

Long-term seismic background level variations are consistent with volcanic activity at Kusatsu-Shirane volcano, Japan

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Abstract

Kusatsu-Shirane volcano in central Japan has repeatedly experienced phreatic eruptions, with the Yugama crater being one of the main centers of activity. To clarify long-term variations in volcanic activity around the Yugama crater, we analyzed more than 20 years of continuous seismic records using a statistical approach to calculate the seismic background level (SBL). This method enables the detection of weak volcanic signals that are buried in background noise. The results revealed that the SBL increased during the unrest episodes in 2014 and 2018, with a good temporal correspondence with both deep and shallow sources of ground deformation. The SBL increase followed the onset of enhanced seismic activity in 2014, whereas it preceded the seismic activation in 2018. The inter-station SBL ratio also differed between the two unrest periods. One possible interpretation is that the source region of the vibrations contributing to the SBL differed between the 2014 and 2018 unrests. Variations in SBL were also detected during non-unrest periods, coinciding with minor surface phenomena such as color changes of the Yugama crater lake and the appearance of new fumaroles. These correspondences suggest that the SBL may reflect volcanic activity, even without strong seismic or deformation signals. Overall, we infer that the SBL variations over the 20 years were related to volcanic activity, possibly associated with the supply of volcanic fluids.

1. Introduction

Long-term analysis of seismic data is important, because volcanic activity variations commonly progress over timescales of years to decades. Furthermore, in order to establish a reliable baseline for interpreting changes in seismic metrics, the analysis period must include both quiescent and active phases. In addition to the long-term analysis, combining various observations provides a more reliable picture of the state of a volcano because we cannot necessarily evaluate volcanic activity using individual datasets alone (Poland and Anderson 2020; Burchardt et al. 2022; Acocella et al. 2024; Stix et al. 2025). Recent studies have shown that an eruption forecasting model using data from multiple sensors or data streams with the Bayesian network method performs better than models using any single dataset (Behr et al. 2025).

In recent years, attempts have been made to detect weak volcanoseismic signals buried in background noise and to track volcanic activity through long-term analysis. Ichihara et al. (2023a, b) statistically processed seismic waveforms recorded during the nighttime period with low noise levels and defined the daily seismic background level (SBL). They extracted weak volcanic signals (SBL vibrations), which increased several months before the eruptions of Shinmoe-dake, an active cone of the Kirishima volcanic group in southern Kyushu, Japan. GNSS analysis also detected inflation several months before the eruptions, but the deformation source was located deep and away from Shinmoe-dake (Nakao et al. 2013). The SBL signals are inferred to have originated from shallow regions directly beneath the volcano, and the fact that such weak signals were detected several months in advance is particularly significant. Ichihara et al. (2023a, b) suggested that SBL amplitude variations may reflect changes in the state of the

subsurface hydrothermal system or aquifer caused by interactions with magmatic fluids, and that the SBL can serve as a new indicator for volcano monitoring.

The SBL analysis may also be useful for understanding the behavior of shallow fluids in volcanic environments where phreatic eruptions occur. Kurihara (2023) applied the SBL analysis and detected a temporal increase in noise amplitude associated with the 2015 phreatic eruption at Hakone volcano, suggesting that variations in background seismic noise may reflect changes in volcanic activity. Stix and De Moor (2018) discussed the heating processes of hydrothermal systems and near-surface aquifers caused by the supply of volcanic fluids prior to eruption. Similarly, at Kusatsu-Shirane volcano, detecting variations in the subsurface hydrothermal system is crucial for understanding the state of volcanic activity because a well-developed hydrothermal system exists beneath the Yugama crater at Kusatsu-Shirane volcano (Hirabayashi 1999; Terada 2018).

At Kusatsu-Shirane volcano, recent activity is dominated by phreatic eruptions (Terada 2018; Ishizaki et al. 2025). There, long-term evaluations of volcanic activity have been conducted through various types of observations, such as geochemical monitoring of lake water in the Yugama crater and adjacent fumarolic gases (Ohba and Yaguchi 2025) and geomagnetic measurements (Takahashi and Fujii 2014; Kanda et al. 2025).

Seismic observations also have a long history. Continuous monitoring has been conducted since the Japan Meteorological Agency (JMA) installed a seismometer in 1978 (Yamasato 2005). Some seismic instruments have been operated very close to the Yugama crater, making the area an excellent field site for studying phreatic eruptions.

However, studies using seismometer data have mainly focused on short-term earthquake features. For example, Kumagai et al. (2002) analyzed long-period (LP) events and discussed temporal changes in the physical properties of fluid in cracks beneath the Yugama crater lake from August 1992 to January 1993. Long-term evaluations of volcanic activity at Kusatsu-Shirane using seismic data remain insufficient.

The aim of this study is to clarify how the SBL corresponds to volcanic activity. To this end, we analyzed more than 20 years of seismic data recorded around the Yugama crater. We identified SBL vibrations around the Yugama crater. These results may provide constraints on the relationship between SBL variations and the shallow aquifer or hydrothermal system in a phreatic-eruption environment.

2. Background of Kusatsu-Shirane Volcano

2.1 Geological setting

Kusatsu-Shirane, an active volcano located in the north-western part of Gunma Prefecture, consists of a group of pyroclastic cones including Shirane, Ainomine, and Motoshirane, which are aligned in a north-south direction (Fig. 1a). At the northernmost cone lies the Yugama crater lake, around which phreatic eruptions have frequently occurred (Terada 2018; Ishizaki et al. 2025).

2.2 Recent activity near the Yugama crater lake (2014–2023)

Since 2014, Kusatsu-Shirane volcano has experienced episodes of volcanic unrest that might have been driven by a supply of volcanic fluids from deeper levels of the system (Munekane 2021). In both 2014 and 2018, seismic activity markedly increased around the Yugama crater (Fig. 1b), accompanied by inflation directly beneath the crater (Terada et al. 2025). Analyses of regional GNSS measurements revealed an inflation source located a few kilometers northwest of the Yugama crater at a depth of approximately 4 km. The inflation at this deep source began before the onset of both the 2014 and 2018 unrests (Munekane 2021).

The 2018 unrest may have approached a pre-eruptive condition, as suggested by several precursory signals. A rapid increase in seismic activity around Yugama was observed on 22 April 2018, accompanied by a crustal deformation signal. Tiltmeter observations indicated a pressure source located to the west of Yugama (JMA 2018a, b). The hypocenters of volcano-tectonic (VT) earthquakes became progressively shallower with time (Kobayashi et al. 2019). During this activity, a very-long-period (VLP) earthquake, which is regarded as an important indicator for assessing the probability of a future eruption (Stix and De Moor 2018; Niu and Song 2020; Takeo et al. 2022; Konstantinou 2024), was recorded, followed by the reversed change of the tilt trend and the gradual decrease of the seismic activity (JMA 2018a, b). The occurrences of VLP earthquakes and migration of VT-earthquake hypocenters suggested that the volcanic system was close to an eruption. Another similar episode of sudden intensification of seismic activity occurred in late September 2018.

In June 2018, a dark-colored change was observed on the surface of the Yugama crater lake (JMA 2018c; Terada and Kuwahara 2025). Such a color change had been observed in the past. In January 1989, similar black floating materials were observed on the lake surface, which were interpreted as evidence of a sudden discharge of volcanic gas and hydrothermal fluid beneath the lake surface (Ida et al. 1989).

These observations indicate that detailed analyses of the 2014 and 2018 episodes of volcanic unrest are crucial for understanding the activity of Kusatsu-Shirane volcano and the mechanisms of phreatic eruptions.

2.3 Long-term observation (late 1990s-2023)

When focusing on the 30-year trend of seismicity, the number of earthquakes has gradually increased since the early 2000s (Fig. 1b). In addition, several surface phenomena have been observed around the Yugama crater, including the appearance of a water jet, the above-mentioned color change, as indicated by blue triangles in Fig. 1b (Volcanic Fluid Research Center, Tokyo Institute of Technology 2004; JMA 2013), and the emergence of new fumaroles around the crater, as indicated by yellow squares in Fig. 1b (JMA 2008a, b, 2013).

These facts may suggest that, after a relatively quiet period following the early 1990s activity, volcanic activity gradually intensified toward the 2014 and 2018 unrests. Therefore, analyzing and interpreting volcanic activity in decades, including the period before the 2014 unrest, is essential for interpreting the 2014 and 2018 unrests and for characterizing the baseline behavior of Kusatsu-Shirane volcano as a site of phreatic eruptions.

3. Data and methods

3.1 Data

Seismogram

We analyzed data from short-period seismometers installed near the Yugama crater by the JMA and the Tokyo Institute of Technology (reorganized to Institute of Science Tokyo in October 2024) (Fig. 2). KSHA is installed at the ground surface, whereas KSAO, KSE, KSW, and KSS are installed at depths of 95, 50, 220, and 110 m, respectively (Mori et al. 2003).

We processed nearly 20 years of data covering the period from 2 March 2002 to 31 December 2023, although the starting dates of the analysis differ among the stations.

JMA catalog

We used the JMA catalog for seismicity analysis, including event classification, hypocenter information, and amplitude data. Based on the JMA's event classification, we reclassified the events into three groups: high-frequency (A- and BH-type), low-frequency (BL-type), and harmonic/monochromatic (BP- and BT-type) earthquakes, where the type names follow the JMA classification (JMA 2024). A-type earthquakes are VT events, whereas B-type earthquakes are low-frequency events with unclear phase onsets. Among the B-type earthquakes, those with relatively high-frequency components are classified as BH-type, those with relatively low-frequency components as BL-type, those exhibiting harmonic oscillations as BP-type, and those with a gradually decaying monochromatic tail as BT-type.

In this study, this grouping is introduced to compare temporal variations between relatively high-frequency seismic activity and harmonic/monochromatic seismic activity. Although A-type (VT) and BH-type earthquakes may reflect different physical mechanisms, this grouping is based on frequency characteristics and does not imply that A-type and BH-type earthquakes share the same source mechanism.

3.2 Method

SBL

We analyzed the data using the SBL calculation method. A schematic diagram of the procedure is shown in Fig. 3, and the detailed calculation method is described in Ichihara et al. (2023b).

We adopted the same settings as Ichihara et al. (2023b), including the analysis time window (18:00 of the previous day to 06:00 of the following day), the time window length for the power spectral density (PSD) calculation (10.24 s), the frequency band used to calculate seismic power (3.5–7.0 Hz), and the criterion for determining the SBL (lowest 20th percentile) (Fig. 3a). The selection of the frequency band is described in detail in the section “Adaptation of frequency band.” In contrast to Ichihara et al. (2023b), who used all three components of the seismometer data, we used only the vertical component because the horizontal components occasionally exhibited data quality issues (e.g., temporary loss of low-frequency signals at the KSHA station).

The calculation of PSDs was performed on an hourly basis, and time periods with more than 30% missing data were excluded from the analysis because the data acquisition was unstable during those periods.

We also adopted the smoothing procedure (Fig. 3b) to exclude short-term fluctuations by selecting the 20th percentile of the SBL values within the previous seven days, including the current day (up to 14 samples). In the smoothing process, when fewer than 70% of the data (i.e., fewer than 10 samples) were available, the value for that day was excluded from the analysis.

SBL ratio

To identify differences in the temporal evolution of the SBL among stations, we calculated the SBL ratios between station pairs. First, we computed the normalized SBL by dividing the smoothed SBL by its mean value over a reference period, and then took the ratio between stations. This normalization is only to compare relative temporal changes among stations on a common scale, independent of differences in their absolute SBL levels. For the reference period, we selected December 2019 to January 2020, when the station with the longest continuous record (KSHA) exhibited its highest SBL levels. In addition, this period contained relatively few missing data across all observation sites and thus provided a stable reference interval.

SBL spectra

We also calculated daily SBL spectra to examine variations in the spectral components and to obtain supplementary information on the onset and termination of weak signals.

Specifically, we stacked the PSDs of time windows corresponding to the 5th to 20th percentiles of seismic power. Although Ichihara et al. (2023b) normalized the stacked spectra by the maximum value within 1–15 Hz, we used the maximum within the 3.5–7.0 Hz band used for the SBL calculation. This approach was adopted to focus on the spectral characteristics within the SBL calculation band.

Adaptation of frequency band

We readjusted the frequency bands used for SBL referring to the SBL spectra. Figure 4a shows the SBL at station KSHA, calculated with different lower frequency bounds (3.0, 3.5, and 4.0 Hz). Figure 4b shows

the corresponding SBL spectra. Before the seismometer replacement on 13 November 2012, continuous strong power was observed around 3 Hz (Fig. 4b). Because this signal is confined to a very narrow frequency band, it is likely related to site or installation conditions rather than volcanic activity.

From the comparison among SBLs in 3.0–7.0 Hz, 3.5–7.0 Hz, and 4.0–7.0 Hz, we confirmed that although the influence of narrowband noise around 3 Hz is evident in the absolute amplitudes, the overall temporal variations of the SBL throughout the entire observation period remain similar. Thus, we used the 3.5–7.0 Hz band for the SBL calculations with no significant leakage of the noise component above 3.5 Hz.

4. Results

4.1 Overview of temporal changes of SBL

4.1.1 SBL

Figure 5b shows the temporal changes in the SBL, whereas Fig. 5a shows the periods defined primarily based on the temporal evolution of the SBL at KSHA, which has the longest observation record. Independent observations, particularly ground deformation data (e.g., areal strain; see Section 4.2), were used as supporting information to confirm the timing of changes and transitions in trends. The specific periods and their characteristic trends are summarized in Table 1. Although some uncertainty remains in the definition of the period boundaries, we evaluated the temporal trends of the SBL by performing linear regression analysis for each period (Supplementary Information, Figs. S10 and S11). There are slight differences among the stations; however, they exhibit similar variation trends. No obvious annual periodicity (seasonal variation) is observed.

Table 1
Period defined from the SBL at KSHA.

Period	start	end	SBL
I	2004 (1 Jan 2004)	April 2005 (30 Apr 2005)	increase
II	around May 2005 (1 May 2005)	around May 2007 (31 May 2007)	decrease
III	around May 2007 (1 Jun 2007)	2008 (31 Dec 2008)	increase
IV	2009 (1 Jan 2009)	around April 2014 (30 Apr 2014)	no significant change
V	around May 2014 (1 May 2014)	around May 2015 (31 May 2015)	increase
VI	around May 2015 (1 Jun 2015)	mid-2017 (31 Aug 2017)	decrease
VII	late 2017 (1 Sep 2017)	around January 2020 (31 Dec 2019)	increase
VIII	January 2020 (1 Jan 2020)	around January 2022 (31 Dec 2021)	no significant change (keeping high levels)
IX	January 2022 (1 Jan 2022)	April 2022 (30 Apr 2022)	decrease
X	May 2022 (1 May 2022)	May 2023 (31 May 2023)	no significant change
XI	around June 2023 (1 Jun 2023)		decrease
[footnote]			
* Dates in parentheses correspond to the time intervals used for color coding in Fig. 5.			

4.1.2 SBL ratio

Figure 5c shows the SBL ratios (see Section 3.2) since November 2010, when station KSAO was installed. For each station pair, we selected KSAO, the station farthest from the Yugama crater, as the

reference and compared the ratios of KSHA/KSAO and KSW/KSAO. The SBL ratio of KSHA/KSAO increased during the 2018 unrest, while it remained low during the 2014 unrest. In contrast, KSW/KSAO remained approximately constant (~ 1) throughout both unrest periods, although short-term fluctuations are present (e.g., a temporary decrease around 2017). A comparison of SBLs and SBL ratios for all station pairs after 2012 is provided in Supplementary Information (Fig. S7).

4.2 Comparison with seismicity and ground deformation

We compared the temporal variations in the SBL with both seismic activity and ground deformation to investigate their temporal correspondence and characteristic differences between the unrest episodes. Figure 5d shows the monthly number of earthquakes since August 2002, mainly those occurring around the Yugama crater and Ainomine areas (JMA 2013). For ground deformation, we used two types of geodetic data to examine the depth dependence of the sources of activity. Figure 5e shows the time series of baseline length changes between the GNSS stations G03 and G07, which are located on opposite sides of the Yugama crater (Fig. 2b). The baseline length is about 1,227 m, and such a local-scale baseline is generally sensitive to shallow deformation sources. Figure 5f presents the regional-scale areal strain calculated from three GEONET stations (Fig. 2a), which is instead sensitive to deeper crustal deformation sources. It should be noted that the areal strain calculation was not corrected for the postseismic deformation following the 2011 Tohoku-Oki earthquake.

4.2.1 Before 2014 unrest (Periods I–IV)

During Period I (2004–around April 2005), the SBL showed an increasing trend (Fig. 5b). During Period II (around May 2005–around May 2007), the SBL decreased. Both periods exhibit no notable changes in seismic activity or areal strain (Fig. 5d, f). In Period III (around May 2007–2008), seismicity slightly increased in 2007, and the SBL also showed an increasing trend (Fig. 5b, d). However, no obvious increase in areal strain was observed (Fig. 5f). In Period IV (2009–around April 2014), there were periods when the number of earthquakes exceeded that of the 2007 activity (Fig. 5d). The SBL remained at higher levels than in the previous years, but no distinct increase was observed (Fig. 5b). This period includes the 2011 Tohoku-Oki earthquake, and volcanic deformation cannot be distinguished from the postseismic deformation (Fig. 5f).

The local baseline length appears to show an overall contraction trend throughout Periods I–IV (Fig. 5e); however, the data sampling was insufficient during these periods, and therefore the changes remain uncertain.

4.2.2 2014 unrest (Periods V–VI)

Period V (around May 2014–around May 2015)

The left column of Fig. 6 focuses on the 2014 unrest. The unrest characterized by increased seismic activity began on 6 March 2014 (left blue dashed line through Fig. 6a–k). According to JMA (2014), small-amplitude volcanic earthquakes with shallow hypocenters beneath the Yugama crater started to

increase around 16:00 on 6 March 2014. The seismic activity became more intense in early May 2014 (Fig. 6d). The events were classified as high-frequency earthquakes (Fig. 6f).

The SBL began to increase around May 2014 (Fig. 6a), slightly delayed relative to the onset of seismic activity. In the SBL spectra, a spectral component around 3 Hz appeared in March 2014, around the time indicated by the left blue dashed line in Fig. 6c. In May 2014, the 3 Hz component became more pronounced, and another component around 4–5 Hz strengthened. Although the daily number of earthquakes decreased in July 2014, the SBL continued to increase.

The areal strain had begun to increase in early 2014 (Fig. 5f), before the increase in seismicity. The onset of local extension during the 2014 unrest is uncertain due to the sparse sampling interval of the GNSS data (Fig. 5e). The detailed comparison between the SBL and the local deformation is limited because of the sparse sampling interval, which we discuss in Section 5.1.1. The increase in areal strain slowed down around February 2015.

Period VI (around May 2015–around mid-2017)

The SBL began to decline between July and September 2015, during which the seismic activity further decreased (Fig. 5d). The local extension seems to continue until the measurement in May 2016 (Fig. 5e). More precisely, the turning point occurred between the October 2015 and September 2016 measurements, although the extension persisted at least until October 2015. The detailed turning point is discussed in Section 5.1.1. The subsequent baseline measurements (September 2016 and June 2017) show that the local deformation was in a contraction phase in the latter half of Period VI (Fig. 5e), when the SBL had returned to its pre-2014 level. The SBL continued to decrease until late 2016, when the spectral components around 3 Hz and 4–5 Hz disappeared (Fig. 6a, c).

4.2.3 2018 unrest (Periods VII–IX)

Period VII (late 2017–around January 2020)

A prolonged unrest occurred from 2018 to 2022. The SBL and areal strain began to increase in late 2017, before the increase in seismic activity (Fig. 5b, d, f). However, the relative timing between the onset of the deep deformation and the SBL increase in 2018 is unclear, because both changes were gradual, and because the areal strain and the SBL time series were smoothed over 30 days and seven days, respectively (Fig. 5b, f).

The right column of Fig. 6 focuses on the first half of the 2018 unrest. In 2018, the SBLs at KSHA, KSE, and KSW showed synchronous fluctuations, with the fluctuation pattern most clearly visible at KSW (Fig. 6g). The SBL kept growing until early 2020. Signals around 5–6 Hz appeared in late 2017 (Fig. 6i), when the SBL started increasing, and became more pronounced in April 2018. Volcanic earthquakes also increased in April 2018 (Fig. 6j). This increase was characterized by a sudden rise in amplitudes (Fig. 6k), as well as event number. The sharpness of this onset was particularly striking compared with that of the 2014 unrest. At the beginning of the 2018 activity, high-frequency earthquakes were

dominant. The local extension data in May 2018 showed extension compared with the previous measurements around the boundary between VI and VII (Fig. 5e), suggesting that the preceding contraction trend had at least weakened. In late September 2018, another sudden increase in seismic activity was observed. Subsequently, harmonic events became predominant (Fig. 6l).

Period VIII (around January 2020–around January 2022)

The SBL levels remained high, with no significant changes in their trends (Fig. 5b). There were no major changes in seismic activity or crustal deformation trends, either (Fig. 5e, f).

Period IX (January 2022–April 2022)

Around early 2022, when the number of earthquakes markedly decreased (Fig. 5d), the SBL began to show a slight decline (Fig. 5b). The baseline length turned to a contraction trend in 2022 (Fig. 5e), and the increasing trend in areal strain became less obvious (Fig. 5f).

5. Discussion

5.1 Relationship between SBL and volcanic activity

Table 2 summarizes the sequences presented in Section 4. Here we assume that the GNSS observations of the local extension (Fig. 5e) and the areal strain (Fig. 5f) represent shallow and deep deformation, respectively (see Supplementary Information, Section S6). We combine the results in Table 2 and other observations to discuss possible relationships between the SBL variations and volcanic activity.

Table 2
Summary of the sequences presented in Section 4.

SBL	before 2014 unrest	2014 unrest (May 2014–mid 2017)	2018 unrest (2018–2022)
	2004–around Apr 2005 (I): increase Around May 2005–around May 2007(II): decrease Around May 2007–2008 (III): increase 2009–around Apr 2014 (IV): no significant change	May 2014–May 2015 (V): increase May 2015–mid 2017 (VI): decrease	Late 2017–Jan 2020 (VII): increase (In 2018, unstable) Jan 2020–Jan 2022 (VIII): no significant change (keeping high levels) Jan 2022–Apr 2022 (IX): decrease
SBL spectra	-	Mar 2014–late 2016: 3Hz May 2014–late 2016: 4–5Hz	mid to late 2017–: 5–6Hz
Seismicity: (number, amplitude, type)	[Event number] Nov 2007 (II) slight increase 2011 (IV) slight increase [Event type] High-frequency	[Event number] 6 Mar 2014: increase Early May 2014: further increase Jul 2014: decrease [Event type] High-frequency	[Event number] Apr 2018: rapidly increase Sep 2018: rapidly increase Early 2022: markedly decrease [Amplitude] larger than 2014 unrest [Event type] High-frequency to harmonic
Ground deformation: Shallow source	not clearly identified	2014–2015: inflation 14 Mar 2014–Oct 2015: inflation*	2018–2021: inflation Apr 2018–Nov 2021: deformation*
Ground deformation:	no volcanic signals	Early 2014–2015: inflation	Late 2017–2021: inflation
*Section 5.1.1 referring to Terada et al. (2025). **Section 5.1.1 referring to JMA (2018a, b).			

Deep source	Feb 2015: inflation slows down	Apr 2018: inflation**
*Section 5.1.1 referring to Terada et al. (2025). **Section 5.1.1 referring to JMA (2018a, b).		

5.1.1 The 2014 and 2018 unrests

We identified two common features related to deep deformation and seismic activity in the two unrests. First, the SBL tends to increase during the inflation phases of the deep deformation source, and to decrease when the inflating trend slows down, stagnates, or reverses. Second, the SBL increases before or during the enhanced volcanic seismic activity. These common temporal relationships suggest that the SBL variations are related to volcanic activity.

We referred to the tiltmeter observations around the Yugama crater (JMA 2018a, b; Terada et al. 2025) to better constrain the deformation sequence at the onset of the unrest episodes, because these observations complement the sparse GNSS data of the local extension (Fig. 5e). Terada et al. (2025) reported a radial pattern of uplift from 14 March 2014 to October 2015, which was interpreted as inflation of a shallow source around Yugama. A comparison between the tiltmeter observations and the SBL variations suggests the follows. During the 2014 unrest, inflation of a shallow source may have started before the increase in the SBL, and the SBL began to decrease during the period when the uplift around Yugama continued. During the 2018 unrest, the onset of the abrupt seismic activation in late April 2018 (Fig. 6j) was accompanied by tilt changes, which were explained by a deep inflation source west of Yugama (JMA 2018a, b). It was followed by another tilt change attributable to shallow deformation around Yugama (Terada et al. 2025).

The initial sequences of the two unrest episodes can be summarized as follows. During the 2014 unrest, deep deformation was observed first, followed by enhanced seismic activity and shallow deformation, and then by the increase in SBL. During the 2018 unrest, in contrast, the increase in SBL and the deep deformation were observed first, followed by the increase in seismic activity and shallow deformation. This contrasting lead–lag relationship may reflect differences in the state of the volcanic system prior to each unrest episode. For example, the volcanic system in 2018 may have been in a more responsive state due to preceding activity. Further evaluation of this possibility requires additional constraints on the pre-unrest state of the volcanic system.

5.1.2 Before 2014 unrest

The SBL increased during Period I, decreased during Period II, and then increased again during Period III without an intervening stable stage. The SBL level was always higher than this boundary between II and III over Periods I–IV. This temporal behavior suggests that SBL during Periods I–IV may have reflected persistent vibrations with modulating amplitudes. During Periods I and III, when the SBL increased, other observations also suggested increasing activity, including surface phenomena such as a water jet, a color change of the lake surface (Volcanic Fluid Research Center, Tokyo Institute of Technology 2004), and the appearance of new fumaroles around Yugama (JMA 2008a, b, 2013), as well as a slight increase

in seismicity during Period III. Terada and Kuwahara (2025) reported that the daily mean temperature of the Yugama crater lake never fell below 0°C even during winter in Period IV. Based on these temporal correspondences, we consider that the vibrations contributing to these SBL variations may have been related to volcanic activity.

Periods I–IV corresponded to a part of longer-term cooling processes of the hydrothermal system beneath Yugama that had begun before these periods (Takahashi and Fujii 2014), during which the supply of magmatic fluids from the deeper part of the system was suppressed (Yaguchi et al. 2021). We infer that, even with the cooling trend, some degree of heat or fluid was continuously supplied to the shallow region beneath Yugama, based on the temporary increases in SBL and the surface phenomena.

5.2 Possible mechanism of the SBL vibrations

Preliminary examination of the source region of the SBL vibrations

As a preliminary step toward understanding the mechanism of SBL vibrations, we examined the likely source region of the signals. The observation of SBL vibrations at multiple stations surrounding the Yugama crater suggests that the source region is located beneath or near the crater.

To obtain additional constraints on the source region of the SBL vibrations, we conducted a polarization analysis based on a Rayleigh-wave-like surface-wave assumption, following the method of Hirose and Ueda (2025) (see Supplementary Information, Section S7). We used the same settings as those adopted for the SBL calculation, namely a frequency band of 3.5–7.0 Hz and an analysis time window from 18:00 of the previous day to 06:00 of the following day. The analysis targeted the period from December 2019 to January 2020, when the SBL level was relatively high. The joint probability distribution obtained from the combined analysis of KSHA, KSE, KSW, and KSS showed a high probability around the Yugama crater, close to the epicentral area of the high-frequency earthquakes (Fig. 7a, b). The horizontal distance between the seismometers and the high-probability region was less than approximately 1 km. If the dominant signals are interpreted as Rayleigh-wave-like surface waves, the source is expected to be relatively shallow.

We note that the present analysis does not uniquely constrain either the dominant wave type or the precise source location. Therefore, these results should be regarded as qualitative constraints on the source region of the SBL vibrations.

Possible interpretation of the SBL ratio changes

The KSHA/KSAO SBL ratio was higher during the 2018 unrest than during the 2014 unrest (Fig. 5c). Similar variations were also observed for SBL ratios involving KSE (Fig. S7), which is located near KSHA. In addition, comparison of the peak SBL amplitudes at each station showed that the amplitudes at KSHA and KSE were larger during the 2018 unrest than during the 2014 unrest, whereas the opposite pattern was observed at the other stations. These observations indicate that the source region of the vibrations contributing to the SBL differed between the 2014 and 2018 unrests. During the 2018 unrest, the source

regions of the vibrations dominating in the observed SBL were closer to KSE and KSHA than those during the 2014 unrest.

Other observations also suggest differences in the source locations of activity between the 2014 and 2018 unrests. In the horizontal direction, the epicenters of high-frequency earthquakes during the 2018 unrest were located slightly to the northeast compared with those during the 2014 unrest, that is, closer to KSE and KSHA (Fig. 7c, d). In addition, in the vertical direction, geomagnetic total-field observations reported that the thermal demagnetization sources were shallower during the 2018 unrest than during the 2014 unrest (Kanda et al. 2025). Although these activity sources do not necessarily coincide with the source region of the SBL vibrations, these spatial differences are consistent with the interpretation of the SBL variations.

The source-region interpretation presented above needs further confirmation. The SBL ratio changes alone cannot uniquely determine changes in the vibration source locations because the SBL amplitudes may be affected by multiple factors, including wave-propagation characteristics and radiation patterns, as well as the source locations.

Possible mechanism

We consider it more reasonable to assume a non-destructive mechanism for the SBL vibration source, because the vibrations persist continuously over long periods. In volcanic regions, one possible continuous vibration source is tremor associated with fumarolic activity. A geothermal zone developed on the northern outer slope of the Yugama crater rim, where fumaroles are present (Ohba and Yaguchi 2025). However, we have no evidence that this fumarolic area generates the SBL vibration. The source regions estimated by the above-mentioned preliminary analyses appear to differ from this area.

Another possible interpretation is that the SBL vibrations are related to non-destructive processes within a shallow hydrothermal system. Jolly et al. (2020) suggested that persistent tremor observed at Whakaari (White Island) may be generated by frothing within a hydrothermal system. Ichihara et al. (2023b) inferred that the SBL vibrations at Kirishima volcano may involve similar processes.

Around the Yugama crater, a well-developed hydrothermal system and shallow groundwater aquifers are present (Hirabayashi 1999; Terada 2018). Volcanic fluids, whether magma itself or volcanic gases separated from it, supplied heat to the shallower region beneath Yugama and affected these subsurface systems. Bubbles due to the interaction of the heat supplied by the volcanic fluid and the subsurface hydrothermal or water system generate the SBL vibrations. If the SBL source region is located in a shallow region beneath or near the Yugama crater, conditions allowing the coexistence of gas and liquid phases would be plausible (Kumagai et al. 2002; Taguchi et al. 2018).

Constraining the SBL vibration source locations and comparing them with the subsurface structure, such as that derived from magnetotelluric (MT) sounding method (Matsunaga and Kanda 2025), would contribute to a more detailed understanding of the vibration mechanism.

6. Conclusion

In this study, we applied a statistical approach to long-term seismic observations around the Yugama crater at Kusatsu-Shirane volcano and clarified temporal variations in the SBL. Analysis of nearly 20 years of data revealed that the SBL increased and decreased on a few-year timescale. The SBL variations showed temporal correspondence with surface phenomena around Yugama.

The long-term SBL variations exhibit significantly high levels during the two unrest episodes in 2014 and 2018, with temporal correspondences to both deep and shallow ground deformation, and seismic activity. The temporal relationship between the SBL and seismic activity differed between the two unrest episodes. The SBL increase followed the onset of enhanced seismic activity in 2014. In contrast, the SBL increase preceded the seismic activation in 2018. The inter-station SBL ratios also differ between the two unrests. These observations may indicate that different source regions and processes are involved in the two unrest episodes.

Overall, the 20-year SBL variations may be related to volcanic activity. We infer they are associated with the supply of volcanic fluids. Monitoring SBL and comparing its variation with other observations will provide useful information about volcanic and hydrothermal activity.

Abbreviations

GEONET

GNSS Earth Observation Network System

GNSS

Continuous global navigation satellite system

GSI

Geospatial Information Authority of Japan

JMA

Japan Meteorological Agency

MT

Magnetotelluric

PSD

Power spectral density

SBL

Seismic background level

VLP earthquake

very-long-period earthquake

VT earthquake

volcano-tectonic earthquake

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Funding

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Authors' contributions

TK and MI drafted the manuscript. TK and YY prepared the SBL data. TK performed the data analysis. TK, AK, and KN contributed to the interpretation. All authors discussed the results and contributed to the final manuscript.

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Availability of data and materials

Continuous seismic waveform data used in this study were obtained from the Japan Meteorological Agency and Tokyo Institute of Technology (reorganized as the Institute of Science Tokyo in October 2024) through institutional access. The seismic data and GNSS campaign observation data were accessed through institutional access. Access to these data is subject to the data policies of the respective institutions. GNSS GEONET data are publicly available from the Geospatial Information Authority of Japan (GSI). The smoothed SBL datasets are provided as Supplementary Information.

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Figures

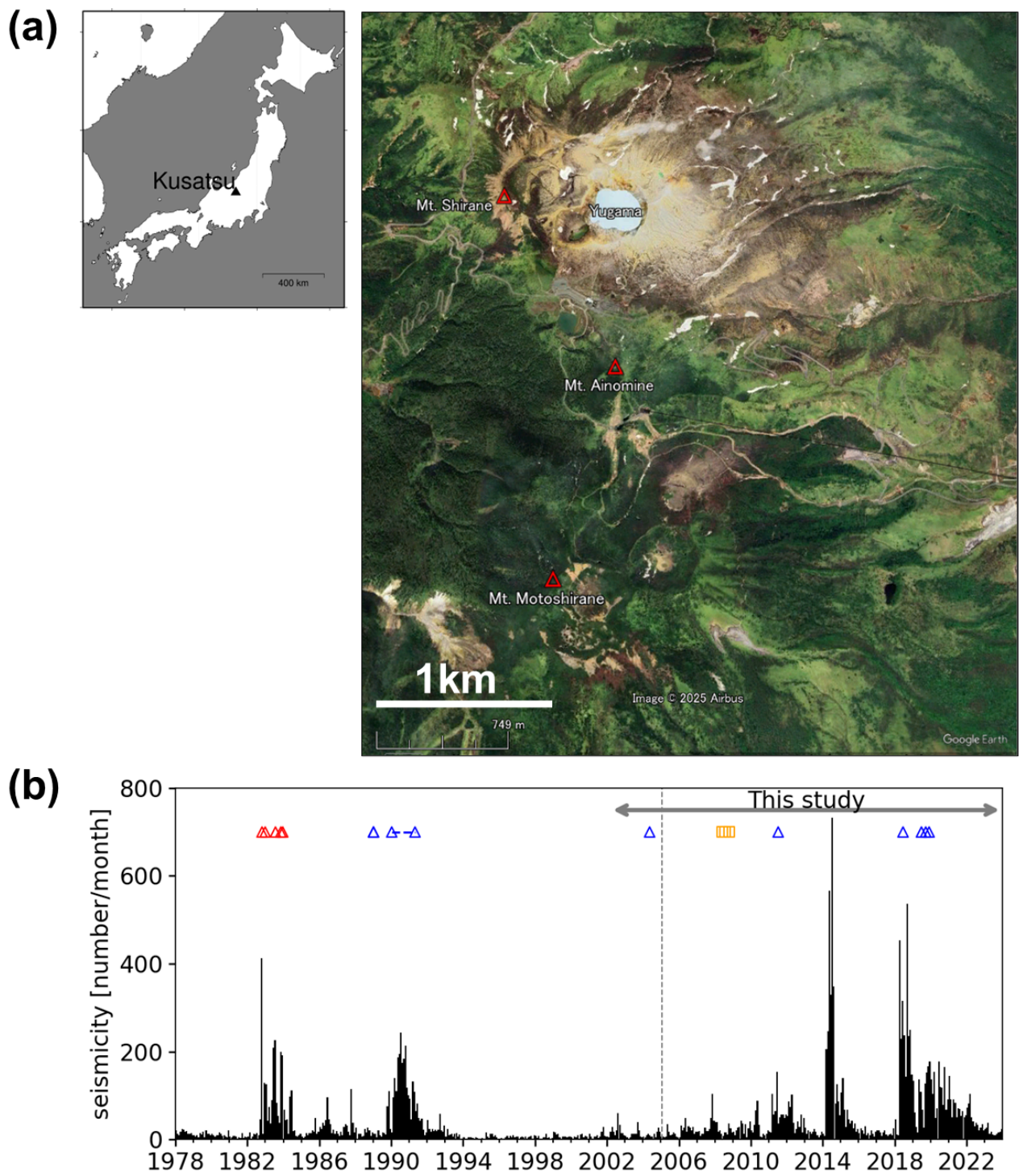


Figure 1

Location of Kusatsu, and seismicity and volcanic surface phenomena near the Yugama crater.

(a) Location of Kusatsu and Yugama.

(b) Monthly number of earthquakes and volcanic surface phenomena near the Yugama crater.

Black bars show the monthly number of earthquakes counted by JMA.

Gray dashed line indicates the change in earthquake-counting rules.

Red triangles indicate eruptions.

Blue triangles indicate color changes of the Yugama crater lake and water jets.

Orange squares indicate the appearance of new fumaroles near Yugama.

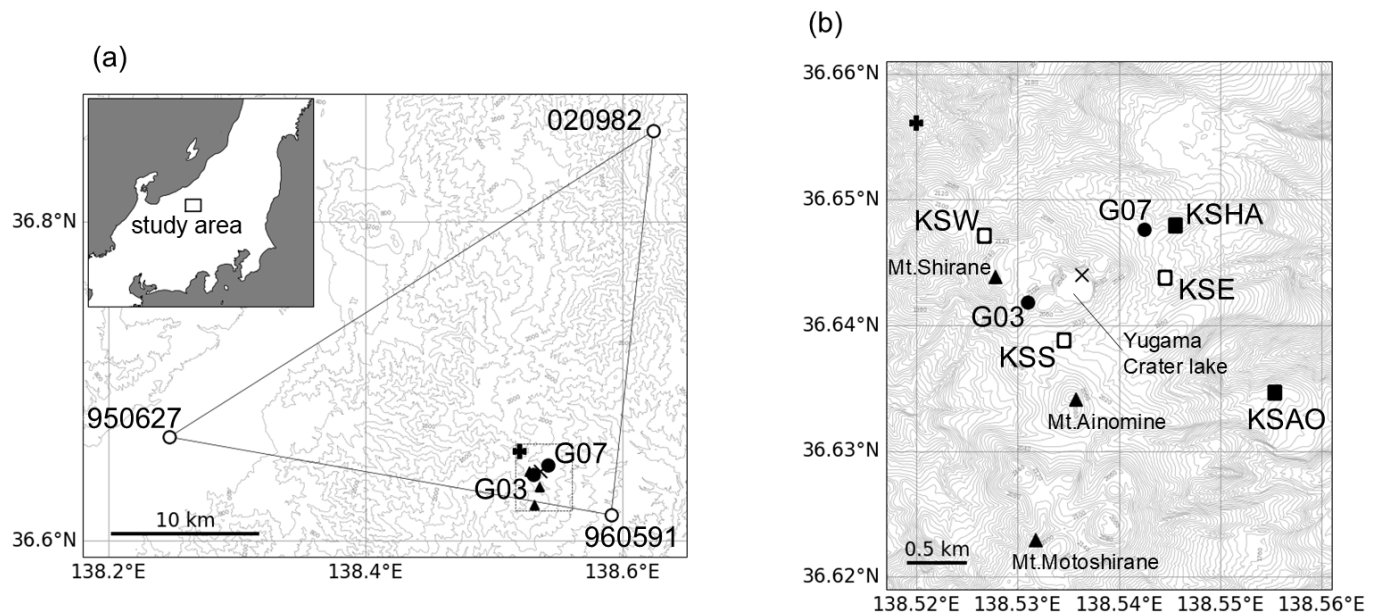


Figure 2

Locations of observation sites and sources of ground deformation.

(a) Regional map. The dashed square shows the area shown in panel (b).

(b) Local map around the Yugama crater.

Squares indicate seismometers. Filled symbols are installed by the JMA, and open symbols by the Institute of Science Tokyo.

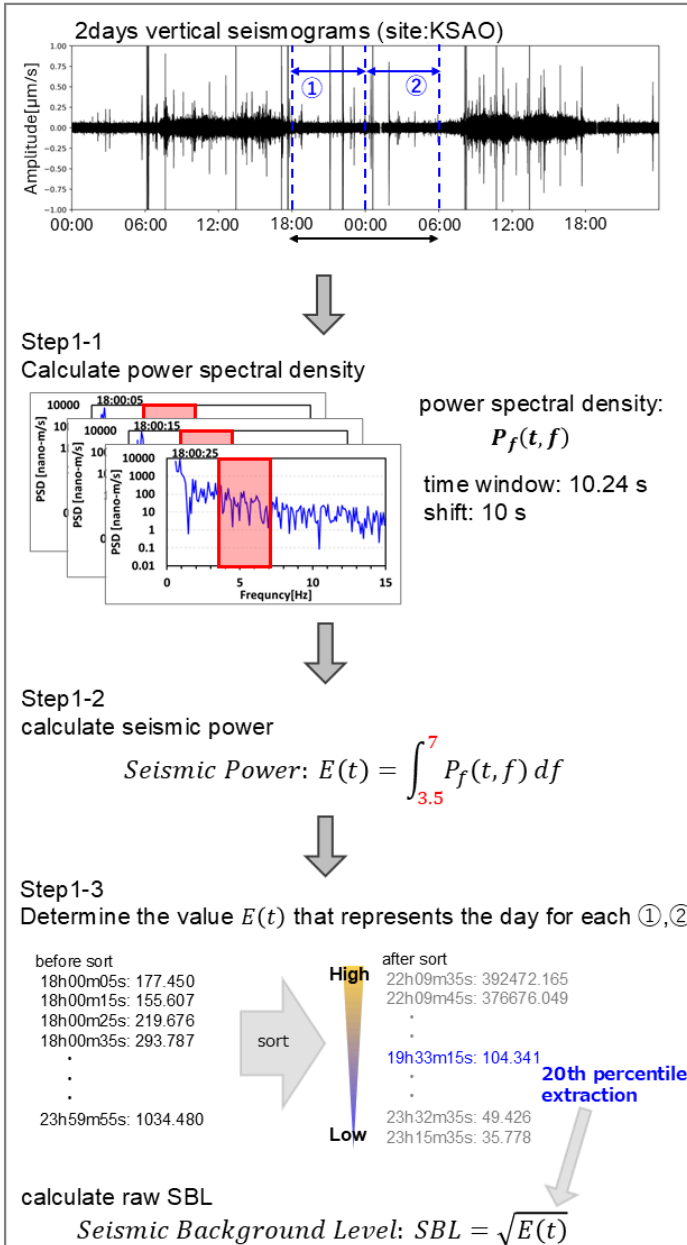
Circles indicate GNSS stations. Filled symbols are installed by JMA, and open symbols by the Geospatial Information Authority of Japan (GSI).

Plus sign indicates deep source of ground deformation reported by Munekane (2021).

Cross indicates the near-Yugama source of ground deformation reported by JMA (2016).

Flowchart of SBL calculation

(a) Step1: Daily calculation of SBL



Time series

(b) Step2: calculate time series of smoothed SBL

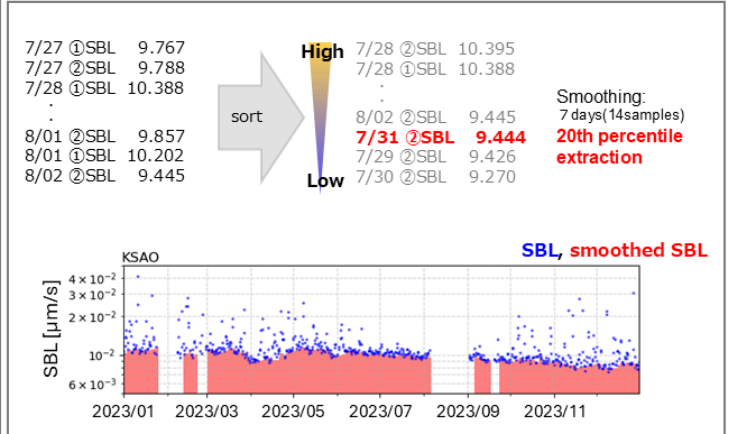


Figure 3

Schematic illustration of the calculation method for the seismic background level (SBL).

(a) Daily calculation of SBL (example: site KSAO, vertical component).

(b) Calculation of time series of smoothed SBL.

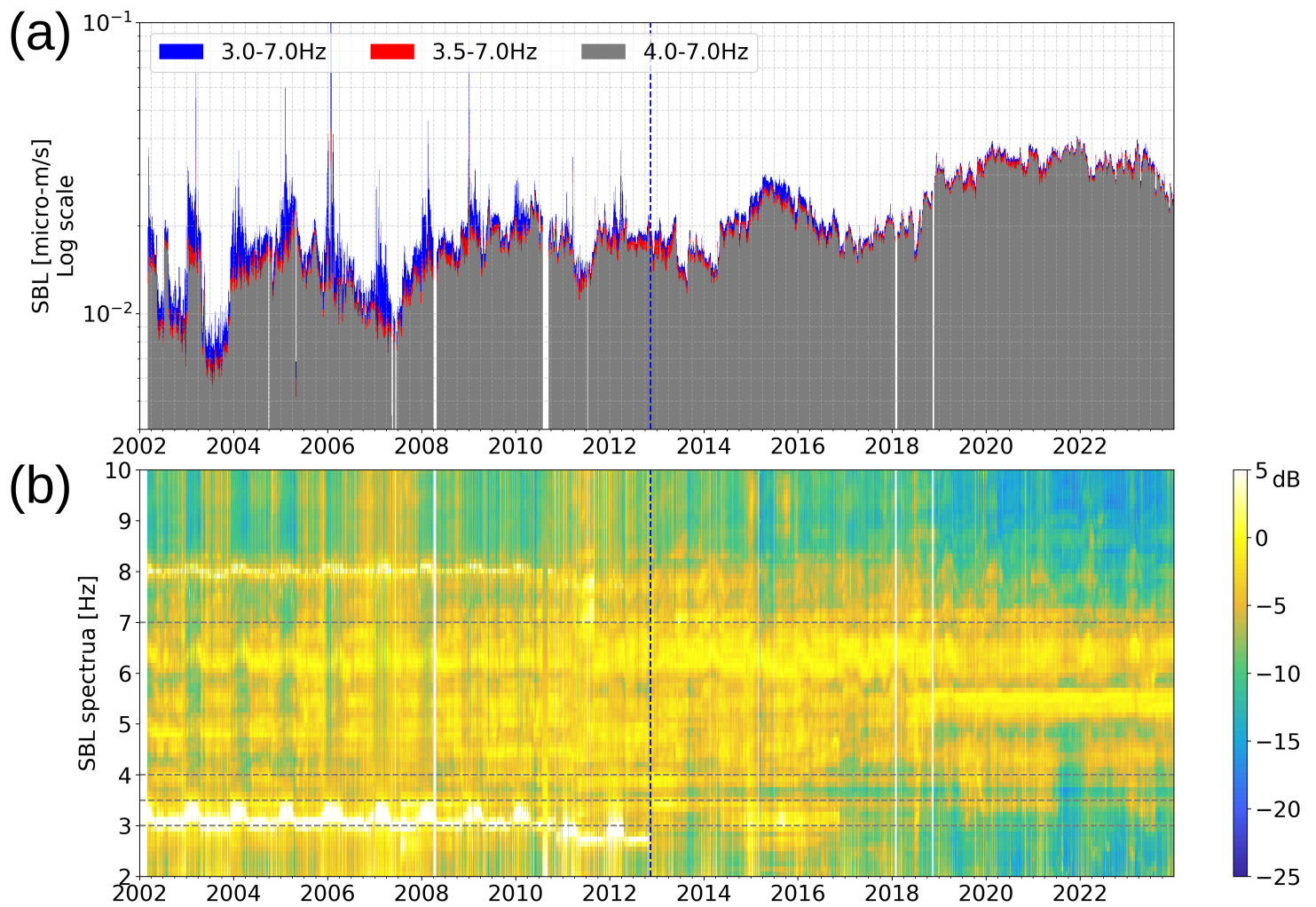


Figure 4

The SBL at station KSHA calculated with different lower frequency bounds and SBL spectra.

(a) The SBL at station KSHA calculated with different lower frequency bounds. Blue, red, and gray indicate results for 3.0–7.0 Hz, 3.5–7.0 Hz, and 4.0–7.0 Hz, respectively. The vertical blue dashed line indicates the seismometer replacement on 13 November 2012.

(b) Daily SBL spectra normalized by maximum value within the 3.5–7.0 Hz band.

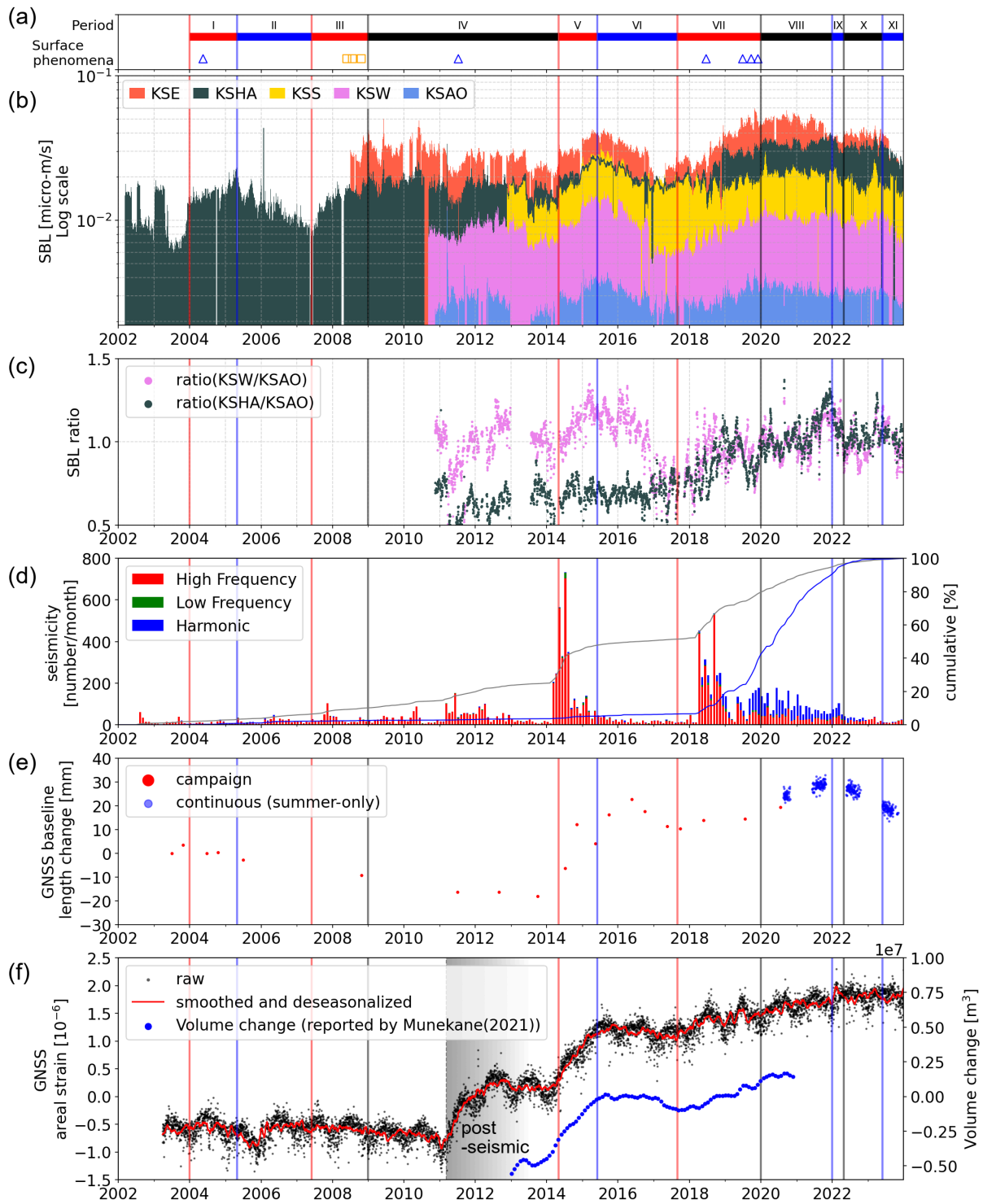


Figure 5

Long-term variations in the SBL, seismicity, and ground deformation (shallow and deep).

(a) Periods listed in Table 1 and volcanic surface phenomena. The symbols are the same as in Figure 1b.

(b) The SBL at sites around the Yugama crater (KSE, KSHA, KSS, KSW, KSAO).

(c) SBL ratio. The reference period for normalization is December 2019 to January 2020. Green shows KSHA/KSAO. Pink shows KSW/KSAO.

(d) Seismicity (monthly number of high-frequency, low-frequency, and harmonic and monochromatic events). Data shown is from August 2002 onwards.

(e) GNSS baseline length change, mainly reflecting deformation of the shallow source.

Red symbols indicate results from GNSS campaign observations, and blue symbols indicate continuous GNSS data (observations suspended during the snowy season).

(f) GNSS areal strain, mainly reflecting deformation of the deep source. Black dots show the raw areal strain calculated from GEONET, and the red line shows the strain after smoothing and removing the seasonal trend. Blue dots show volume change reported by Munekane (2021). The dashed line indicates the date of the Tohoku–Pacific Ocean earthquake on March 11, 2011. The deformation drawn by gray background color immediately after the event was due to postseismic deformation.

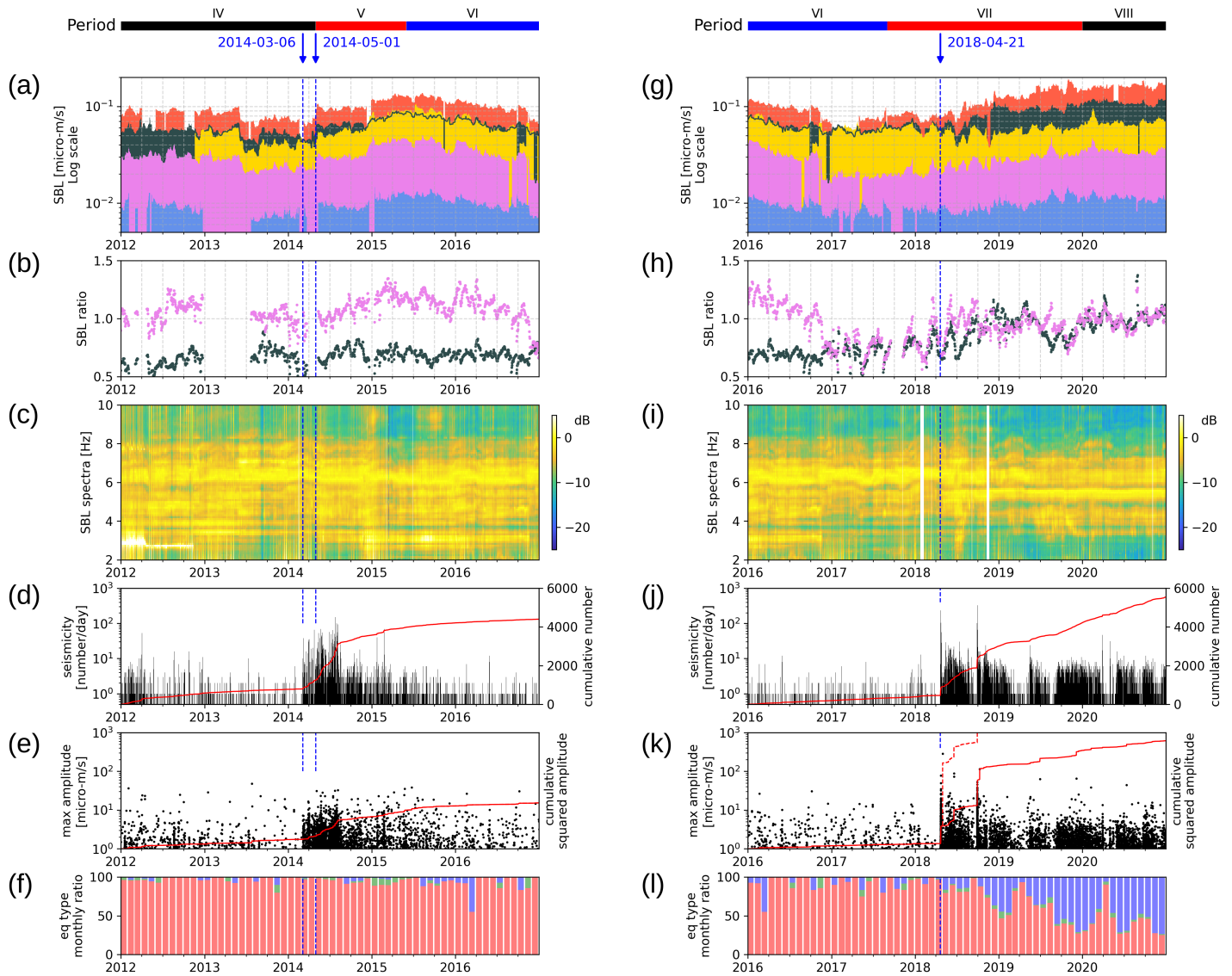


Figure 6

Comparison of the onset of volcanic unrest in 2014 and 2018.

The left column shows the 2014 unrest. In all left-column panels, the left and right blue dashed lines indicate March 6, 2014 and May 1, 2014, respectively. These dates are reference dates for the onset of enhanced seismic activity and the subsequent development of the 2014 unrest, respectively. The right column shows the 2018 unrest. In all right-column panels, the blue dashed line indicates April 21, 2018.

(a) The SBL at sites around the Yugama crater (KSE, KSHA, KSS, KSW, KSAO).

(b) SBL ratio. Dark green shows KSHA/KSAO. Pink shows KSW/KSAO.

(c) Daily SBL spectra at KSHA.

(d) Seismicity (daily number of earthquakes).

(e) Seismicity (maximum amplitudes of earthquakes). In the 2018 unrest graph, the dashed line shows all earthquakes, whereas the solid line excludes the earthquake that occurred at 18:10 on April 30, 2018. This earthquake was the largest event since 2014 (JMA, 2018) and had a magnitude of 0.6 (JMA catalog).

(f) Monthly ratio of volcanic earthquake types. Red indicates high-frequency earthquakes, green indicates low-frequency earthquakes, and blue indicates harmonic and monochromatic earthquakes.

(g-l) Same as (a-f), respectively, but for the 2018 unrest.

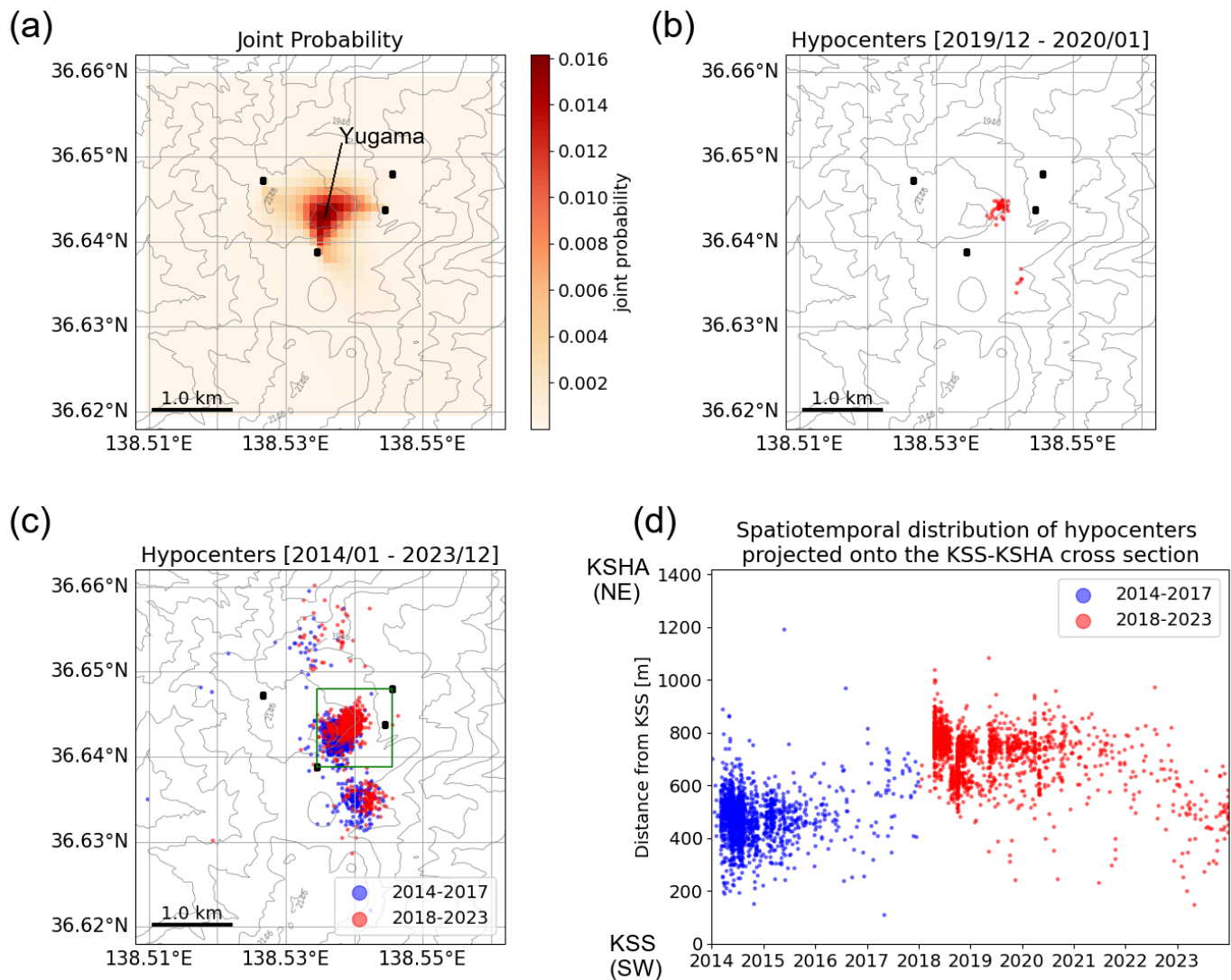


Figure 7

Location of the SBL vibration source estimated by polarization analysis and the joint-probability method, and distribution of hypocenters around the Yugama crater.

(a) Result of the joint-probability analysis. Black squares indicate seismic stations used for the polarization analysis (KSE, KSHA, KSW, KSS).

(b) Distribution of hypocenters of high-frequency earthquakes during the same period as the polarization analysis.

(c) Distribution of hypocenters of high-frequency earthquakes. Blue shows the 2014 unrest (January 2014 – December 2017), and red shows the 2018 unrest (January 2018 – December 2023). The green rectangle shows the area of hypocenters used in panel (d).

(d) Spatiotemporal distribution of hypocenters projected onto the KSS–KSHA cross section. Colors of the plots are the same as in panel (c).

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