

1           **Seismic wavefield change preceding the eruption of**  
2           **Shinmoe-dake, Kirishima volcano, Japan, inferred from**  
3           **polarization analysis**

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9           **Key Points:**

- 10           • The Rayleigh wave source back azimuths were estimated by polarization analysis of single-station seismograms at the Kirishima volcano.
- 11
- 12           • At the nearest seismometer to the Shinmoe-dake crater, Rayleigh waves from the crater dominated 7 months before the October 2017 eruption.
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- 14           • A noticeable increase in the amplitudes of retrograde Rayleigh waves originating from the crater direction was detected since August 2016.
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## Abstract

A volcanic tremor is a seismic event linked to volcanic processes, identified by ongoing ground shaking. While there are different theories regarding the mechanism of volcanic tremors, they play a crucial role in understanding internal volcanic activities and forecasting eruptions. Detecting weak volcanic tremor signals before an eruption has remained a difficult task. This study utilized polarization analysis on continuous seismograms at Kirishima volcano, Japan, to extract data on retrograde Rayleigh wave sources. Back azimuth estimates focused on the direction of the Shinmoe-dake crater before and during the volcanic eruptions in 2011, 2017, and 2018. Rayleigh waves originating from the crater direction, particularly in the 1.3–2.5 Hz band, were observed starting around March 2017, approximately 7 months prior to the October 2017 eruption. In the 1.3–2 Hz band, the back azimuths steadily moved closer to the crater’s direction between January and March 2017. A noticeable increase in the amplitudes of retrograde Rayleigh waves from the crater direction was observed starting in August 2016. Enhancing the growth in amplitude was achieved by utilizing a filter on the seismograms. As polarization analysis requires only a single three-component seismometer, this approach allows for the timely identification of weak Rayleigh waves from the crater direction, even in volcanoes with limited seismic station coverage. The results obtained in this study contribute to the growing knowledge on volcanic tremors and their potential use in volcano monitoring and eruption forecasting.

## Plain Language Summary

Volcanic tremors, seismic events linked to volcanic activity, are crucial for understanding volcanoes and predicting eruptions. This study focused on Kirishima volcano in Japan, analyzing seismic data to trace Rayleigh wave sources, especially pre-eruption in 2011, 2017, and 2018. Rayleigh waves from the crater direction, with frequencies between 1.3 and 2.5 Hz, were notable around March 2017, months before the October eruption. The study showed Rayleigh wave amplitudes increased from August 2016, and their origin shifted closer to the crater over time. By filtering seismic data, researchers isolated waves from the crater, using a single seismometer, which aids in monitoring with limited stations. These insights advance understanding of volcanic tremors and eruption forecasting.

## 1 Introduction

Volcanic tremor is a seismic phenomenon associated with volcanic activity, characterized by continuous ground shaking. It is a key signal in volcanology, providing insights into the internal processes of volcanoes and aiding in eruption forecasting. Volcanic tremor is linked to the movement and interaction of magmatic fluids with the surrounding bedrock, and its characteristics can vary widely among different volcanoes. The onset of tremor and its amplitude often correlate directly with volcanic activity, and its frequency spectrum typically shows sharp peaks between 0.1 and 7 Hz, which may represent fundamental frequencies and their harmonics or a random distribution. The tremor can precede or follow eruptions, lasting from minutes to months, and the depth of the source can range from a few hundred meters to tens of kilometers (Konstantinou & Schlindwein, 2002; Burlini et al., 2007). Volcanic tremors offer valuable insights into the internal volcanic processes. The frequency and amplitude of volcanic tremor can change with the intensity of volcanic activity, and these changes can be used to infer the size and dynamics of the volcanic source (Gordeev et al., 1990). Long-period (12 sec) volcanic tremors at Usu volcano correlate with the uplift rate of the eruption area and are attributed to the flow-induced vibration of a magma chamber and its outlet (Yamamoto et al., 2001). The location of tremor sources can migrate over time and may be associated with changes in volcanic activity, potentially altering the conduit conditions (Ichimura et al., 2018).

66 While volcanic tremors have been widely recognized as short-term (ranging from days  
67 to minutes) indicators of volcanic eruptions (Swanson et al., 1985; Hotovec et al., 2013),  
68 there have been instances where eruptions have taken place without these evident warn-  
69 ing signs (Castruccio et al., 2016; Reckziegel et al., 2016). One possible explanation is  
70 that they might be overshadowed by other signals due to the weak energy of their sig-  
71 nals (Ichihara et al., 2023). Hence, the early detection of volcanic tremor signals prior  
72 to an eruption continues to be difficult. Additionally, in situations where volcanic tremor  
73 signals are weak, they might only be captured by a limited number of seismometers near  
74 the source of the tremor (Ichihara et al., 2023), highlighting the need for an analysis tech-  
75 nique suitable for such scenarios.

76 Polarization analysis, which can be applied with a single three-component seismo-  
77 gram, has contributed to the advancement of our understanding of wave propagation char-  
78 acteristics and sources. Polarization analysis of long-term continuous seismogram records  
79 has been used primarily to study the source of microseisms (Tanimoto et al., 2006; Koper  
80 & Hawley, 2010; Takagi et al., 2018). Takagi et al. (2018) applied polarization analysis  
81 to Hi-net data and investigated the characteristics of the ambient noise wavefield in Japan  
82 over 1 year. The back azimuths of both Rayleigh and P wave sources were sensitive to  
83 adjacent oceanic activities and exhibit seasonal directional variations. Long-term polar-  
84 ization analysis of seismic data can help to reveal changes in volcanic activity and po-  
85 tentially indicate changes in source properties. Falsaperla, S., J. Wassermann, and F.  
86 Scherbaum (2002) applied polarization analysis to broadband seismic data recorded at  
87 Stromboli volcano, Italy, during 1996–1999. They observed statistically significant changes  
88 in the wavefield parameters over the long term, ranging from several months to a year.  
89 During the period between late 1997 and early 1998, the observed changes were under-  
90 stood as potentially resulting from the increased intensity of a subsurface reservoir, likely  
91 due to the influx of fluids from a lower section of the magma conduit. Polarization anal-  
92 ysis can be a useful tool for studying seismic signals related to volcanic activity.

93 Kirishima volcano is a cluster of basaltic-andesite volcanoes located in the south-  
94 ern region of Kyushu, Japan. These volcanoes have shown activity within the last 22,000  
95 years (Kagiyama, 1994; Kato & Yamasato, 2013). Shinmoe-dake has emerged as the most  
96 active volcano in the Kirishima group in recent years. The current cycle began with a  
97 small phreatic explosion on 19 January 2011. The first magmatic eruption occurred from  
98 26 January 2011 to 27 January 2011 (Nakada et al., 2013). The eruption that took place  
99 in 2011 involved sub-Plinian events, the movement of lava, and Vulcanian explosions. It  
100 lasted from January 27 to February 7, with a prolonged lava stream reaching about 1.2  
101 km from the crater towards the southeast. Following a subsequent period of inactivity  
102 lasting six years, Shinmoe-dake experienced another eruption on October 11, 2017. This  
103 marked the first explosive eruption in seven years, with sporadic eruptions persisting un-  
104 til October 17, 2017 (Japan Meteorological Agency, 2017). Volcanic ash emissions and  
105 volcanic tremors were observed continuously until October 21, 2017 in this timeframe.  
106 Another explosive eruption took place on March 6, 2018, with a total of 47 explosive erup-  
107 tions documented between March 1 and 9, 2018 (Japan Meteorological Agency, 2018).  
108 Throughout this period of eruptive activity, both volcanic ash emissions and lava flows  
109 were verified. Between March 10 and June 27, 2018, there were occasional Vulcanian erup-  
110 tions. Throughout this time, Shinmoe-dake encountered multiple explosive eruptions,  
111 releasing volcanic ash into the air. The eruption column rose up to 3,000 m at its peak.  
112 During the eruption on June 27, the volcanic ash dispersed towards the southeast, im-  
113 pacting regions on the downwind side. These consecutive eruptive events notably enlarged  
114 the crater of Shinmoe-dake. Tracking volcanic tremor activity by polarization analysis  
115 in the Kirishima volcano that repeats eruptive and quiescent periods at intervals of sev-  
116 eral years can provide insights into the internal processes of volcanoes.

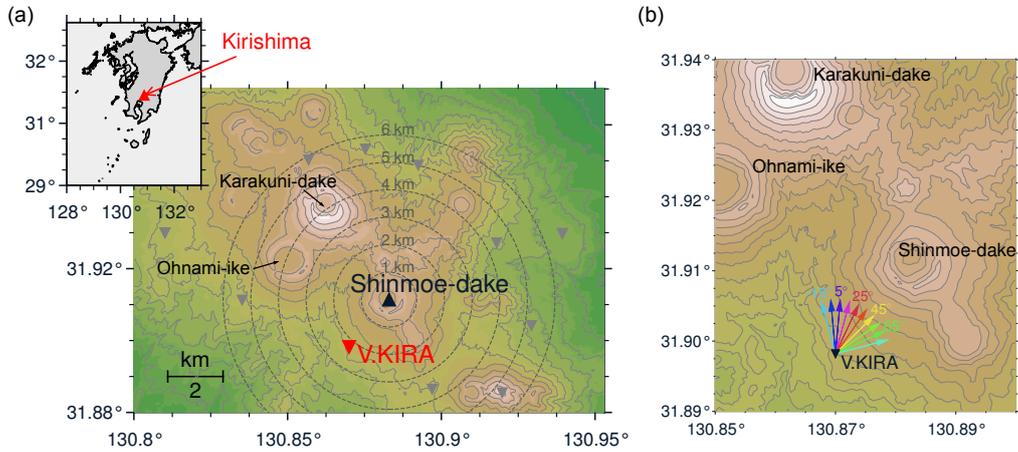
117 This study used polarization analysis on continuous seismograms at the Kirishima  
118 volcano to estimate the back azimuth of Rayleigh wave sources. The objective of this

119 study is to discover variations in the seismic ambient noise wavefield that are associated  
 120 with volcanic activities.

## 121 2 Data and Methods

### 122 2.1 Data

123 Figure 1 displays the location of the Kirishima volcano and the spatial arrangement  
 124 of the seismic stations. We used the V.KIRA seismic station, which is maintained by the  
 125 Japan Meteorological Agency (JMA) and positioned closest to the Shinmoe-dake crater  
 126 (approximately 2 km away). A short-period seismometer with three components and a  
 127 natural period of 1 s was installed on the ground surface. The seismograms were recorded  
 128 at a sampling rate of 100 Hz. We analyzed continuous seismograms for the period from  
 129 January 1, 2011, to December 31, 2022 (a span of 12 years). All continuous seismograms  
 130 can be accessed at the Data Management Center of the National Research Institute for  
 131 Earth Science and Disaster Resilience (NIED) ([https://hinetwww11.bosai.go.jp/auth/  
 132 ?LANG=en](https://hinetwww11.bosai.go.jp/auth/?LANG=en)).



**Figure 1.** (a) Topographic map of Kirishima volcano and location of the V.KIRA seismic station, which is mainly used in this study (red inverted triangle). The other seismic stations maintained by JMA and NIED are shown by gray inverted triangles. The black triangle represents the Shinmoe-dake crater. Gray contours show elevations with an interval of 100 m. (b) The spatial connection between back azimuth values and the Shinmoe-dake crater's location is illustrated. The hues of each arrow align with the back azimuth colors depicted in Figures 3 and 4.

### 133 2.2 Estimation of the dominant back azimuths of Rayleigh wave sources

134 Polarization properties are valuable instruments for distinguishing and segregat-  
 135 ing various kinds of waves found in a signal with multiple components. This study fo-  
 136 cuses on Rayleigh waves and estimates back azimuths of their sources. The polarization  
 137 state of Rayleigh waves is elliptical, which can be either retrograde or prograde, with a  
 138 phase difference of  $\pm \frac{\pi}{2}$  between the radial and vertical components. In this study, we ap-  
 139 ply the Stockwell transform (Stockwell et al., 1996) for the mapping between time and  
 140 time-frequency domains (Meza-Fajardo et al., 2015). The Stockwell transform is an ex-  
 141 tension of the short-time Fourier transform that utilizes a Gaussian window that can be

142 moved and scaled. Figure 2 displays the diagrammatic representation of the back azimuth  
 143 estimation technique. We calculate the dominant back azimuth of the retrograde Rayleigh  
 144 wave source every 30 minutes: we first calculate the dominant back azimuth for a 2-minute  
 145 time window and then iterate the estimation by shifting the time window by 1 minute  
 146 within the 30-minute window.

147 Details of the data processing are as follows. Initially, we corrected the instrument-  
 148 al response of the seismometers (Maeda et al., 2011) and reduced the sampling rate of  
 149 the seismograms from 100 to 20 Hz to speed up the calculations. The 30-minute seis-  
 150 mogram was then segmented into 2-minute windows with a 50% overlap, and the Stock-  
 151 well transform was applied to each 2-minute segment  $u_\ell(t)$  ( $\ell = \text{N, E, V, R, T}$ ):

$$S_\ell(\tau, f) = \int_{-\infty}^{\infty} u_\ell(t) \frac{|f|}{\sqrt{2\pi}} \exp\left[-\frac{(\tau-t)^2 f^2}{2}\right] \exp[-2\pi i f t] dt, \quad (1)$$

152 where  $\tau$  is the center of the Gaussian window and  $f$  represents frequency. The Stock-  
 153 well transforms of the signal's north, east, and vertical components are represented as  
 154  $S_N(\tau, f)$ ,  $S_E(\tau, f)$ , and  $S_V(\tau, f)$ , respectively. We recognize that each of the discrete Stock-  
 155 well transforms is a matrix defined in the discretized  $(\tau, f)$  space. Moreover, each ele-  
 156 ment  $S_\ell(\tau, f)$  of the discretized space is a complex number. The vertical component's  
 157 two-element vector, for instance, is specified as:

$$\mathbf{V}(\tau, f) = \begin{pmatrix} \text{Re}[S_V(\tau, f)] \\ \text{Im}[S_V(\tau, f)] \end{pmatrix}. \quad (2)$$

158 The reference angle of the direction of propagation  $\theta_r(\tau, f)$  is calculated as follows:

$$\theta_r(\tau, f) = \tan^{-1} \left[ \frac{\mathbf{E}(\tau, f) \cdot \hat{\mathbf{V}}(\tau, f)}{\mathbf{N}(\tau, f) \cdot \hat{\mathbf{V}}(\tau, f)} \right], \quad \left( -\frac{\pi}{2} < \theta_r < +\frac{\pi}{2} \right). \quad (3)$$

159 Where  $\hat{\mathbf{V}}(\tau, f)$  represents the function  $\mathbf{V}(\tau, f)$  shifted in phase by  $+\frac{\pi}{2}$  in the case of ret-  
 160 rograde Rayleigh wave. We assume here that the fundamental-mode Rayleigh wave domi-  
 161 nates, and these phases generally show retrograde motions (Tanimoto & Rivera, 2005).  
 162 The direction of propagation  $\theta$  is calculated as follows:

$$\theta(\tau, f) = \theta_I + \frac{\pi}{2} \{ \text{sign}[\sin(\theta_I)] - \text{sign}(x_{pr}) \}, \quad (4)$$

163 in which

$$\begin{aligned} \theta_I(\tau, f) = & \theta_r + \pi \{ 1 - \text{sign}[\sin(\theta_r)] \} \\ & + \pi \{ 1 - \text{sign}[\cos(\theta_r)] \} \text{sign}[\sin(\theta_r)] / 2. \end{aligned} \quad (5)$$

164 The value of  $\text{sign}(x_{pr})$  is 1 (or -1) when the Rayleigh wave is traveling towards the east  
 165 (or west). It should be noted that we do not have any previous information about the  
 166 location of the Rayleigh wave source, and the function  $\theta(\tau, f)$  is subject to a  $\pi$  ambigu-  
 167 ity. We address this uncertainty by computing both instances of  $\theta(\tau, f)$  under the as-  
 168 sumptions that  $\text{sign}(x_{pr}) = 1$  and  $\text{sign}(x_{pr}) = -1$ . Subsequently, we compute the nor-  
 169 malized inner product (NIP) between  $\mathbf{R}_\theta(\tau, f)$  and  $\hat{\mathbf{V}}(\tau, f)$ , as well as between  $\mathbf{R}_{\theta+\pi}(\tau, f)$   
 170 and  $\hat{\mathbf{V}}(\tau, f)$ , taking into account the propagation in both  $\theta$  and  $\theta + \pi$  directions. The  
 171 NIP between the radial and vertical components is defined as:

$$\text{NIP}_{\mathbf{R}_\theta \hat{\mathbf{V}}}(\tau, f) = \frac{\text{Re}[S_{\mathbf{R}_\theta}(\tau, f)] \text{Re}[S_{\hat{\mathbf{V}}}(\tau, f)] + \text{Im}[S_{\mathbf{R}_\theta}(\tau, f)] \text{Im}[S_{\hat{\mathbf{V}}}(\tau, f)]}{|\mathbf{R}_\theta(\tau, f)| |\hat{\mathbf{V}}(\tau, f)|}. \quad (6)$$

172 When retrograde Rayleigh waves are predominant, the NIP value approaches 1. The di-  
 173 rection of propagation is ultimately determined by comparing the NIP values, with the  
 174 one having a higher value being chosen:

$$\theta(\tau, f) = \begin{cases} \theta(\tau, f), & \text{if } \text{NIP}_{\mathbf{R}_\theta \hat{\mathbf{V}}}(\tau, f) \geq \text{NIP}_{\mathbf{R}_{\theta+\pi} \hat{\mathbf{V}}}(\tau, f) \\ \theta(\tau, f) + \pi, & \text{if } \text{NIP}_{\mathbf{R}_\theta \hat{\mathbf{V}}}(\tau, f) < \text{NIP}_{\mathbf{R}_{\theta+\pi} \hat{\mathbf{V}}}(\tau, f) \end{cases}. \quad (7)$$

175 The back azimuth  $\theta_{\text{baz}}(\tau, f)$  is calculated as  $\theta_{\text{baz}}(\tau, f) = \theta(\tau, f) + \pi$ . The subsequent  
 176 stage involves determining the dominant back azimuth for the 2-minute window. This  
 177 is accomplished by computing a circular mean (Mardia & Jupp, 1999) for each frequency.

$$\overline{\theta_{\text{baz}}^{2\text{min}}}(f) = \arg \left( \sum_{j=1}^n e^{i\theta_{\text{baz}}(\tau_j, f)} \right). \quad (8)$$

178 The process is iterated by shifting the 2-minute window by 1 minute. Given that the pri-  
 179 mary focus of this research is on persistent signals like tremors rather than transient sig-  
 180 nals like earthquakes, a data processing method is utilized where the back azimuths are  
 181 averaged every 2 minutes and subsequently averaged over a 30-minute period.

$$\overline{\theta_{\text{baz}}^{30\text{min}}}(f) = \arg \left( \sum_{k=1}^n e^{i\overline{\theta_{\text{baz}}^{2\text{min}}}(f)_k} \right). \quad (9)$$

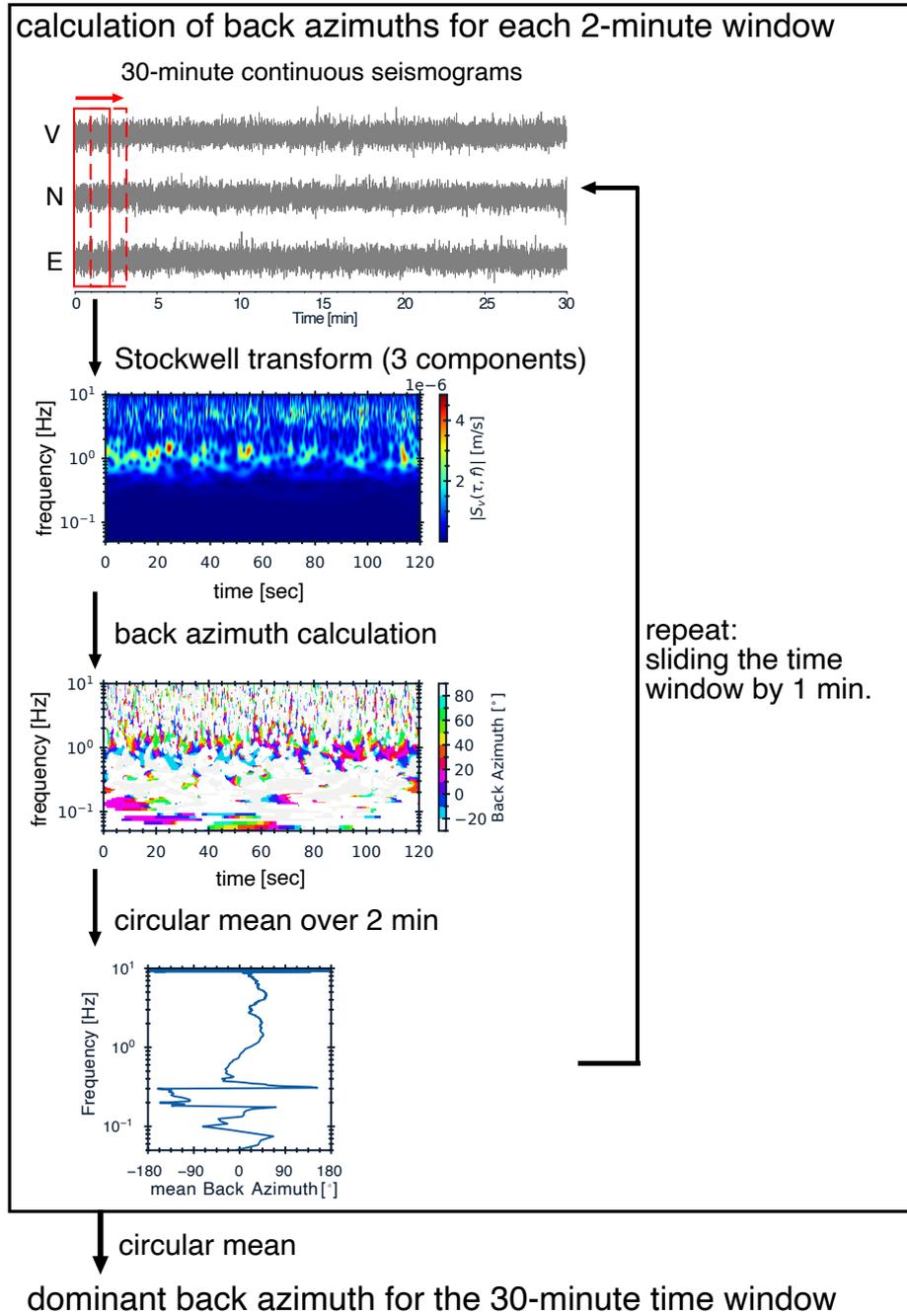


Figure 2. Schematic illustration of estimation method of back azimuth.

### 3 Results

#### 3.1 Examples of the back azimuth estimation

We present examples of estimating the back azimuth of retrograde Rayleigh waves using seismic data recorded during both eruptive and non-eruptive periods at the Shinmoe-dake crater. Figure 3a illustrates an example of estimating the back azimuth of retrograde Rayleigh waves using 2-minute seismograms from 01:10 on October 15, 2017 (JST) amid the eruptive phase at the V.KIRA seismic station, while Figure 3c shows the same analysis for the data during 01:10–01:12 on January 1, 2017 (JST), when no active volcanic activity was reported. The velocity seismograms on the vertical component for both time periods are illustrated in the first panels of Figures 3a and 3c, respectively. The Stockwell transform spectrograms on the vertical component for both time periods are shown in the second panels of Figures 3a and 3c. The spectrograms clearly demonstrate the difference in the dominant frequencies of seismic waves between the eruptive and non-eruptive periods. During the eruptive phase (Figure 3a), seismic waves exhibit high energy levels within the frequency bands of 0.7–2 Hz and 3–7 Hz, whereas during the non-eruptive period (Figure 3c), the dominant frequencies of recorded seismic waves are notably distinct, with high energy levels in the 0.5–1 Hz band. Higher-frequency seismic waves are more energetic amid the eruptive phase, probably because of volcanic tremor occurrence.

The third panels of Figures 3a and 3c illustrate the calculated back azimuths at each lapse time and frequency for the respective time periods. During the eruptive phase (Figure 3a), the back azimuth is more commonly estimated towards the crater direction, back azimuth of 30°–50° (N30°E–N50°E), at around 1 Hz, likely due to the predominance of volcanic tremors. In contrast, during the non-eruptive period (Figure 3c), back azimuths are typically not estimated in the direction of the crater, except for the 0.05–0.1 Hz band. In the fourth panels of Figures 3a and c, the  $\text{NIP}_{\mathbf{R}_0\hat{\mathbf{V}}}$  values are displayed for each lapse time and frequency. During the eruptive phase (Figure 3a), the NIP values often surpass 0.9 at approximately 1 Hz, which coincides with the frequency where the dominant back azimuth is calculated towards the crater. In contrast, during the non-eruptive phase (Figure 3c), the NIP values are typically reduced, except for frequencies below 0.1 Hz, indicating the absence of high-energy retrograde Rayleigh waves arriving from the crater at around 1 Hz.

Figures 3b and 3d illustrate the circular mean of back azimuths for every frequency within the 2-minute window for the eruptive and non-eruptive periods, respectively. During the eruptive phase (Figure 3b), the circular means of back azimuth values show a significant focus on the back azimuths ranging from 30° to 50° (crater direction) at frequencies between 1.3 and 2.5 Hz, with a maximum variation of approximately  $\pm 8^\circ$ . In contrast, during the non-eruptive period (Figure 3d), the mean back azimuths in the same frequency band exhibit significant dispersion and do not show a clear focus towards the crater direction.

These results demonstrate the potential of our analysis method for detecting changes in the seismic wavefield related to volcanic activity. In the next subsection, we apply this method to long-term continuous seismic data to investigate temporal variations in the seismic wavefield over the course of multiple eruptive cycles at the Shinmoe-dake crater.

#### 3.2 Long-term polarization analysis results

Analyzing the polarization of continuous seismograms over an extended period, encompassing both eruptive and non-eruptive phases, may enable us to detect variations in the seismic wavefield linked to volcanic activities. Figure 4 shows temporal changes in estimated back azimuths of retrograde Rayleigh wave sources from 2011 to 2022 (12 years). As illustrated in Figure 2, we calculated the dominant back azimuth value every 30 minutes, and in this section, we present the circular mean of these 30-minute back

232 azimuth values during the night hours (18:00–05:59 JST) to mitigate the impact of hu-  
233 man activities (Nakata et al., 2019). Furthermore, by performing such an averaging pro-  
234 cess, the influence of short-term transient signals will be minimized, and persistent sig-  
235 nals like volcanic tremors will be emphasized more.

236 Throughout the study period, Shinmoe-dake experienced three notable eruptive  
237 events. The initial one was the sub-Plinian eruption that took place on January 26, 2011  
238 (Nakada et al., 2013). The back azimuths of retrograde Rayleigh wave sources were de-  
239 termined in the vicinity of the crater’s direction from the beginning of January 2011 to  
240 early June 2011 within the frequency range of 1.3–8 Hz (Figure 2a). Below the frequency  
241 of 1 Hz during the eruptive phase, the back azimuths estimated are mainly directed to-  
242 wards the crater. This pattern was also observed during the eruptions in 2017 and 2018  
243 (refer to Figure 2b). As the seismic data for the V.KIRA station is accessible starting  
244 from January 1, 2011, it is not feasible to determine when exactly before the 2011 erup-  
245 tion the retrograde Rayleigh wave source towards the crater became predominant. Nev-  
246 ertheless, the concentration of back azimuth estimates towards the crater has been ev-  
247 ident since early January, indicating the possibility of Rayleigh wave excitation events,  
248 probably volcanic tremors, occurring in the shallow region beneath Shinmoe-dake. Shinmoe-  
249 dake experienced its initial eruption in six years on October 11, 2017, followed by the  
250 first explosive eruption since 2011 on March 6, 2018 (Japan Meteorological Agency, 2017,  
251 2018). During these eruptive phases, the back azimuths of retrograde Rayleigh wave sources  
252 were estimated toward the crater (see Figure 4b). The dominant frequency range of ret-  
253 rograde Rayleigh waves originating from the crater direction closely resembles that ob-  
254 served during the sub-Plinian eruption of 2011. What stands out is the increasing pres-  
255 ence of retrograde Rayleigh waves originating from the crater direction, particularly in  
256 the frequency band of 1.3–2.5 Hz, starting around March 2017, approximately 7 months  
257 prior to the eruption in October 2017. No eruptions took place at Shinmoe-dake dur-  
258 ing this period. Between the eruptions in 2017 and 2018, the dominance of retrograde  
259 Rayleigh waves from the crater direction persisted. During this interval, Rayleigh waves  
260 of higher frequencies ( $>3$  Hz) were more prevalent compared to the period before the  
261 2017 eruption and the 2011 eruption. However, with the onset of the 2018 eruption, these  
262 high-frequency Rayleigh waves became less prominent. By the end of May 2018, the es-  
263 timated source of Rayleigh waves from the crater direction had decreased.

264 The dominance of retrograde Rayleigh waves originating from the crater direction  
265 during the period without eruptions was also observed from August 2013 to April 2014  
266 (Figure 4a) and in 2020–2022 (Figure 4c). A notable increase in seismic amplitudes was  
267 observed in 2020 and 2022 at seismic stations located around 1 km from the Shinmoe-  
268 dake crater (Japan Meteorological Agency, 2022). The timings of these amplitude in-  
269 creases are in alignment with those of dominance of the retrograde Rayleigh waves that  
270 arrive from the direction of the crater. These observations suggest that the dominance  
271 of retrograde Rayleigh waves originating from the crater direction during the period with-  
272 out eruptions is related to volcanic activities. A slight inflation of the deep source was  
273 observed in 2013 and 2014 (Japan Meteorological Agency, 2014). The dominant frequency  
274 range of retrograde Rayleigh waves originating from the crater direction is nearly iden-  
275 tical to that observed during eruptive phases in the 2020–2021 period. On the contrary,  
276 retrograde Rayleigh waves in the 5–8 Hz range are more prevalent from August 2013 to  
277 April 2014. The observed variations in the dominant frequency of retrograde Rayleigh  
278 waves may be related to various factors. These factors could include the depth of the source,  
279 the physical properties of the magma (e.g., viscosity, gas content, and temperature), the  
280 geometry and size of the conduit, and the differences in the source processes such as magma  
281 ascent, degassing, and fragmentation. The complex interplay of these factors can result  
282 in observed variations in the dominant frequency of retrograde Rayleigh waves. A de-  
283 tailed examination of these factors is beyond the scope of this paper and is not discussed  
284 further. However, the results presented in this study may provide valuable information

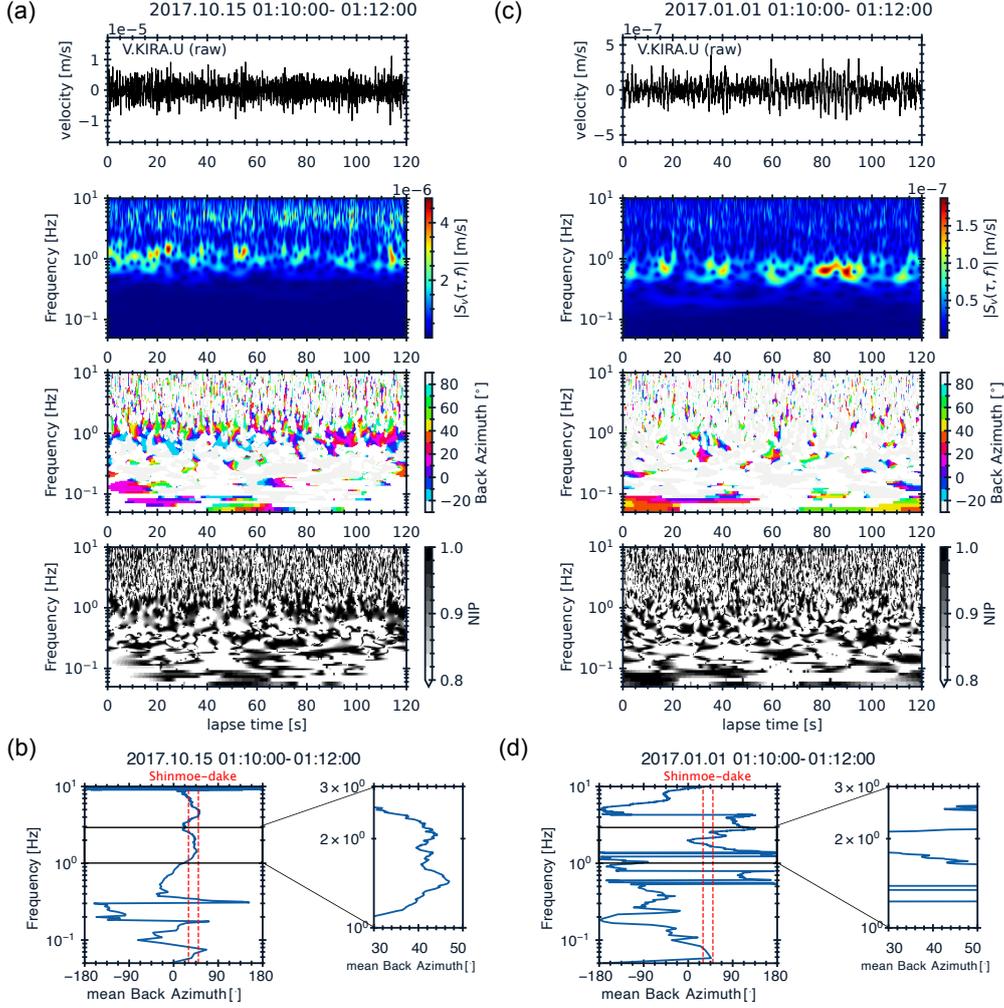
285 on the excitation processes of volcanic tremors and the dynamic changes of the magma/hydrothermal  
 286 system in the shallow part of the volcano.

### 287 **3.3 Polarization analysis results for each frequency band**

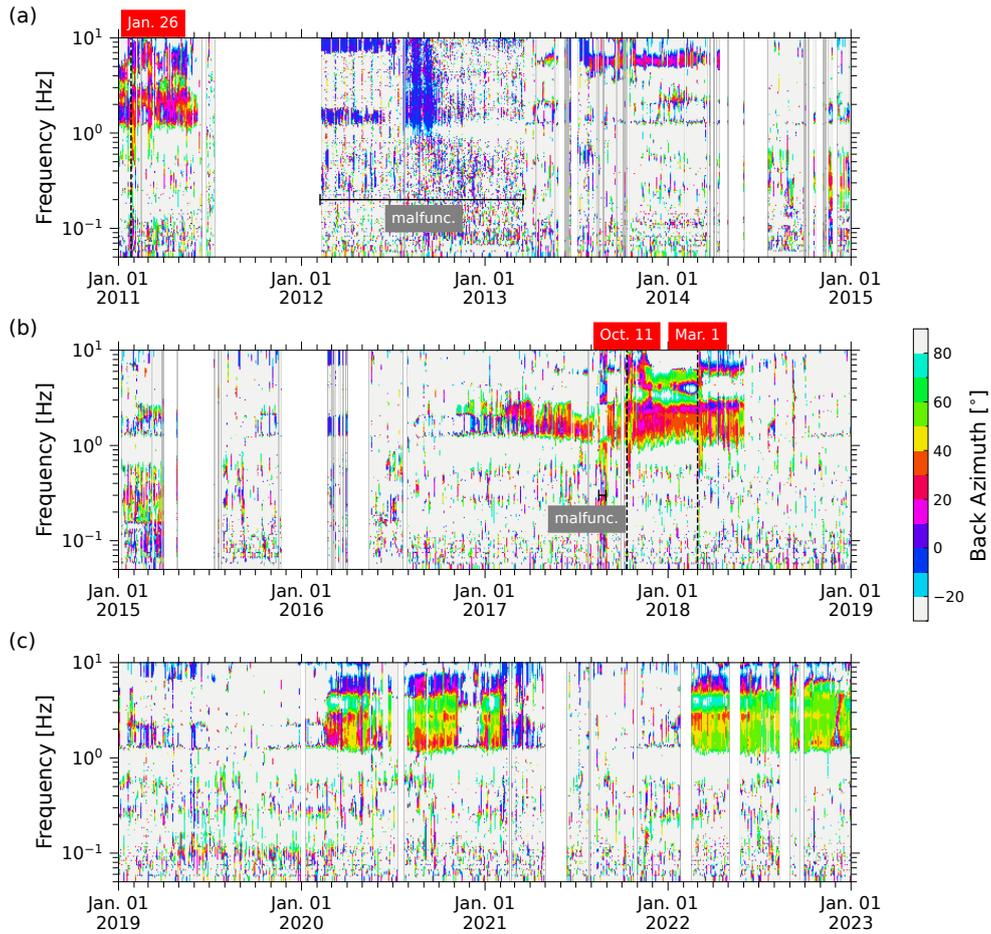
288 In order to observe how the estimated back azimuths vary with frequency, we present  
 289 the back azimuth estimation outcomes for specific frequency ranges. Figure 5 illustrates  
 290 a histogram of the back azimuth data for 30-minute windows overnight (18:00–05:59 JST)  
 291 in frequency bands of 1–1.3 Hz, 1.3–2 Hz, 2–2.5 Hz, and 2.5–3 Hz over 12 years. Dur-  
 292 ing the period from the sub-Plinian eruption on January 26 to early February, the es-  
 293 timated back azimuths were predominantly focused towards the crater direction at fre-  
 294 quencies above 1.3 Hz, suggesting that the volcanic tremor source was located beneath  
 295 the Shinmoe-dake crater. This level of focus was maintained until the beginning of June.

296 The results across all frequency bands above 1.3 Hz consistently show a notable  
 297 clustering of back azimuth estimates for retrograde Rayleigh waves towards the crater  
 298 direction from shortly before the October 2017 eruption until May 2018. This finding  
 299 further supports the idea of a volcanic tremor source located beneath the Shinmoe-dake  
 300 crater during this period. Interestingly, a clustering of back azimuth has been observed  
 301 towards the crater direction starting from approximately March 2017 within the frequency  
 302 range of 1.3–2.5 Hz, with the exception of July and August 2017 at 2–2.5 Hz. In the 1.3–  
 303 2 Hz band, the back azimuths have been steadily moving closer to the crater’s direction  
 304 between January and March 2017: estimated back azimuths were approximately  $-40^\circ$  (N40°W)  
 305 between October and December 2016, and they gradually shifted to  $30^\circ$  (N30°E) with  
 306 speed of roughly  $18^\circ$ /month. This gradual migration of the possible volcanic tremor source  
 307 towards the crater in the months leading up to the 2017 eruption is a significant obser-  
 308 vation. It is worth noting that similar back azimuths were estimated for the period from  
 309 October to December 2016, as in previous years (e.g., 2013–2015), indicating that the  
 310 seasonal variation of the sources is predominant during these periods. The factors con-  
 311 tributing to this seasonal variation are not well understood and require further inves-  
 312 tigation. However, it is important to recognize that there was no observed gradual mi-  
 313 gration of retrograde Rayleigh wave sources towards the crater during the period of 2013–  
 314 2015, suggesting that the migration observed in 2016–2017 is likely related to changes  
 315 in volcanic activity rather than seasonal effects.

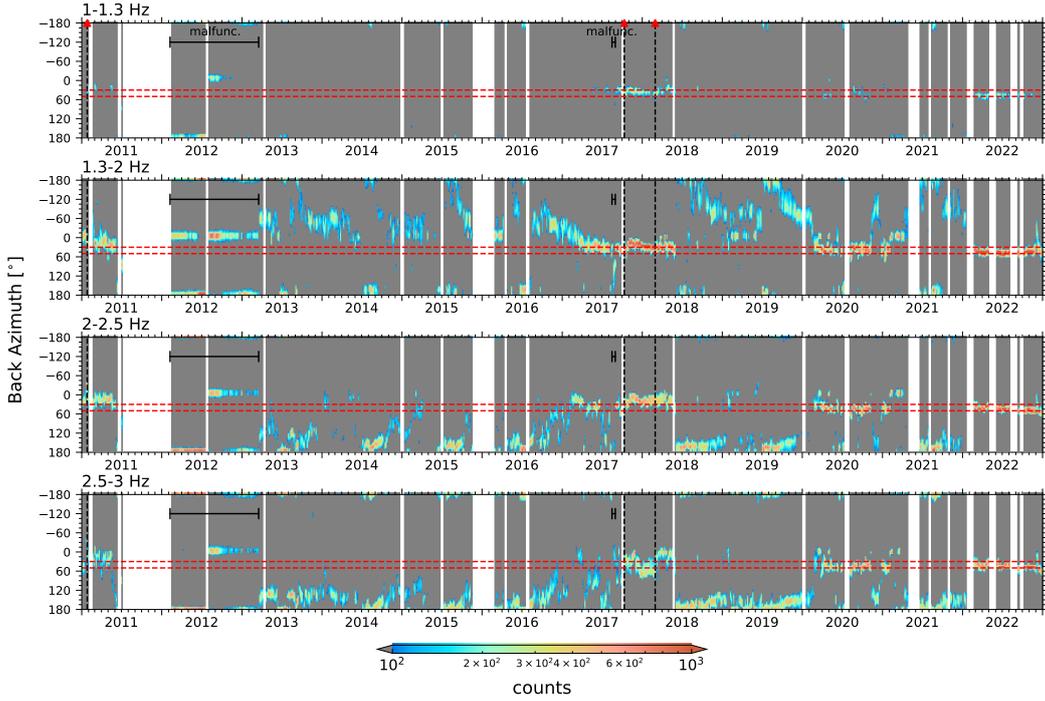
316 The results suggest a possible shift in the back azimuth of retrograde Rayleigh wave  
 317 sources, moving from a northwesterly direction towards the western side of the Shinmoe-  
 318 dake. This shift in the location of the volcanic tremor source, as inferred from the back  
 319 azimuth estimates across multiple frequency bands, provides valuable insights into the  
 320 changes in volcanic activity leading up to the 2017 eruption. Although the seasonal vari-  
 321 ation of sources cannot be entirely ruled out, the gradual migration of the tremor source  
 322 towards the crater, particularly in the 1.3–2 Hz band, suggests a link to the evolving vol-  
 323 canic processes beneath the Shinmoe-dake crater.



**Figure 3.** Examples of the back azimuth estimation of retrograde Rayleigh waves for 2-minute-long seismograms. (a) The result of 01:10-01:12 on October 15, 2017. (a1) Velocity seismogram on the vertical component at the V.KIRA seismic station. (a2) Stockwell transform spectrograms on the vertical component. (a3) Estimated back azimuths for each lapse time and frequency. The regions are depicted in white to indicate a normalized inner product (NIP) value lower than 0.8. (a4) NIP values for each lapse time and frequency. (b) Mean back azimuths for each frequency for the time period from 01:10 to 01:12 on October 15, 2017. These values were determined by taking the average of the estimated back azimuths shown in the third panel of (a) across the lapse time. The smaller panel on the right of (b) provides a detailed view. The red vertical dashed lines indicate the back azimuth range of the Shinmoe-dake crater (N30°E–N50°E). (c)–(d) Similar to (a) and (b), respectively, but for 01:10-01:12 on January 1, 2017.



**Figure 4.** Temporal changes in the estimated back azimuths between 0.05–10 Hz at the V.KIRA seismic station over 12 years. The vertical dashed line in black indicates the occurrence of the sub-Plinian eruption of Shinmoedake on January 26, 2011, as well as the eruptions on October 11, 2017, and March 1, 2018. The seismometer is believed to have experienced malfunctions from around February 2012 to March 2013 and in late August 2017.



**Figure 5.** Temporal changes in the daily distribution of back azimuths during nighttime over 12 years. The vertical lines marked with black dashes and red stars indicate the occurrence of eruptions on January 26, 2011, October 11, 2017, and March 1, 2018. The red dashed lines running horizontally indicate the back azimuth aligned with the Shinmoe-dake crater’s direction, back azimuths of  $30^{\circ}$ – $50^{\circ}$  ( $N30^{\circ}E$ – $N50^{\circ}E$ ). Regions shaded in gray denote counts below 100, while gaps in the data are depicted in white.

324 **4 Discussions**

325 In the Discussion section, we first compare the results of this study with those of  
 326 previous studies at the Kirishima volcano (4.1). Then, we suggest a candidate for the  
 327 Rayleigh wave sources mechanism (4.2). Finally, we discuss the implications of our po-  
 328 larization analysis for volcano monitoring (4.3).

329 **4.1 Comparison with results of previous studies**

330 **4.1.1 Seismic wave amplitudes growth**

331 In the Results section, our attention is directed towards the temporal variations  
 332 in the back azimuths of retrograde Rayleigh wave sources, revealing alterations occur-  
 333 ring before Shinmoe-dake eruptions. On the other hand, a previous study reported pre-  
 334 cursory changes in seismic amplitude before the 2017 Shinmoe-dake eruption (Ichihara  
 335 et al., 2023). They introduced the “seismic background level (SBL)”, the root-mean-squared  
 336 (RMS) amplitude of the seismogram during night. The SBL indicates the amplitude level  
 337 in quiet time for each day. They observed a rise in SBL preceding the eruptions of Shinmoe-  
 338 dake in 2011, as well as those in 2017 and 2018, at seismic stations located approximately  
 339 1 km away from the Shinmoe-dake crater. Here, we discuss temporal changes in the am-  
 340 plitude of retrograde Rayleigh waves that arrive from the direction of the Shinmoe-dake  
 341 crater.

342 Meza-Fajardo et al. (2015) introduced the "Normalized Inner Product (NIP) fil-  
 343 ter" to extract Rayleigh waves originating from the epicenter of an earthquake. Apply-  
 344 ing this filter to continuous seismograms can allow us to extract Rayleigh waves origi-  
 345 nating from the crater. We use this filter in the calculation of the RMS amplitudes of  
 346 retrograde Rayleigh waves that arrive from the direction of the Shinmoe-dake crater. The  
 347 NIP filter is defined as follows (Meza-Fajardo et al., 2015):

$$F_{\theta}(x) = \begin{cases} 0, & x < x_r - \Delta x \\ \frac{1}{2} \cos \left[ \frac{\pi(x-x_r)}{\Delta x} \right] + \frac{1}{2}, & x_r - \Delta x < x < x_r \\ 1, & x_r < x \end{cases} \quad (10)$$

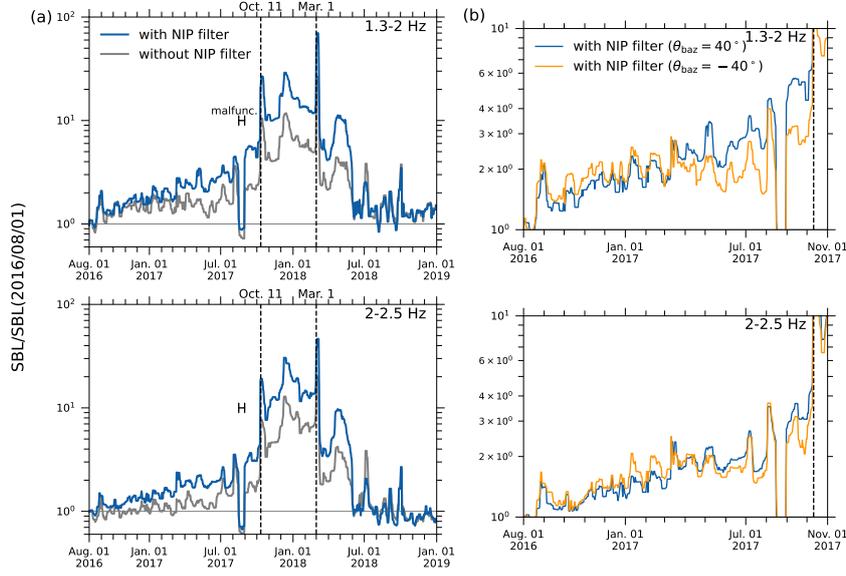
348 Where  $x = \text{NIP}_{\mathbf{R}_{\theta}, \hat{\mathbf{V}}}$ ,  $\theta$  represents the radial direction (i.e., direction of propagation of  
 349 Rayleigh wave),  $x_r$  is the threshold of the NIP value, and  $\Delta x$  is the width of the cosine  
 350 taper. We used  $\theta = -140^\circ$  (representing the propagation direction from the Shinmoe-dake  
 351 crater to V.KIRA), which corresponds to the reverse direction of the back azimuth. We  
 352 defined  $x_r = 0.8$  and  $\Delta x = 0.1$  to construct the filter.

353 We calculated SBLs using NIP filtered continuous seismograms. The SBL for the  
 354 V.KIRA seismic station is determined by computing the RMS amplitudes of the seis-  
 355 mograms on the vertical component within a 2-minute window in 1.3–2 Hz and 2–2.5  
 356 Hz bands. These frequency bands correspond to the range where retrograde Rayleigh  
 357 sources were identified towards the crater both prior to and following the eruptions (Fig-  
 358 ure 5). Daily SBL was determined by averaging the bottom 20% values of the 2-minute  
 359 RMS amplitudes. The blue lines in Figure 6a show the temporal changes in the SBL for  
 360 the retrograde Rayleigh waves originating from the crater between 2016 and 2018. A 9-  
 361 day median filter was used on daily SBLs to reduce daily fluctuations, which were then  
 362 normalized based on the SBL measurement on August 1, 2018. The decrease in SBL lev-  
 363 els towards the end of August 2017 could be attributed to a malfunction in the seismome-  
 364 ter. For comparison, we also calculated the ordinary SBLs (i.e., SBLs without NIP fil-  
 365 tering) in the same manner (gray lines in Figure 6a). The increase in SBL with NIP fil-  
 366 tering before the 2017 eruption is more substantial when compared to SBL without NIP  
 367 filtering. In the frequency band of 1.3–2 Hz, the SBL value using NIP filtering had al-  
 368 ready increased to 1.8 times its value on August 1, 2016, by June 1, 2017, whereas the  
 369 SBL value without NIP filtering was around 1.2 times higher. Furthermore, the SBL val-  
 370 ues obtained with NIP filtering demonstrate a steady increase in comparison to those  
 371 without NIP filtering within the frequency band of 2 to 2.5 Hz. Specifically, the SBL val-  
 372 ues without NIP filtering in the 2–2.5 Hz band do not exhibit a noticeable increase un-  
 373 til mid-June 2017, whereas those with NIP filtering begin to show an increase from Au-  
 374 gust 2016. In contrast to the scenario lacking NIP filtering, a notable characteristic is  
 375 the considerable size of the SBL with NIP filtering during the time frame between the  
 376 2017 and 2018 eruptions in comparison to the period before the eruptions.

377 As shown in the Results section, the estimated back azimuths in the 1.3–2 Hz band  
 378 have been steadily moving closer to the crater direction between January and March 2017  
 379 (Figure 5). The growth of SBL with the NIP filter shown in the top panel of Figure 6a  
 380 possibly reflect the migration of retrograde Rayleigh wave sources. Figure 6b shows tem-  
 381 poral changes in SBLs for various back azimuths in the 1.3–2 Hz and 2–2.5 Hz bands.  
 382 The blue line is the same as that in Figure 6a, and the orange line represents SBL for  
 383 retrograde Rayleigh waves with a source in the  $N40^\circ W$  direction. SBLs in the 1.3–2 Hz  
 384 band, which shows migration of retrograde Rayleigh wave sources, The SBL values for  
 385  $\theta_{\text{baz}} = -40^\circ$  are slightly greater than those for  $\theta_{\text{baz}} = 40^\circ$  (crater direction) until February  
 386 2017. On the contrary, the SBL values for  $\theta_{\text{baz}} = 40^\circ$  starting from March 2017 are sig-  
 387 nificantly higher than those for  $\theta_{\text{baz}} = -40^\circ$ . These results suggest that the migration of  
 388 retrograde Rayleigh wave sources could have influenced the increase in SBL for  $\theta_{\text{baz}} = 40^\circ$ .

389 For the amplitude growth of retrograde Rayleigh waves arriving from the crater  
 390 direction, it is difficult to evaluate the effect of migration of the retrograde Rayleigh wave

391 sources separately from the intensity change of the Rayleigh wave excitation itself. How-  
 392 ever, the results shown in this subsection suggest that the NIP filter is useful for detect-  
 393 ing weak Rayleigh waves that arrive from the crater direction.



**Figure 6.** (a) Temporal changes in SBLs at V.KIRA for 1.3–2 Hz and 2–2.5 Hz bands. The 9-day median filter was applied to the daily SBL time series and these time series are then normalized by the value on August 1, 2016. The SBLs were computed and shown as blue lines after the NIP filter was used for  $\theta = -140^\circ$ , indicating the direction of propagation from the Shinmoedake crater to the V.KIRA. Gray lines represent the SBLs without NIP filtering. The vertical dashed black lines represent the timings of the 2017 and 2018 Shinmoedake eruptions. (b) Temporal changes in SBLs with the NIP filter for various  $\theta$  values. Note that the ranges of the x-axis and y-axis are different from the panel (a).

394 **4.1.2 Tremor locations**

395 Previous studies estimated the locations of the tremor source that occurred around  
 396 the Shinmoedake. Nakamichi et al. (2013) estimated a location of volcanic tremor sources  
 397 in early February 2011 by using seismic array data at a site 5 km east of Shinmoedake.  
 398 The continuous tremor source was estimated between Karakuni-dake, Ohnami-ike, and  
 399 Shinmoedake (see Figure 1) at depths between 1 km below sea level and 1 km above  
 400 sea level. Estimated back azimuths of retrograde Rayleigh wave sources in this study are  
 401 approximately  $20^\circ$  between 1.3 and 2.5 Hz for the end of February 2011 (Figure 5). Hence,  
 402 the findings of this study align with the results of Nakamichi et al. (2013) indicating that  
 403 the continuous tremor source was located on the western side of the Shinmoedake. Ichihara  
 404 et al. (2023) estimated the locations of tremor sources that represent high SBL by uti-  
 405 lizing the amplitude-based method for source location within the frequency range of 3.5–  
 406 7 Hz. Tremor sources related to the 2011 eruption and the 2017–2018 eruptions are lo-  
 407 cated in a comparable area beneath the Shinmoedake. By analyzing the SBL ratio for  
 408 stations located west and north of Shimoe-dake, they found that the tremor sources be-  
 409 fore the 2011 and 2017 eruptions were shallower and located further to the west com-  
 410 pared to the tremors before the 2018 eruption. These results suggest that volcanic tremor  
 411 sources are distributed in a shallow region beneath/around the Shinomoe-dake. Our find-

ings that Rayleigh waves from the crater’s direction are significantly dominant before and during the eruption are in line with the results of previous studies that estimated the sources of volcanic tremors in shallow regions around Shinmoe-dake. Because the locations of the tremor sources estimated by these previous studies are shallow, the Rayleigh waves detected in this study probably originate from these tremors.

#### 4.1.3 Geodetic deformations

Geodetic deformations caused by the deep pressure source and shallow ones beneath the Kirishima volcano have been revealed by GNSS and interferometric synthetic aperture radar (InSAR) analyses. Japan Meteorological Agency (2017) reported an extension of the GNSS baseline at the Kirishima volcano from June 2017. This baseline change originates from the inflation of the deep pressure source located 5 km to the northwest of the summit at a depth of 8 km (Nakao et al., 2013). The back azimuth of the retrograde Rayleigh wave source, which is speculated to be located in shallow regions, was concentrated in the direction of the Shinmoe-dake crater since about 3 months before the GNSS baseline extension (Figures 4 and 5). Moreover, the increase in SBLs of the retrograde Rayleigh wave from the crater direction also preceded the extension of the baseline (Figure 6). These observations suggest that the volcanic process just beneath the Shinmoe-dake and changes in deeper regions are not completely synchronized.

Temporal changes in the shallow pressure source were revealed by using InSAR time-series analysis. Yunjun et al. (2021) reported  $\sim 5$  cm inflation of the western flank of the Shinmoe-dake prior to the 2017 eruption. In the LOS time series, inflation appears to have become more pronounced since March 2017, which is consistent with our polarization analysis results and the SBL changes. They explained this inflation by assuming an ellipsoidal pressure source at  $\sim 700$  m depth beneath the Shinmoe-dake. Their results are observational facts supporting the hypothesis that volcanic activity changed in the shallow area directly beneath the Shinmoe-dake before the 2017 eruption, and multiple observational terms support the change in volcanic activity in the shallow region of Shinmoe-dake. The results of polarization analysis in this study indicate the possibility of detecting changes in volcanic activity in the shallow part of the volcano just beneath the Shinmoe-dake.

## 4.2 Candidate for Rayleigh wave source mechanism

Volcanic tremor may be caused by fluid-flow-induced oscillations in conduits, resonance of fluid-filled cracks, bubble dynamics due to hydrothermal boiling, or oscillations of magma bodies with varying geometries (Konstantinou & Schlindwein, 2002). The depth of the tremor source estimated by Nakamichi et al. (2013) was located in a low resistivity layer, suggesting that hydrothermal processes are a more plausible mechanism for the generation of the tremor. They interpreted that the weak continuous tremor may have been caused by the boiling of water in the heated water-saturated layer (Leet, 1988; Canata et al., 2010). Ichihara et al. (2023) references the explanation of how tremors are produced as discussed in the study by Jolly et al. (2020). Jolly et al. (2020) observed a gradual development of faint and ongoing tremors associated with the establishment of the quiet dome on White Island, New Zealand. They explained that the occurrence of these weak and continuous tremors was a result of the interaction between the hydrothermal system and the slowly propagating magma. Since the results of this study are consistent with the results of Nakamichi et al. (2013) and Ichihara et al. (2023), those mechanisms are also likely candidates for the Rayleigh wave generation mechanism that preceded the eruption captured in this study.

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### 4.3 Seismic wavefields during daytime

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To highlight the differences in seismic wavefield characteristics between day and night, we present histograms of estimated back azimuths for day (06:00–17:59 JST) and night (18:00–05:59 JST) separately. Figure 7a (7b) illustrates daily histograms of estimated back azimuths at day and night in the 1.3–2 (2–2.5) Hz band throughout the study period. The results show a clear difference in back azimuth distributions between day and night, except for the period from March 2017 to March 2018, where the distributions are relatively similar. The difference in back azimuth distributions can be attributed to the influence of cultural noise, mainly from human activities, which is predominant above 1 Hz during daytime. This noise typically propagates as surface waves and attenuates within several kilometers (Nakata et al., 2019). Consequently, nighttime data analysis is more effective in detecting retrograde Rayleigh waves from the crater direction.

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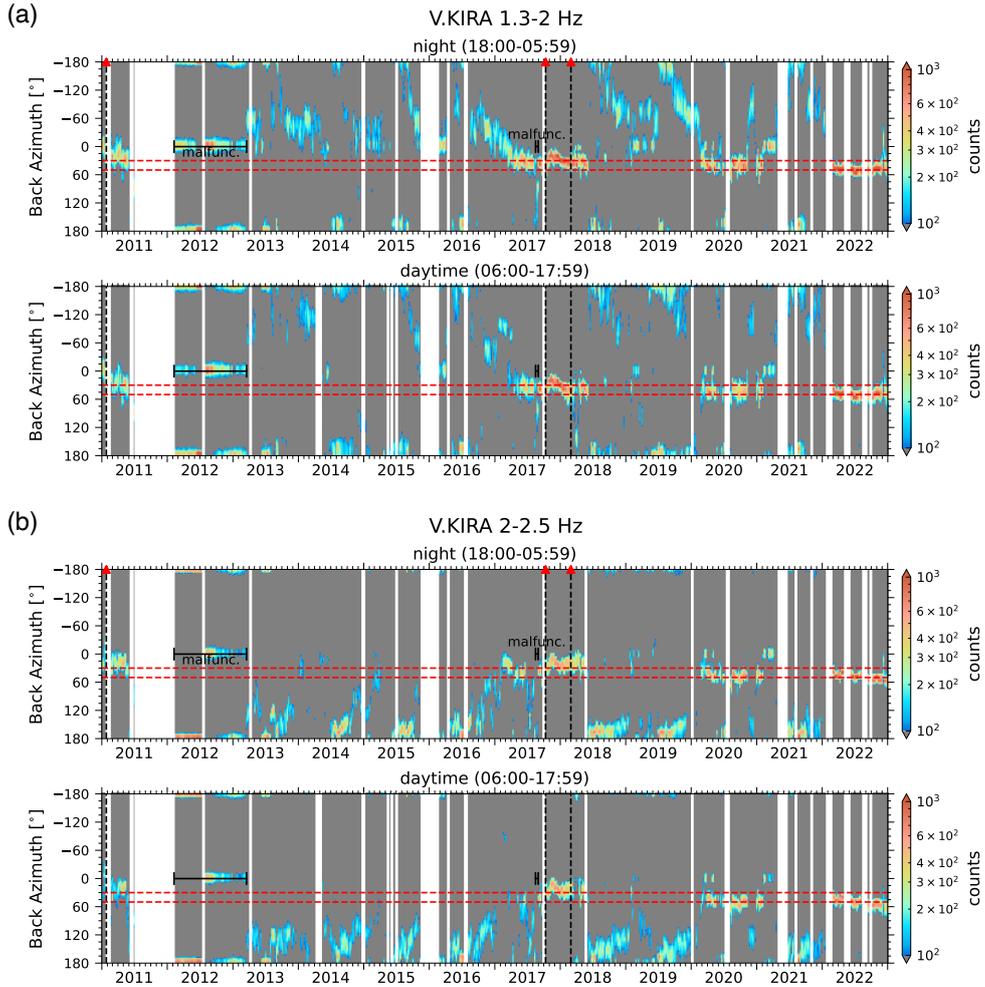
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It is important to note that although our polarization analysis is specifically designed for Rayleigh waves, this approach can be applied even if only one three-component seismometer is deployed. This makes the method useful for monitoring volcanoes, particularly those with a small number of seismic stations. However, caution should be exercised when interpreting daytime data due to the increased influence of cultural noise. In conclusion, the proposed polarization analysis method demonstrates its effectiveness in detecting weak Rayleigh waves from the crater direction, especially during nighttime. Despite its limitations, this single-station approach has the potential to contribute to improved monitoring of volcanoes with limited seismic station coverage. Further research is needed to develop strategies for mitigating the influence of cultural noise and enhancing the applicability of the method to daytime data.



**Figure 7.** Temporal changes in daily histograms of back azimuths during night and daytime over 12 years at the (a) 1.3–2 Hz and (b) 2–2.5 Hz bands.

## 5 Conclusion

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483 This study demonstrated the effectiveness of polarization analysis using continu-  
 484 ous seismograms for investigating volcanic tremors, which are crucial for advancing our  
 485 understanding of the internal processes of volcanoes and predicting eruptions. By ap-  
 486 plying this method to the Kirishima volcano in Japan, we aimed to reveal the tempo-  
 487 ral changes in the seismic wavefield associated with volcanic activities and to evaluate  
 488 the potential of this approach for the early detection of precursor signals. The back az-  
 489 imuths of retrograde Rayleigh wave sources were estimated from January 2011 to De-  
 490 cember 2022 (12 years). Three significant eruptive activities occurred at the Shinmoe-  
 491 dake crater during our study period, and this allowed us to study temporal changes in  
 492 back azimuths before and after the eruptions. The estimated back azimuths of retrograde  
 493 Rayleigh wave sources during nighttime were clearly concentrated in the direction of the  
 494 Shinmoe-dake crater before and after the 2011, 2017, and 2018 eruptions in the frequency  
 495 band of 1.3–2.5 Hz. In the case of the 2011 January eruption, this concentration was es-  
 496 timated from early January and continued until early June 2011. In the case of the 2017

497 October eruption, weak retrograde Rayleigh wave signals that arrived from the crater  
 498 direction were detected from March 2017, and the concentrations of back azimuths lasted  
 499 until the end of May 2018, 3 months since the 2018 March eruption. Retrograde Rayleigh  
 500 wave sources in the 1.3–2 Hz band migrated prior to the 2017 October eruption. The  
 501 estimated back azimuths were  $-40^\circ$  (N40°W) between October and December 2016 and  
 502 gradually shifted to the western flank of the Shinmoe-dake crater direction (back azimuth= $30^\circ$ ,  
 503 N30°E) with speed of roughly  $18^\circ$ /month. We applied the NIP filter to extract retro-  
 504 grade Rayleigh waves that arrived from the direction of the crater and calculated the seis-  
 505 mic background levels (SBLs) (i.e., RMS amplitudes during the night) of these Rayleigh  
 506 waves. The growth of retrograde Rayleigh waves from the crater direction was estimated  
 507 since August 2016. In the 1.3–2 Hz band, the SBL value using the NIP filter had already  
 508 increased to 1.8 times its value on August 1, 2016, by June 1, 2017 (four months before  
 509 the eruption), while the SBL value without the NIP filter was around 1.2 times higher.  
 510 This indicates that NIP filtering could be beneficial in detecting weak Rayleigh wave sig-  
 511 nals from the crater earlier. The results obtained in this study show that the retrograde  
 512 Rayleigh wave sources approached the crater direction and increased in amplitude as the  
 513 2017 eruption approached. These findings may contribute to the assessment of the im-  
 514 minence of volcanic eruptions. Although our polarization analysis is only applicable to  
 515 Rayleigh wave data, this single-station-based approach will contribute to improving mon-  
 516 itoring at volcanoes with a small number of seismic stations. Furthermore, improving  
 517 the detection capability of weak Rayleigh waves (volcanic tremors) originating in shal-  
 518 low regions of volcanoes is important. This can contribute to a better understanding of  
 519 the internal processes of volcanoes, regardless of the number of seismometers.

## 520 6 Open Research

521 Continuous seismograms are available from the Data Management Center of the  
 522 NIED (<https://hinetwww11.bosai.go.jp/auth/?LANG=en>). DEM data, the ALOS Global  
 523 Digital Surface Model “ALOS World 3D - 30m (AW3D30),” used to create a topographic  
 524 map, are available at [https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30](https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm)  
 525 [\\_e.htm](https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm). The “pycpt” package (<https://github.com/j081ue/pycpt>) was used to make  
 526 color maps in some figures. Data and scripts for creating the figures are available at [https://](https://zenodo.org/doi/10.5281/zenodo.10884533)  
 527 [zenodo.org/doi/10.5281/zenodo.10884533](https://zenodo.org/doi/10.5281/zenodo.10884533); Hirose, (2024).

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