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Monitoring of velocity changes based on seismic ambient noise: A brief review and perspective

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Key Points:

- We list some state-of-the-art monitoring methods
- We summarize substantial applications of noise-based monitoring at different scales and with different mechanisms
- The noise-based monitoring technique can be used to track changes in diverse physical parameters for both terrestrial and extraterrestrial seismology

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Abstract: Over the past two decades, the development of the ambient noise cross-correlation technology has spawned the exploration of underground structures. In addition, ambient noise-based monitoring has emerged because of the feasibility of reconstructing the continuous Green's functions. Investigating the physical properties of a subsurface medium by tracking changes in seismic wave velocity that do not depend on the occurrence of earthquakes or the continuity of artificial sources dramatically increases the possibility of researching the evolution of crustal deformation. In this article, we outline some state-of-the-art techniques for noise-based monitoring, including moving-window cross-spectral analysis, the stretching method, dynamic time wrapping, wavelet cross-spectrum analysis, and a combination of these measurement methods, with either a Bayesian least-squares inversion or the Bayesian Markov chain Monte Carlo method. We briefly state the principles underlying the different methods and their pros and cons. By elaborating on some typical noise-based monitoring applications, we show how this technique can be widely applied in different scenarios and adapted to multiples scales. We list classical applications, such as following earthquake-related co- and postseismic velocity changes, forecasting volcanic eruptions, and tracking external environmental forcing-generated transient changes. By monitoring cases having different targets at different scales, we point out the applicability of this technology for disaster prediction and early warning of small-scale reservoirs, landslides, and so forth. Finally, we conclude with some possible developments of noise-based monitoring at present and summarize some prospective research directions. To improve the temporal and spatial resolution of passive-source noise monitoring, we propose integrating different methods and seismic sources. Further interdisciplinary collaboration is indispensable for comprehensively interpreting the observed changes.

Keywords: ambient noise correlation; noise-based monitoring; seismic wave velocity changes; the evolution of physical properties of the crust

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1. Introduction

Studying the stress state of the crust is essential to understand the mechanisms relevant to various tectonic and nontectonic processes of the earth. Monitoring seismic wave velocity changes is a useful tool for probing changes in the stress state of the crust, as has been verified both theoretically and experimentally (Birch, 1961; Nur and Simmons, 1969; O'Connell and Budiansky, 1974; Schoenberg, 1980; Yamamura et al., 2003). The existence of persistent and extensive seismic noise allows us to reconstruct the Green's function by continuously cross- or auto-correlating seismic ambient noise recordings (Aki, 1957; Claerbout, 1968; Lobkis and Weaver, 2001; Campillo and Paul, 2003; Shapiro and Campillo, 2004; Larose et al., 2005a; Campillo, 2006, 2011). Thus, this noise allows us to monitor the seismic wave velocity changes with time. By measuring the changes in seismic velocity, we can investigate the stress state of the crust at depth and continuously in time, which provides essential constraints on dynamic processes in the crust, such as those attributable to earthquakes, volcanoes, and other activities. The ambient noise-based monitoring method can

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also be used to monitor subsurface velocity changes caused by various types of environmental changes. In addition, cross-correlation noise monitoring can be applied on small scales, such as at landslides and reservoirs, for possible disaster prediction and as an early warning system. Here we briefly review the methods of ambient seismic noise-based monitoring and the main fields where it can be applied. We then discuss some prospective research topics that are urgently needed and possible directions for future development.

2. Methodology of Ambient Seismic Noise-Based Monitoring

Conventional ambient noise-based seismic wave velocity monitoring is a coda wave-based technology collectively referred to as coda wave interferometry. The concept of coda wave-based seismic velocity monitoring was from Poupinet et al. (1984), who retrieved the subtle phase shift of waveforms between earthquake doublets along seismograms. Snieder et al. (2002) later proposed a similar concept to measure the time change by using different lapse time moving windows to evaluate the relative seismic wave velocity changes by linear regression. This evaluation assumes that changes in the wavefield are homogeneous; therefore, they obey a linear relationship in which a travel-time shift is opposite seismic velocity changes:

$$\delta t/t = -\delta v/v. \qquad (1)$$

Four different methods are mainly used for measuring the travel time shift based on coda waves. Brenguier et al. (2008a, b) and Clarke et al. (2011) applied what they termed a moving-window cross-spectral analysis to continuously record noise cross-correlations. A moving-window cross-spectral analysis is a frequency-domain analysis based on measuring the phase shift in a sliding window of specific lengths. Through two linear regressions, we can obtain the velocity changes between any two cross-correlation functions. This method requires us to define the width of the sliding window, the lapse time on the cross-correlation function, and a set of quality filtering restrictions, among others.

Alternatively, the stretching method (Lobkis and Weaver, 2003; Sens-Schönfelder and Wegler, 2006) is based on a time-domain analysis. It works by optimizing the cross-correlation coefficient between any two comparable cross-correlation functions after deforming one of them with a stretching coefficient. The changes in seismic velocity are equal to the stretching coefficient producing the maximum cross-correlation coefficient. This method can potentially be polluted by changes in the spectrum of noise sources (Zhan ZW et al., 2013).

Along with the two classical methods for measuring the time shift, there is dynamic time warping by Mikesell et al. (2015). Dynamic time warping utilizes all the information, the time shift from coda waves as well as the amplitude and decoherence information. Recently, Mao SJ et al. (2020) proposed a new approach based on a wavelet cross-spectrum analysis, a continuous wavelet transform. This approach provides optimal time-frequency joint resolution with full lapse time measurement. This method has a powerful computational advantage for multiple bands, and thus depth analysis. All four methods of measuring the time shift can further be used with linear inversion, based on the relationship below by Brenguier et al. (2014). Brenguier et al. (2014) showed that the difference in relative seismic velocity changes at time j and time i is approximately equal to the change between the two times:

$$\delta v_j - \delta v_i \approx \delta v_{ij}, \qquad (2)$$

where i and j indicate any two different times. This inversion-supplemented procedure helps avoid the choice of an arbitrary reference correlation function by the usual stacking. Accurate continuous velocity changes are retrieved by using a Bayesian least-squares inversion. This inversion procedure improves the precision of the measurements by separately computing velocity changes for all the possible correlation functions for each station pair.

A regularization during the inversion allows us to focus on either rapid or long-term changes in seismic wave velocity. When dealing with high-temporal-resolution data or long time series, the inversion of the matrix will require a relatively large storage volume. Taylor and Hillers (2020) developed a new method of determining the seismic velocity time series by using a Bayesian Markov chain Monte Carlo (MCMC) approach. This method can effectively tackle the problem of having a large volume of data. The MCMC seeks to construct a full posterior probability distribution of the changes in seismic velocity. It provides a robust way to compute the time series of velocity changes by incorporating the information on measurement uncertainty.

The four measurement methods together with the further inversion and MCMC methods, which can increase measurement stability, are the most commonly used and updated techniques. They cover almost all the possibilities for conventional coda wave-based monitoring. It provides stable time series of seismic velocity changes at different depths. However, the disadvantage is that coda wave-based monitoring is often hindered by insufficient spatial resolution and difficulty in locating depth because of the complexity of the scattering paths of waves, and thus the sensitivity kernel of coda waves.

To avoid insufficient spatial resolution and the difficulty of determining the specific depth when using coda waves, Brenguier et al. (2020), Takano et al. (2020), and Mordret et al. (2020) began to do the monitoring using ballistic waves, including both body waves and surface waves (both the fundamental mode and the first overtone of Rayleigh waves) recovered from the seismic noise correlation. This technology relies on the deployment of small-scale targeted dense arrays, which have developed rapidly in recent years. These stations are usually arranged around critical faults; hence, the technology is essential for accurately tracking small-velocity changes within small areas adjacent to faults.

This new ballistic wave-based methodology provides better depth localization of the detected changes in seismic velocity. At the same time, it relies on the dense array to reduce possible bias from the high intrinsic sensitivity of reconstructed ballistic waves to the noise source properties. Currently, this is the main limitation encountered with ballistic wave-based monitoring. In contrast, coda wave-based monitoring is less sensitive to the noise source properties because of the phase velocity bias resulting from the anisotropic distribution of ambient noise energy (Yao HJ et al., 2009). One can successfully apply coda wave-based monitoring even without perfect reconstruction of the Green's function (Hadziioannou et al., 2009). Froment et al. (2010), Weaver et al. (2011), and Colombi et al. (2014) also estimated the travel time error by considering different distribution sources, and they confirmed the stability of using coda waves to do the monitoring. This is because the long duration and disorder of the scattering process can enhance the signal-to-noise ratio and reduce the dependency of the correlation function quality on the noise source properties (Larose et al., 2008).

We usually apply these methods in the continuous Green's functions reconstructed from long-term recorded background signals for passive source-based noise monitoring. Similarly, we can apply these methods to signals obtained from active sources. The Green's functions obtained from active sources, both earthquake-produced and artificial (Reasenberg and Aki, 1974; Karageorgi et al., 1992; Ikuta et al., 2002; Yamamura et al., 2003; Niu FL et al., 2008; Yang W et al., 2018; Wang BS et al., 2020), have excellent advantages in the signal to noise ratio, and controllable repeatability in time for the latter one. Therefore, monitoring with active sources can improve the accuracy of tracking instantaneous coseismic changes. This may progress the possible underestimated momentary velocity drop by the earthquake that can hardly be measured by passive wave-based monitoring because of the compromise between the temporal resolution and the convergence time of stability. For this reason, it is also possible to use direct waves other than coda waves to tackle the problem of spatial localization. However, we need to consider the cost of artificial seismic sources and the relatively limited detection scale. The combination of both seismic sources with the methods above will significantly improve the accuracy of detection.

3. Application and Observation of Ambient Seismic Noise-Based Monitoring

Of the different methods mentioned, noise-based monitoring has been applied at different scales and with different research objectives to investigate the responses of the crust under the impacts of various mechanical processes in the past dozen years or more. Here we summarize the main origins of changes in seismic wave velocity as dynamic and static stress–strain-related earthquake co- and postseismic procedures, pressure buildup, and magma migration in the volcanic area, external forces from environmental perturbations, and the activities of natural and human-made reservoirs. In this section, we list some representative investigations of noise-based monitoring with different forcing origins.

3.1 Earthquake-Related Co- and Postseismic Velocity Changes

Studies of the mechanical responses of the earth's crust to large earthquakes can provide us with unique insights into the processes of stress buildup and release at depth (Bürgmann and Dresen, 2008). At this stage, we mainly observe a rapid coseismic velocity reduction followed by a slow postseismic exponential recovery process (Field et al., 1998; Wegler and Sens-Schönfelder, 2007; Brenguier et al., 2008a, Xu ZJ and Song XD, 2009; Sawazaki et al., 2009; Chen JH et al., 2010; Cheng X et al., 2010; Zhao PP et al., 2012; Froment et al., 2013; Acarel et al., 2014; Brenguier et al., 2014; Liu ZK et al., 2014; Hong TK et al., 2017; Liu ZK et al., 2018; Wang QY et al., 2019; Poli et al., 2020). The predominant mechanism underlying the observed earthquake-related velocity drop is referred to as shallow dynamic shaking (Sleep, 2015) and deep stress changes by the earthquake. The classical observation by Brenguier et al. (2008a) in the San Andreas fault zone (Figure 1) suggests that the observed seismic velocity changes (0.08%) should come from both coseismic damage in the shallow layers and a deep coseismic stress change and postseismic stress relaxation within the fault zone. A similar phenomenon has been explained both experimentally and numerically by nonlinear elastic behavior, including both anomalous nonlinear fast dynamics and slow dynamics (Lyakhovsky et al., 1997, 2009; Johnson and Sutin, 2005; Sens-Schönfelder et al., 2019).

Here we present a recent study by Wang QY et al. (2019) related to the 2011 M_w 9.0 Tohoku-Oki earthquake off the coast of Japan. The authors identified depth (frequency)-dependent seismic velocity changes. A shallow seismic velocity decrease (~0.07% in the 1–7 s period band; Figure 2a) was observed to be related to a mechanical weakening of the crust by the dynamic stress (represented by a map of the peak ground velocity (PGV); Figure 2b) associated with seismic waves. Brenguier et al. (2014) also studied the sensitivity of stress perturbations to changes in the seismic wave velocity due to the Tohoku-Oki earthquake. Their results revealed that the seismic wave velocity changes in the central volcanic region of Japan were highly susceptible to coseismic dynamic stress perturbations. Distinct from the map of changes in this relatively short period, the map of velocity changes in the 8–30 s band (~0.04%; Figure 2c) disclosed that the static strain caused by the earthquake at depth dominated the velocity decrease over a relatively long period. This was the first observation of static strain-related decreases in co- and postseismic velocity.

3.2 Seismic Velocity Changes in Volcanic Areas

Another crucial application is relatively small-scale observation in volcanic regions (Brenguier et al., 2016). One of the most classic and representative cases is the observation of systematic seismic velocity decrease (~0.05%) as a precursor to the eruption of volcanoes at Piton de la Fournaise (Brenguier at al., 2008b; Figure 3). Similar volcanic process-related observations (Mordret et al., 2010; Sens-Schönfelder et al., 2014; Donaldson et al., 2017; Hirose et al., 2017) indicated that velocity changes were strongly correlated with the dilatation or compression of the volcanic system. The heterogeneous spatial stress distribution can lead to opposite seismic velocity responses to the same volcanic activity. Liu ZQ et al. (2019) separated the observed velocity changes at the Kilauea volcano into two phases, which they explained by compression from upward migration of the magma and the injection of magma into the veins and fractures.

Recently, Takano et al. (2020) also applied ballistic wave-based monitoring to the Piton de la Fournaise volcano. They showed that the velocity changes as a result of strain complexity in response to the subtle pressurization of the shallow magma reser-

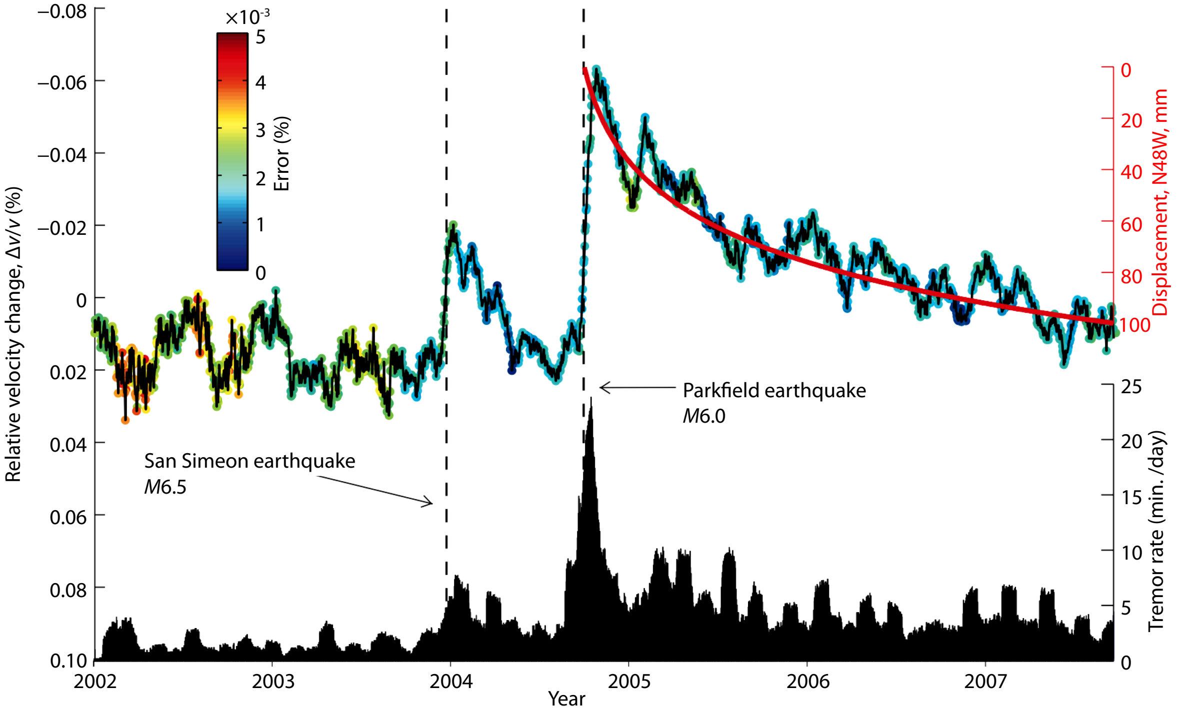

Figure 1. Seismic velocity changes, surface displacements from GPS, and tremor activity near Parkfield, California. The red curve represents the postseismic fault-parallel displacements along the San Andreas fault as measured by a GPS station. After Brenguier et al. (2008a).

voir. Noise-based monitoring thus provides a robust means of studying the processes of pressure buildup at depth and magma transport in the volcanic edifices so as to improve the ability to predict volcanic eruptions.

3.3 Environmental Seismic Velocity Changes

Apart from both tectonic- and volcanic-related seismic velocity changes, commonly existing environmental perturbations from multiple sources also play a significant role in the seismic wave velocity. Studying the transient velocity changes related to those environmental perturbations can help isolate the tectonic-related deformation and contribute to understanding the behavior of the crust under diverse external forcing mechanisms.

Groundwater- and rainfall-related seismic velocity decreases up to ~10^{-2} % to 10^{-1} % that show the importance of hydraulic effects on seismic wave velocity have been widely discussed (Sens-Schönfelder and Wegler, 2006; Meier et al., 2010; Tsai, 2011; Hillers et al., 2014; Hotovec-Ellis et al., 2014; Wang QY at al., 2017; Lecocq et al., 2017; Poli et al., 2020). When rainfall increases, the infiltration of rainwater produces delayed pore pressure enhancements in the top kilometers of the crust. This in turn leads to a decrease in the shear modulus and consequently to decreases in the seismic wave velocity. Simultaneously, the velocity changes are delayed slightly because of hydraulic diffusion compared with the daily peaks in precipitation.

Figure 4b illustrates how rainfall in Kyushu, Japan, significantly decreased the velocity of the seismic waves in July 2011 and July 2012. Figure 4a shows a map of the averaged seismic velocity changes in July 2011 and July 2012 after Gaussian smoothing of a width of 100 km. The highlighted velocity decreases beneath volcanoes (Figure 4a, red triangles) also demonstrate the identical conclusion reached by Brenguier et al. (2014) of the high susceptibility of the volcanic area.

In the shallow layer, thermoelastic stress changes the velocity of seismic waves in an annual cycle (Meier et al., 2010; Richter et al., 2014; Hillers et al., 2015a; Lecocq et al., 2017), as does atmospheric pressure (Silver et al., 2007). Subtle tidal effects (Yamamura et al., 2003; Takano et al., 2014; Hillers et al., 2015b; Mao SJ et al., 2019; Wang BS et al., 2020) as well as permafrost freeze and melt (James et al., 2017) can also have a considerable effect in modulating the seismic wave velocity changes. In addition, snowfall, precipitation, and changes in sea surface height can cause direct elastic loading effects (Wang QY et al., 2017; Donaldson et al., 2019). These directly generated stresses usually have a compacting effect on the adjacent subsurface media. Media at different depths, distances, and fault orientations may have opposite responses to seismic velocity under the impact of the same environmental factor. Among them, the role of snowfall can be the most complicated. Not only does it generate direct elastic stress, but it also changes the pore pressure after melting when the temperature rises or when different geologic conditions are encountered (Mordret et al., 2016). The superposition and interaction of the environmental factors mentioned can generate combined effects on the underground media, which in turn affect the seismic wave velocity in a non-negligible way.

3.4 Other Applications

In addition to the major monitoring applications highlighted above, noise-based monitoring as it is currently being researched has further practical applications at different scales. The observed Rayleigh wave velocity drop (7%) before a landslide caused by a

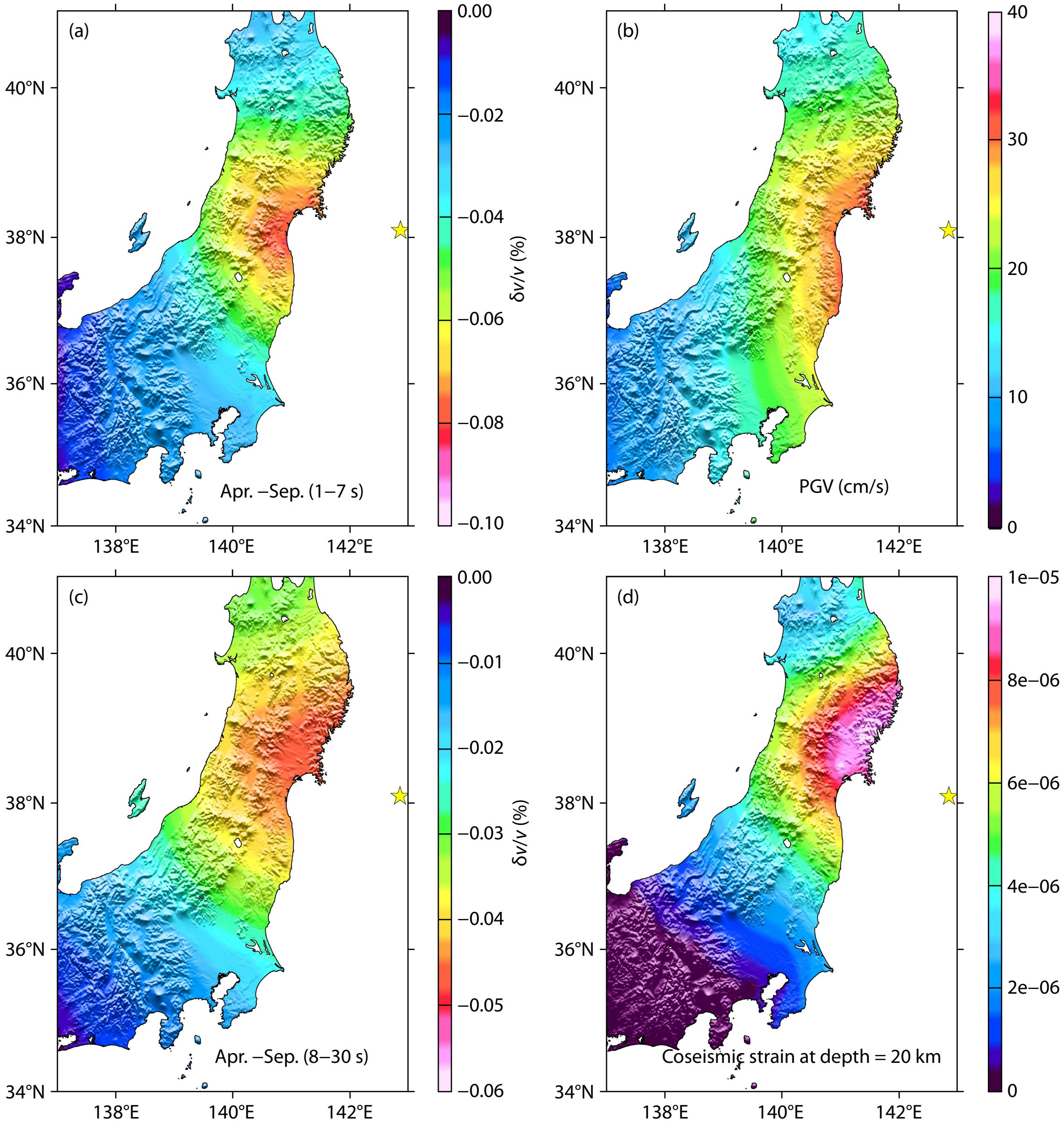

Figure 2. (a, c) Separate spatial seismic velocity changes measured at 1–7 s and 8–30 s. (b) Map of peak ground velocity (PGV, cm/s). (d) Coseismic strain modeled at a depth of 20 km. After Wang et al. (2019).

decay in the mechanical rigidity of the clay suggests the possibility of applying ambient noise-based monitoring to predict failure on a local scale (Mainsant et al., 2012). Its failure prediction potential provides us with the opportunity to apply it in landslide monitoring and disaster prediction. Active source experiments both in the laboratory (Scuderi et al., 2016) and at a fault zone (Niu FL et al., 2008) have confirmed that the short-term velocity changes preceding failure can indicate earthquake nucleation. All these studies serve as essential references for tracking the changes in seismic wave velocity to predict and provide early warning of earthquakes and geological disasters. In addition, certain industrial activities, such as mine activities (Olivier et al., 2015) and fluid injection at geothermal sites (Hillers et al., 2015c; Obermann et al., 2015), can be tracked by the changes in velocity and decoherence in the waveform. Planès et al. (2016) and Olivier et al. (2017) successfully observed changes in the stress field of dams resulting from changes in the groundwater level and in the porosity of the medium, which caused changes in the seismic wave velocity. Their work verifies the potential for tracking the internal deformation and pressure state at small-scale applications, such as at dams and reservoirs. Monitoring the evolution of the stress state at small-scale reservoirs is crucial for disaster prevention.

4. Prospective Research in Ambient Seismic Noise-Based Monitoring

The preceding introduction to the methodology of ambient seismic noise-based monitoring and examples of its application verify the feasibility of this method for continuously tracking the evolution of the crustal medium to study the stress state of the earth's crust. Ambient seismic noise-based monitoring is a useful tool for observing the crustal responses to deformation sources of differ-

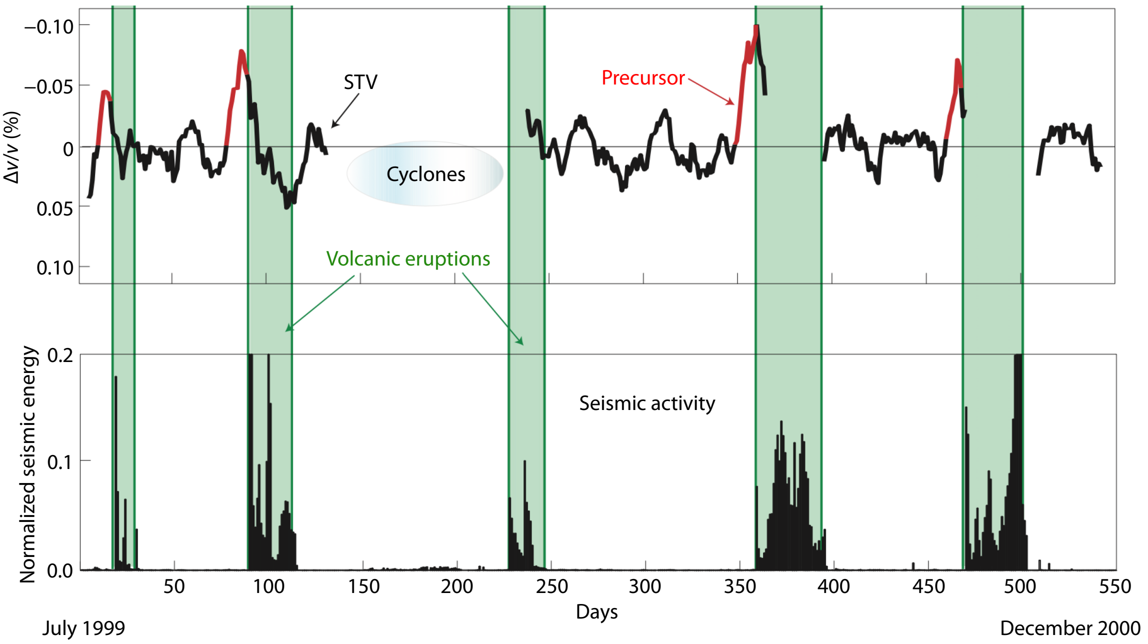

Figure 3. Seismic velocity reductions preceding eruptions of the Piton de la Fournaise volcano versus seismic energy, which is computed as the daily averaged root mean square (RMS) value of continuous seismic signals recorded at Piton de la Fournaise. The green columns show the periods of eruption by Brenguier et al. (2008b).

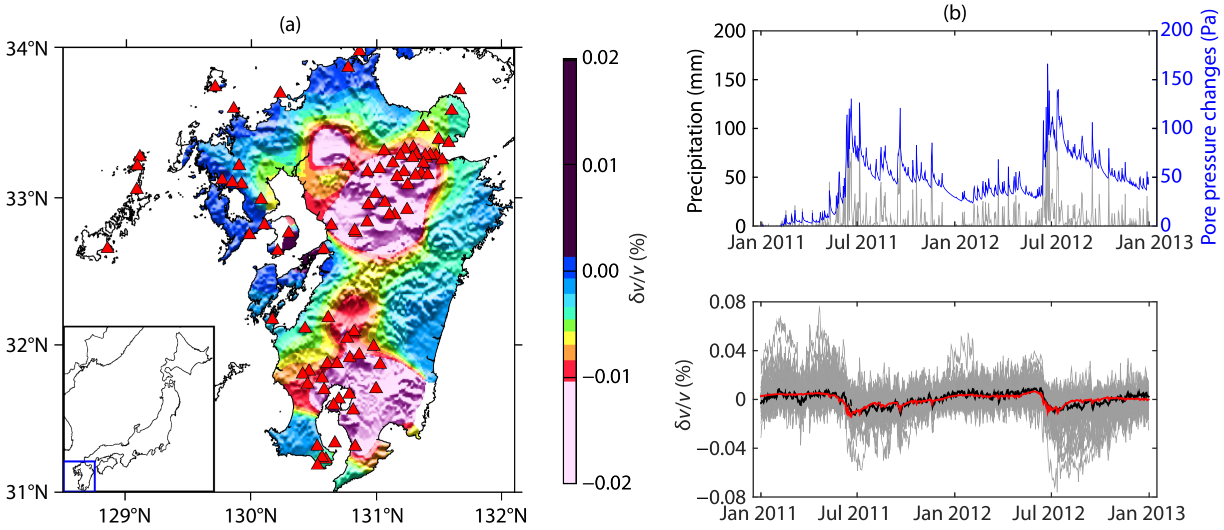

Figure 4. (a) Mapping of the mean seismic velocity changes in July 2011 and July 2012 at 74 High-Sensitivity Seismograph Network Japan (Hi-net) stations. The red triangles represent the locations of quaternary volcanoes. (b) Upper record: daily mean precipitation for Kyushu (gray) and computed relative diffused pore pressure changes (blue) from 129 meteorological stations. Lower record: time series of seismic velocity changes for the Hi-net stations (gray) and the averaged δ*v*/*v* time series (black). The red curve represents the synthetic velocity changes. After Wang et al. (2017).

ent origins and is applicable from a small laboratory scale to local or regional scales. Further research is also needed in the following areas to improve noise-based monitoring.

Regarding the spatial resolution, current 2-D or 3-D imaging based on coda wave monitoring usually proceeds from a linear interpolation or inversion, and the analytical solution of the coda wave sensitivity kernel is based on the diffusion regime or radiative transfer theory. The sensitivity kernel is usually calculated under the assumption of isotropic scattering with a uniform energy velocity and transport mean free path (Pacheco and Snieder, 2005; Obermann et al., 2013a, b, 2014, 2019; Mayor et al., 2014; Planès et al., 2014; Margerin et al., 2016; Zhang YX et al., 2016; Nakahara and Emoto, 2017). Figure 5 illustrates a case by Obermann et al. (2019) showing that the linear combination of kernels from the body and surface waves is effective in constraining the depth of changes in a 3-D multiple-scattering medium.

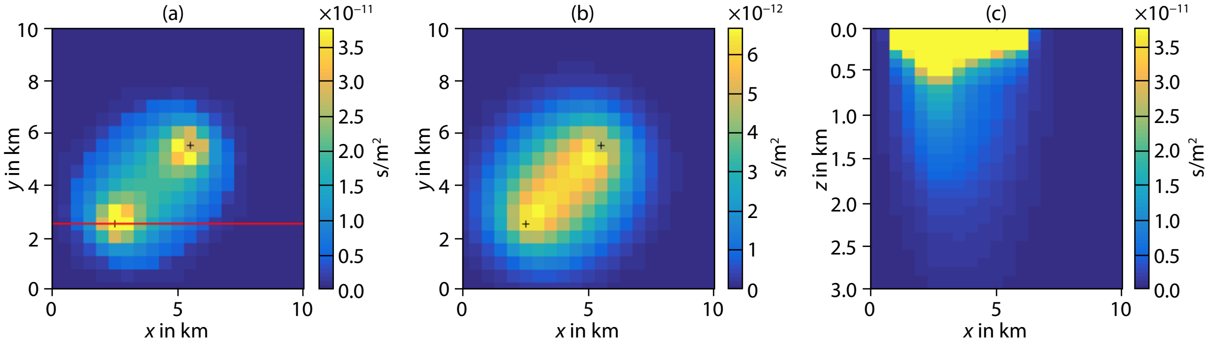

Figure 5. Combined coda kernel from 3-D body- and surface-wave kernels by Obermann et al. (2019). Horizontal slices at depths of 0.5 km (a) and 1.5 km (b) and a vertical slice (c) along the red line indicated in (a). The crosses mark the source and receiver positions.

We can see greater sensitivity around the two stations, and the shallow part seems more important than the deep part. Using similar sensitivity kernels, we can localize the measured travel time perturbations in the space and interpret the origins of the deformation more accurately. However, because of the complexity of the travel paths, we currently do not have an exact sensitivity kernel that can accurately characterize the travel time perturbations of coda waves and thus localize the measured changes with precision. Therefore, further studies of 2-D and 3-D scattered wave sensitivity kernels are imperative. With ballistic wave-based monitoring, spatial localization becomes relatively simple. However, the temporal resolution and the stability of the velocity changes are lower than those of coda waves. Knowing how to improve the signal-to-noise ratio of ballistic wave-based monitoring will thus become essential.

In terms of the temporal resolution, the current minimum detectable temporal resolution of passive-source noise monitoring is usually as little as one day or one hour according to the convergence rate of the Green's functions at different frequencies. With active sources, the repeatability of the Green's function is controllable and so is the temporal resolution. The ability to capture instantaneous changes can contribute to a better understanding of the momentary stress changes of earthquakes or other ruptures or volcanic eruptions, which will advance knowledge of their mechanisms and processes. Therefore, improving the temporal resolution will also become a vital research objective.

Pei SP et al. (2019) observed pronounced coseismic velocity reductions (~4%) after the 2008 Wenchuan earthquake by tracking the travel time changes in Pg waves of earthquakes more precisely. They located changes in depth ranging from 2 to 20 km with a 3-D tomographic inversion. This order of magnitude is much higher than the classical results from coda wave-based methods. Consequently, the existence of repetitive events from both artificial sources (Yang W et al., 2018; Wang QY et al., 2019) and repeating earthquakes (Sawazaki et al., 2015) extends the possibility of the combined use (Hirose et al., 2017) of ambient noise and other sources to detect changes in seismic wave velocity. Multiple approaches to monitoring can also effectively complement each other to improve the temporal and spatial resolution and extend the scope and sustainability of a region that can be monitored.

With the powerful computing capabilities currently available, real-time noise monitoring is becoming particularly realistic. Continuous changes in a seismic time series can be measured while being recorded in permanent seismic networks. It is necessary to analyze the local environmental factors simultaneously to distinguish among them and correct possible transient velocity changes related to nontectonic forcing. The purpose of real-time monitoring is to detect possible velocity anomalies in order to forecast potential disasters. Thus, statistical analysis of the seismic wave speed becomes vital follow-up work. Nakahara et al. (2020) used the extensive noise monitoring results in Japan to conduct a statistical analysis to quantify and detect velocity anomalies associated with volcanic eruptions or earthquakes. According to the mathematical distribution law, further criteria can be added to the real-time monitoring system automatically to predict possible anomalies.

With the acquisition of new, continuous seismic data and information from other planets (e.g., the moon and Mars), researchers have successfully applied the noise-based correlation technique to monitor seismic velocity changes on the moon (Larose et al., 2005b; Sens-Schönfelder and Larose, 2010). These applications investigate the moon by using diffusive waves in a frequency range outside of and higher than the typical microseismic bands. They have succeeded in extracting the Rayleigh waves by cross-correlating seismic noise recordings. The results have disclosed dynamic lunar processes related to the subsurface temperature, which Tanimoto et al. (2008) verified by comparing the amplitude of Rayleigh waves and the statistics on thermal moonquakes. Schimmel et al. (2018) verified the emergence of Rayleigh waves and normal modes by testing different correlational approaches with one station recording. The applications described above show the feasibility of applying the noise cross-correlation technique in extraterrestrial seismology for future planetary missions. The ambient noise correlation technology can be an effective method of investigating the internal structure of planets and following their temporal deformation.

In addition to monitoring changes in seismic wave velocity, the continuous Green's function provided by noise cross-correlation can track changes in other physical parameters of the crust over time. Obermann et al. (2014) located independent changes in seismic velocity and scattering properties of the crust from waveform decoherence to provide complementary information on the crustal evolution. Hirose et al. (2019) studied changes in the scattering and intrinsic absorption parameters of the crust based on envelopes of the cross-correlations. Durand et al. (2011) reported temporal variations in the polarization of surface waves that revealed changes in the orientation of distributed cracks in the medium. By studying multiple physical parameters independently, they can restrict each other and better explain the nature of the changes.

It is also worth noting that instead of seismic methods, other geophysical tools, such as geodesy, can also be applied to monitor the changes in underground physical properties. An interdisciplinary study has great potential to lead to a more comprehensive perspective on the underground stress field and its physical processes.

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