

In-Situ Vp/Vs ratio variations in seismic swarms as indicator of magmatic processes: Fagradalsfjall volcanic activity, SW Iceland

Ali Masihi¹ and Tomas Fischer²

Charles University, Faculty of Science, Albertov 6, 12843 Prague 2, Czech Republic. E-mail: masihia@natur.cuni.cz

Accepted 2025 March 26. Received 2025 March 24; in original form 2024 October 23

SUMMARY

In this study, we applied the ‘*in-situ* Vp/Vs method’ to monitor variations of seismic velocity ratio (Vp/Vs) within swarms, providing insights into eruption processes. This method, particularly effective in volcanic regions, estimates Vp/Vs by comparing *P*- and *S*-wave arrival times of closely located earthquake pairs, reducing errors from unknown crustal velocity variations and is well-suited for detecting rapid changes associated with volcanic swarms. Our study focused on seismic swarms on the Reykjanes Peninsula, south-west Iceland where, swarms have been frequent since 2017 and led up to eruptions in 2021, 2022 and 2023. We analysed the entire period (2017–2023) as well as the 2021 swarm separately using data from over 40 000 seismic events recorded by the REYKJANET network. We observed significant decrease in the Vp/Vs ratio before major pre-eruption swarms, compared to the background Vp/Vs value of 1.78. From the 2020 swarm, we observed a lower Vp/Vs of 1.72, but the lowest estimated value was 1.70, associated with the 2021 pre-eruption swarm that preceded Fagradalsfjall’s first eruption after 7000 yr. Reduced Vp/Vs ratios were also noted before the 2022 and 2023 eruptions, suggesting supercritical fluids in the crust during these stages. We also introduce the concept of ‘*change points*’ to interpret Vp/Vs variations along the dyke. Change points denote specific locations or times of significant Vp/Vs shifts, potentially indicating subsurface changes such as fluid influx or new fracturing from magma intrusion. Identifying these points allows us to pinpoint key moments when the system undergoes substantial changes, offering insights into eruption timing and location. Focusing on 2021 pre-eruption swarm, interestingly the spatial change point found in a location very close to the eruption site. Temporal analysis identified two main change points: the first corresponding with initial activity in the northern dyke and the second with a shift to the southern segment, ultimately leading to eruption. These points mark stages in magma progression, with each showing an initial rapid Vp/Vs drop that could indicate CO₂-rich fluid infiltration, followed by an increase as magma enters. The *in-situ* Vp/Vs method’s sensitivity to changes in seismic properties makes it a powerful tool for real-time volcanic monitoring. By detecting critical Vp/Vs changes with minimal computational demand, this method has potential for integration with online seismic networks, providing an effective early warning system for volcanic hazards.

Key words: Seismic tomography; Rheology: crust and lithosphere; Eruption mechanism and flow emplacement; Volcano monitoring; Volcano seismology.

1. INTRODUCTION

Predicting volcanic eruptions is a significant goal in volcanological research (Voight & Cornelius 1991; Chardot *et al.* 2015; Boué *et al.* 2016; Salvage & Neuberg 2016; Bell *et al.* 2018; Poland & Anderson 2020). This task is challenging due to the complex and diverse nature of precursory activities. Thus, identifying these signals is a major focus in volcano seismology. Following the Sundhnúkur eruptions in December 2023, which caused significant damage and

evacuations in Grindavík, detecting volcanic activity signals has become a central focus in Iceland. Analysing volcanic seismicity and observing changes in the rheological properties of Earth materials, exemplified by the Vp/Vs ratio, are crucial, as these efforts not only enhance eruption forecasting but also advance our understanding of the fundamental processes governing volcanic eruptions.

This study identifies changes in rheological properties near an eruption site as potential precursory signals for volcanic eruptions. To achieve this, we employ the *in-situ* Vp/Vs method (Lin & Shearer

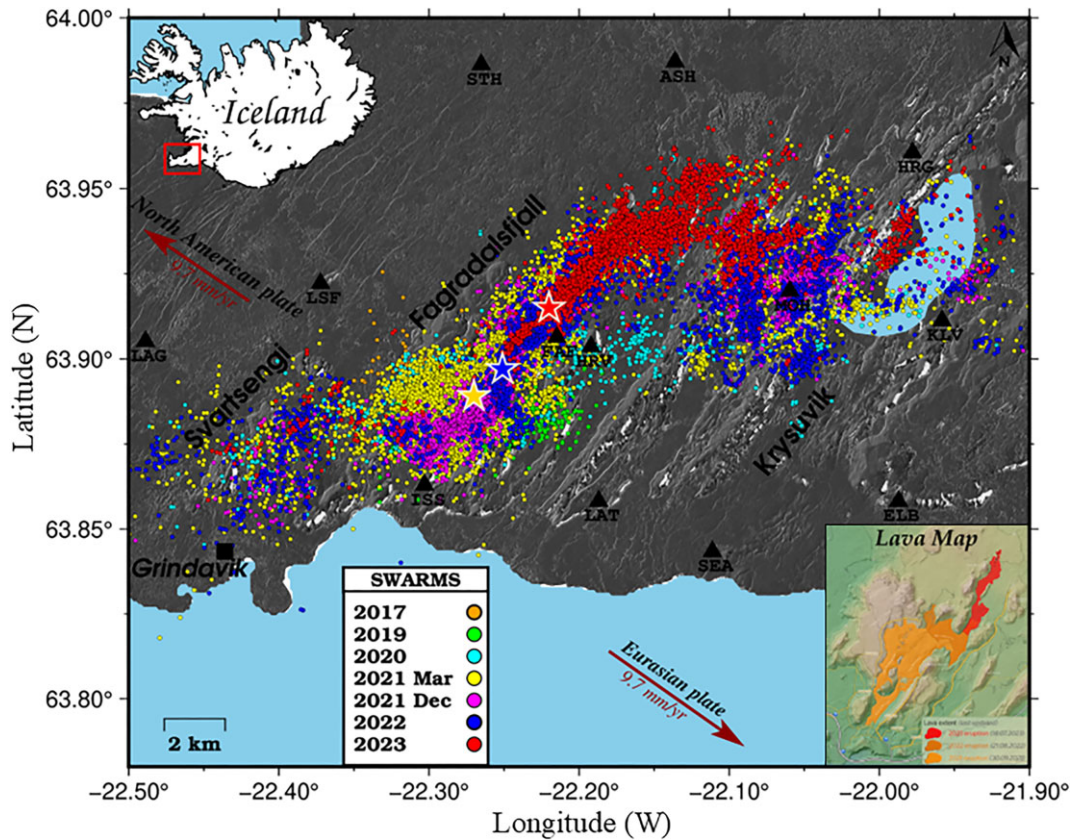


Figure 1. Seismicity map of the Reykjanes Peninsula (RP) from 2017 July 26 to 2023 September 29. Events from seven swarm periods are colour-coded as indicated in the legend. Black triangles represent the locations of REYKJANET network seismic stations operated by Czech Academy of Science. Yellow, blue and red stars mark the locations of the 2021, 2022 and 2023 eruptions, respectively. Brown arrows show the direction of plate spreading between the North American and Eurasian plates. The red rectangle in the inset map of Iceland highlights the study area on the RP. Another inset shows the extent of lava fields from the 2021 (yellow), 2022 (orange) and 2023 (red) eruptions (Hennig 2023). The volcanic systems on the RP—Svartsengi, Fagradalsfjall and Krýsuvík—are labelled in bold from west to east. The location of Grindavík city is also marked on the map.

2007) to assess changes in the V_p/V_s velocity ratio over specific time intervals and spatial regions, including pre-eruption, eruption and post-eruption periods.

Our case study focuses on the Fagradalsfjall volcano in the central Reykjanes Peninsula, Iceland. Several seismic swarms occurred in this region in 2017, 2019 and 2020, with the 2021 swarms leading to an eruption. Additional swarms in 2022 and 2023, two of which resulted in eruptions, provide a unique natural laboratory for testing our method (Fig. 1).

This method's robustness makes it valuable for various type of studies and field like lithological and petrological characterization (Wcislo *et al.* 2018; Merrill & Bostock 2019), fluid detection and monitoring (Lin & Shearer 2009; Dahm & Fischer 2014; Bachura & Fischer 2016), geothermal exploration (Megies & Wassermann 2014; Lin 2019; Roth *et al.* 2023), induced seismicity (He *et al.* 2021), structural and tectonic studies (Mesimeri, Ganas & Pankow 2022; Liu *et al.* 2023), crustal studies (Bloch *et al.* 2018; Yoshida 2021), aftershock analysis (Maeda *et al.* 2019; Lin & Fan 2024), and volcanic monitoring (Lin *et al.* 2015; Schuler *et al.* 2015; Yukutake *et al.* 2015; Lin & Shearer 2021). The method is not sensitive to earthquake location errors and is less affected by velocity variations in the surrounding crust (Lin 2007), making it well-suited for monitoring volcanic areas where path and site effects can be significant (McNutt 2005). Recent applications have shown its ability to reveal fine-scale structures beyond traditional V_p/V_s estimation methods like tomography (Lin & Shearer 2009; Lin *et al.* 2015, 2019) or

methods that separately estimate V_p and V_s (Gritto & Jarpe 2014). The robustness of the method was enhanced by Liu *et al.* (2023) by excluding event pairs with calculated V_p/V_s ratios that fell outside a reasonable range. This refinement allows the method to identify even minor variations in the *in-situ* V_p/V_s ratio of the focal volume.

Since Iceland is the only part of the Mid-Atlantic Ridge exposed above sea level, it provides a unique opportunity to study a divergent boundary onshore. Many studies have prepared 2-D and 3-D velocity and tomography models for this area using different methods (e.g. Allen *et al.* 2002; Du *et al.* 2002; Mitchell *et al.* 2013). Some focused on the southwest of Iceland (Bjarnason *et al.* 1993; Foulger *et al.* 1995; Amoroso *et al.* 2022), particularly the Reykjanes Peninsula (Weir *et al.* 2001; Tryggvason, Rögnvaldsson, & Flóvenz 2002; Jousset *et al.* 2016; Malek, Brokešová, & Novotný 2019; Martins, Hey & Höskuldsson 2020; Hobe *et al.* 2021; Růžek 2021; Rahimi Dalkhani *et al.* 2024). Ambient seismic noise has also been used to monitor volcanic systems (e.g. Donaldson *et al.* 2019; Lee *et al.* 2024), but results can be affected by temperature variations, changes in groundwater level and rainfall and noise source distribution (i.e. Bièvre *et al.* 2018; Guillemot *et al.* 2021).

The high-resolution V_p/V_s estimation method excels due to its sensitivity to near-source materials and ability to detect rapid spatiotemporal variations, unlike traditional tomography that often misses short-term changes (Lin & Fan 2024). Additionally, it effectively studies spatial and temporal variations by selecting specific events, overcoming non-uniqueness issues in classic tomography,

and is applicable in investigating changes in volcanic areas (Lin & Shearer 2021).

In this paper, we analyse the spatial and temporal variations of local Vp/Vs ratio, which were estimated using the *in-situ* Vp/Vs method near the Fagradalsfjall eruption site. This analysis focuses on seismic swarms recorded by the REYKJANET seismic network between 2017 and 2023. Special attention is given to the 2021 seismic swarm, which led to the first eruption in the area. We highlight the key locations and time along the dyke where significant changes occurred (referred to as ‘change points’) and provide interpretations of these changes.

1.1. Fagradalsfjall 2021 eruption

Iceland, situated on the Mid-Atlantic Ridge where the Eurasian and North American tectonic plates diverge, experiences divergent tectonic activity and mantle plume hotspots, with a spreading rate of 18–19 mm yr⁻¹ in a N105°E direction (Martinez 2020). The Reykjanes Peninsula (RP) in southwest Iceland, a key segment of this plate boundary, connects the Reykjanes Ridge with the Hengill Triple Junction (Sigmundsson 2020). This region, characterized by the Reykjanes Peninsula Oblique Rift, experiences extensive volcanic and seismic activity across six volcanic systems (Einarsson 1991, 2008) defined by NE–SW fissure swarms, N–S strike-slip faults, high-temperature geothermal activity, and episodic volcanic eruptions (Einarsson *et al.* 2023).

Seismic activity on the RP occurs in episodic bursts approximately every 30 yr (Einarsson 2008). Crustal deformation happens in two modes: seismic (dry) mode involving strike-slip faulting, and magmatic (wet) mode involving dyke intrusions and activation (Hreinsdóttir *et al.* 2001). Magmatic activity in RP is highly episodic, occurring roughly every 800–1000 yr. The last major eruptive period on RP ended 781 yr ago, with the Fagradalsfjall volcanic system’s last eruptive activity occurring more than 6000 yr ago. Activity appears to migrate from east to west with a temporal spacing of 100–200 yr (Saemundsson *et al.* 2020). In recent decades, there has been no significant evidence of magmatic contributions (Einarsson 2008).

The seismicity pattern along the RP demonstrates a systematic transition from earthquake swarms in the west to mainshock–aftershock sequences in the east, associated with a shift from normal to oblique strike-slip stress states, reflecting underlying tectonic and geological structures (Keiding 2009). The brittle–ductile transition (BDT) zone beneath the RP, typically at a depth of 6–7 km, ascends to 3–5 km in high-temperature areas (Blanck *et al.* 2020; Flóvenz *et al.* 2022; Rahimi Dalkhani *et al.* 2024).

Fagradalsfjall, centrally located on the Reykjanes Peninsula between the Svartsengi and Krísvík systems, lacks its own geothermal system (Fig. 1). The 2021 and 2022 eruptions there were driven by magmatic intrusions along NE–SW trends and surface fractures along N–S faults. The stress field, with a maximum principal stress oriented N45°E and a minimum N135°E, influences fault structures. Earthquakes and magmatic activity are closely linked. As dikes propagate to shallower depths where the crust becomes more brittle, magma flow may be diverted into pre-existing N–S striking strike-slip faults, potentially triggering faulting before leading to an eruption. These faults can also serve as pathways for magma ascent, particularly during dike intrusion and eruption episodes, as observed in the Fagradalsfjall volcanic system (Einarsson 2023). The Fagradalsfjall area shows pronounced swarm activity with significant swarms in August 1998, November 2000 and July 2004, characterized by high *b* values in the west and lower *b* values in the

east and Krísvík. The area has a consistent low background seismicity rate, punctuated by episodic bursts during swarms (Keiding 2009).

Before 2021 March 19 eruption, several precursors were observed, including increased seismic activity in the RP. Between 2013 and 2019, earthquake swarms concentrated in the Fagradalsfjall volcanic system. An aseismic dyke identified during the 2017 swarm ($M < 3.7$) indicated crustal weakening and potential ductile magmatic intrusion (Hrubcová, Doubravová & Vavryčuk 2021; Hrubcová & Vavryčuk 2023). Another swarm ($M < 3.7$) occurred in December 2019, followed by three significant seismic swarms ($M < 4.3$) in 2020, accompanied by inflation and deflation in the RP (Cubuk-Sabuncu *et al.* 2021).

The 2021 Fagradalsfjall volcanic eruption was preceded by significant seismic activity. The sequence began with a major earthquake (ML 5.3) on 2021 February 24, triggering a swarm in the region. This mainshock and subsequent seismic bursts were linked to magma movement and dyke propagation (Fischer *et al.* 2022). Notably, there were 64 ML ≥ 4.0 earthquakes, nearly 20 more than recorded in the previous two decades (Sigmundsson *et al.* 2022).

Detailed seismic data analysis identified two main clusters: one trending NE–SW mapping the dyke and another WSW–ENE along the oblique plate boundary. Seismic activity progressed in stages, initially activating the northern dyke segment, followed by the central, and then the southern segment, and finally erupted at centre, indicating dyke propagation driven by magma intrusion.

The seismic swarm before the 2021 eruption indicated a complex interplay between tectonic stress and magmatic activity, concentrated at depths of 2–6 km (Fischer *et al.* 2022). The 9 km dyke breached the surface on 2021 March 19, leading to a six-month effusive eruption, forming a 120 m high volcanic cone with a steady magma discharge of about 7 m³ s⁻¹ (Pedersen *et al.* 2022). The eruption created a lava field covering 5 km², with an estimated dense rock equivalent volume of 0.1 km³ (Bindeman *et al.* 2022). Notably, seismicity and deformation rates declined before the eruption, deviating from typical patterns (Sigmundsson *et al.* 2022).

After the Fagradalsfjall eruption in 2021, a seismic swarm in December 2021 did not result in a successful dyke intrusion. On 2022 August 3, Fagradalsfjall erupted in Meradalir valley, and on 2023 July 10, an eruption occurred at Litli-Hrutur, lasting about four weeks (Fig. 1). In December 2023, seismic activity shifted, causing a fissure near Grindavík and leading to evacuations. This was followed by another eruption in January 2024.

2. METHOD

2.1. *In-situ* Vp/Vs method

The robust *in-situ* Vp/Vs method was utilized to evaluate the near-source *P*-wave to *S*-wave velocity ratio, denoted as $\gamma = V_p/V_s$ (gamma ratio) (Lin & Shearer 2007), as a means of detecting magma presence across different temporal and spatial intervals.

The classical Wadati diagram (Wadati 1928), estimates average Vp/Vs ratios by plotting differences between *P* and *S* wave arrival times. Though primarily used for earthquake location (Kisslinger & Engdahl 1973), the method has been enhanced with cross-correlation techniques and double-difference methods to improve relative event location accuracy (Poupinet *et al.* 1984; Ito 1985; Maurer & Deichmann 1995; Slunga *et al.* 1995; Shearer 1997; Menke 1999; Waldhauser 2000).

Lin & Shearer (2007) introduced the ‘*in-situ* Vp/Vs method’ to estimate local Vp/Vs ratios by using accurate *P* and *S* waves differential times (dtp and dts) derived from waveform cross-correlation.

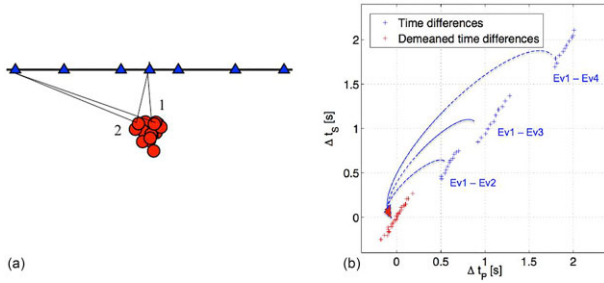


Figure 2. A schematic diagram illustrating how the *in-situ* Vp/Vs method works. (a) Triangles represent seismic stations, and circles indicate earthquakes that occurred in the focal zone. 1 and 2 are two arbitrary earthquakes that occurred close to each other within the cluster. (b) Blue: Differential *P*-wave arrival times (Δt_P) compared to differential *S*-wave arrival times (Δt_S) for various pairs of events inside a compact cluster. Red: Demeaned Δt_P versus demeaned Δt_S .

This approach is particularly useful for evaluating medium properties near earthquake sources. Building on this concept, Dahm & Fischer (2014) modified the method to simultaneously determine Vp/Vs ratios at both the seismic network scale and the local focal volume scale, referring to it as the ‘*Double-Difference Wadati method*’. To enhance robustness, they incorporated a least median of squares regression to reduce the influence of outliers.

2.2. Application of the method

This method estimates the Vp/Vs velocity ratio in the earthquake swarm’s source region. A key advantage is that it is not sensitive to earthquake location errors and has reduced sensitivity to unknown velocity variations in the crust beyond the source region. Unlike tomography methods, this approach is not bound to the resolution of the grid as it focuses on source cluster. Additionally, it is straightforward to implement and does not require significant computational power, making it suitable for monitoring purposes (Lin 2007, 2021).

To achieve this, two closely located earthquakes within the focal volume are selected, ensuring nearly identical ray paths due to their proximity (Fig. 2a). Differences in their *P* and *S* traveltimes at various stations are attributed to velocity changes within the focal volume. The local Vp/Vs ratio within the focal zone is deduced from the slope of the scatter plot of *P*-wave versus *S*-wave arrival time differences for a specific event pair (Fig. 2b). For numerous event pairs situated within the focal volume, each contributing to *P* versus *S* arrival time differences, the resulting scatter plots showed parallel lines with a consistent slope. These lines are shifted from zero due to variations in their origin times. By demeaning each event pair from the mean of all stations within the focal volume, a conclusive slope is obtained, signifying the Vp/Vs ratio specific to the focal volume.

Eq. (1) illustrates the fundamental concept of this method for event pairs in a focal volume recorded by common stations, where i is the event pair index, and j is the station index. The terms inside the angle brackets denote the mean of the arrival time differences for each event pair i across all stations j .

$$\Delta t_{ij}^P - \langle \Delta t_{ij}^P \rangle_j = \left(\frac{V_P}{V_S} \right) \left(\Delta t_{ij}^S - \langle \Delta t_{ij}^S \rangle_j \right) \quad (1)$$

The bootstrap approach (Efron & Gong 1983; Efron & Tibshirani 1991) is employed to estimate errors, wherein pairs of differential *P* and *S* times within the same cluster are randomly resampled 500 times. This approach provides a local measurement of the average

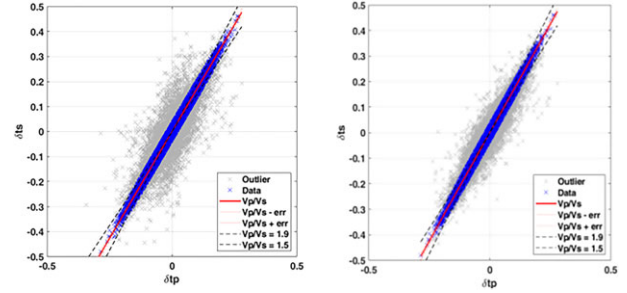


Figure 3. Representation of the 2021 swarm data before (left) and after (right) filtering out unreliable measurements using the method of Liu *et al.* (2023). Each point corresponds to the differential body-wave traveltime differences (δt_s versus δt_p) for an event pair recorded at a single station. The blue crosses correspond to different event pairs that were retained for estimating the Vp/Vs slope, while grey crosses indicate outlier differential times that were removed using the hybrid L1–L2 method (Huber 1973).

Vp/Vs within earthquake clusters, typically a few kilometers across. It is particularly effective for analysing volcanic swarms, as their 3-D distribution helps mitigate errors from variations in *P* and *S* wave take-off angles (Lin & Shearer 2007).

2.3. Data pre-processing and regression

The data for this study was sourced from the REYKJANET seismic network (Horalek 2013) on the Reykjanes Peninsula, operational since 2013 under the Czech Academy of Science and comprising 15 stations equipped with broad-band 3-component velocity meters. Earthquake arrival times (*P* and *S*) required for the *in-situ* Vp/Vs method were automatically obtained using Pepin (Fischer 2003; Káldy and Fischer 2025). For stronger events, manually processed high-quality picks provided by IG (Institute of Geophysics of Czech Academy of Science) were used. These arrival times were further refined through waveform cross-correlation, and the event locations were subsequently improved using Growclust (Trugman & Shearer 2017).

The available data set consists of 40 245 events from swarms occurring between 2017 and 2023, containing approximately 3630 000 differential times and about 58 800 event pairs. Pre-processing techniques play a crucial role in ensuring the effectiveness of our methodology, as outliers can significantly skew results, especially in smaller clusters. Initially, in the quality-control procedure, the input catalogue is refined by filtering events with magnitudes greater than 0 ML and depths less than 12 km (the typical focal depth of the region). Events with location root mean square error (rms) values exceeding 0.5 are excluded. Event pairs exhibiting cross-correlation coefficients below 0.85 are eliminated to mitigate the influence of potentially inaccurate phase picks, which could distort traveltimes. Event pairs with both *S* and *P* arrival times recorded at more than six stations are selected to ensure the robustness of the data set.

For pre-processing step, the method proposed by Liu *et al.* (2023) is adopted to calculate the Vp/Vs ratio for each event pair within the focal volume. Event pairs with ratios falling outside the reasonable interval of 0.5 to 3 are excluded. The data are then fitted using orthogonal regression, integrating a hybrid L1–L2 method (Huber 1973), similar to Bachura & Fischer (2016). This approach effectively addresses outliers in the differential traveltime data, which could otherwise bias numerical fitting. These two processing steps collectively contribute to enhanced accuracy and reliability of the results. Fig. 3 illustrates the results before and after using Liu *et al.* (2023) method for the 2021 swarm.

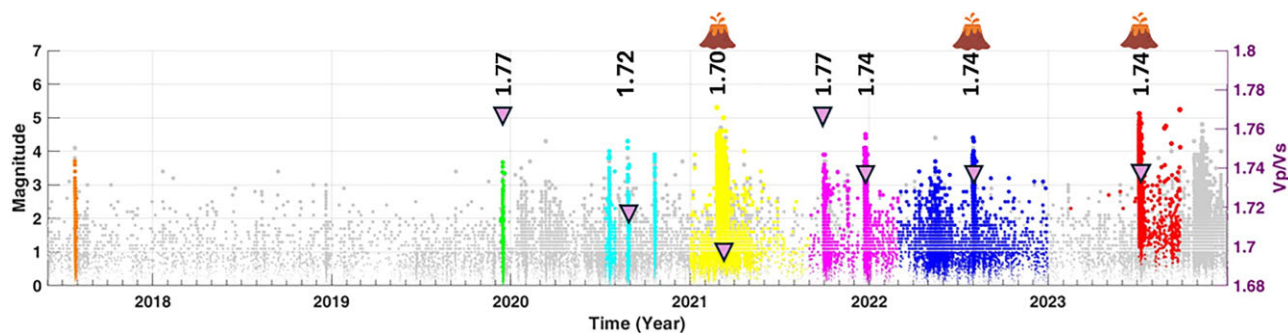


Figure 4. Time–magnitude evaluation of seismic activity in the Fagradalsfjall region, along with the temporal variation of the Vp/Vs ratio representative of each swarm from 2017 to 2023. Swarms are colour-coded as shown in Fig. 1. Triangles indicate the Vp/Vs ratio for each swarm, positioned at their respective swarm periods and aligned with the right Y-axis labels for reference. Eruption icons mark the onset of the 2021, 2022 and 2023 eruptions. The Vp/Vs ratio for the 2017 swarm is not shown due to its higher error compared to other swarms.

Table 1. Number of events, the number of observations (common *P* and *S* differential times), Vp/Vs value for the whole cluster, and the estimated bootstrap error for each swarm from 2017 to 2023.

Swarm	No. of events	No. of observations	Vp/Vs	Bootstrap error
2017	974	1021	1.766	0.280
2019	925	1803	1.768	0.018
2020	2634	1304	1.723	0.014
2021(Feb–Mar)	14 446	178 040	1.699	0.002
2021(Sep)	1494	9375	1.774	0.015
2021(Dec)	5125	34 334	1.738	0.005
2022	3797	3904	1.737	0.010
2023	4345	20 487	1.738	0.008

To ensure reliability, clusters with at least 40 events and more than 200 event pairs are included. This ensures at least 1200 observations (common dtp and dts) for fitting the regression line, strengthening the credibility of the analyses. This exceeds the criteria (1000 observations) set by Roth *et al.* (2023) for obtaining trustworthy results.

3. RESULTS

3.1. Overview of swarms and Vp/Vs ratios

The 2021 swarm continues the series of swarms from 2017, 2019 and 2020 in the central part of the Reykjanes Peninsula. To study long-term changes in Vp/Vs ratios, the *in-situ* Vp/Vs method was applied to swarms from 2017 to 2023. Table 1 lists the corresponding Vp/Vs values, and Fig. 4 shows the computed values for each swarm along a magnitude plot. The lowest Vp/Vs value is associated with the pre-eruption 2021 swarm, which preceded the first eruption of Fagradalsfjall. The calculated Vp/Vs for the 2020 swarms is 1.72, while for the pre-eruption 2021 swarm, it is 1.70. For comparison, Blanck *et al.* (2020) reported that the background seismicity in the area during 2014–2015 had a Vp/Vs of approximately 1.78, consistent with earlier studies by Menke *et al.* (1994), Wier *et al.* (2001), and Brandsdóttir & Menke (2008). Thus, the computed Vp/Vs values for these swarms are notably lower than the background seismicity Vp/Vs value, especially from 2020.

3.2. Spatial and temporal evolution of the 2021 swarm

According to Fischer *et al.* (2022), the 2021 Fagradalsfjall swarm began in the northern region, moved to the central part, migrated southwards and eventually returned to the central area, where the

eruption occurred. This temporal evolution and spatial distribution of the swarm are illustrated in Fig. 5. For a thorough investigation, the entire area was divided into four distinct parts. The calculated Vp/Vs values for different active areas during the 2021 swarm are presented in Fig. 5 and Table 2. These values indicate lower Vp/Vs ratios in the southern regions compared to the northern part of Fagradalsfjall.

3.2.1. Vp/Vs variation along the dyke (spatial analysis)

The study aimed to understand the velocity changes along the dyke during the pre-eruption swarm. To analyse the spatial distribution of Vp/Vs ratios during the 2021 pre-eruption swarm, the method was applied to data collected along the dyke using equally spaced windows. The data, rotated along the dyke, with Vp/Vs ratios calculated at equal 0.5 km windows, are shown in Fig. 6. Several changes in Vp/Vs values along the dyke raise questions about the significance of these variations. To identify the most significant point, the concept of the Change Point was introduced, where the measured quantity shows the most significant change in terms of its uncertainty.

To determine this point, an expanding window was used instead of the moving window shown in Fig. 6, spanning from the beginning to the end of the dyke. At each step, the mean Vp/Vs values in two windows—one to the left and one to the right of the separation point—were computed and compared (Supplementary Material 2) and (Fig. 7c). To account for the uncertainty and identify the point of greatest difference in Vp/Vs values (ΔV) between the two sides, the following formula was applied:

$$\Delta V = \frac{(g_L - g_R)}{(\sigma_L + \sigma_R)} \quad (2)$$

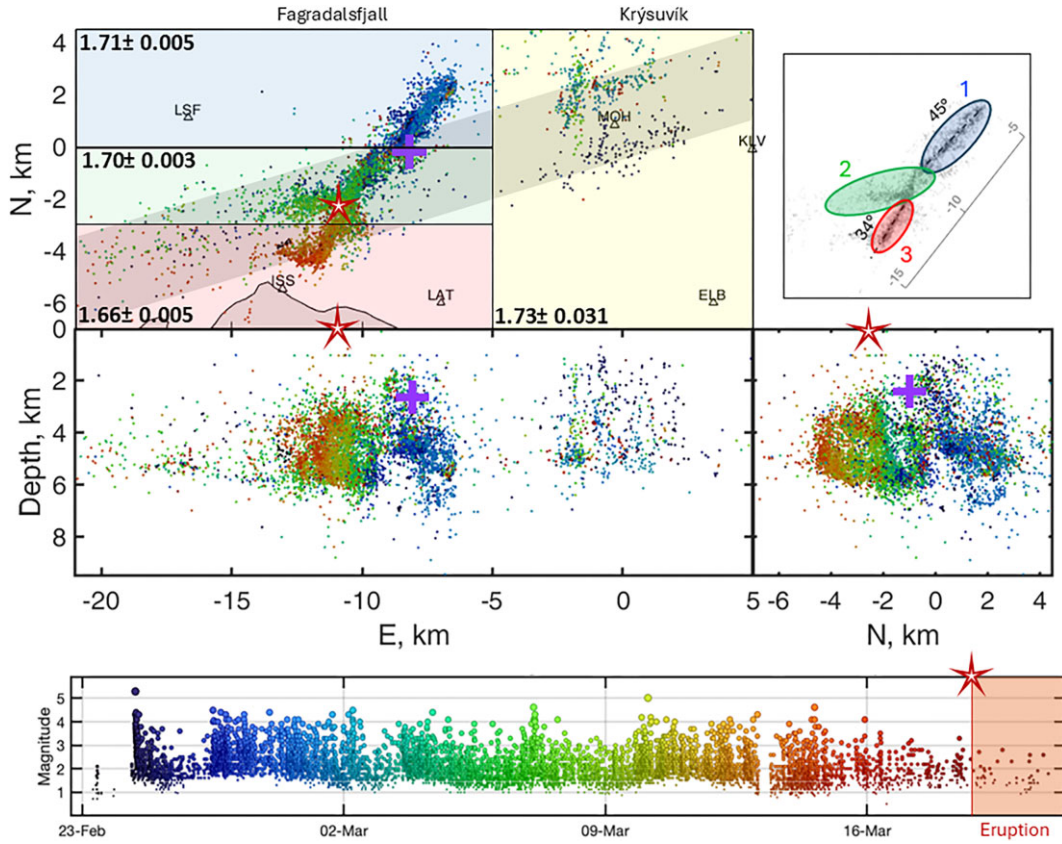


Figure 5. (a) Map view and two perpendicular cross-sections of relocated seismic events from the February–March 2021 swarm, colour-coded by origin time. (b) Time–magnitude distribution of the swarm leading up to the 2021 March 19, Fagradalsfjall eruption, based on Fischer *et al.* (2022). The red star marks the eruption point, while the cross indicates the hypocentre of the M5.3 earthquake on February 24. Triangles represent seismic stations from the Reykjanet network. The rift zone is shown as a grey band. The active region is divided into four parts: Northern Fagradalsfjall (blue), Central region (green), Southern region (red) and Krýsuvík area (yellow). The Vp/Vs ratio for each region during the swarm is annotated within the respective area. The inset in the upper right corner illustrates two segments of dyke and also rift zone activity, along with their orientations and respective activity levels.

Table 2. Number of events, the number of observations (common *P* and *S* differential times), the Vp/Vs value for whole cluster, and the estimated bootstrap error for each divided area shown in Fig. 5 during the 2021 pre-eruption Fagradalsfjall swarm.

Area	Fagradasfajl northern part	Fagradasfajl central part	Fagradasfajl southern part	Krisuvik
Vp/Vs	1.71	1.70	1.66	1.73
No. of events	4199	6490	3156	1118
No. of observations	46 956	70 603	42 105	1403
Errors	0.005	0.003	0.005	0.031

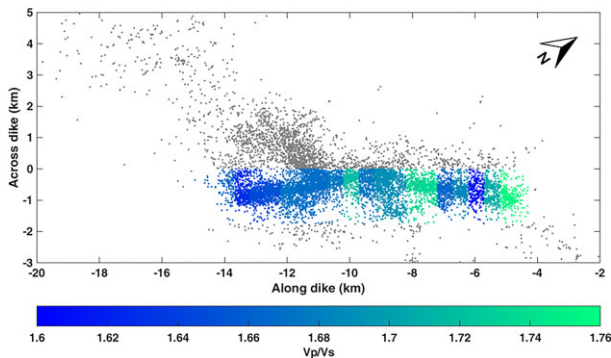


Figure 6. Spatial analysis of the Vp/Vs ratio along the dyke during the 2021 swarm events, with Vp/Vs values calculated at 0.5 km window in a rotated coordinate system. The colours represent Vp/Vs values, as indicated in the legend. The north arrow in the northwest corner indicates the orientation of the plot relative to geographic north.

where g_L and g_R represent the mean values of the Vp/Vs for the left and right windows, respectively, and σ_L and σ_R are the standard deviations in these left and right windows at each step (e.g. Fig. 7d).

The significance of ΔV is tested using the Kolmogorov–Smirnov (KS) test (Massey 1951), which compares the Vp/Vs distributions in the left and right windows of the change points to check for dissimilarity. To find multiple potential change points, the method was applied recursively to the left windows and right windows separately. This process continued until either an insufficient number of event pairs for the analysis was encountered or the KS test failed, indicating that the distributions in the left and right windows were the same.

Using the change point analysis we identified one significant change point (Fig. 7). It occurs very close to the eruption site, with mean Vp/Vs ratio of 1.66 to in the left window and 1.71 in the right window. Its coincidence with the eruption site points to different rock properties on either side of the eruption.

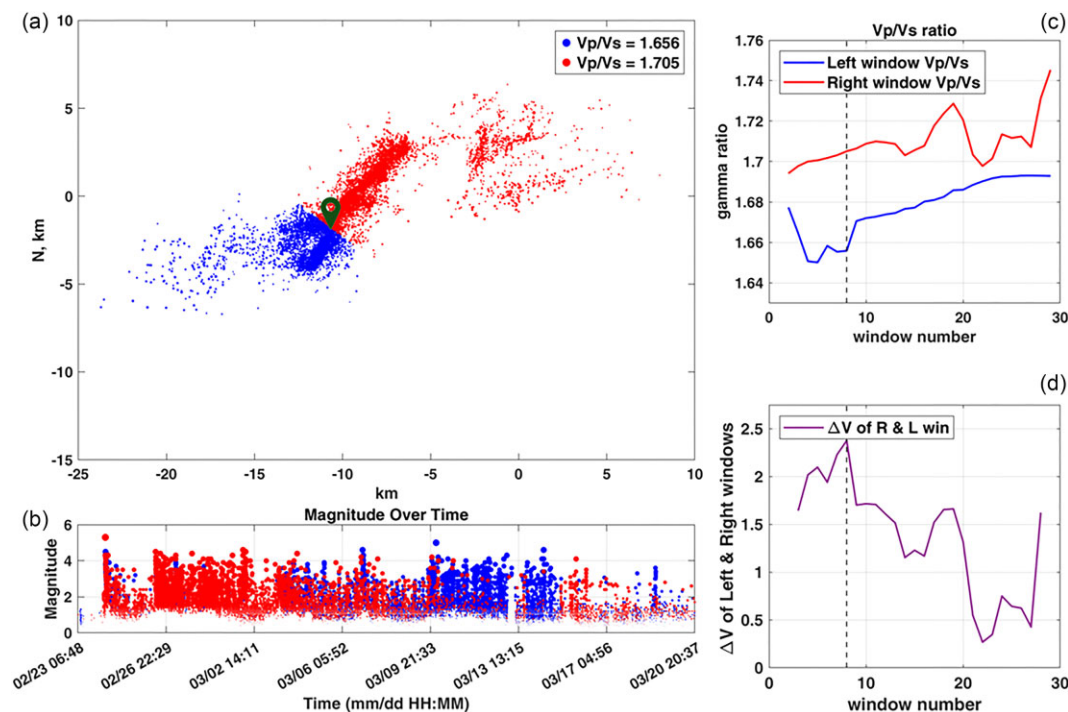


Figure 7. (a) Map view showing the spatial distribution of events before the change point (blue) and after the change point (red) in space. (b) Time–magnitude distribution of events before and after the change point in space during the 2021 swarm. (c) Cumulative Vp/Vs values on the left and right sides of the extended window, with the window size incrementally increased by 0.3 km at each step along the dyke. (d) Differences in Vp/Vs values between the left and right windows, normalized by their standard deviation. The dark green marker indicates the eruption point.

3.2.2. V_p/V_s variation along the dyke (temporal analysis)

The temporal variation of V_p/V_s for the 2021 pre-eruption swarm, shown in Fig. 8(a), was computed using windows with the same number of event-pairs ensuring consistent statistical sampling across all intervals. This approach was necessary because the seismic activity is strongly clustered in time and using equidistant time windows would have resulted in poorly constrained V_p/V_s values in windows with only a few event pairs (see Fig. S1, Supplementary Material 1). To generate Fig. 8(a), 600 event pairs were utilized for each data point analysis. Larger and smaller numbers of event pairs were also tested, revealing that while the trends remained consistent, the error margins varied. Specifically, using longer event-pair intervals resulted in reduced errors, whereas fewer event pairs provided more detailed insights into the variations. The trend of variation shown as a moving average (the magenta line) remained the same, regardless of the number of event pairs used. Fig. 8(b) illustrates similar results using a time-equidistant axis. In fact, Fig. 8(b) was created to present the results in a standard time-equidistant format, while Fig. 8(a) is included to demonstrate how the method works. The resulting graph shows sharp and rapid declines during two distinct periods, followed by notable peaks in subsequent windows.

Application of the change point method to the temporal variation of V_p/V_s of the 2021 swarm identified the first change point on 2021 February 27 at 07:20 (Fig. 9a). Prior to this point, the V_p/V_s value is lower at 1.65, (left window) and after this point, the V_p/V_s value increased to 1.69 (right window). By recursively applying the method to the right window, another change point was found on 2021 March 09 at 09:00 (Fig. 9e). Interestingly, the second change point separates the entire swarm into two episodes, which are also separated in space. The first episode involves activity in the northern and central parts (dark green events), while

the second episode involves activity in the southern part (orange events).

To identify which part of the dyke relates to the occurrence of the two change points in time, we analysed the temporal variation of the V_p/V_s ratio separately for the northern region (blue in Fig. 5) and the central and southern regions (green and red in Fig. 5). By comparing the timing of change points with these trends (Fig. 10), one can see that the first change point aligns with activity in the northern dyke, while the second change point aligns with activity in the southern dyke. Each change point is characterized by a notable drop in V_p/V_s values, followed by an increase.

Finally, Fig. 11 illustrates the variation of V_p/V_s over time from 2019 to 2023. Three Fagradalsfjall pre-eruption swarms and one unsuccessful dyke swarm, along with their V_p/V_s variations, are highlighted in the figures.

4. DISCUSSION

The V_p/V_s ratio depends on elastic moduli and density of the medium which is influenced by various factors such as mineral composition, fluid composition, rock porosity, hydrothermal alteration, pore fluid pressure and saturation and temperature (Toksoz *et al.* 1976; Ito *et al.* 1979; Tryggvason *et al.* 2002; Mavko *et al.* 2009; Amoroso 2022).

4.1. Previous studies on V_p/V_s anomalies in Reykjanes

Low V_p/V_s anomalies beneath the Hengill volcanic system have been interpreted as high-porosity regions containing supercritical fluids rather than extensive zones of partial melt, based on the 3-D velocity model of SW Iceland by Tryggvason *et al.* (2002).

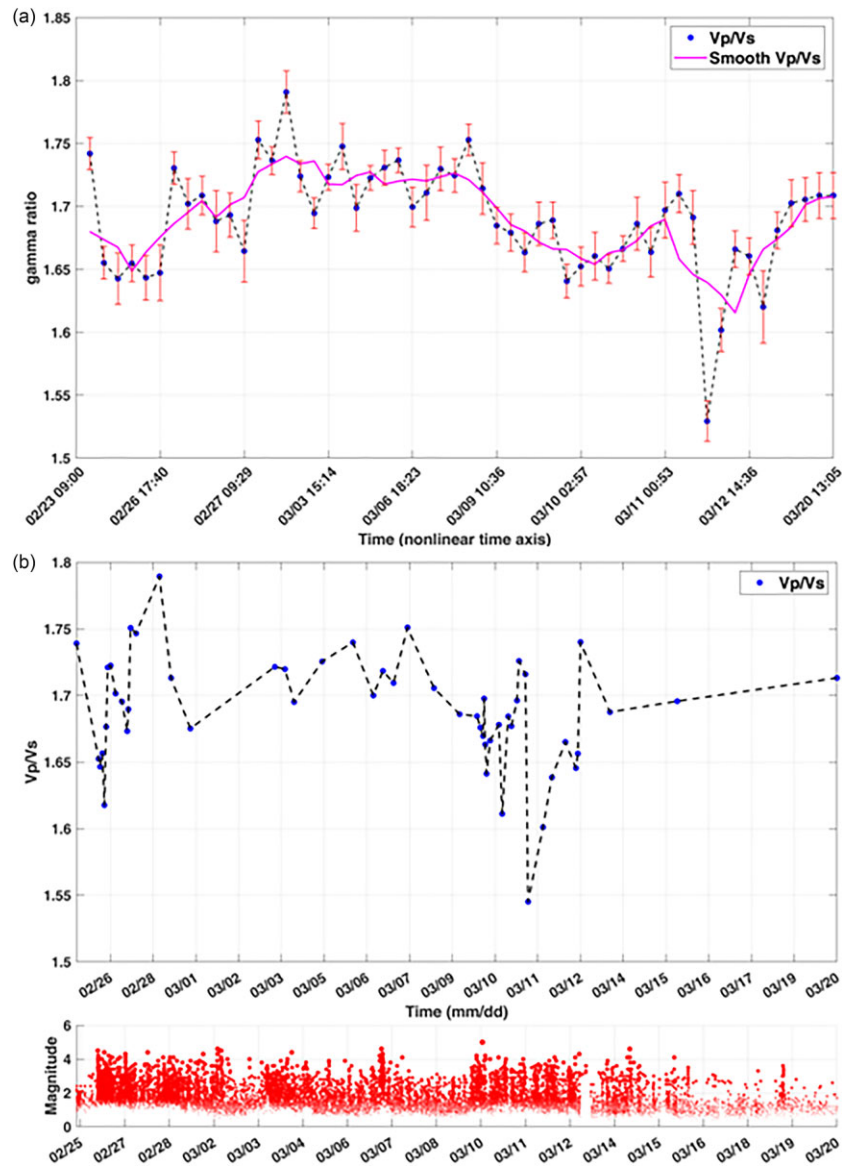


Figure 8. (a) Temporal analysis comparing the variation of Vp/Vs values within equal event pair windows (600 event pairs per window) during the 2021 pre-eruption swarm. The magenta line represents the smoothed variation (for each point 5 windows were used). (b) Time-equidistant variation of Vp/Vs during the 2021 pre-eruption swarm. Each point represents the mean Vp/Vs value for 600 event pairs.

The greater reduction in P -wave velocities compared to S -wave velocities suggests the presence of supercritical fluids within the volcanic fissure system. This interpretation is supported by evidence that pore content significantly influences rock compressibility and P -wave velocities but has less impact on S -wave velocities. Similar low Vp/Vs ratios during swarm episodes in NW Bohemia (Dahm & Fischer 2014) further support this view.

Geoffroy & Dorbath (2008) identified low Vp/Vs ratios in the lower brittle crust in their 3-D tomography model for the RP, attributing them to high fluid pressures rather than magma chambers. They suggested these anomalies result from trapped supercritical geothermal fluids, which enhance crustal deformation through hydrofracturing and stress-corrosion microcracking. Large seismic events temporarily increase permeability, enabling fluid infiltration and recharging of lower crustal reservoirs.

Time-dependent tomography below Krysuvik and neighbouring areas (2004–2018) also showed two low Vp/Vs anomalies

(Hobe *et al.* 2021). One, located in Fagradalsfjall, is linked to seismic activity and disappears when seismicity ceases, as fractures heal and Vp/Vs values return to regional averages. The other, beneath the centre of inflation in Krysuvik, remains stable over time and is interpreted as a supercritical reservoir. These anomalies are attributed to magma degassing, fluid expansion fracturing an impermeable barrier or a combination of both mechanisms.

Amoroso *et al.* (2022) also interpreted low Vp/Vs ratios as steam-dominated zones and high temperatures near the Nesjavellir geothermal field reservoir.

4.2. Long-term Fagradalsfjall Vp/Vs variations

In this paper, by analysing the variation in Vp/Vs values for seismic swarms between 2017 and 2023, we demonstrate that most swarms since 2020 have exhibited lower Vp/Vs values compared to the background seismicity. Notably, the pre-eruption swarm of 2021

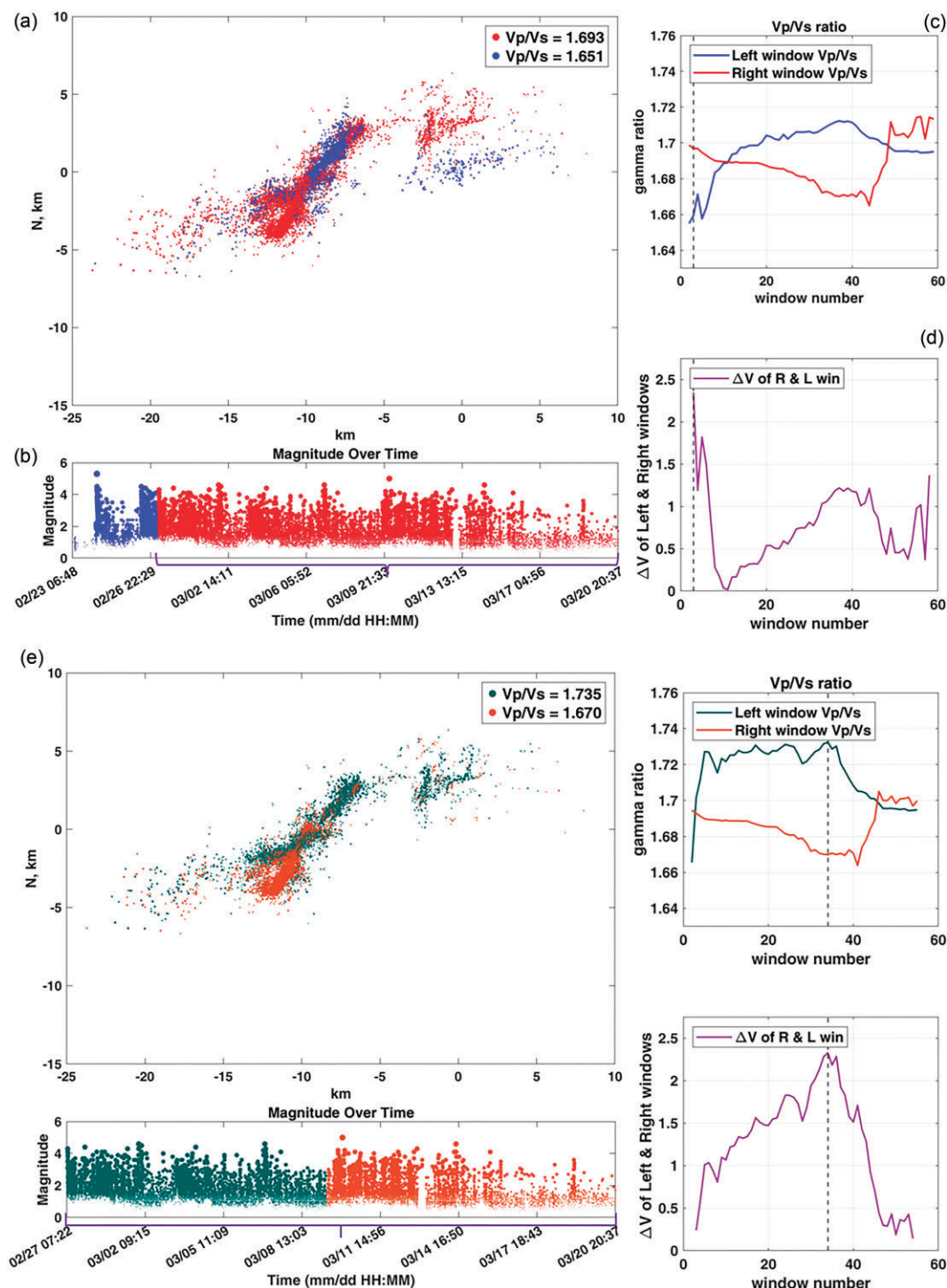


Figure 9. First (top) and second (bottom) change points in time. (a) Map view showing events occurring before the first change point in time along the dyke (blue), and events after the change point (red). (b) Time–magnitude distribution of events before and after the change point in time during the 2021 swarm. (c) Cumulative Vp/Vs values on the left and right sides of the extended window, with the window size incrementally increased by 8 hr at each step for events along the dyke. (d) Differences in Vp/Vs values between the left and right windows, normalized by their standard deviation. (e) The same analyses for the second change point, which corresponds to the right window of the first change point (marked by purple braces). Events before the second change point are shown in dark green, and those after are in orange.

had a Vp/Vs value of 1.70, the lowest estimated during this period. This value was 4 per cent lower than for the background seismicity and occurred just before the first eruption at Fagradalsfjall. In terms of the interpretation reviewed above, this suggests the presence of significant amounts of supercritical fluids and magma, which could

be considered eruption precursors. Additionally, the 2020 swarms exhibited a reduced Vp/Vs value of 1.72, indicating overpressurized gas and/or water vapour from magma at that time.

Similar velocity drops were observed by Cubuk *et al.* (2021) during these three episodes of rapid inflation and associated seismic

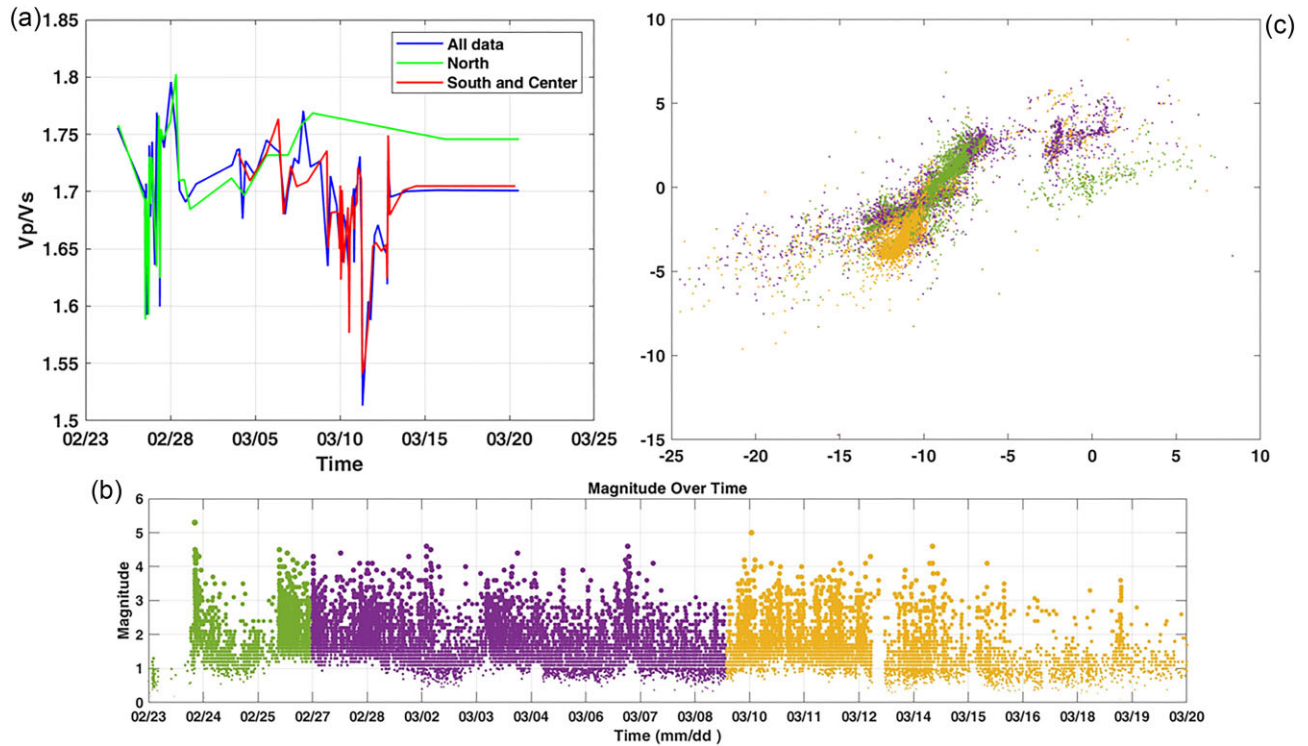


Figure 10. (a) Time-equidistant variation of Vp/Vs for two distinct segments compared to the overall activity during the 2021 pre-eruption swarm. The northern dyke segment is represented in green, the southern dyke segment in red and the entire data set by a blue line. (b) Time-magnitude distribution of the 2021 swarm episodes, illustrating two distinct change points in time. Events before the first change point are shown in green, those between the first and second change points in violet and events occurring after the second change point in orange. (c) Map view depicting the spatial distribution of events relative to the two change points. The colour coding follows the scheme in panel (b).

activity near inflation source at Mt. Þorbjörn-Svartsengi, Iceland, in 2020, using the seismic ambient noise method. By analysing data from April 2018 to November 2020, they suggested that these decreases in seismic velocity were likely caused by crustal magma intrusions and the formation of new cracks to accommodate magma propagation. Centroid moment tensors for earthquakes with magnitudes greater than 2.7 predominantly exhibited shallow strike-slip mechanisms with significant positive isotropic components during the 2020 swarms in the RP, indicating coseismic volume expansion (Büyükcakınar *et al.* 2025). They interpret these positive isotropic (M_{iso}) components as being associated with coseismic widening of dikes and an increase in gas-saturated pore spaces near faults, driven by magmatic intrusions.

As detailed in the results section, applying the method to equal eventpair windows and representing it on a time-equidistant axis for the 2021 pre-eruption swarm (Fig. 8b) generates a graph showing sharp and rapid declines during two distinct periods, followed by notable peaks in subsequent windows (pulse-like trend in Fig. 8b) which is the most significant observation during the swarm. This pattern suggests the presence of supercritical fluids (CO₂ and/or water) originating from magma within pores and fractures, followed by intruding magma characterized by higher Vp/Vs.

Such rapid declines have been observed in pre-eruption swarms at other volcanoes. For example, Hong *et al.* (2014) reported a rapid decrease in the Vp/Vs ratio before the 2009 Redoubt Volcano eruption, which they attributed to increasing amounts of overpressurized gas and water in the medium. Similarly, Lin *et al.* (2015) found a cluster with a very low Vp/Vs ratio near the Kilauea caldera. Their discussion on velocity variations with CO₂, water and melt

inclusions as a function of porosity aspect ratios, based on the Theoretical Crack Model (Kuster & Toksoz 1974), suggests that low Vp/Vs values are associated with CO₂-filled cracks in that area.

4.3. Role of CO₂ in magmatic processes

The intrusion of magma-derived volatiles, particularly CO₂, into a sealed aquifer led to cycles of inflation and rapid subsidence, which may have triggered intense earthquake swarms in 2017 and 2019 on the RP, according to the Flovenz *et al.*'s (2022) poroelastic model. This model is based on the migration of magmatic volatiles from a sub-Moho reservoir located at depths of 15–20 km. Accumulation of gases at the BDT zone caused overpressure buildup, leading to periodic releases of gas into shallow geothermal aquifers and resulting in surface uplift. The final overpressure event in February 2021 generated enough stress to fracture the brittle crust, causing a magmatic dyke intrusion and subsequent eruption. The injected fluid is interpreted as either pure CO₂ or a CO₂ mixture with up to 33 per cent magma.

Another conceptual model, based on geochemical analysis of lava, suggests that melts form in the mantle and rise to a storage area near the Moho, where they undergo crystallization, mixing and degassing processes before eventually erupting (Halldórsson *et al.* 2022). This idea, that volatile-charged magma injections into deep crustal levels trigger eruptions on the RP, is further supported by Fischer *et al.* (2024), who found that CO₂ emissions during the 2023 eruption at Litli Hrófur originated from fresh, undegassed magma, distinct from the magma remaining after the 2022 eruption.

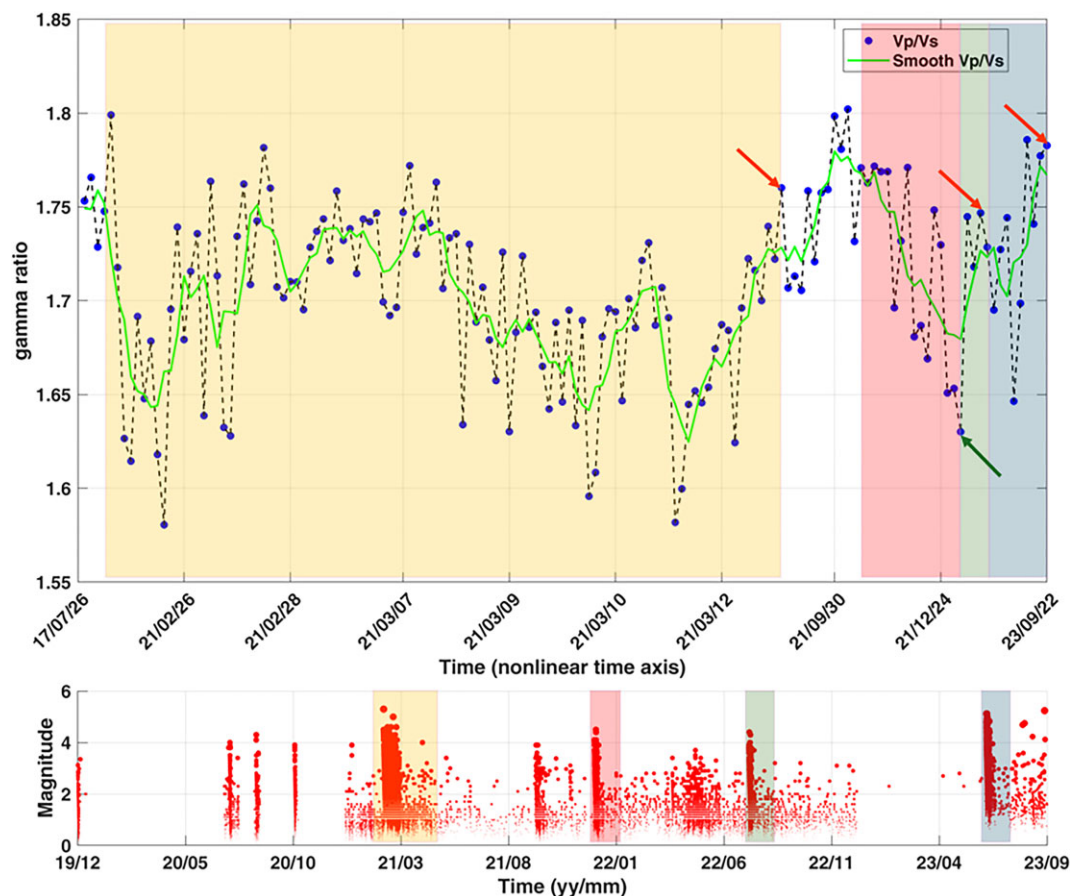


Figure 11. (Top): Temporal analysis showing the variation of Vp/Vs values within equal event pair windows (400 event pairs) from 2019 to 2023; the time axis is not linear. The green line represents the smoothed variation using a window of 400 points length. **(Bottom):** Time–magnitude view of the swarm; the time axis is linear. Different swarm episodes are colour-coded in both figures. The 2021, 2022 and 2023 eruptions are indicated by orange arrows, while the unsuccessful dyke (December 2021 swarm) is indicated by a dark green arrow.

Eruptions cease once the magma degasses and resume only with new injections of volatile-rich magma.

Water degassing of ascending magmas was confined to the upper few hundred meters below the surface during the 2021 eruption (Radu *et al.* 2023). So, CO₂ exsolution played a dominant role at deeper depths in the pre-eruptive phase, significantly contributing to pressure buildup and triggering volcanic activity at Fagradalsfjall. At least 70 per cent of CO₂ exsolved from the magma, along with other volatiles, leading to the formation and accumulation of gas bubbles within the magma reservoir.

The migration of CO₂-rich fluids through fractures, or the high strain rates caused by magma intrusion, has been considered the primary cause of deep long-period (DLP) earthquakes that occurred in June 2020 and August 2021 at depths of 10–12 km. This is a shift from the earlier belief that these earthquakes were triggered by active magma transport near the magma storage region (Greenfield *et al.* 2022). Notably, DLP seismicity stopped at the onset of the dyke intrusion but reappeared in a different location during periods of varying eruption discharge rates and fountaining styles (Greenfield *et al.* 2022).

The ascent of magmatic fluids, primarily CO₂, from a mid-crustal basaltic dyke intrusion in Iceland, triggered shallow seismic events. This occurred because the gas weakened pre-existing fractures, which were under relatively low elastic stress due to the dyke's inflation (Martens and White 2013). This is supported by the fact

that many of the early high-magnitude events of 2021 swarm, including the 5.3 magnitude event on February 24, the 4.4 on March 4, the 4.6 on March 7 and the 4.6 on March 14, occurred throughout the rift zone, most probably the weakest area in the region. Fractures developed along existing weakness planes within the rift zone's widespread fabric.

The pore pressure from the volatiles reduced effective normal compressive stress on faults, which raised the chances of failure. This reduction allowed even minor stress changes from the intrusion to trigger further failure. The time delay between the deep intrusion and the shallow earthquake clusters can be attributed to the movement of volatiles through the crust (Martens and White 2013).

CO₂ triggering is also discussed by Shelly (2011) for swarms at Mammoth Mountain, California, Reyners (2007) on the southwestern end of the Taupo Volcanic Zone in New Zealand or Fischer *et al.* (2017) and Hainzl *et al.* (2016) for West Bohemia, Europe.

While our initial interpretation emphasized the role of supercritical fluids in explaining low Vp/Vs ratios, we should also consider additional mechanisms. Poisson's ratio of the solid matrix determines whether increasing fluid-saturated porosity leads to higher or lower Vp/Vs, depending on pore geometry. Thin cracks tend to lower Vp/Vs as porosity increases, while spherical pores may increase it, depending on the fluid-to-solid bulk modulus ratio (Brantut and David 2019). In our study, the observed low Vp/Vs

values could be partially attributed to cracks in the host rock, aligned with critical Poisson's ratio conditions where fluid-saturated porosity reduces Vp/Vs. Also, laboratory experiments reveal that pore shape (cracks versus vesicles) and rock lithology significantly affect Vp/Vs ratios. Vesicle-dominated rocks show minimal pressure dependence, while cracked rocks exhibit substantial sensitivity to pressure changes (Bustos & Adam 2023).

4.4. Interpretation of change points

Seismicity of the 2021 pre-eruption swarm at Fagradalsfjall has been interpreted by several studies using a two-segment dyke model. Fischer *et al.* (2022) divided the swarm migration into several episodes: from the main shock on February 24 to March 2, activity was concentrated in the northern part (blue in Fig 5a); from March 2 to March 9, the central part and rift zone were active; and from March 9 onward, the southern part became active (red in Fig 5a). Similarly, the dyke was modelled as a two-segment structure by Sigmundsson *et al.* (2022), with distributed opening and slip, in alignment with relocated seismicity.

As shown in the results section, the Vp/Vs change points in time identified on February 27 and March 9 (Fig. 9) coincide with the northern and southern parts of the dykes, respectively (Fig. 10). We infer that the two change points are associated with successive opening of the northern and southern parts of the dyke, as discussed in related studies. Additionally, a change in surface deformation after March 9 is observed in the Interferometric Synthetic Aperture Radar (InSAR) data (extended data fig. 6 in Sigmundsson *et al.* 2022).

Interestingly, a decreasing trend followed by fast Vp/Vs increase was observed during the successful dyke intrusion and eruption of the February–March swarm. In contrast, only a decreasing trend was exhibited by the unsuccessful dyke swarm in December 2021. This is consistent with interpreting the Vp/Vs decreases by gas occurrence in the rock volume and Vp/Vs increases by magma emplacement in the dyke.

Our finding are in agreement with the Halldórsson and Flovenz models. Geochemical analysis of lava samples reveals that the magma contains approximately 70 per cent CO₂. Water degassing, however, is limited to just a few hundred meters below the surface, indicating that CO₂ plays a more significant role at greater depths. It is suggested that batches of CO₂ are responsible for triggering seismic activity by migrating from the BDT zone along pre-existing fractures. This movement increases pore pressure, reduces effective normal stress, weakens the crust, and facilitates the opening of dykes, allowing magma to intrude. This explanation also accounts for the rapid migration of seismicity observed during the swarm. Initially, gas batches from magma migrate from deeper layers to just beneath the BDT zone, causing DLP earthquakes. As the gas escapes from this zone, it triggers seismic swarms in shallower layers, resulting in lower Vp/Vs ratios compared to the normal Vp/Vs in the region.

While the presence of supercritical fluids remains a plausible explanation for low Vp/Vs values, this interpretation should be integrated with alternative mechanisms. Pore geometry (Brantut & David 2019), pore shape and rock lithology (Bustos & Adam 2023) can independently or synergistically produce similar seismic signatures. These findings suggest that crack formation during dyke intrusion or stress accommodation may explain the observed Vp/Vs anomalies, alongside the potential role of supercritical fluids.

5. CONCLUSION

This study presents a comprehensive analysis of temporal and spatial Vp/Vs variations using the *in-situ* Vp/Vs method, focused on seismic swarms near Fagradalsfjall, a volcanic system on Iceland's Reykjanes Peninsula, from 2017 to 2023. The findings show a notable decrease in Vp/Vs ratios during swarm periods since 2020, with the lowest values recorded prior to the 2021 pre-eruption swarm which culminated by the first eruption at Fagradalsfjall in 7000 yr, and similarly low values were also noted prior to the 2022 and 2023 eruptions. These decreased Vp/Vs ratios could be interpreted as a sign of supercritical fluids in the subsurface medium. Additionally, crack formation during dyke intrusion and stress accommodation could also contribute to these low values, either independently or in combination.

A focused examination of the 2021 pre-eruption swarm revealed a sharp and rapid decline in Vp/Vs values during two distinct intervals, followed by notable peaks (pulse-like trend), which likely suggest the presence of supercritical magmatic fluids within the pore and fracture network, subsequently followed by magma intrusion. To identify significant changes along the dike, we applied a change point detection method. Spatially, the identified change point aligns closely with the eruption site. Temporally, two distinct change points were detected: the first one correlates with increased activity in the northern segment of the dike, and the second one with elevated activity in the southern segment, with both timings aligning with InSAR-detected stress changes and seismicity variations documented in previous studies.

Temporal Vp/Vs variations can serve as valuable indicators for forecasting upcoming eruptions, offering a potential early warning signal for public safety. When integrated with online networks like Reykjanet, this method could enable efficient, near real-time volcanic monitoring with minimal computational demands, making it a powerful tool for both understanding and tracking volcanic activity.

ACKNOWLEDGMENTS

We sincerely thank the editor and reviewers for their valuable comments and suggestions, which have greatly contributed to improving the quality of the article. This research was supported by the Grant Agency of Charles University, project No. 120624, titled “*Seismic velocity variations accompanying shallow magmatic dyke activity*”, implemented at the Faculty of Science, Charles University. Additional support was provided by the Johannes Amos Comenius Programme (P JAC), project No. CZ.02.01.01/00/22.008/0004605, Natural and anthropogenic georisks. AM is grateful for the financial support of the Martina Roeselová Memorial Fellowship granted by the IOCB Tech Foundation. Fig. 1 was generated using the visualization packages pyGMT (Tian *et al.* 2025).

SUPPORTING INFORMATION

Supplementary data are available at [GJIRAS](https://doi.org/10.1017/gjir.2026.1) online.

suppl. data: – Supplementary Material 1: Seismic Event and Event Pair Distributions During the 2021 Pre-Eruption Swarm. – Supplementary Material 2: Animation Demonstrating Detection of Significant Vp/Vs Changes Using the Change Point Method.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the paper.

DATA AVAILABILITY

The data and code are available on request.

REFERENCES

- Aguilera Bustos, J.P. & Adam, L., 2023, Experimental insights into factors influencing Vp/Vs ratios at the Nevado del Ruiz Volcano, Colombia, *Volcanica*, **6**(2) 283–299.
- Allen, R.M. *et al.*, 2002, Imaging the mantle beneath Iceland using integrated seismological techniques, *J. Geophys. Res. Solid Earth*, **107**(B12), ESE 3–1–ESE 3–16.
- Amoroso, O., Jeanne, P., Romano, G., Vilardo, G., Dietrich, M., van Dongen, B.E. & Arnason, K., 2022, 3-D seismic imaging of the Nesjavellir geothermal field, SW-Iceland, *Front. Earth Sci.*, **10**, 994280. doi:10.3389/feart.2022.994280.
- Bachura, M. & Fischer, T., 2016, Detailed velocity ratio mapping during the aftershock sequence as a tool to monitor fluid activity within the fault plane, *Earth planet. Sci. Lett.*, **453**, 215–222.
- Bell, A.F., Naylor, M., Hernandez, S., Main, I.G., Gaunt, H.E., Mothes, P. & Ruiz, M., 2018, Volcanic eruption forecasts from accelerating rates of drumbeat long-period earthquakes, *Geophys. Res. Lett.*, **45**, 1339–1348.
- Bièvre, G., Franz, M., Larose, E., Carrière, S., Jongmans, D. & Jaboyedoff, M., 2018, Influence of environmental parameters on the seismic velocity changes in a clayey mudflow (Pont-Bourquin Landslide, Switzerland), *Eng. Geol.*, **245**, 248–257.
- Bindeman, I.N., Deegan, F.M., Troll, V.R., Carley, T.L., Stanek, K.P. & Eiriksson, D., 2022, Diverse mantle components with invariant oxygen isotopes in the 2021 Fagradalsfjall eruption, Iceland, *Nat. Commun.*, **13**, 3737. doi:10.1038/s41467-022-31348-7.
- Bjarnason, I.T., Menke, W., Flóvenz, Ó.G. & Caress, D., 1993, Tomographic image of the Mid-Atlantic Plate Boundary in southwestern Iceland, *J. Geophys. Res.*, **98**(B4), 6607–6622.
- Blanch, H., Jousset, P., Hersir, G., Ágústsson, K. & Flóvenz, Ó., 2020, Analysis of 2014–2015 on- and off-shore passive seismic data on the Reykjanes Peninsula, SW Iceland, *J. Vol. Geotherm. Res.*, **391**, 106548. doi:10.1016/j.jvolgeores.2019.02.001.
- Bloch, W., John, T., Kummerow, J., Salazar, P., Krüger, O.S. & Shapiro, S.A., 2018, Watching dehydration: seismic indication for transient fluid pathways in the oceanic mantle of the subducting Nazca slab, *Geochem. Geophys. Geosyst.*, **19**(9), 3189–3207.
- Boué, A., Lesage, P., Cortés, G., Valette, B., Reyes-Dávila, G. & Arámbula-Mendoza, R., 2016, Performance of the ‘material Failure Forecast Method’ in real-time situations: a Bayesian approach applied on effusive and explosive eruptions, *J. Volc. Geotherm. Res.*, **327**, 622–633.
- Brandsdóttir, B. & Menke, W. H., 2008, The seismic structure of Iceland, *Jökull*, **58**, 17–35.
- Brantut, N. & David, E.C., 2019, Influence of fluids on VP/VS ratio: increase or decrease?, *Geophys. J. Int.*, **216**(3), 2037–2043.
- Büyükkapınar, P. *et al.* 2025, Understanding the seismic signature of transtensional opening in the Reykjanes Peninsula Rift Zone SW Iceland, *J. Geophys. Res. Solid Earth*, **130**, e2024JB029566. doi:10.1029/2024JB029566.
- Chardot, L., Jolly, A.D., Kennedy, B.M., Fournier, N. & Sherburn, S., 2015, Using volcanic tremor for eruption forecasting at White Island volcano (Whakaari), New Zealand, *J. Volc. Geotherm. Res.*, **302**, 11–23.
- Cubuk-Sabuncu, Y., Jónsdóttir, K., Caudron, C., Lecocq, T., Parks, M.M., Geirsson, H. & Mordret, A., 2021, Temporal seismic velocity changes during the 2020 rapid inflation at Mt. Þorbjörn-Svartsengi, Iceland, using seismic ambient noise, *Geophys. Res. Lett.*, **48**, e2020GL092265. doi:10.1029/2020GL092265.
- Dahm, T. & Fischer, T., 2014, Velocity ratio variations in the source region of earthquake swarms in NW Bohemia obtained from arrival time double-differences, *Geophys. J. Int.*, **196**(2), 957–970.
- Donaldson, C., Winder, T., Caudron, C. & White, R.S., 2019, Crustal seismic velocity responds to a magmatic intrusion and seasonal loading in Iceland’s northern volcanic zone, *Sci. Adv.*, **5**(11), eaax6642. doi:10.1126/sciadv.aax6642.
- Du, Z., Foulger, G.R., Julian, B.R., Allen, R.M., Nolet, G. & Morgan, W.J., 2002, Crustal structure beneath western and eastern Iceland from surface waves and receiver functions, *Geophys. J. Int.*, **149**(2), 349–363.
- Efron, B. & Gong, G., 1983, A leisurely look at the bootstrap, the Jackknife, and cross-validation, *Am. Stat.*, **37**(1), 36–48.
- Efron, B. & Tibshirani, R. 1991 Statistical data analysis in the computer age, *Science*, **253**(5018), 390–395.
- Einarsson, P., 1991, Earthquakes and present-day tectonism in Iceland, *Tectonophysics*, **189**, 261–279.
- Einarsson, P., 2008, Plate boundaries, rifts and transforms in Iceland, *Jökull*, **58**, 35–58.
- Einarsson, P., Eyjólfsson, V. & Hjartardóttir, Á.R., 2023, Tectonic framework and fault structures in the Fagradalsfjall segment of the Reykjanes Peninsula Oblique Rift, Iceland, *Bull. Volcanol.*, **85**, 9. doi:10.1007/s00445-022-01624-x.
- Fischer, T. *et al.*, 2024, CO₂ emissions during the 2023 eruption in Reykjanes, Iceland: $\delta^{13}\text{C}$ tracks magma degassing, 21 March 2024, PREPRINT (Version 1) available at Research Square. doi:10.21203/rs.3.rs-4001457/v1.
- Fischer, T., 2003, Automatic location of swarm earthquakes from local network data, *Stud. Geophys. Geod.*, **47**(1), 83–98.
- Fischer, T., Hrubcová, P., Salama, A., Doubravová, J., Ágústsdóttir, T., Gudnason, E.Á. & Horálek, J., 2022, Swarm seismicity illuminates stress transfer prior to the 2021 Fagradalsfjall eruption in Iceland, *Earth planet. Sci. Lett.*, **594**, 117685. doi:10.1016/j.epsl.2022.117685.
- Fischer, T., Matyska, C. & Heinicke, J., 2017, Earthquake-enhanced permeability—evidence from carbon dioxide release following the ML 3.5 earthquake in West Bohemia, *Earth planet. Sci. Lett.*, **460**, 60–67.
- Flóvenz, Ó.G., Wang, R., Hersir, G.P., Ágústsson, K., Dahm, T. & Hensch, M., 2022, Cyclical geothermal unrest as a precursor to Iceland’s 2021 Fagradalsfjall eruption, *Nat. Geosci.*, **15**, 397–404.
- Foulger, G.R., Miller, A.D., Julian, B.R. & Evans, J.R., 1995, Three-dimensional Vp and Vp/Vs structure of the Hengill triple junction and geothermal area, Iceland, and the repeatability of tomographic inversion, *Geophys. Res. Lett.*, **22**, 1309–1312.
- Goffroy, L. & Dorbath, C., 2008, Deep downward fluid percolation driven by localized crust dilatation in Iceland, *Geophys. Res. Lett.*, **35**, L17. doi:10.1029/2008GL034514.
- Greenfield, T., Winder, T., Rawlinson, N., White, R.S., Brandsdóttir, B., Gudmundsson, M.T. & Sigmundsson, F., 2022, Deep long period seismicity preceding and during the 2021 Fagradalsfjall eruption, Iceland, *Bull. Volcanol.*, **84**, 101. doi:10.1007/s00445-022-01603-2.
- Gritto, R. & Jarpe, S.P., 2014, Temporal variations of Vp/Vs-ratio at the Geysers geothermal field, USA, *Geothermics*, **52**, 112–119.
- Guillemot, A., Baillet, L., Garambois, S., Bodin, X., Helmstetter, A. & Larose, E., 2021, Modal sensitivity of rock glaciers to elastic changes from spectral seismic noise monitoring and modelling, *The Cryosphere*, **15**, 501–529.
- Hainzl, S., Fischer, T., Čermáková, H., Bachura, M. & Vlček, J., 2016, Aftershocks triggered by fluid intrusion: evidence for the aftershock sequence occurred 2014 in West Bohemia/Vogtland, *J. Geophys. Res. Solid Earth*, **121**(4), 2575–2590.
- Halldórsson, S.A., Marshall, E.W., Caracciolo, A., Guðmundsson, Á., Larsen, G., Guðmundsson, M.T. & Sigmundsson, F., 2022, Rapid shifting of a deep magmatic source at Fagradalsfjall volcano, Iceland, *Nature*, **609**, 529–534.
- He, L., Wu, Q., Chen, X., Sun, X., Guo, Z. & Chen, Y.J., 2021, Detailed 3-D seismic velocity structure of the Prague, Oklahoma fault zone and the implications for induced seismicity, *Geophys. Res. Lett.*, **48**(24), e2021GL096137. doi:10.1029/2021GL096137.
- Hennig, B., 2023, *Lava flow map of the 2023 Litli-Hrútur volcanic eruption*. University of Iceland Geovisualization Portal. Available at: <https://geovis.hi.is/maps/litlihrutur-lava-flow-map/> (accessed 3 April 2025).
- Hobe, A., Gudmundsson, Ó. & Tryggvason, A. & The SIL Seismological Group, 2021, Imaging the 2010–2011 inflationary source at Krysuvik,

- SW Iceland, using time-dependent Vp/Vs tomography, World Geothermal Congress 2020+1, Reykjavik, Iceland.
- Hong, T.-K., Hough, S.E. & Jo, E., 2014. Temporal changes of medium properties during explosive volcanic eruption, *Geophys. Res. Lett.*, **41**, 1944–1950.
- Horalek, J., 2013. *Reykjanet [Data set]*. International Federation of Digital Seismograph Networks.
- Hreinsdóttir, S., Einarsson, P. & Sigmundsson, F., 2001. Crustal deformation at the oblique spreading Reykjanes Peninsula, SW Iceland: GPS measurements from 1993 to 1998, *J. Geophys. Res.*, **106**(B7), 13803–13816.
- Hrubcová, P. & Vavryčuk, V., 2023. Tectonic stress changes related to plate spreading prior to the 2021 Fagradalsfjall eruption in SW Iceland, *Tectonophysics*, **851**, 229761. doi:10.1016/j.tecto.2023.229761.
- Hrubcová, P., Doubravová, J. & Vavryčuk, V., 2021. Non-double-couple earthquakes in 2017 swarm in Reykjanes Peninsula, SW Iceland: Sensitive indicator of volcanotectonic movements at slow-spreading rift, *Earth planet. Sci. Lett.*, **563**, 116875. doi:10.1016/j.epsl.2021.116875.
- Huber, P.J. 1973. Robust regression: asymptotics, conjectures and Monte Carlo, *Ann. Stat.*, **1**, 799–821.
- Ito, A., 1985. High resolution relative hypocenters of similar earthquakes by cross-spectral analysis method, *J. Phys. Earth*, **33**(4), 279–294.
- Ito, H., Vilbiss, D.J. & Nur, A., 1979. Compression and shear waves in saturated rock during water-steam transition, *J. Geophys. Res.*, **84**, 4731–4735.
- Jousset, P. et al., 2016. Seismic tomography in Reykjanes, SW Iceland, European geothermal congress 2016, Strasbourg, France.
- Káldy, E. & Fischer, T., 2025. Performance of Automatic Detector & Locator Tested on Synthetic Seismograms: Case Study from Litomerice in Czech Republic. *Seismica*, (1), 4. doi:10.26443/seismica.v4i1.1373.
- Keiding, M., Lund, B. & Árnadóttir, T., 2009. Earthquakes, stress, and strain along an obliquely divergent plate boundary: Reykjanes Peninsula, southwest Iceland, *J. Geophys. Res.*, **114**, B09306. doi:10.1029/2008JB006253.
- Kisslinger, C. & Engdahl, E., 1973. The interpretation of the Wadati diagram with relaxed assumptions, *Bull. seism. Soc. Am.*, **63**, 1723–1736.
- Kuster, G.T. & Toksöz, M.N., 1974. Velocity and attenuation of seismic waves in two-phase media: Part 1. Theoretical formulations, *Geophysics*, **39**(5), 587–606.
- Lee, M.K., Tan, Y.J., Russell, J.B., Tolstoy, M. & Waldhauser, F., 2024. Relative seismic velocity variations at Axial Seamount observed with ambient seismic noise capture transition point in volcanic inflation, *Geophys. Res. Lett.*, **51**, e2024GL108883. doi:10.1029/2024GL108883.
- Lin, G. & Fan, W., 2024. Spatiotemporal variations of in situ Vp/Vs ratios during the 2019 Ridgecrest earthquake sequence suggest fault zone condition changes, *Geophys. Res. Lett.*, **51**, e2024GL109171. doi:10.1029/2024GL109171.
- Lin, G. & Shearer, P.M., 2007. Estimating local Vp/Vs ratios within similar earthquake clusters, *Bull. seism. Soc. Am.*, **97**(2), 379–388.
- Lin, G. & Shearer, P.M., 2009. Evidence for water-filled cracks in earthquake source regions, *Geophys. Res. Lett.*, **36**, L17315. doi:10.1029/2009GL039098.
- Lin, G. & Shearer, P.M., 2021. Spatiotemporal variations of focal mechanism and in situ Vp/Vs ratio during the 2018 Kīlauea eruption, *Geophys. Res. Lett.*, **48**, e2021GL094636. doi:10.1029/2021GL094636.
- Lin, G., 2019. Spatiotemporal variations of in situ Vp/Vs ratio within the Salton Sea Geothermal Field, southern California, *Geothermics*, **84**, 101740. doi:10.1016/j.geothermics.2019.101740.
- Lin, G., Amelung, F., Shearer, P.M. & Okubo, P.G., 2015. Location and size of the shallow magma reservoir beneath Kīlauea caldera, constraints from near-source Vp/Vs ratios, *Geophys. Res. Lett.*, **42**, 8349–8357.
- Liu, T., Gong, J., Fan, W. & Lin, G., 2023. In-situ Vp/Vs reveals fault-zone material variation at the westernmost Gofar Transform Fault, East Pacific Rise, *J. geophys. Res.*, **128**(3), e2022JB025310. doi:10.1029/2022JB025310.
- Maeda, S., Matsuzawa, T., Yoshida, K., Umino, N. & Hasegawa, A., 2019. Causes of the N–S compressional aftershocks of the E–W compressional 2008 Iwate–Miyagi Nairiku earthquake (M7.2) in the northeastern Japan arc, *Earth Planets Space*, **71**, 94. doi:10.1186/s40623-019-1073-z.
- Málek, J., Brokešová, J. & Novotný, O., 2019. Seismic structure beneath the Reykjanes Peninsula, southwest Iceland, inferred from array-derived Rayleigh wave dispersion, *Tectonophysics*, **753**, 1–14.
- Martens, H.R. & White, R.S., 2013. Triggering of microearthquakes in Iceland by volatiles released from a dyke intrusion, *Geophys. J. Int.*, **194**(3), 1738–1754.
- Martinez, F., Hey, R. & Höskuldsson, Á., 2020. Reykjanes Ridge evolution: effects of plate kinematics, small-scale upper mantle convection and a regional mantle gradient, *Earth-Sci. Rev.*, **206**, 102956. doi:10.1016/j.earscirev.2019.102956.
- Martins, J.E., Weemstra, C., Ruigrok, E., Verdel, A., Jousset, P. & Hersir, G.P., 2020. 3D S-wave velocity imaging of Reykjanes Peninsula high-enthalpy geothermal fields with ambient-noise tomography, *J. Volc. Geotherm. Res.*, **391**, 106685. doi:10.1016/j.jvolgeores.2019.106685.
- Massey, F.J., Jr. 1951. The Kolmogorov-Smirnov Test for Goodness of Fit, *J. Am. Stat. Assoc.*, **46**, 68–78.
- Maurer, H. & Deichmann, N., 1995. Microearthquake cluster detection based on waveform similarities, with an application to the western Swiss Alps, *Geophys. J. Int.*, **123**(2), 588–600.
- Mavko, G., Mukerji, T. & Dvorkin, J., 2009. *Rock Physics Handbook: Tools for Seismic Analysis in Porous Media*. Cambridge University Press, Cambridge.
- McNutt, S.R., 2005. Volcanic seismology, *Annu. Rev. Earth Planet. Sci.*, **33**, 461–491.
- Megies, T. & Wassermann, J., 2014. Microseismicity observed at a non-pressure-stimulated geothermal power plant, *Geothermics*, **52**, 36–49.
- Menke, W., 1999. Using waveform similarity to constrain earthquake locations, *Bull. seism. Soc. Am.*, **89**(4), 1143–1146.
- Menke, W., Brandsdóttir, B., Jakobsdóttir, S. & Stefánsson, R., 1994. Seismic anisotropy in the crust at the Mid-Atlantic plate boundary in southwest Iceland, *Geophys. J. Int.*, **119**, 783–790.
- Merrill, R. & Bostock, M., 2019. An earthquake nest in Cascadia, *Bull. seism. Soc. Am.*, **109**(5), 2021–2035.
- Mesimeri, M., Ganas, A. & Pankow, K.L., 2022. Multisegment ruptures and Vp/Vs variations during the 2020–2021 seismic crisis in western Corinth Gulf, Greece, *Geophys. J. Int.*, **230**, 334–348.
- Mitchell, M.A., White, R.S., Roecker, S.W. & Greenfield, T., 2013. Tomographic image of melt storage beneath Askja Volcano, Iceland using local microseismicity, *Geophys. Res. Lett.*, **40**, 5040–5046.
- Pedersen, G.B.M., Belart, J.M.C., Óskarsson, B.V., Gudmundsson, M.T., Gies, N. & Högnadóttir, T., 2022. Volume, effusion rate, and lava transport during the 2021 Fagradalsfjall eruption: results from near real-time photogrammetric monitoring, *Geophys. Res. Lett.*, **49**, e2021GL097125. doi:10.1029/2021GL097125.
- Poland, M.P. & Anderson, K.R., 2020. Partly cloudy with a chance of lava flows: Forecasting volcanic eruptions in the twenty-first century, *J. Geophys. Res.*, **125**(1), e2018JB016974. doi:10.1029/2018JB016974.
- Poupinet, G., Ellsworth, W.L. & Frechet, J., 1984. Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras Fault, California, *J. geophys. Res.*, **89**(B7), 5719–5731.
- Radu, I.B., Skogby, H., Troll, V.R., Deegan, F.M., Geiger, H., Müller, D. & Thordarson, T., 2023. Water in clinopyroxene from the 2021 Geldingadalir eruption of the Fagradalsfjall Fires, SW-Iceland, *Bull. Volcanol.*, **85**, 31. doi:10.1007/s00445-023-01641-4.
- Rahimi Dalkhani, A., Ágústadóttir, T., Gudnason, E.Á., Hersir, G.P., Zhang, X. & Weemstra, C., 2024. Transdimensional ambient-noise surface wave tomography of the Reykjanes Peninsula, SW Iceland, *Geophys. J. Int.*, **236**(1), 621–643.
- Reyners, M., Eberhart-Phillips, D. & Stuart, G., 2007. The role of fluids in lower-crustal earthquakes near continental rifts, *Nature*, **446**(7139), 1075–1078.
- Roth, M.P., Verdecchia, A., Harrington, R.M. & Liu, Y., 2023. Inferring rock strength and fault activation from high-resolution in situ Vp/Vs estimates surrounding induced earthquake clusters, *Seismica*, **2**(2). doi:10.26443/seismica.v2i2.498.

- Růžek, B., 2021. Seismic anisotropy in the rift of the Reykjanes Peninsula, SW Iceland, calculated using a new tomographic method, *Pure appl. Geophys.*, **178**, 2871–2903.
- Saemundsson, K., Sigurgeirsson, M. & Fridleifsson, G.Ó., 2020. Geology and structure of the Reykjanes volcanic system, *J. Volc. Geotherm. Res.*, **391**, 106501. doi:10.1016/j.jvolgeores.2018.11.022.
- Salvage, R.O. & Neuberg, J.W., 2016. Using a cross correlation technique to refine the accuracy of the Failure Forecast Method: application to Soufrière Hills volcano, Montserrat, *J. Volc. Geotherm. Res.*, **324**, 118–133.
- Schuler, J. *et al.* 2015. Seismic imaging of the shallow crust beneath the Krafla central volcano, NE Iceland, *J. Geophys. Res. Solid Earth*, **120**, 7156–7173.
- Shearer, P.M., 1997. Improving local earthquake locations using the L1 norm and waveform cross correlation: application to the Whittier Narrows, California, aftershock sequence, *J. geophys. Res.*, **102**(B4), 8269–8283.
- Shelly, D.R. & Hill, D.P., 2011. Migrating swarms of brittle-failure earthquakes in the lower crust beneath Mammoth Mountain, *Geophys. Res. Lett.*, **38**, L20307. doi:10.1029/2011GL049336.
- Sigmundsson, F. *et al.*, 2020. Geodynamics of Iceland and the signatures of plate spreading, *J. Volc. Geotherm. Res.*, **391**, 106436. doi:10.1016/j.jvolgeores.2018.08.014.
- Sigmundsson, F., Parks, M., Hooper, A., Spaans, K., Guðmundsson, M.T., Eibl, E.P.S., Reynolds, H.I. & Hjartardóttir, Á.R., 2022. Deformation and seismicity decline before the 2021 Fagradalsfjall eruption, *Nature*, **609**, 523–528.
- Slunga, R., Rögnvaldsson, S.T. & Böðvarsson, R., 1995. Absolute and relative locations of similar events with application to microearthquakes in southern Iceland, *Geophys. J. Int.*, **123**, 409–419.
- Tian, D. *et al.*, 2025. PyGMT: A Python interface for the Generic Mapping Tools (v0.14.2), *Zenodo*. <https://doi.org/10.5281/zenodo.14868324> (accessed 7 April 2025).
- Toksoz, M.N., Cheng, C.H. & Timur, A., 1976. Velocities of seismic waves in porous rocks, *Geophysics*, **41**, 621–645.
- Trugman, D.T. & Shearer, P.M., 2017. GrowClust: a hierarchical clustering algorithm for relative earthquake relocation, with application to the Spanish Springs and Sheldon, Nevada, earthquake sequences, *Seismol. Res. Lett.*, **88**, 379–391.
- Tryggvason, A., Rögnvaldsson, S.T. & Flóvenz, Ó.G., 2002. Three-dimensional imaging of the *P*- and *S*-wave velocity structure and earthquake locations beneath Southwest Iceland, *Geophys. J. Int.*, **151**, 848–866.
- Voight, B. & Cornelius, R., 1991. Prospects for eruption prediction in near real-time, *Nature*, **350**, 695–698.
- Wadati, K., 1928. Shallow and deep earthquakes, *Geophys. Mag.*, **1**, 162–202.
- Waldhauser, F. & Ellsworth, W.L., 2000. A double-difference earthquake location algorithm: method and application to the Northern Hayward Fault, California, *Bull. Seism. Soc. Am.*, **90**, 1353–1368.
- Weislo, M., Stabile, T.A., Telesca, L. & Eisner, L., 2018. Variations of attenuation and *V_p/V_s* ratio in the vicinity of wastewater injection: a case study of Costa Molina 2 well (High Agri Valley, Italy), *Geophysics*, **83**, B25–B31.
- Weir, N.R.W., White, R.S., Brandsdóttir, B., Einarsson, P., Shimamura, H. & Shiobara, H., 2001. Crustal structure of the northern Reykjanes Ridge and Reykjanes Peninsula, southwest Iceland, *J. geophys. Res.*, **106**(B4), 6347–6368.
- Yoshida, K., 2021. Detection of temporal change in near-source attenuation during intense fluid-driven seismicity following the 2011 Tohoku-Oki earthquake, *Geophys. J. Int.*, **224**(1), 138–150.
- Yukutake, Y., Honda, R., Harada, M., Arai, R. & Matsubara, M., 2015. A magma-hydrothermal system beneath Hakone volcano, central Japan, revealed by highly resolved velocity structures, *J. Geophys. Res. Solid Earth*, **120**, 3293–3308.