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A Model of Seismic Velocity Structure Derived from Local Tomographic Inversion Beneath the Jailolo Mountain Complex, North Maluku

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Abstract

In late 2015, the Mount Jailolo complex was shaken by a prolonged earthquake swarm. Mount Jailolo is an ancient volcano that has shown no activity since 1600. The occurrence of an earthquake swarm in the region has sparked speculation about a resurgence of volcanic activity at this ancient volcano. To study the swarm phenomenon in Jailolo, a local scale high-resolution seismic tomography study with a nonlinear approach was conducted beneath the Mount Jailolo complex —a first of its kind. The primary objective of this study is to image the P- and S-wave velocity structures in the upper crust down to a depth of 15 km in 3D for the Mount Jailolo complex (0.8°–1.3° N; 127.2°–127.9° E). Using data from 524 microearthquakes that occurred beneath the Mount Jailolo complex, collected by the GFZ-Potsdam and BMKG collaborative seismic network over a 12-month period, a negative S-wave velocity anomaly was detected beneath Mount Jailolo at depths below 5 km, which is believed to correspond to a magma chamber. The upper crust at depths of less than 5 km is dominated by positive P- and S-wave velocity anomalies, except in the Idamdehe Caldera Complex, west of the Mount Jailolo complex, which is characterized by negative velocity anomalies. The positive velocity anomalies are believed to represent igneous rocks resulting from past volcanic activity at Mount Jailolo.

Keywords: Local-scale seismic tomography; Earthquake swarms; Volcanic activity; Mount Jailolo

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INTRODUCTION

In late 2015, the people of North Maluku were startled by a series of small-magnitude earthquakes occurring at a high frequency and persisting over a long period in a very localized area. This sequence of earthquakes was not followed by a large earthquake serving as a mainshock. This phenomenon is commonly known as an earthquake swarm (Mogi, 1963). Observations conducted by the Ternate Geophysical Station (TNTI) from November 8, 2015, to December 31, 2015, identified 1,164 earthquake swarms in the Jailolo region and its surroundings, with local magnitudes ranging from 1 to 4.5 (Figure-1(a)).

Tectonically, Mount Jailolo is part of the Halmahera volcanic arc, which has long shown no activity. This stratovolcano stands on the Maluku Islands, which have a complex tectonic structure, forming part of the Maluku Sea plate collision zone, commonly known as - the Molucca Collision Zone (Mccaffrey et al., 1980; Hall & Wilson, 2000; Widiyantoro & Van Der Hilst, 1997). The occurrence of an earthquake swarm in the region has sparked speculation about the resurgence of volcanic activity at Mount Jailolo.

To explain the phenomenon causing the earthquake swarm in Jailolo, the German research institute GFZ-Potsdam collaborated on a survey and research project with the BMKG in West Halmahera, named the Halmahera Project. This project was conducted to carry out a series of seismic surveys from August 2016 to July 2017. During this monitoring, GFZ-Potsdam recorded seismic activity in the Jailolo region by operating 35 seismic sensors in West Halmahera Regency and the city of Ternate. A total of 524 microearthquakes were detected and used in this study.

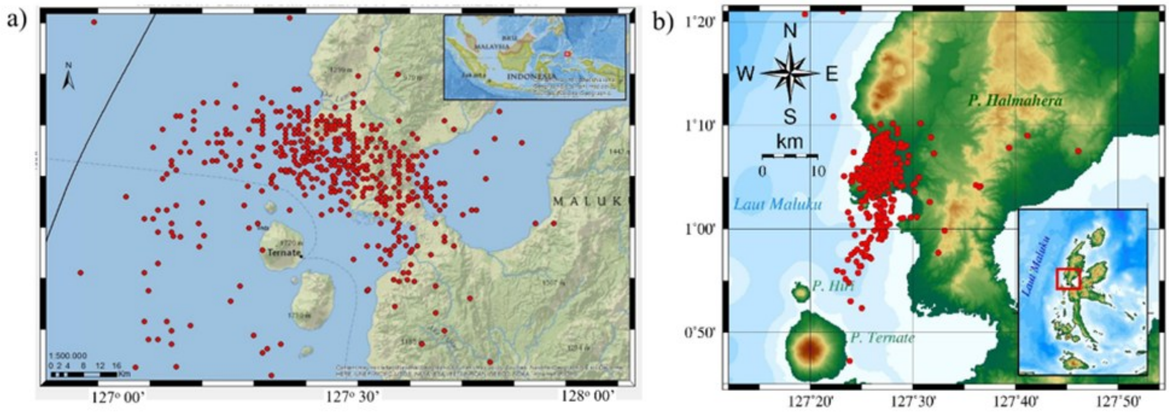

Figure 1. (a) Distribution of swarms recorded by the Ternate Geophysical Station (TNTI) between November 8 and December 31, 2015. A total of 1,164 events were recorded. (b) Distribution of microearthquakes in the Mount Jailolo area based on data recorded by the temporary seismic network operated jointly by BMKG and GFZ-Potsdam Germany from August 2016 to July 2017. A total of 531 events were recorded.

The objective of this study is to image the seismic wave velocity structure beneath the Mount Jailolo complex and to evaluate its possible relationship with the 2015 earthquake swarm from a seismological perspective. To achieve this objective, this study applies high-resolution local seismic tomography using the LOTOS (Local Tomography Software) algorithm to construct three-dimensional P-wave velocity, S-wave velocity, and Vp/Vs ratio models beneath the study area. Seismic tomography has been widely applied in volcanic and tectonically active regions to investigate subsurface structures associated with magma migration, fluid accumulation, and volcanic unrest. Previous tomographic studies have identified upwelling structures beneath the Toba Caldera complex (Wandono, 2006; Wandono, 2007), anisotropic and velocity structures beneath the Merapi Volcano and Toba Caldera complexes (Koulakov, Jakovlev, et al., 2009; Koulakov, Yudistira, et al., 2009; Ramdhan, 2018), crustal structures beneath the Bukit Barisan Mountains in Bengkulu (Sudiyanto, 2014; Pranata et al., 2023), reservoir dynamics beneath the Nevado del Ruiz Volcano in Colombia (Vargas et al., 2017), and upwelling zones beneath volcanic regions in West Java (Wandono et al., 2025). However, despite the significance of the 2015 Jailolo earthquake swarm, a high-resolution local-scale seismic tomography study focusing on the Mount Jailolo complex has not yet been conducted.

This study addresses this gap by providing a local three-dimensional seismic velocity model of the upper crust beneath the Mount Jailolo complex. Specifically, this study aims to identify P- and S-wave velocity anomalies, characterize the Vp/Vs ratio distribution, and examine whether the observed subsurface structures indicate the presence of magma or fluid-related processes beneath the volcano. By linking the tomographic model with the distribution of microearthquakes recorded by the BMKG–GFZ temporary seismic network, this study is expected to provide new geophysical evidence for interpreting the origin of the Jailolo earthquake swarm and for improving understanding of the internal structure of a long-dormant volcano in the Halmahera volcanic arc.

METHOD

To obtain a model of the seismic wave velocity structure in the Jailolo region, high-resolution local seismic tomography software known as LOTOS was used. LOTOS is software with tomography algorithms designed to simultaneously invert P- and S-wave arrival time data to obtain high-resolution P- and S-velocity structures (Koulakov, 2009). The advantage of this software is that it can be operated without complex parameter settings. It is designed for seismic tomography research in highly localized areas, such as volcanic and geothermal regions.

Model Parameterization

A critical step in the tomography process is model parameterization. The model parameterization process involves determining the grid and the initial velocity model to be used (Table 1). In this study, node parameterization using LOTOS-13 software was employed to calculate the P-wave velocity model for a depth of 3 km. This parameterization uses nodes or points in a grid with a distance of 0.4 km between points or nodes, centered at coordinates 1.07° N – 127.45° E. The selection of the node interval was based on the highly localized study area, which required a sufficiently high level of accuracy. Meanwhile, the initial 1-D seismic wave velocity model used for 3-D inversion is the IASPI91 velocity model (Kennett & Engdahl, 1991). Specifically, this is the 1-D IASPI91 velocity model that had been optimized using seismic data from Jailolo and its surrounding with the Velest software (Kissling et al., 1994; Kissling et al., 1995).

Table 1. The initial velocity model used for tomographic inversion, the optimized IASP91 velocity model

Depth (km)	IASP91 Velocity Model (km/s)		Optimized IASP91 Velocity Model (km/s)	
	P	S	P	S
-1	5,80	3,36	5,243	3,034
2	5,80	3,36	5,895	3,409
5	5,80	3,36	6,288	3,627
7	5,80	3,36	6,289	3,627
10	5,80	3,36	6,422	3,709
15	5,80	3,36	6,792	3,913
20	6,50	3,75	6,793	3,913
27	6,50	3,75	6,794	3,914
35	8,04	4,47	7,163	4,162
50	8,04	4,47	8,794	5,057

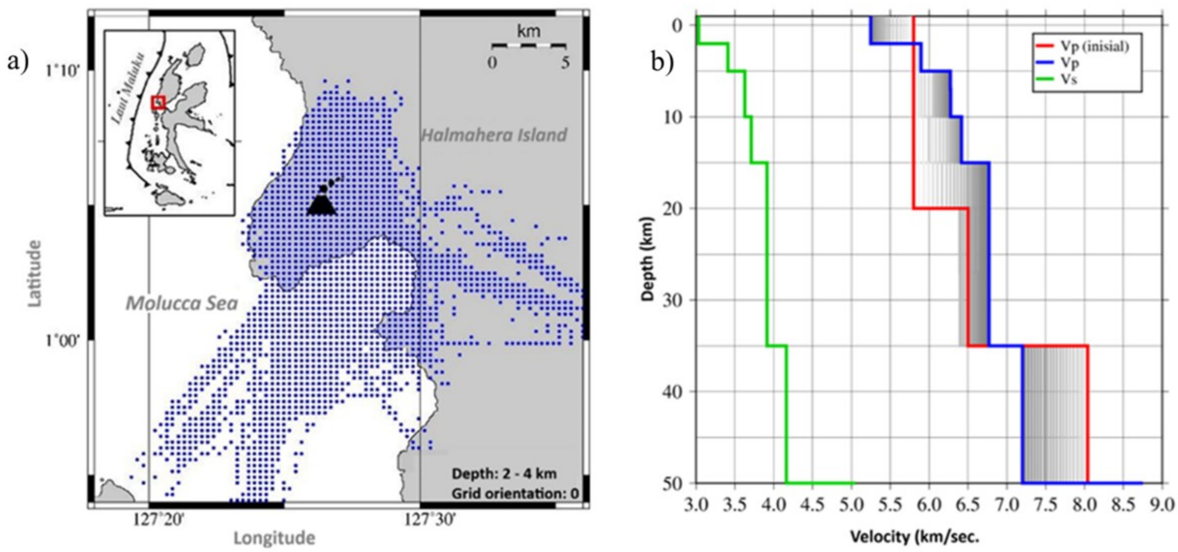

Figure 2. (a) Node parameterization was performed in the Jailolo region with a grid spacing of 0.4 km. (b) The IASPI91 velocity model, which has been optimized using seismic data from Jailolo and the surrounding area.

The data used for this study consists of seismic activity records from Mount Jailolo and the surrounding area, collected by the temporary network established as part of the BMKG–

GFZ-Potsdam collaborative project in West Halmahera. Data recording was conducted from August 12, 2016, to July 15, 2017, by deploying 35 seismic sensors, consisting of 29 short-period seismographs (SPS) and 6 broadband seismographs (BBS). In this study, 524 microearthquakes were selected from the period of August 2016 to July 2017, specifically those identified by adding the S-wave phase. The criteria for earthquakes used in the study were: (1) detected by at least 6 stations, (2) azimuth gap less than 165 degrees. The distribution of the epicenters of the microearthquakes used in this study is shown in Figure-1(b). The number of P-wave and S-wave raypaths was 7,366 and 5,525, respectively.

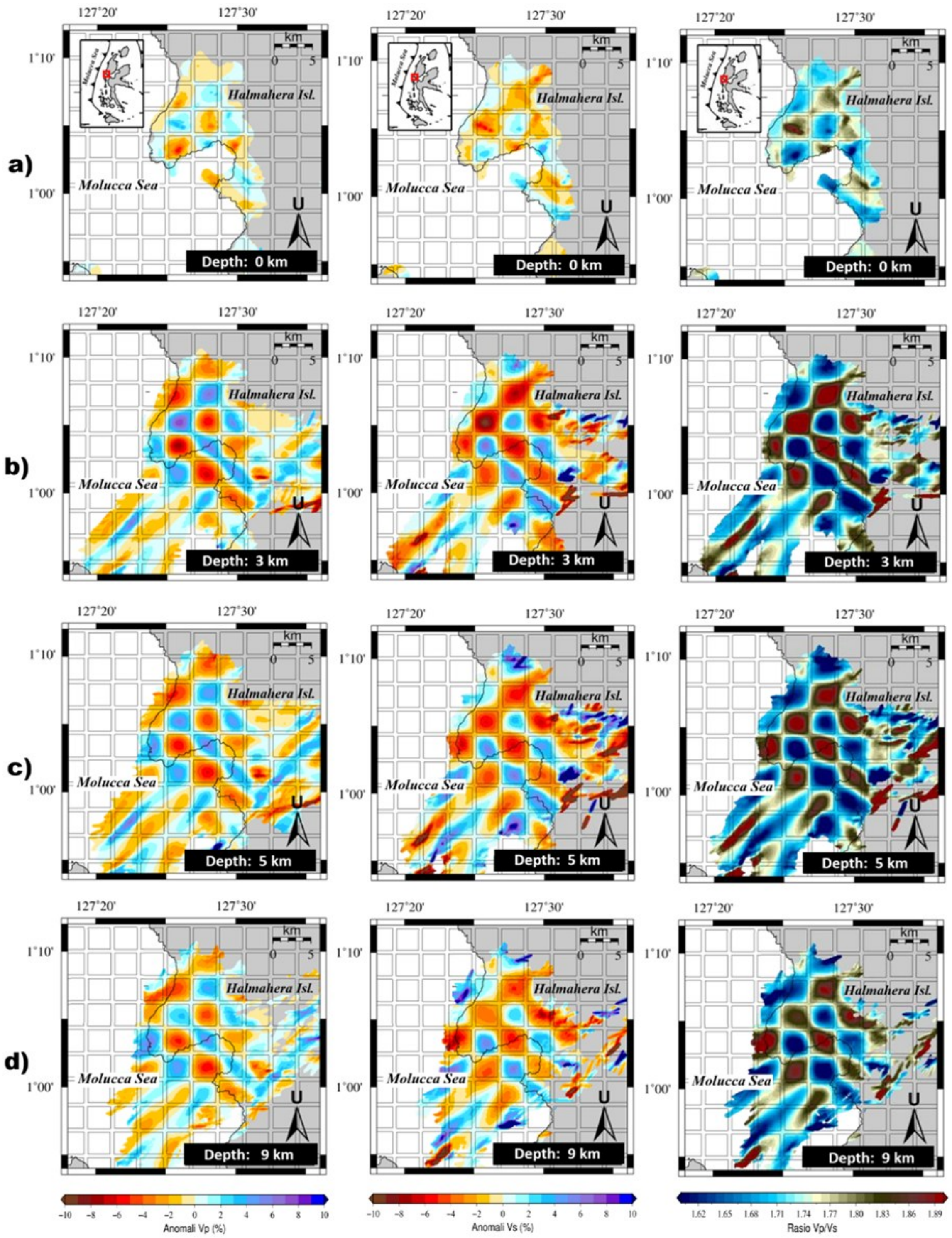

Figure 3. CRT results in the depths of 0, 3, 5, and 9 km (a–d). The left panel shows the CRT results for Vp, the middle panel shows the CRT results for Vs, and the right panel shows the CRT results for Vp/Vs.

Checkerboard Test

To test the resolution of the inversion results, a chessboard resolution test (CRT) (e.g., Humphreys and Clayton, 1988) was conducted using an anomaly area measuring 5 x 5 km². Each block was assigned a 10% variation in velocity anomaly, alternating between +10% (blue) and -10% (red), resembling a chessboard. The results of the resolution test for several layers are shown in Figure-3. The chessboard reconstruction from the inversion using data from Jailolo is clearly visible in the study area, the Mount Jailolo complex and its surroundings. The reconstruction capability is indicated by color gradients expressed as percentages.

Based on the CRT results shown in Figure 3, the resolution beneath the Jailolo Mountains complex appears quite good. The ability to reconstruct the input pattern—or resolution—ranges between 50–90% of the input pattern, especially at depths of 3, 5, and 9 km. This is evident from the color reconstruction results—compare with the color bars in each image—on a scale of 5 to 9 out of 10, for positive anomalies (blue) and negative anomalies (red). These CRT results are then used to identify valid boundaries of the area to be analyzed, namely the area that exhibits a checkerboard pattern.

RESULTS AND DISCUSSION

Images of P- and S-wave velocity anomalies beneath Mount Jailolo

This study investigated the P- and S-wave velocity structures using the local tomography (Thurber, 1993 and Eberhart-Phillips, 1993) method in the area beneath Mount Jailolo. Figure-4 show images of P- and S-wave velocity anomalies and the Vp/Vs ratio for the Mount Jailolo region and its surroundings. These results were obtained from the inversion of real data from a seismic network established through a collaborative survey and research effort between BMKG and GFZ-Potsdam in West Halmahera during 2016–2017. During the inversion process, the results converged at the 9th iteration, with root mean square (RMS) values and residual variances of 0.1055 seconds and 28.6% for P-waves, and 0.141 (24.9%) for S-waves. P-wave and S-wave velocity anomalies are represented by a color scale (in %), where blue indicates positive anomalies and red indicates negative anomalies relative to the initial structural model at the same layer.

From the one year of recorded seismic data that was subsequently analyzed, we were only able to map P-wave and S-wave velocity anomalies with sufficiently high resolution down to a depth of 13 km. This is understandable, first because the distribution of microearthquakes used in this study was mostly at depths of less than 15 km and concentrated around Mount Jailolo. Second, the inversion results from the checkerboard in Figure-3 show that the checkerboard model around the study area could be inverted well to a depth of 13 km, with a model recovery of 50%–90%.

An interesting finding from these tomographic inversion results is the S-wave velocity anomaly, which exhibits extreme changes with depth beneath Mount Jailolo, particularly between depths of 3 km and 5 km, where it shifts from a positive to a negative anomaly. In contrast, the P-wave velocity anomaly remains consistently positive across all layers, although its magnitude does vary.

Layers at depths of 0–3 km. In areas with sufficiently good resolution, as indicated by the checkerboard results, the distribution of positive P-wave and S-wave anomalies nearly covers the entire Mount Jailolo complex, except in Tocim, Suhu District, where negative anomalies are visible around the geothermal area. At this depth, Ternate Island appears to be located in an area with negative anomalies. However, the checkerboard does not show an area with good resolution, so this result can be disregarded.

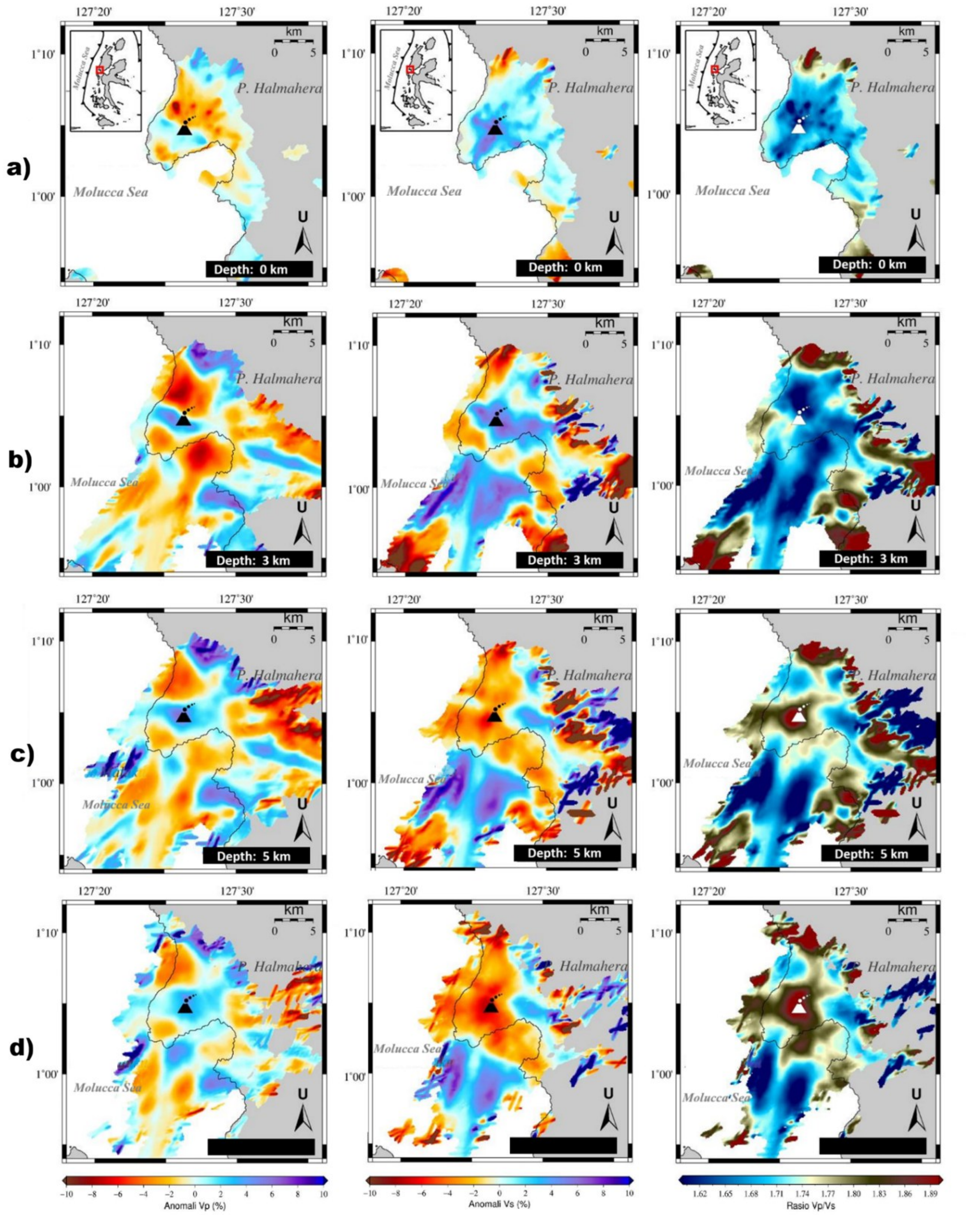

Figure 4. Horizontal tomograms of the study area at depths of 0, 3, 5, and 9 km (a–d) showing P-wave velocity anomalies (left), S-wave velocity anomalies (center), and the Vp/Vs ratio (right). The Vp and Vs anomalies are expressed as percentages relative to the initial velocity model for each layer.

Layers at depths of 5–11 km. The change in S-wave velocity anomalies beneath Mount Jailolo is very significant. At a depth of 3 km beneath Mount Jailolo, there is a positive anomaly of approximately 30%, but in the layers below that (at depths of 5–11 km), it changes to a negative anomaly. This change is limited only to the area beneath Mount Jailolo. However, the P-wave velocity anomaly remains consistently positive despite significant variations in magnitude. Based on the checkerboard test, this area has the highest resolution compared to other layers. A similar pattern is observed in the V_P/V_S ratio image beneath Mount Jailolo, showing values above the average (approaching the value of 2).

Microearthquake distribution resulting from seismic tomography inversion

Using the SeiscomP3 (Hanka et al., 2010) software, we identified 610 events in the Mount Jailolo area and its surroundings during the August 2016–July 2017 period. After relocation using tomographic inversion, 518 events were confirmed. Figure-5 shows the distribution of these events in the study area, beneath Mount Jailolo and its surroundings. The colors blue, light blue, green, and red represent micro-earthquakes occurring during the periods of August –October 2016, November 2016–January 2017, February–April 2017, and May–July 2017, respectively. Most of the microearthquake were concentrated in the area beneath Mount Jailolo, particularly those occurring between May and July 2017. Vertically, the microearthquake were distributed between 0 and 16 km. The histogram in Figure 5 (bottom right) shows that about 60% of these events occurred at depths of 3–7 km below the surface. The pattern of the relocation results is almost the same as the distribution of the swarm earthquakes that occurred on November 8 - December 31, 2015 Jailolo (Passarelli et al., 2018; Putri at al., 2016)

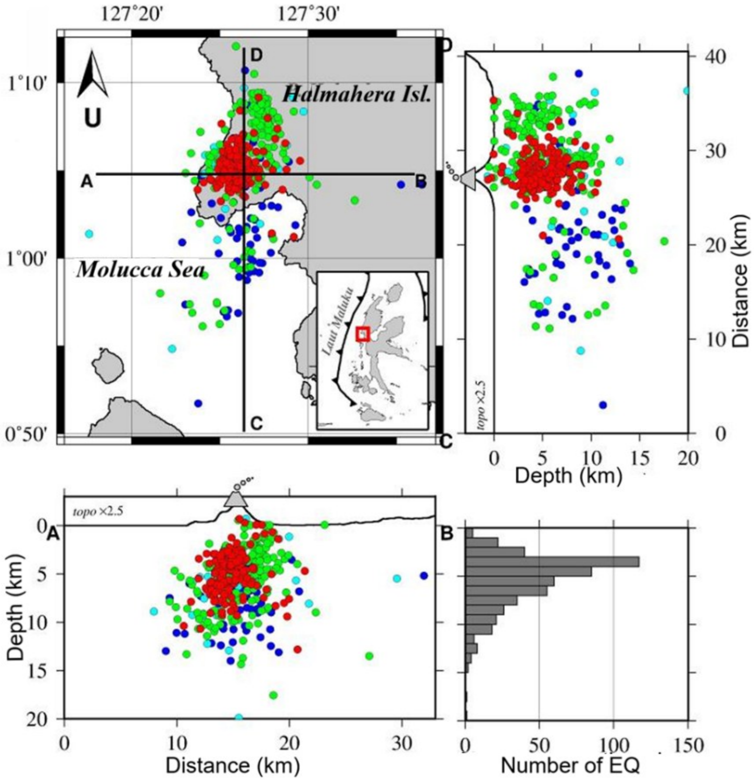

Figure 5. 3D-distribution of 518 microearthquake from August 2016 to July 2017 beneath Mount Jailolo and the surrounding area. The blue, light blue, green, and red circles indicate microearthquakes that occurred during the periods of August–October 2016, November 2016–January 2017, February–April 2017, and May–July 2017, respectively.

Discussion

Mount Jailolo is a Quaternary volcano with no clear historical record of eruptions, and therefore does not fall into any of the three types of volcanoes in Indonesia. Prior to the 2015 swarm, the PVMBG classified Mount Jailolo as a Type B volcano—that is, a volcano that has not experienced a magmatic eruption since 1600 but still exhibits signs of volcanic activity, such as solfataric activity. Volcanoes of this type can be said to be dormant but still have the potential to erupt. The occurrence of a series of micro-earthquakes in the Mount Jailolo volcanic complex over a fairly long period of time at the end of 2015 has sparked speculation about a resurgence of activity at Mount Jailolo in the future—is this true?

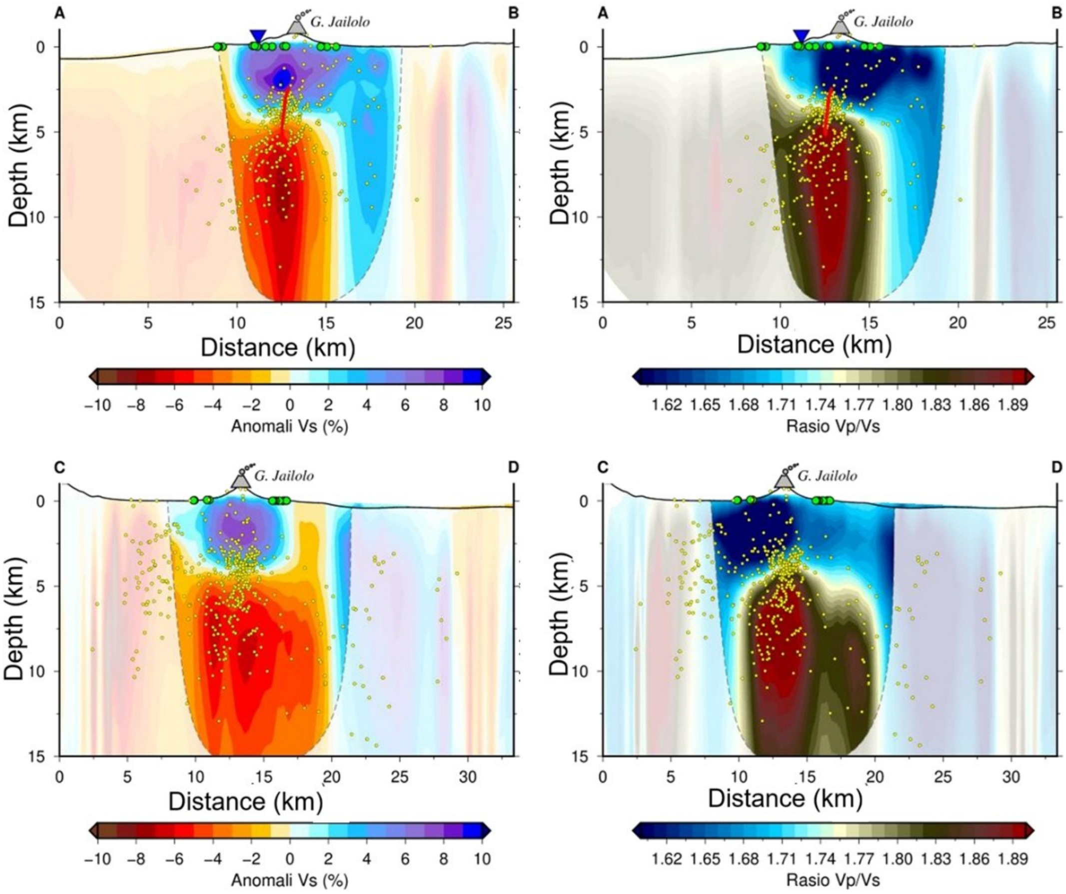

Figure 6. Cross-section of S-wave velocity anomalies (left) and the Vp/Vs ratio (right) beneath Mount Jailolo [as shown in Figure-5(a)]. The yellow dots indicate the locations of microearthquakes during the period from August 2016 to July 2017. The distribution of earthquakes is concentrated in the critical zone between the positive anomaly (blue) and the negative anomaly (red).

The distribution of microseismicity and seismic tomography beneath the Jailolo Volcano complex, as shown in Figure-6, indicates the presence of dynamic (volcanic) processes that trigger microearthquake or tremors. This is clearly evident from the occurrence of events directly beneath Jailolo Volcano. Geometrically, the clusters of microearthquakes (yellow dots) are concentrated in the transition zone between low S-wave velocity anomalies (red) and high S-wave velocity anomalies (blue), as well as between low and high Vp/Vs ratios. These conditions are similar to those observed in a study of Mount Uturncu in Bolivia. Kukarina et al. (2017) explain that changes in the Vp/Vs ratio in this volcanic region are caused by the decompression of liquid volatile compounds (high Vp/Vs ratio) into gas (low Vp/Vs ratio). A high Vp/Vs ratio (~1.9) is associated with high-temperature fluid material, specifically a magma reservoir. Previous researchers have interpreted masses with low S-wave velocity anomalies and high Vp/Vs ratios beneath volcanic areas as magma reservoirs (resulting from partial melting of the slab), as seen in studies of the Toba caldera complex (Wandono et al., 2006, Wandono, 2007, and Koulakov et al., 2009.b), Mount Merapi (Koulakov et al., 2009. A; Ramdhan,M. 2017), and the Kluschevskoy volcanic group (Koulakov et al., 2013). Seismic activity beneath a volcano may reflect significant volume changes when volatile compounds suddenly transform into the gaseous phase.

Figure 6 shows a unique microseismic pattern. This seismic pattern was also identified by Koulakov et al. (2013) in their study of the Kluchevskoy Mountains in Russia, and by Kukarina et al. (2017) at Mount Uturuncu in Bolivia. Unlike at Mount Uturuncu in Bolivia, seismic activity beneath Mount Jailolo is concentrated in a transition zone between low Vp/Vs ratios (blue) and high Vp/Vs ratios (red), at depths of 3–5 km. In this context, a high Vp/Vs ratio at depth may represent a very hot crust containing a significant percentage of melt rich in volatile compounds. The rise of this magma would cause the overlying rocks to undergo mechanical cooling, leading to increased seismicity. The results of this study help to explain and support previous studies that identified the 2015 swarm as a result of magmatic activity beneath the long-dormant Mount Jailolo (Passarelli et al., 2018; Putri et al., 2016; Kukarina et al., 2017).

CONCLUSION

The S-wave velocity anomaly map of the upper layer of the Mount Jailolo complex is dominated by positive anomalies, except to the west of Mount Jailolo, which corresponds to the Idamdehe Caldera area. Positive anomalies, or high-velocity structures, represent cool, hard rocks such as igneous rocks resulting from past volcanic activity at Mount Jailolo.

The results of this local seismic tomography study in West Halmahera generally complement and reinforce the findings of previous tomographic studies in volcanic areas. These results provide new 3D evidence of the presence of a negative anomaly (low-velocity structure) with a high Vp/Vs ratio beneath the summit of Mount Jailolo at a depth of more than 5 km, which represents a magma reservoir.

The earthquake swarm that occurred in the Mount Jailolo complex and its surroundings is suspected to have resulted from volcanic activity. This is evident as the majority of the microearthquakes in this study occurred in the transition zone between the low-velocity structure and the high-velocity structure, which constitutes the wall of the magma dome.

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AUTHOR CONTRIBUTIONS STATEMENT

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Wandono	√	√	√	√	√	√		√	√	√			√	√
Bayu Merdeka TFN		√	√					√	√		√			
Nova Heryandoko				√			√			√				
Karyono					√		√			√		√		

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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