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Key Points:
- Repetitive very-long-period signals (VLP) in Aso volcano (aka long-period tremor, LPT) do not show detectable response against major tidal constituents, barometric pressure and temperature
- Strong surface waves from the 2011 Tohoku earthquake (> 0.01 m/s) preferentially modulate depressurization LPT events for several days
- Response of hydrothermal reservoir to pressure change induced by periodic loadings is likely stress-rate dependent

Supporting Information:
Supporting Information may be found in the online version of this article.

The Response of Repetitive Very-Long-Period Seismic Signals at Aso Volcano to Periodic Loading

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Abstract Triggering of volcano seismic activity and eruptions by tides, atmosphere pressure, rainfall, and earthquakes have been in constant debate. However, there is limited evidence concerning the triggering of very-long-period signals (VLPs), which are closely linked to volcano conduit dynamics. Persistent and repetitive VLP event beneath the Aso volcano, historically termed long-period tremor (LPT), manifests episodic pressurization and depressurization events in a crack-like shallow conduit. Here we show that LPT activity display no appreciable spectral peaks associated with major diurnal/semidiurnal tidal constituents or barometric pressure. Instead, passing surface waves of ~0.01 m/s from the 2011 Tohoku earthquake elevated LPT activity and preferentially increased the likelihood of depressurization events. We suggest that the hydrothermal reservoir near the LPT source behaves like a confined (unconfined) aquifer against short-period (long-period) stress. A high stress rate of ~10^2 Pa/s is sufficient to enhance the permeability of the conduit plug/wall and preferentially promotes depressurization events.

Plain Language Summary At one of the most active volcanoes in Japan, Aso volcano, long-period tremor (LPT) was first discovered in the 1930s by Prof. Sassa in Kyoto University and such LPT activity have persisted since. It offers a unique natural laboratory and controlled experiment to systematically explore how periodic loadings trigger or modulate LPT activity in a persistently degassing volcano equipped with a well-developed hydrothermal system. After carefully considering the background noise level modulated by the local wind and meteorological condition, we find no evidence of modulation or triggering by tides, barometric pressure, or temperature. Systematic analysis of surface wave amplitudes from great earthquakes suggests a common triggering threshold (~0.01 m/s) shared by LPT (pressure change events) in Aso and volcano-tectonic earthquakes (brittle failure events) in some geothermal areas, supporting key processes of pressure oscillations and unclogging fractures by dynamic stress.

1. Introduction

Tidal and hydrological loading has been shown to modulate volcanic eruption over semidiurnal to seasonal periodicities (Dzurisin, 1980; Hamilton, 1973; Mason et al., 2004; Mauk & Johnston, 1973; McNutt & Beavan, 1987; Sottili & Palladino, 2012). Earthquake-induced dynamic stress changes, on the other hand, suggest the possibility of a more imminent change in eruption activities due to seismic waves of a much shorter period (seconds to minutes) (Hill et al., 2002; Linde & Sacks, 1998; Manga & Brodsky, 2006; Namiki et al., 2019). As volcanic eruptions are generally not frequent, attention has been paid to exploring how seismic activities near the volcanic plumbing system are triggered or modulated by these external loadings. Since seismic signals detected near the volcanic plumbing system reflect the internal dynamics (Blake, 1981; Sturtevant et al., 1996; Tait et al., 1989), variations of the overpressure or/and the rheology of conduit and country rock, it is critical to understand and validate how seismic activities are triggered/modulated by external loadings.

At a long time scale, tidal, atmospheric, and hydrological control of volcanic seismic activities has been extensively investigated (Custodio et al., 2003; Emter, 1997; Fadeli, 1992; Girona et al., 2018; Neuberg, 2000; Petrosino et al., 2018; Sassa, 1936; Tolstoy et al., 2002). At a short time scale, dynamic triggering of seismic activities by surface waves from large earthquakes is also well documented (Freed, 2005; Hill et al., 1993; Hill & Prejean, 2015; Husen et al., 2004; Manga & Brodsky, 2006; Prejean et al., 2004; Yukutake et al., 2013). In most cases, these investigations focus on volcano-tectonic earthquakes (VT), which represent shear

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failures of the brittle country rock as a result of stress changes in the plumbing system (Chouet & Matoza, 2013; McNutt, 2005; Roman & Cashman, 2006).

On the other hand, other volcano-seismic activities such as tremors, long-period signal (LP), and very-long-period signal (VLP) are excited by a transient pressure/force change associated with the movement of magma or/and gas (e.g., Bercovici et al., 2013; Chouet & Matoza, 2013; Fujita et al., 2011; Girona et al., 2019; Lipovsky & Dunham, 2015; Nishimura & Iguchi, 2011) and they are probably much better suited for a direct probe of external modulation on degassing or/and conduit overpressure (Custodio et al., 2003; Neuberg, 2000). However, there is very limited observational evidence concerning the dynamic triggering of LP or VLP (Cannata et al., 2010; Jousset et al., 2013; Miyazawa et al., 2005; Prejean & Hill, 2018). Most importantly, no analysis systematically assesses how LP or VLP in a single volcanic system responds to periodic loadings ranging from tidal periods to seismic frequencies.

We aim to provide observational evidence and understand broadly how VLPs in a persistently degassing volcano respond to periodic loadings ranging from the tidal diurnal period to seismic frequencies. Specifically, we take advantage of the newly available VLP catalog in Aso volcano over the 2011–2016 eruption cycle (Niu & Song, 2020). The repetitive VLP activity during the quiescent and active episodes in Aso volcano provides a unique opportunity to tease out the effect of external triggering/modulation from internal mechanisms. It offers a natural laboratory to systematically explore how tidal, atmospheric forcing, and dynamic stress associated with surface waves may trigger or modulate LPT activity, informing us of internal conduit dynamics and in-situ conduit rheology.

1.1. Aso Volcano and Repetitive VLP Activity

Aso volcano, located in Kyushu of southwest Japan, is known for its frequent eruptions and activities (Ono et al., 1995) and persistent degassing (Shinohara et al., 2015). While there is a long history in the observation of the VLP signal at Aso (e.g., Kaneshima et al., 1996; Kawakatsu et al., 2000; Niu & Song, 2020; Sassa, 1935; Yamamoto et al., 1999), the VLP signal was historically termed long-period tremor (LPT) and we follow this nomenclature hereafter. As noted by Kawakatsu et al. (2000), LPT has a short duration (∼60 s) compared to their dominant period (∼15 s), it can be understood as a distinct event rather than a tremor. LPT is characterized by a predominantly isotropic source mechanism (Legrand et al., 2000) and is located in a crack-like shallow conduit about ∼200 m southwest of the Naka-dake First crater, ∼100–600 m below the sea level (Figure 1a).

LPTs with opposite waveform polarities have been systematically detected and categorized as pressurization and depressurization events in the same crack-like shallow conduit (Kaneshima et al., 1996; Kawakatsu et al., 2000; Niu & Song, 2020). As noted previously, LPTs are likely triggered by a transient pressure source such as outgassing (depressurization event) and vapourization (pressurization event) in a well-developed hydrothermal system (Hase et al., 2005; Kanda et al., 2008; Terada et al., 2012). Regardless of surface volcanic activities, it is repetitive with a steady source location and mechanism during the quiescent period between 2011 and 2013 and significant unrest (Niu & Song, 2020), that is, the 2014 Strombolian eruption and the 2015/2016 phreatomagmatic eruptions (Miyabuchi & Hara, 2019; Sato et al., 2018).

In the following sections, we briefly review the data analysis and the methodology implemented in the construction of the LPT catalog. We scrutinize the LPT catalog in the frequency domain against external periodic loadings (e.g., tides, atmospheric pressure, rainfall) and the result is validated by the time-domain analysis or the statistics of LPT activity (i.e., amplitude-frequency relation). To examine the triggering/modulations of LPT activity by seismic waves, we perform β-statistics test to verify the significance in the change of LPT activity before and after great earthquakes.

Critically, we systematically scrutinize the LPT catalog and devise a scheme to minimize the bias in the detection capability due to changes in the background noise level. Often underappreciated, the wind-generated noise, generally coupled with meteorological conditions, can profoundly hinder the robustness of triggering analysis. Finally, we propose that LPT activity serve as a piezometer of pressure change within a hydrothermal reservoir and the response of LPT to periodic loadings is likely stress-rate dependent.
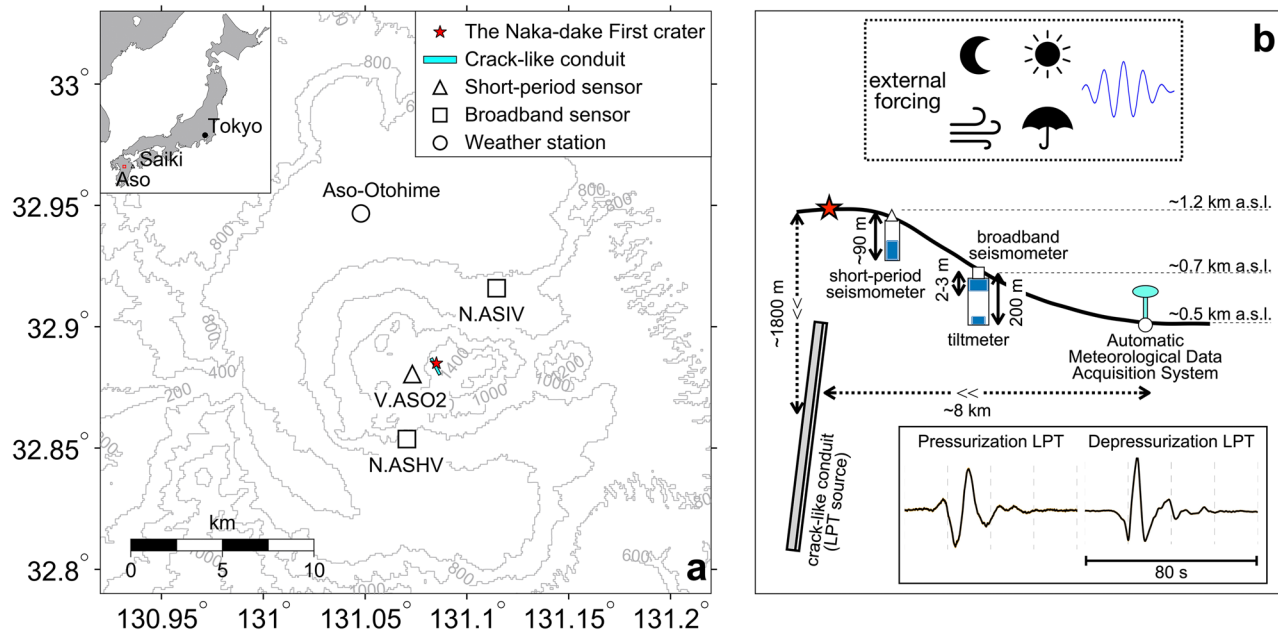
Figure 1. Map of seismic, weather, and tidal stations near Aso volcano. (a) displays the geographical locations of seismic, weather (Aso-Otohime), and tidal stations (Saiki) close to the volcano. Each broadband seismic station is equipped with a barometric pressure gauge and a borehole tiltmeter. (b) sketches the LPT source and station configuration in an east-west vertical profile. The lower inset displays representative unfiltered velocity waveforms of pressurization and depressurization LPT events in the vertical component of the ASO2 station. LPT, long-period tremor.

2. Data Analysis and LPT Catalog in 2011–2016

The detection and construction of the LPT event catalog in 2011–2016 have been extensively documented by Niu and Song (2020) and here we briefly review their methodology and the data analysis. The seismic data set includes two three-component broadband seismometers (N.ASHV and N.ASIV, a natural period of ~250 s) from the Fundamental Volcano Observation Network (V-net, Tanada et al., 2017) and a three-component short-period seismometer (V.ASO2, a natural period of ~1 s) from the Volcanic Seismometer Network operated by Japan Meteorological Agency (JMA) (Figure 1). The two broadband sensors are installed in a 3 m-deep surface vault, whereas the short period sensor is installed in a ~90 m-deep borehole. The choice of these stations reflects the quality and continuity of these seismic recordings. After removing the sensor response, the proximity of the short-period borehole station (ASO2) to the LPT source offers consistent and high-quality LPT waveforms similar to those recorded at the broadband stations (Niu & Song, 2020).

A continuous wavelet transform scheme was implemented by Niu and Song (2020) to identify LPT pressurization and depressurization events. After constructing waveform template stacks against these diverse event families, Niu and Song (2020) applied the matched-filter technique (Turin, 1960) and constructed the LPT catalog associated with the 2011–2016 eruption cycle. With the cutoff threshold cross-correlation coefficient CC ≥ 0.45 and the event signal-to-noise ratio SNR ≥ 1.8, the LPT catalog constitutes over 490,000 events, which is the basis of this study. In section 3, we examine if LPTs are modulated by long-period loadings such as tides and atmosphere conditions (e.g., pressure, temperature, and wind). In section 4, we explore if LPTs are modulated by short-period loadings such as seismic waves.

3. LPT Modulated by Tides, Atmosphere Pressure, Temperature, or Rainfall?

To assess tidal or/and atmospheric modulation against LPT activity, we focus on the spectral feature in the Fourier frequency domain to objectively tease out periodicity that may otherwise be difficult to recognize in the time domain. Specifically, we count the number of LPT events in hourly non-overlapped sliding window and construct an hourly sampled time series of LPT event numbers with a sampling rate of 1 h. A Hann taper is applied to the time series before calculating the amplitude spectra with the Fast Fourier transform.

The same process is also done against continuous borehole tilt (Sato et al., 1980) and surface barometric pressure recordings at the station N.ASHV. Note that tilt records before the 2011 Tohoku-oki earthquake are excluded to avoid tilt offset induced by the earthquake.

Hourly temperature, wind speed, and rainfall data at the meteorological station Aso-Otohime and hourly oceanic tidal data at the nearest tidal gauge station Saiki are directly provided by JMA (Figure 1). To complement the frequency domain analysis, LPT event number, the median amplitude as well as other meteorological attributes are also inspected against the local daily hours in the time domain (Figure S1). For completeness, we examine the statistics of LPT activity, that is, the amplitude-frequency relation, against the local daily hours.

To minimize the effect of internal triggering during the active period in 2014–2016, we highlight the result against background LPT activity during the quiescence period in 2011–2013 in the main text. As shown in Figure 2a and Figure 2b, there is no distinct spectra peak associated with rainfall. Borehole tilt associated with the major tidal constituents, such as principal lunar semidiurnal (M2, 12.4206 h), lunar diurnal (K1, 23.9345 h), lunar diurnal (O1, 25.8191 h), solar diurnal (P1, 24.0656 h), and lunar elliptic semidiurnal (N$_2$, 12.6588 h) can be easily identified. Contrary to the pressure spectra peaks, the LPT spectra peaks are associated with a strong solar diurnal (S1, 24 h) and a minor principal solar semidiurnal (S2, 12 h), very similar to the spectra peaks displayed against the wind speed and temperature (Figures 2a and 2b). Similar observations can be made when surface volcanic activity is high (Figures S2a–S2b). The strong diurnal peak (S1) associated with the LPT activity can also be corroborated by the day-night variation observed in the time domain (Figure 2c and Figure S2c) and in the amplitude-frequency relation (Figure 2d and Figure S2d).

3.1. Diurnal LPT Activity: A Genuine Observation or a Result of Conjecture?

To critically examine the LPT activity against the meteorological and weather conditions, it is important to evaluate if the LPT catalog is biased by the detection capability or the background noise level, which can be modulated by changes in atmospheric pressure (Beauduin et al., 1996; Ewing & Press, 1953; Haubrich, 1965; Zürn et al., 2007), temperature (Doody et al., 2018; Wielandt & Streckeisen, 1982; Wolin et al., 2015), and wind (De Angelis & Bodin, 2012; Dybing et al., 2019; Smith & Tape, 2019; Wolin et al., 2015). In particular, the ground tilt induced by atmosphere pressure (Savino et al., 1972; Webb, 1998; Zürn & Widmer, 1995) and wind (Kenda et al., 2017; Sorrells, 1971; Sorrells & Goforth, 1973; Webb, 1998; Ziolkowski, 1973), results in more substantial noise in the horizontal components than in the vertical component (Rodgers, 1968; Sorrells, 1971; Stutzmann, 2000, see also Figure S3).

Since the LPT amplitude-frequency relation follows an exponential scaling (Sandanbata et al., 2015), the detection threshold cannot be simply identified by identifying the breakdown of a power-law scaling as often done against crustal earthquakes (Davies, 1972; Flinn et al., 1972; Knopoff & Gardner, 1972; Rydelek & Sacks, 1989; Tan et al., 2019; Wiemer & Wyss, 2000). Following the same signal processing procedure and the matched-filter scheme as those implemented by Niu and Song (2020), we construct a sister LPT catalog with the three-component data from the borehole short-period seismometer and only the vertical-component data from two surface broadband seismometers. Removing surface horizontal components during the catalog construction allows us to critically evaluate how the background noise level may result in a systematic bias in the LPT catalog. Consequently, given the same CC and SNR cut-off thresholds used in the original catalog, the sister catalog contains a higher event number of ~550,000.

We find that the 24 h (S1) and 12 h (S2) periodicities observed in the original catalog no longer appear in the spectral peaks of the sister catalog (Figures 2a and 2b, Figures S2a and S2b). The day-night variations of the LPT event number (Figure 2c and Figure S2c) and the amplitude-frequency relation also disappear (Figure 2d and Figure S2d). As the local wind speed varies between the day and night (Figure 2c and Figure S2c), the diurnal change in the background noise induced by the local wind systematically biases the detection capability in the original LPT catalog. Evidently, such a bias is minimized in the sister LPT catalog.
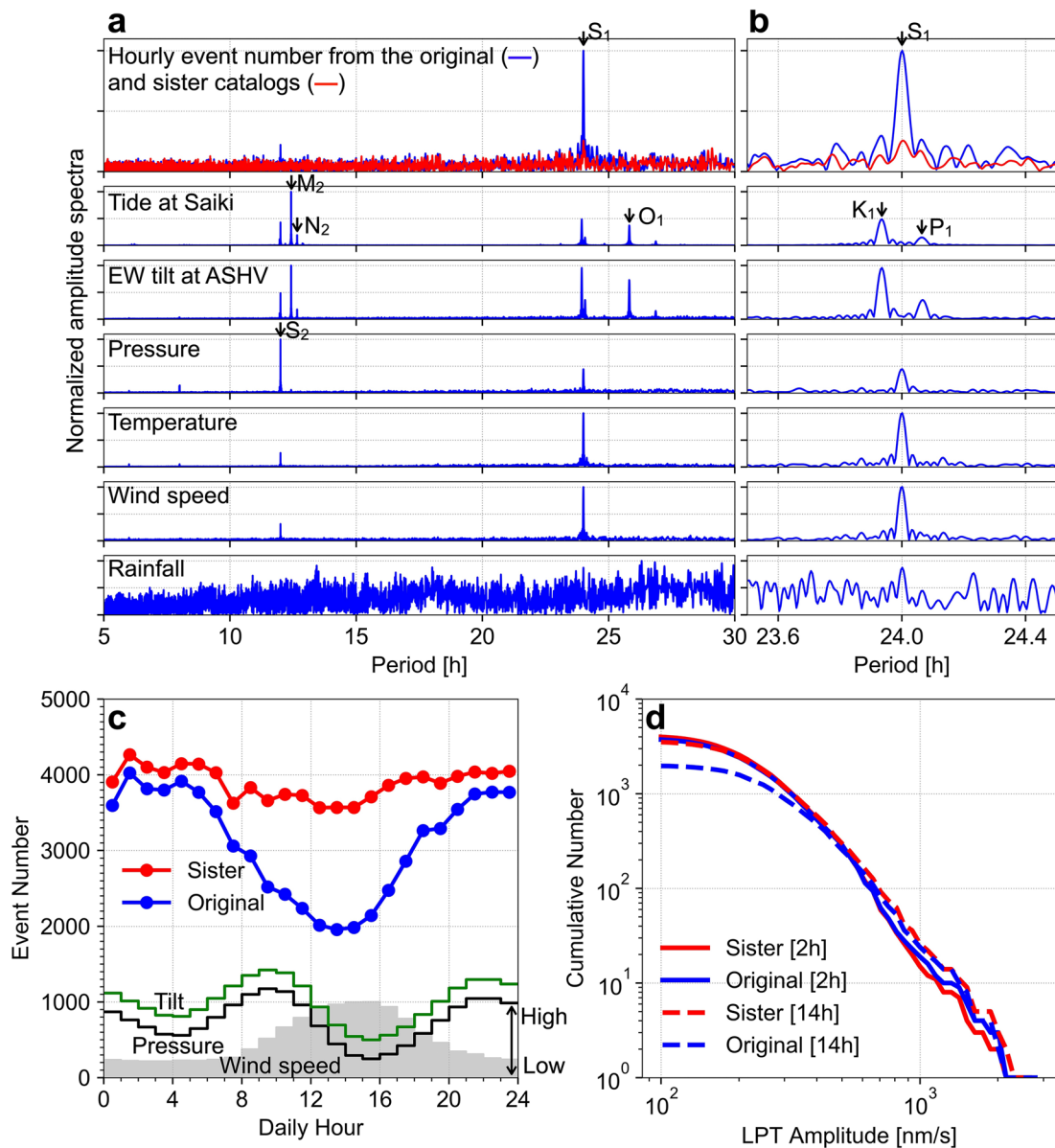
Figure 2. Comparison of LPT activity in 2011–2013 against tides, tilt, and meteorological observations. (a) displays the Fourier spectra of hourly event numbers from the original LPT catalog, the sister LPT catalog, tide, tilt, barometric pressure, surface temperature, wind speed, and rainfall rate. The LPT spectra from the sister catalog are normalized against the amplitude of the diurnal spectra peak in the original catalog. Major tidal diurnal constituents discussed are marked for reference. (b) zooms in the spectra around the diurnal peak. (c) compares the 24 h LPT activity of the two catalogs against the wind speed, tilt, and barometric pressure. (d) compares the amplitude-frequency relations from the two catalogs at 02:00 and 14:00 local time. LPT, long-period tremor.

4. Seismic Waves from Great Earthquakes Modulate LPT Activity?

Since LPT has a dominant period comparable to the period of passing seismic waves from great earthquakes, the analysis of instantaneous LPT triggering from passing seismic waves is not straightforward. Instead, we analyze the LPT activity before and after great earthquakes in 2011–2016, including the 2011 Mw 9.0 Tohoku-oki earthquake (Figures 3a and 3b). Figure 3c also displays the weekly number ratio between the depressurization and pressurization event, which is computed in a sliding window of 7 days with an overlap of 6 days. Because of the data loss, the 2016 Kumamoto earthquake is excluded from the analysis.

To quantify the statistical significance of LPT activity modulated by great earthquakes, we compute β-statistics (Reasenberg & Simpson, 1992, see also Supporting Information) against the standardized event numbers
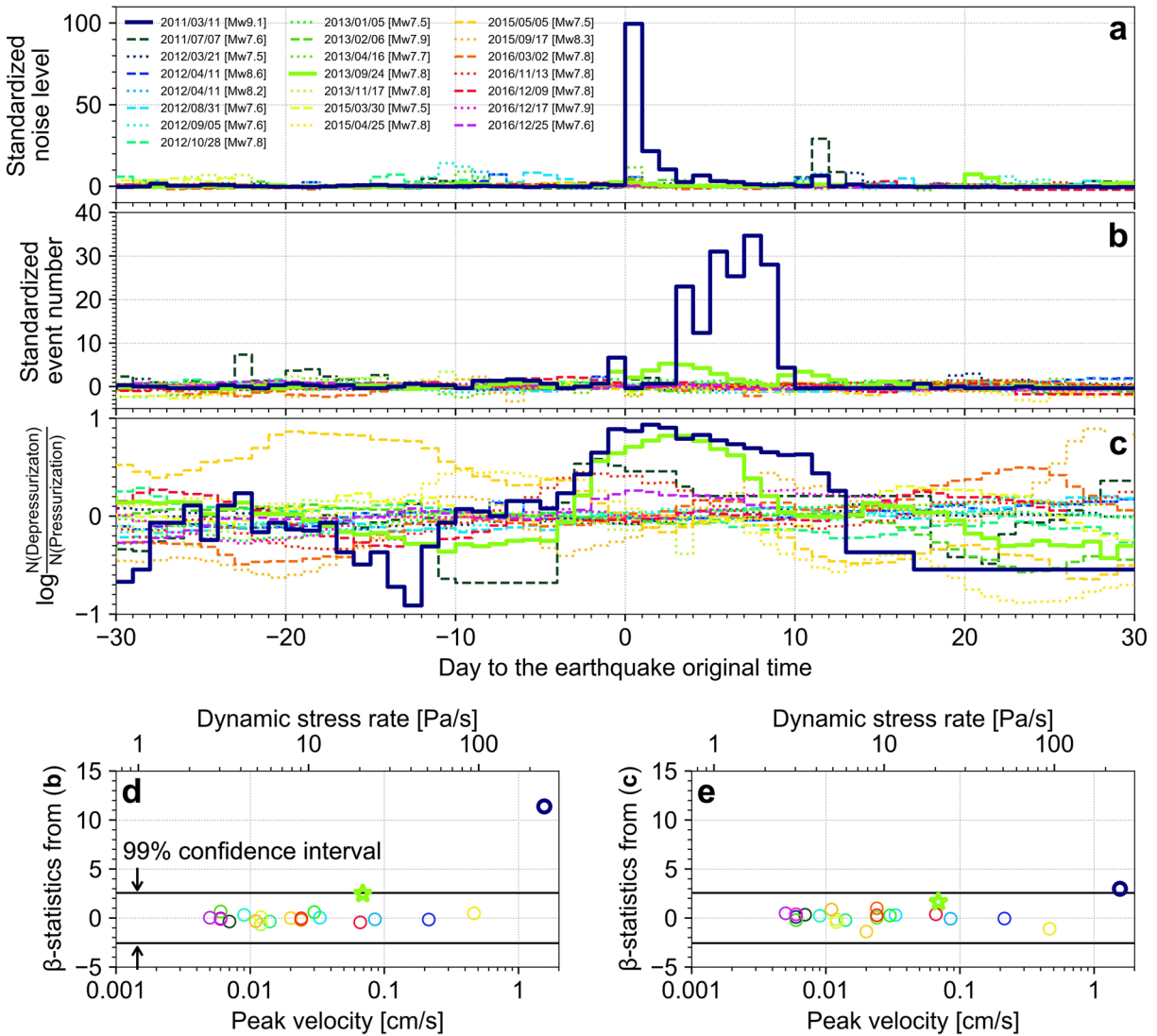
Figure 3. Analysis of seismic noise level, LPT event number, and weekly number ratio against great earthquakes. (a) displays the background noise level in the period band of 10–30 s in the vertical component of N.ASHV. (b) displays the standardized daily number of LPT events. (c) displays the weekly number ratio between the depressurization and pressurization LPT events. (d) and (e) display the β-statistics of the event number and the weekly number ratio, respectively, against the peak velocity of passing surface waves. Black lines in (d) and (e) depict the 99% confidence level. Note that volcanic earthquake activity began intensified 1 day before the 2013/09/24 earthquake (marked by star), resulting in a high β-statistics value. LPT, long-period tremor.

and the weekly number ratios before and after a given earthquake using a pre (post)-seismic time interval of 20 (10) days. The standardized event number is expressed as $(N - med) / iqr$, where N is the event number and med and iqr are the median value and interquartile range, respectively. As illustrated in Figure 3d, we identify a significant change in LPT activity before and after the 2011 Tohoku-oki earthquake above the 99% confidence level ($|\beta| = 2.57$). Similarly, we also identify a significant change in the weekly number ratios before and after the 2011 Tohoku-oki earthquake at the 99% confidence level (Figure 3e), indicating a greater proportion of depressurization events after the earthquake. Other great earthquakes do not significantly modulate LPT activity (Figure 3d) or the weekly number ratios (Figure 3e). Regardless of the choice of the catalog cutoff thresholds (Figure S4) or the pre (post)-seismic data time interval (Figure S5), the results of these statistical tests remain the same.

5. Discussions

5.1. Periodic Changes of Seismic Noises Associated with the Wind

As discussed in section 3.1, the wind-generated noise can systematically alter the background noise in the diurnal and semidiurnal periods. However, a fortnightly spring-neap cycle in oceanic tidal currents can excite a similar fortnightly variation of the sea surface temperature in many shallow seas and near-coastal zones (Ray & Susanto, 2019) and modulate the surface wind speed (Iwasaki et al., 2015). Seasonal variations of air temperature and wind speed could be substantial (McVicar et al., 2008; Young, 1999). We stress that, as the wind can generate broadband noises (Figure S3) and systematically bias the detection capability, it is important to scrutinize volcano-seismic activities over periodic changes in the background noise level, including day-night variations, fortnightly cycles, and seasonal and annual variations. As illustrated in this study, collocated surface and borehole sensors may prove to be essential in evaluating genuine external modulation of volcano-seismic activities.

5.2. The Absence of Atmospheric, Tidal Modulation of LPT Activity

We have shown that LPT is not modulated by tides or atmospheric conditions (i.e., wind speed, temperature, and pressure). The semidiurnal tidal stress typically reaches 1–10 kPa (Manga & Brodsky, 2006), the average stress rate over 12 h is only about ∼0.01–0.1 Pa/s. The lack of tidal modulation of LPT suggests that the stress or/and stress rate may be too small to trigger LPT, consistent with the observations in other volcanoes (Neuberg, 2000). The diurnal change of barometric pressure is even lower, typically on the order of ∼1 hPa (Dai & Wang, 1999, see also Figure S1f), and the average stress rate over 24 h is very low, that is, 10^{-3} Pa/s, unlikely to trigger LPT.

5.3. LPT Modulated by Dynamic Stress of Seismic Waves?

Eruptions in some volcanoes occur at a higher rate after a great earthquake, especially when earthquakes are close to volcanoes (0–200 km) when the static stress change is high (Linde & Sacks, 1998; Nishimura, 2017). However, the majority of great earthquakes are thousands of kilometers away from Aso volcano and the dynamic stress should dominate. Since the detection capability is compromised during the passage of strong seismic waves from the Tohoku earthquake and its early aftershocks (Figure 3a), it is difficult to identify instantaneous triggering. However, a sustained increase in the LPT activity over 5–10 days (Figure 3b) is likely caused by the passing surface waves from the Tohoku earthquake.

The dynamics stress σ can be estimated as $\sigma = \mu A / c$, where A is the peak velocity and c is the phase velocity of Rayleigh waves (Gomberg & Agnew, 1996; Hill, 2010). Assuming $c = 3.5$ km/s, shear modulus μ of 5 GPa in the shallow crust beneath Aso (Tsutsui & Sudo, 2004), and the source depth of LPT at ∼1 km below the surface, the dynamic stress associated with the 20 s Rayleigh waves from the 2011 Tohoku-oki earthquake ($A \sim 1.5 \times 10^{-2}$ m/s, Table S1) reaches ∼4.5 kPa, comparable to tidal stress (∼1–10 kPa). However, the stress rate is much higher at ∼230 Pa/s (Figure 3d). The peak velocity from other great earthquakes is 5×10^{-5}–4.5×10^{-3} m/s, corresponding to dynamic stress of ∼15 Pa–1.4 kPa and a stress rate of 1–70 Pa/s (Figure 3d).

5.4. Permeability Enhancement by Dynamic Stress?

The observations discussed in sections 5.2 and 5.3 suggest that the internal dynamic process relevant to LPT triggering likely operates at a stress rate of 70–230 Pa/s, or ∼O (10^2) Pa/s, which is very similar to the triggering threshold of VT established in other geothermal areas (Prejean et al., 2004). A high ground velocity on the order of 0.01 m/s may be sufficient to induce hydrodynamic shear stress at the pore scale and promote colloid mobilization (Manga et al., 2012) or fractures unclogging (Brodsky et al., 2003; Candela et al., 2014), which enhances the permeability (Brodsky et al., 2003; Elkhoury et al., 2006; Manga et al., 2012) near the shallow conduit wall or/and plug beneath Aso volcano.

To evaluate variations of conduit plug/wall permeability and rheology, Niu and Song (2020) contrasts the activity of the pressurization event against the depressurization event at a given time, where a period prone
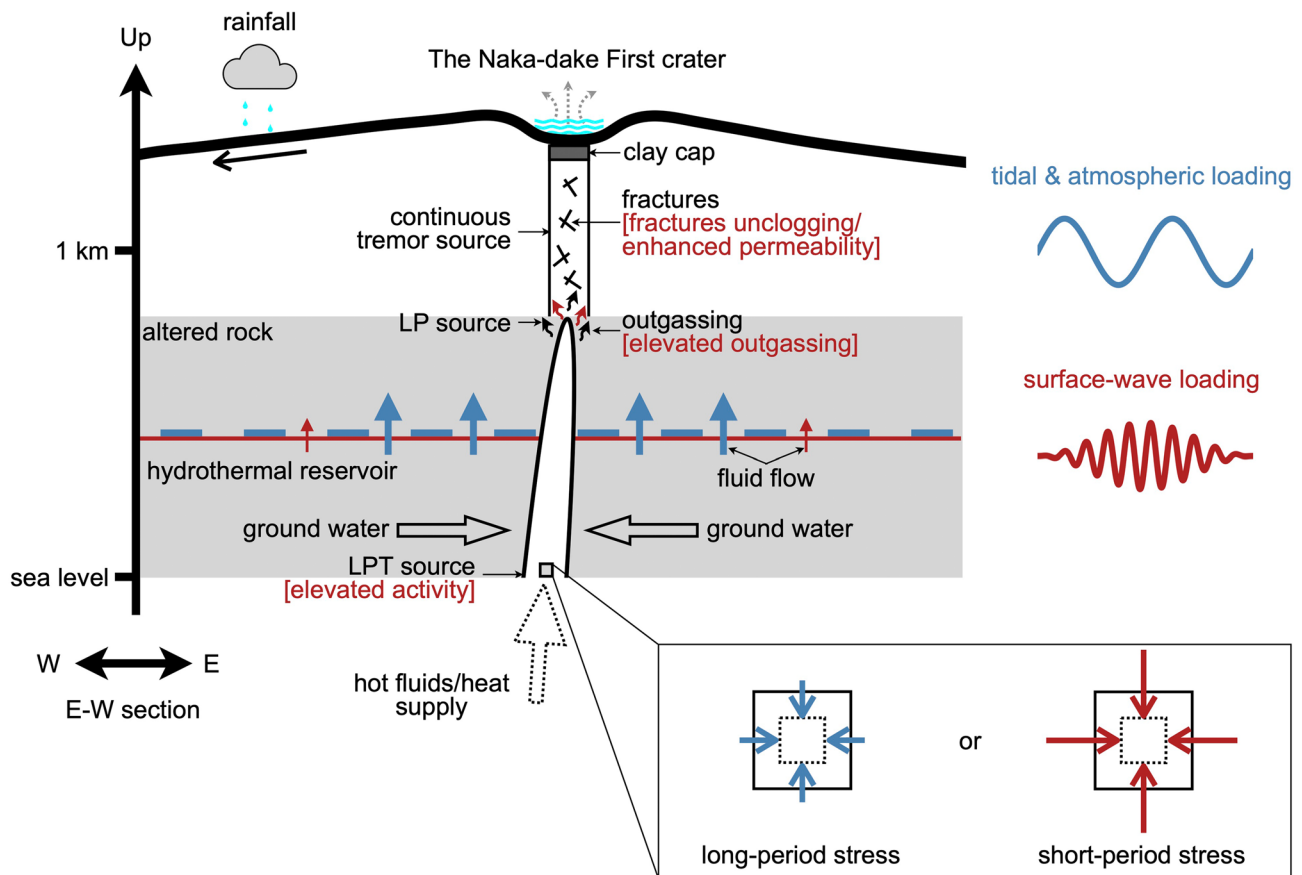
Figure 4. A schematic response of the hydrothermal reservoir beneath Aso volcano under periodic loadings. The diagram illustrates the framework governing how LPT activity in the crack-like fluid-filled conduit beneath Aso volcano respond to period loadings. Under long-period strain (or stress) such as tides, the hydrothermal reservoir behaves like a partially unconfined aquifer (dashed blue line) with marked fluid flows (upward blue arrows). The crack-like conduit does not react to a small pressure oscillation (blue arrows in the lower inset). Under short-period strain (or stress) from seismic waves, the hydrothermal reservoir behaves like a confined aquifer (thin red line) and limited upward fluid flow (upward red arrows). The crack-like conduit reacts to a strong oscillation of pore pressure (red arrows in the lower inset), facilitating fracture/unclogging and promoting outgassing and preferentially depressurization LPT events. LPT, long-period tremor.

to pressurization (depressurization) indicates a lower (higher) permeability in the conduit plug/wall. If the permeability is indeed enhanced by dynamic stress, we expect elevated LPT activity and a greater proportion of depressurization LPT events after great earthquakes, consistent with our observations (Figures 3b–3d). The elevated LPT activity subside after ~5–10 days, possibly due to permeability recovery under high background temperature (Yasuhara, 2004).

5.5. LPT as a Piezometer of Pressure Change in the Fluid-Filled Crack-like Conduit

Our observations of LPT modulation against periodic loadings such as tides, barometric pressure, and surface waves emphasize the importance of stress (or strain) rate, in a way similar to earlier studies on triggering of VT in the Geysers (Gomberg & Agnew, 1996). We draw an analogy to the well water level monitoring of pressure change induced by periodic strain in an aquifer (Cooper et al., 1965; Kano & Yanagidani, 2006; Kümpel, 1997; Roeloffs, 1996; Wang & Manga, 2010). Instead of monitoring the water level of a well connected to an aquifer under a periodic loading, LPT resonance in the crack-like conduit provides a direct means to monitor pressure change in the fluid-filled crack-like conduit embedded within a hydrothermal reservoir (Figure 4).

As shown in Figure 4, the top-end of the conduit is connected to a fractured/permeable conduit plug topped with a clay cap (Kanda et al., 2008), whereas continuous tremors and LP occur in the plug (Takagi

et al., 2006) and near the upper end of the crack-like conduit (Mori et al., 2008), respectively. Under low-frequency stress (strain) oscillation, the hydrothermal reservoir behaves like a partially unconfined aquifer with marked upward groundwater flows and the fluid-filled crack-like conduit does not react to a small pressure change (Figure 4). Under oscillatory stress of seismic wave frequency, the hydrothermal reservoir behaves like a confined aquifer with limited upward fluid flows. The conduit reacts to a strong oscillation of pore pressure, promoting fractures unclogging and enhancing the permeability of the conduit wall or/and plug. As a result, it elevates outgassing and preferentially triggers depressurization LPT events.

While a number of internal triggering mechanisms exist (e.g., Chouet & Matoza, 2013; Fujita et al., 2011; Girona et al., 2019; Lipovsky & Dunham, 2015; Manga & Brodsky, 2006; Sturtevant et al., 1996), our observations and the proposed framework highlight the dynamic nature of transport properties under external loading, which should be taken into account when evaluating potential dynamic processes governing background LPT activity in Aso and volcano-seismic signals observed elsewhere.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The authors gratefully thank NIED and JMA for providing us the high-quality waveform data of V-net, which can be downloaded from https://www.hinet.bosai.go.jp. The meteorological observations are downloaded from http://www.data.jma.go.jp/gmd/risk/obsdl/index.php. The tidal hourly data recorded by the tide gauge station Saki can be downloaded from http://www.data.jma.go.jp/gmd/kaiyou/db/tide/genbo/genbo.php?stn=X5

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