can be interpreted as the increase in the pore pressure due to ground water recharge by rainfall, after which a change in the velocity can be observed. However, more work is needed to verify this relationship after filtering.

Conclusions

In the model proposed by Mezcua and Rueda (2023), magma ascended from the magma reservoir in the lower crust (at a

depth of ~ 11 km) to the surface starting on 12 September 2021, along dual pathways at an average velocity of 0.21 km/hr, suggesting propagation under high-stress heterogeneity, which was also accompanied by increasing vertical deformation at the two GNSS stations; this process ended on 14 September 2021. This shallow reservoir at 4 km, also proposed by Fernández *et al.* (2022) and Benito *et al.* (2023), may have been filled through dikes opened during the previous activity. From this depth, an accelerating ascent was accompanied by continuous

seismicity and a rapid decrease in the velocity caused by notable magma ascent with a corresponding pressure increase, creating areas of normal extension as well as crack opening. The magma followed a complex system of dikes and sills in its ascent before reaching the surface on 19 September 2021, when the eruption started. This magma ascent track was also considered in other models, such as [Fernández *et al.* \(2022\)](#) and [Montesinos *et al.* \(2023\)](#). This model explains the velocity decrease observed in this study. However, the study of [Cabrera-Pérez *et al.* \(2023\)](#) focusing on the 2021 Cumbre Vieja eruption excluded the stress/strain variation produced by magma ascent as the dominant mechanism for the observed velocity decrease due to the lack of significant deformation between 10 and 14 September 2021, which contradicts our observations at the GNSS stations. The model of [Cabrera-Pérez *et al.* \(2023\)](#) involves a velocity decrease due to the ascent of hydrothermal fluids toward the surface, although the decrease in the velocity on the day before the eruption can be notably affected by magmatic intrusion. We believe that both the models are compatible because the possible hydrothermal fluids can be ascribed to magma ascent, and no large differences in the final results are observed except for the dates of the possible stages of velocity variation.

The suitable results obtained indicate that the implementation of a model involving near real-time velocity variation is a promising volcanic forecasting method that should be considered in volcanic surveillance of the Canary Islands.

Data and Resources

The earthquake seismic locations are obtained from the National Geographic Institute (IGN), Spanish seismic catalog at doi: [10.7419/162.03.2022](https://doi.org/10.7419/162.03.2022) (last accessed July 2023). The seismic and Global Navigation Satellite Systems (GNSS) data used are hosted at the IGN data center, Spain, 1999, Spanish Digital Seismic Network, International Federation of Digital Seismograph (FDSN) Networks, Dataset/Seismic Network at doi: [10.7914/SN/ES](https://doi.org/10.7914/SN/ES). Some of the data are open-access data, and the remaining station data can be obtained upon request at volcanologia@mitma.es. GNSS data can be found at doi: [10.5281/zenodo.6123266](https://doi.org/10.5281/zenodo.6123266) ([De Luca *et al.*, 2022](#)). The supplemental material contains the three cross-components for the six stations considered in this paper at three frequency bands. The time period shown is 1 May–1 November 2021.

Declaration of Competing Interests

The authors acknowledge that there are no conflicts of interest recorded.

Acknowledgments

This work was funded by the National Geographic Institute (IGN, Ministry of Transport, Mobility and Urban Agenda, Spanish Government) and partially by the Fundación José García Siñeriz. The authors are indebted to the IGN staff members who, during the pre-eruption period and afterward, dedicated all their efforts to maintaining all work activities and operational services, which served to provide authorities and news media with information and advice of the highest quality during the Cumbre Vieja eruption. The authors thank Thomas Lecocq for the provided guidance with MSNoise software. The authors sincerely acknowledge the thoughtful comments and careful revisions of the reviewers, which helped to substantially improve the original article and enhance its quality.

References

- Andajani, R. D., T. Tsuji, R. Snieder, and T. Ikeda (2020). Spatial and temporal influence of rainfall on crustal pore pressure based on seismic velocity monitoring, *Earth Planets Space* **72**, 1–17, doi: [10.1186/s40623-020-01311-1](https://doi.org/10.1186/s40623-020-01311-1).
- Benito, M. B., G. E. Alvarado, M. Marchamalo, J. G. Rejas, P. Murphy, R. Franco, D. Castro, C. García-Lanchares, and J. Sánchez (2023). Temporal and spatial evolution of the 2021 eruption in the Tajogaite volcano (Cumbre Vieja rift zone, La Palma, Canary Islands) from geophysical and geodetic parameter analyses, *Nat. Hazards* **118**, 2245–2284, doi: [10.1007/s11069-023-06090-y](https://doi.org/10.1007/s11069-023-06090-y).
- Bensen, G. D., M. Ritzwoller, M. P. Barmin, A. Levshin, F. Lin, M. Moschetti, N. M. Shapiro, and Y. Yang (2007). Processing seismic ambient noise data to obtain reliable broad-band surface wave dispersion measurements, *Geophys. J. Int.* **169**, 1239–1260, doi: [10.1111/j.1365-246X.2007.03374.x](https://doi.org/10.1111/j.1365-246X.2007.03374.x).
- Berezhnev, Y., N. Belovezhets, N. Shapiro, and I. Koulakov (2023). Temporal changes of seismic velocities below Bezymianny volcano prior to its explosive eruption on 20.12.2017, *J. Volcanol. Geotherm. Res.* **433**, 107735, doi: [10.1016/j.jvolgeores.2022.107735](https://doi.org/10.1016/j.jvolgeores.2022.107735).
- Bonelli, J. M. (1950). *Contribución al estudio de la erupción del volcán del Nambroque o San Juan (Isla de La Palma) 24 de junio-4 de Agosto*, Instituto Geográfico y Catastral, Madrid, 24 pp. (in Spanish).
- Brenguier, F., D. Rivet, A. Obermann, N. Nakata, P. Boué, T. Lecocq, M. Campillo, and N. Shapiro (2016). 4-D noise-based seismology at volcanoes: Ongoing efforts and perspectives, *J. Volcanol. Geotherm. Res.* **321**, 182–195, doi: [10.1016/j.jvolgeores.2016.04.036](https://doi.org/10.1016/j.jvolgeores.2016.04.036).
- Brenguier, F., N. Shapiro, M. Campillo, V. Ferrazzin, D. Zacharie, O. Coutant, and A. Nercessian (2008). Towards forecasting volcanic eruptions using seismic noise, *Nature Geosci.* **1**, 126–130, doi: [10.1038/ngeo104](https://doi.org/10.1038/ngeo104).
- Cabrera-Pérez, I., L. D'Auria, J. Soubestre, M. Przeor, J. Barrancos, R. García-Hernández, J. M. Ibáñez, I. Koulakov, D. Martínez van Dorth, V. Ortega, *et al.* (2023). Spatio-temporal velocity variations observed during the pre-eruptive episode of La Palma 2021

- eruption inferred from ambient noise interferometry, *Sci. Rep.* **13**, 12039, doi: [10.1038/s41598-023-39237-9](https://doi.org/10.1038/s41598-023-39237-9).
- Carracedo, J. C., V. R. Troll, J. M. D. Day, H. Geiger, M. Aulinas, V. Soler, F. M. Deegan, F. J. Pérez-Torrado, G. Gisbert, E. Gazel, *et al.* (2022). The 2021 eruption of the Cumbre Vieja volcanic ridge on La Palma Canary Islands, *Geol. Today* **38**, 94–107, doi: [10.1111/gto.12388](https://doi.org/10.1111/gto.12388).
- De Luca, C., E. Valerio, F. Giudicepietro, G. Macedonio, F. Casu, and R. Lanari (2022). Pre- and co-eruptive analysis of the September 2021 eruption at Cumbre Vieja volcano (La Palma, Canary Islands) through DInSAR measurements and analytical modeling, *Geophys. Res. Lett.* **49**, e2021GL097293, doi: [10.1029/2021GL097293](https://doi.org/10.1029/2021GL097293).
- de Plaen, R. S. M., A. Cannata, F. Cannavo, C. Caudron, T. Lecocq, and O. Francis (2019). Temporal changes of seismic velocity caused by volcanic Activity at Mt. Etna revealed by the autocorrelation of ambient seismic noise, *Front. Earth Sci.* **6**, 251 pp., doi: [10.3389/feart.2018.00251](https://doi.org/10.3389/feart.2018.00251).
- de Plaen, R. S. M., T. Lecocq, C. Caudron, V. Ferrazzini, and O. Francis (2016). Single station monitoring of volcanoes using seismic ambient noise, *Geophys. Res. Lett.* **43**, 8511–8518, doi: [10.1002/2016GL070078](https://doi.org/10.1002/2016GL070078).
- Donaldson, C., C. Caudron, R. G. Green, W. A. Thelen, and R. S. White (2017). Relative seismic velocity variations correlate with deformation at Kilauea volcano, *Sci. Adv.* **3**, e1700219, doi: [10.1126/sciadv.1700219](https://doi.org/10.1126/sciadv.1700219).
- Donaldson, C., T. Winder, C. Caudron, and R. S. White (2019). Crustal seismic velocity responds to a magmatic intrusion and seasonal loading in Iceland's northern volcanic zone, *Sci. Adv.* **5**, eaax6642, doi: [10.1126/sciadv.aax6642](https://doi.org/10.1126/sciadv.aax6642).
- Fernández, J., J. Escayo, A. G. Camacho, M. Palano, J. F. Prieto, Z. Hu, S. V. Samsonov, K. F. Tiampo, and E. Ancochea (2022). Shallow magmatic intrusion evolution below La Palma before and during the 2021 eruption, *Sci. Rep.* **12**, 20257, doi: [10.1038/s41598-022-23998-w](https://doi.org/10.1038/s41598-022-23998-w).
- Flinders, A. F., C. Caudron, I. A. Johanson, T. Taira, B. Shiro, and M. Haney (2020). Seismic velocity variations associated with 2018 lower East Rift Zone eruption of Kilauea, Hawai'i, *Bull. Volcanol.* **82**, 47, doi: [10.1007/s00445-020-01380-w](https://doi.org/10.1007/s00445-020-01380-w).
- Lecocq, T., C. Caudron, and F. Brenguier (2014). MSNoise, a python package for monitoring seismic velocity changes using ambient seismic noise, *Seismol. Res. Lett.* **85**, 715–726, doi: [10.1785/0220130073](https://doi.org/10.1785/0220130073).
- Machacca-Puma, R., P. Lesage, E. Larose, P. Lacroix, and R. M. Ancasi-Figueroa (2019). Detection of pre-eruptive seismic velocity variations at an andesitic volcano using ambient noise correlation on 3-component stations: Ubinas volcano, Peru, 2014, *J. Volcanol. Geotherm. Res.* **381**, 83–100, doi: [10.1016/j.jvolgeores.2019.05.014](https://doi.org/10.1016/j.jvolgeores.2019.05.014).
- Mezcua, J., and J. Rueda (2023). Seismic swarms and earthquake activity b-value related to the September 19, 2021, La Palma volcano eruption in Cumbre Vieja, Canary Islands (Spain), *Bull. Volcanol.* **85**, 32 pp., doi: [10.1007/s00445-023-01646-z](https://doi.org/10.1007/s00445-023-01646-z).
- Montesinos, F.G., S. Sainz-Maza, D. Gómez-Ortiz, J. Arnosó, I. Blanco-Montenegro, M. Benavent, E. Vélez, N. Sánchez, and T. Martín-Crespo (2023). Insights into the magmatic feeding system of the 2021 eruption at Cumbre Vieja (La Palma, Canary Islands) inferred from gravity data modeling, *Remote Sens.* **15**, 1936 pp., doi: [10.3390/rs15071936](https://doi.org/10.3390/rs15071936).
- Obermann, A., T. Planès, E. Larose, and M. Campillo (2013). Imaging preeruptive and coeruptive structural and mechanical changes of a volcano with ambient seismic noise, *J. Geophys. Res.* **118**, 6285–6294, doi: [10.1002/2013JB010399](https://doi.org/10.1002/2013JB010399).
- Olivier, G., F. Brenguier, R. Carey, P. Okubo, and C. Donaldson (2019). Decrease in seismic velocity observed prior to the 2018 eruption of Kilauea volcano with ambient seismic noise interferometry, *Geophys. Res. Lett.* **46**, 3734–3744, doi: [10.1029/2018GL081609](https://doi.org/10.1029/2018GL081609).
- Patanè, D., P. de Gori, C. Chiarabba, and A. Bonaccorso (2003). Magma ascent and the pressurization of Mount Etna's volcanic system, *Science* **299**, 2061–2063, doi: [10.1126/science.1080653](https://doi.org/10.1126/science.1080653).
- Ratdomopurbo, A., and G. Poupinet (1995). Monitoring a temporal change of seismic velocity in a volcano: Application to the 1992 eruption of Mt. Merapi (Indonesia), *Geophys. Res. Lett.* **22**, 775–778, doi: [10.1029/95GL00302](https://doi.org/10.1029/95GL00302).
- Romero, C. (1991). *Las manifestaciones volcánicas históricas del archipiélago Canario*, Tomo I, Gobierno de Canarias (Consejería de Política Territorial), Tenerife, 695 pp. (in Spanish).
- Rueda, J., R. Abella, M. J. Blanco, E. A. Díaz, I. F. Domínguez, J. Domínguez, M. Fernández de Villalta, C. del Fresno, R. López, C. López, *et al.* (2020). *Revisión del Catálogo sísmico de las Islas Canarias (1341-2000)*, Centro Nacional de Información Geográfica, Madrid, Spain, 230 pp. (in Spanish).
- Snieder, R. (2006). The theory of coda wave interferometry, *Pure Appl. Geophys.* **163**, 455–473, doi: [10.1007/s00024-005-0026-6](https://doi.org/10.1007/s00024-005-0026-6).
- Taira, T., and F. Brenguier (2016). Response of hydrothermal system to stress transients at Lassen Volcanic Center, California, inferred from seismic interferometry with ambient noise, *Earth Planets Space* **68**, 162, doi: [10.1186/s40623-016-0538-6](https://doi.org/10.1186/s40623-016-0538-6).
- Torres-González, P. A., N. Luengo-Oroz, H. Lamolda, W. D'Alessandro, H. Albert, I. Iribarren, D. Moure-García, and V. Soler (2020). Unrest signals after 46 years of quiescence at Cumbre Vieja, La Palma, Canary Islands, *J. Volcanol. Geotherm. Res.* **392**, 106757, doi: [10.1016/j.jvolgeores.2019.106757](https://doi.org/10.1016/j.jvolgeores.2019.106757).

Manuscript received 14 November 2023

Published online 5 January 2024