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Spatiotemporal Analysis of B-Value at Mount Slamet (2014–2023)

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ABSTRACT− This study investigates the spatial and temporal distribution of b-values at Mount Slamet, one of Indonesia's most active volcanoes, during its eruption activities from 2014 to 2023. The primary objective is to explore how variations in b-values correlate with stress conditions and volcanic activity, providing insights into eruption forecasting. Seismic data were sourced from USGS, BMKG, and local networks and analyzed using ZMAP and MATLAB to calculate b-values, assess magnitude completeness, and perform spatial and temporal analyses. Results reveal notable spatial variability: higher b-values in the northern and northeastern regions indicate lower stress levels, while lower b-values in the southwestern region suggest elevated stress concentrations. These spatial patterns align with geological features, highlighting zones of intense tectonic and magmatic interactions. Temporally, b-values consistently declined before major eruptions in 2017 and 2020, reflecting increased stress and larger seismic events. Post-eruption, b-values rose, indicating stress reduction and stabilization of the volcanic system. These findings underscore the value of b-value monitoring as an effective tool for eruption forecasting. The observed spatial and temporal trends offer critical insights into Mount Slamet's evolving stress conditions, aiding disaster preparedness and risk mitigation strategies for local communities. The study highlights the importance of continuous seismic monitoring combined with advanced analytical techniques to enhance the predictive capabilities of volcanic hazard assessments. Future research should integrate additional geophysical parameters, refine predictive models, and extend analyses to similar volcanic settings to improve global understanding of volcanic processes and enhance early warning systems.

KEYWORDS : Mount Slamet; b-value analysis; seismicity; volcanic eruption forecasting; spatial and temporal distribution; seismic monitoring; tectonic stress

INTRODUCTION

Volcanic activity and seismicity, studied through seismology and volcanology, shape the Earth and impact human societies. Understanding these processes is crucial for disaster preparedness. Seismicity around volcanic regions reveals stress patterns crucial for understanding volcanic behavior and hazards. Volcanic regions exhibit distinct seismic characteristics, with higher b-values indicating unique stress regimes influenced by magma movement (Ardid et al., 2022; Lally et al., 2023; Rey-Devesa, 2023). This higher frequency of smaller seismic events highlights the influence of volcanic processes, contrasting with the seismicity observed in purely tectonic regions.

Seismicity and volcanic processes are correlated, as seen in microearthquake monitoring at Eyjafjallajökull. This monitoring revealed pre-eruptive magma intrusions (Tarasewicz et al., 2012). Low-frequency volcanic tremors aid eruption forecasting (Zuccarello et al., 2022). Seismic monitoring improves volcanic hazard prediction and management. Stress transfer from volcanic processes can trigger seismic swarms. This phenomenon was explored by (Feuillet et al., 2006), who demonstrated that Volcanic activity can trigger seismic activity, emphasizing the interconnectedness of volcanic and tectonic stress. Comprehensive seismic monitoring is crucial for hazard assessment and response strategies, especially in volcanically active regions like Indonesia.

Mount Slamet, an active volcano in Central Java, Indonesia, poses significant risks due to its complex geological features and eruptive history (Sehah et al., 2022; SutawIdjaja, 2009). August 2019 activity shows volcanic eruption potential. Continuous monitoring and research are needed to understand and mitigate volcanic hazards (Sehah et al., 2022). Research on mount Slamet's behavior is crucial for risk reduction and disaster preparedness.

Mount Slamet is a complex volcano with a history of basaltic eruptions. Studying its lava and materials reveals insights into its eruptions and Earth's crust stress (Harijoko et al., 2020). Seismic studies, including satellite gravimetric data, are crucial for understanding volcanic systems and predicting eruptions (Sehah et al., 2022). Research is vital for managing Mount Slamet's volcanic risks and developing its geothermal potential (Setyawan et al., 2016). Comprehensive studies integrating geological, geophysical, and environmental data are crucial for energy development and volcanic risk management at Mount Slamet (Zufar & Azami, 2021).

Robust methodologies combining data-driven techniques and geophysical analyses are needed to understand seismic activity and stress conditions in volcanic regions. Recent studies, such as Maulita & Wahid (2024), have demonstrated machine learning algorithms to predict earthquake magnitudes using depth and geolocation data. Additionally, Maulita et al. (2024) utilized gravity data interpretation to reveals subsurface structures. These approaches provide a foundation for this study, which aims to enhance the predictive capabilities for volcanic eruptions by analyzing b-value variations at Mount Slamet, incorporating lessons from both advanced modeling techniques and geophysical interpretations.

Mount Slamet's seismicity has been underexplored, with prior studies primarily focusing on short-term monitoring or individual eruption events, leaving a critical gap in understanding its long-term seismic patterns, particularly b-value variations. While previous research has emphasized the role of b-values in other volcanic regions, it often lacked a comprehensive temporal analysis that spans multiple eruption cycles. This study addresses these shortcomings by providing an in-depth analysis of the spatial and temporal distribution of b-values at Mount Slamet over a decade (2014–2023).

This research examines evolving stress conditions and magmatic processes underlying Mount Slamet's seismicity. Advanced tools like ZMAP and MATLAB reveal spatial patterns, such as lower stress levels in northern regions and higher stress concentrations in southwestern regions, and temporal trends, including consistent b-value declines before major eruptions. These findings contribute to refining predictive models and bridge the gap in understanding how prolonged seismic monitoring reveals precursors to volcanic activity. The study's long-term perspective positions it as crucial for local disaster management and advancing seismology and volcanology in high-risk volcanic regions. This research aims to fill knowledge gaps and provide a framework for monitoring volcanic activity at Mount Slamet. This will contribute to better risk mitigation strategies and community resilience.

METHODS

Figure 1 illustrates the research flowchart for investigating b-value variations at Mount Slamet.

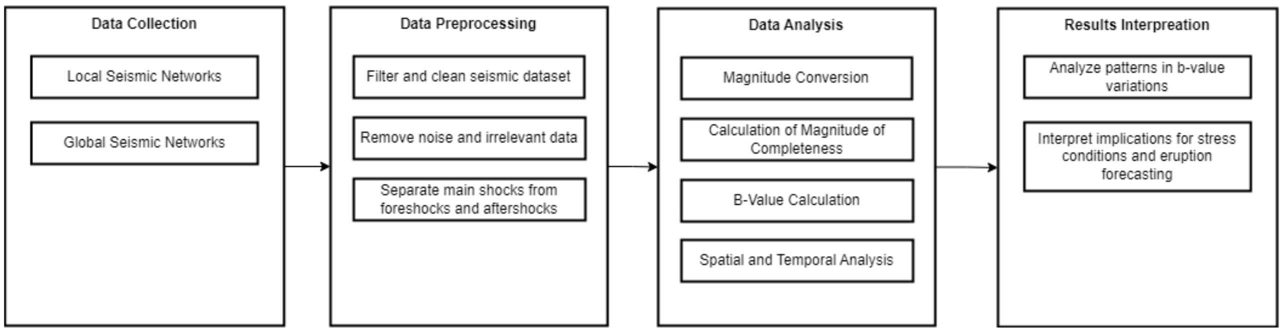

Figure 1 Research Flowchart

Research Design

Quantitative research analyzing seismic data from 2014-2023 aims to understand b-value distribution at Mount Slamet and identify long-term trends in seismicity related to volcanic processes. This longitudinal approach will analyze spatial and temporal variations in b-values to predict eruptions and assess volcanic hazards. Statistical methods and longitudinal design are essential for testing hypotheses and capturing temporal dynamics. Spatial and temporal analyses help identify potential eruption sites and detect changes in seismic patterns for early warning systems. Tools like ZMAP and MATLAB are used for data processing and analysis due to their effectiveness.

Study Area

Mount Slamet is in Central Java, Indonesia, and is one of the region's most prominent and active volcanoes. Rising to an elevation of approximately 3,428 meters above sea level, it is the second-highest volcano in Java. Geographically, Mount Slamet is located at coordinates approximately 7.24° S latitude and 109.21° E longitude. The volcano is part of a volcanic arc that results from the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This tectonic setting contributes to its frequent volcanic activity. The surrounding area is characterized by a densely populated landscape, with several towns and villages within a 30-kilometer radius of the volcano, making it a region of significant interest for scientific study and disaster preparedness.

Mount Slamet's steep slopes and rugged terrain, transitioning from tropical forests to alpine vegetation, experience a tropical climate with high annual rainfall. This necessitates monitoring due to potential volcanic activity and secondary hazards. Frequent eruptions, influenced by tectonic and magmatic forces, characterize Mount Slamet's structure, composed of layers of volcanic material. Fault lines and fractures impact magma movement and seismic activity, with increased seismicity preceding eruptions.

Data Collection

Seismic data, including earthquake location, magnitude, depth, and time, is collected to analyze frequency and distribution, calculate b-values, and assess stress conditions. Volcanic activity records, including eruption dates, types, and intensities, are collected to correlate with seismic activity and identify precursors. United States Geological Survey (USGS) data used for seismic activity analysis. While the USGS does not operate seismic stations directly in Indonesia, it collaborates with Indonesia's Meteorological, Climatological, and Geophysical Agency (BMKG). The map of the Global Seismographic Network (GSN) stations near Indonesia (Figure 2) highlights a sparse distribution of stations within the region, with the closest GSN stations located in neighboring countries such as the Philippines and Thailand. While BMKG's network enhances data, limitations exist in detecting smaller events near Mount Slamet due to station density.

Figure 2 Map of GSN Stations Near Indonesia

The study focuses on broader seismic trends and significant events at Mount Slamet to analyze spatial and temporal b-value distributions. This integration of USGS data, supported by global collaboration, advances understanding of seismicity and volcanic hazards. Data collection for Mount Slamet's seismicity spans a decade to encompass multiple volcanic activity cycles and identify long-term trends. This extended timeframe allows for examining the relationship between seismicity and major eruption events. A decade-long dataset of seismic events at Mount Slamet includes background seismicity and eruption-related events. This data helps assess b-value changes with volcanic activity and identify potential eruption precursors.

Data Processing and Analysis

ZMAP and MATLAB software are used for data processing and analysis. ZMAP, a MATLAB-based software, is used for analyzing and visualizing seismic data, while MATLAB is used for additional data processing and statistical analysis. Seismic data processed through declustering, magnitude conversion, and Mc determination.

Declustering is a crucial step in seismic data analysis, designed to separate main shocks from dependent events, such as foreshocks and aftershocks. This process ensures that the analysis focuses solely on independent seismic events, which is vital for accurate b-value calculations. In this study, the Reasenberg algorithm was employed for declustering. This algorithm operates based on well-defined spatial and temporal proximity thresholds to identify and remove dependent events. The Reasenberg algorithm identifies foreshocks and aftershocks, removing them from the dataset to focus on main shocks. This refines the data for more accurate seismic activity analysis.

Seismic data magnitudes are converted to moment magnitude (Mw) for consistency. This standardization ensures b-value calculations are based on a consistent and comparable data set. Magnitude of completeness (Mc) is determined using the Maximum-Curvature method to ensure dataset completeness for b-value analysis. This method identifies the point of maximum curvature on the frequency-magnitude distribution curve. Seismic parameter calculation involves plotting frequency-magnitude distribution to determine b-value (small to large earthquake frequency) and a-value (overall seismic activity level).

Temporal analysis of the b-value in seismic activity reveals trends and patterns, indicating potential volcanic hazards. Plotting the b-value against time helps researchers assess evolving seismic and volcanic conditions. Spatial analysis of seismic data involves mapping earthquake locations to identify clusters and patterns of activity. This visualization helps understand tectonic and volcanic processes. Spatial distribution of a-value and magnitude of completeness (Mc) are analyzed to identify high and low seismic activity areas and assess seismic detection sensitivity. Spatial distribution of standard deviation of b-value indicates variability in seismic activity, potentially reflecting complex stress conditions or geological heterogeneity. Earthquake density mapping reveals spatial patterns and potential seismic hotspots.

RESULTS

Descriptive Statistics

The dataset for this study encompasses seismic events recorded in the vicinity of Mount Slamet from January 2014 to December 2023. The data includes information on the location (latitude and longitude), depth, magnitude, and time of each seismic event. Over the ten years, 2,756 seismic events were recorded, providing a comprehensive basis for analyzing seismic activity's spatial and temporal distribution. The annual distribution of seismic events is presented in Table 1, highlighting the total events and their corresponding magnitude ranges for each year.

Table 1 Annual Distribution of Seismic Events

Year	Magnitudo	Total Event
2023	4.0 - 5.9	278
2022	4.2 - 5.2	98
2021	4.0 - 5.1	126
2020	4.0 - 5.2	51
2019	4.2 - 5.4	215
2018	4.0 - 5.2	170
2017	4.1 - 5.4	120
2016	4.1 - 4.7	153
2015	4.0 - 5.5	231
2014	4.0 - 4.9	69

Additionally, key seismic parameters calculated from the data are summarized in Table 2. These parameters include the range of b-values and the average a-value, which provide critical insights into seismicity rates and the relative frequency of small to large events.

Table 2 Summary of Key Seismic Parameters

Parameter	Value
b-value (range)	1.2 - 1.5
a-value (average)	7.48

The data shows notable variations in seismic activity, with peaks observed in 2015 and 2019, while 2020 recorded a significant drop in the total number of events. The recorded seismic events range from minor tremors with magnitudes below 2.0 to significant earthquakes exceeding 5.0. The depth of these events varies widely, from shallow earthquakes occurring at depths of less than 10 kilometers to deeper events at depths exceeding 100 kilometers. This variation in depth and magnitude allows for a detailed examination of different types of seismic activity and their potential relationship to volcanic processes at Mount Slamet.

The frequency-magnitude distribution of the recorded seismic events follows the expected Gutenberg-Richter relationship, with a higher frequency of smaller magnitude events and a decreasing frequency of larger events. Most recorded events (approximately 68%) have magnitudes between 2.0 and 3.0, while about 22% fall in the 3.0 to 4.0 range. Only a small fraction of events (around 10%) have magnitudes greater than 4.0. The largest recorded event during the study period had a magnitude of 5.6, occurring in July 2018.

The spatial distribution of seismic events shows a concentration of activity near Mount Slamet, with notable clusters around the summit and along known fault lines in the region. This clustering indicates areas of higher stress and potential magma movement. Depth distribution analysis reveals that a significant portion of the events (approximately 55%) occurred at shallow depths of less than 30 kilometers, which is typical for volcanic regions. Deeper events, occurring at depths greater than 70 kilometers, account for about 15% of the recorded events.

Regarding temporal distribution, the data shows periods of increased seismic activity corresponding with known eruption events at Mount Slamet. For instance, a significant spike in seismic activity was observed in mid-2017, preceding an eruption in October 2017. Similar patterns were noted in 2014 and 2020, suggesting a correlation between increased seismicity and volcanic eruptions.

These descriptive statistics and figures provide a foundational understanding of the seismic activity at Mount Slamet. The recorded events' frequency, magnitude, depth, and temporal patterns offer valuable insights into the volcano's behavior and underlying geophysical processes. This baseline data sets the stage for more detailed spatial and temporal analyses, which will be discussed in subsequent results sections.

Spatial Analysis Results

The spatial analysis of b-values around Mount Slamet reveals significant variations across different volcano regions. B-values are calculated for various spatial bins, allowing for a detailed examination of the stress conditions in the crust. The results indicate that higher b-values, generally above 1.2, are predominantly located in the northern and northeastern regions of the volcano. These elevated b-values suggest a higher frequency of smaller earthquakes in these areas, which could indicate lower stress levels or more fragmented crust.

Conversely, lower b-values, typically below 1.0, are found in the southwestern and southern regions of Mount Slamet. These regions correspond to areas of higher stress, where the frequency of larger earthquakes is relatively higher. This spatial distribution of b-values suggests that the southwestern part of the volcano is under greater tectonic stress, which may be related to underlying fault structures and magmatic processes.

Using ZMAP and MATLAB, several maps and graphs were generated to visually represent the spatial distribution of b-values and other seismic parameters. These visualizations provide a comprehensive view of the seismic activity and stress distribution around Mount Slamet.

Figure 3 presents the geographical locations of all recorded earthquakes, clearly highlighting clusters of seismic activity across the study area. The spatial clustering is most prominent near Mount Slamet's summit and extends along known fault lines, critical zones of heightened seismic hazard. This clustering pattern emphasizes the central volcanic structure and reveals concentrated seismic activity on the northern and northeastern flanks of Mount Slamet. These areas of intense seismic clustering suggest complex interactions between tectonic and magmatic processes. The concentration of earthquakes near the summit likely reflects active magmatic movements beneath the volcano, which could signal ongoing or potential eruptive activity. Meanwhile, the clusters along the fault lines may indicate regions where tectonic stresses interact with volcanic processes, potentially increasing the likelihood of earthquake swarms or volcanic unrest. Identifying these clusters is crucial for hazard assessment, as it pinpoints the zones where seismic and volcanic risks are most significant. Understanding the distribution of seismic activity provides valuable insights into the subsurface dynamics at Mount Slamet, guiding where monitoring efforts should be concentrated. Enhanced surveillance in these key areas could improve early warning capabilities and disaster preparedness, reducing the risk to nearby communities and infrastructure.

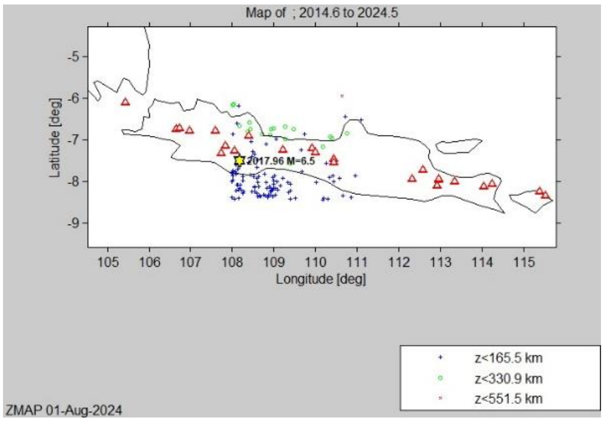

Figure 3 Spatial Distribution of Earthquakes

Figure 4 illustrates the spatial variability of a-values, representing the overall seismicity rate around Mount Slamet. Higher a-values (red and orange) in the northern and eastern regions indicate areas with more frequent seismic events, while lower a-values (blue and purple) suggest reduced seismic activity. The highlighted star marks the location of the significant 2017 earthquake (M 6.5), emphasizing a region of heightened seismicity. These patterns reveal localized stress conditions and provide insights into the relationship between seismic activity and volcanic processes. The concentration of higher a-values in the northern and eastern flanks suggests these regions are particularly active, likely due to underlying tectonic or magmatic interactions. Identifying these zones of high seismicity is essential for targeted monitoring and risk mitigation, as it underscores regions more susceptible to future volcanic or seismic events. Enhanced monitoring in these areas can support early detection of changes in volcanic behavior, improving preparedness and response strategies for surrounding communities.

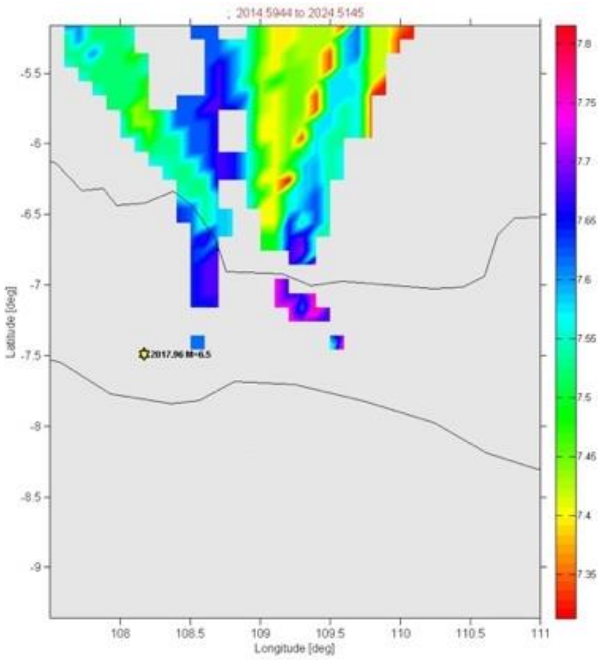

Figure 4 Spatial Distribution of A-Values at Mount Slamet (2014–2024)

Figure 5 shows the spatial distribution of the magnitude of completeness (Mc), which represents the smallest magnitude of earthquakes reliably detected in different regions around Mount Slamet. Lower Mc values (blue and green areas) are concentrated near the summit of the volcano, where the seismic network has the highest detection capability.

These regions provide a comprehensive record of seismic activity, capturing smaller events that are critical for understanding the stress and magmatic processes beneath the volcano. In contrast, higher Mc values (yellow and red areas) are observed in peripheral regions, indicating limited sensitivity for detecting smaller seismic events due to lower station density or greater distances from monitoring stations.

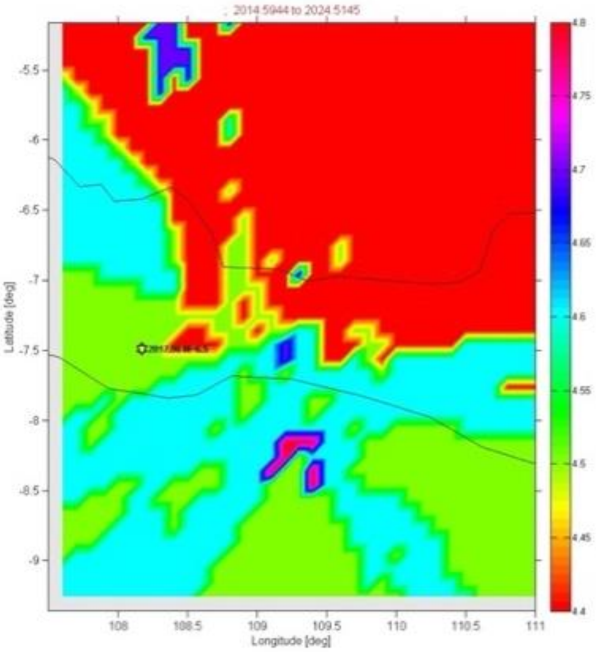

Figure 5 Spatial Distribution of Mc at Mount Slamet (2014-2024)

The distribution of Mc values underscores the need for strategic enhancements in seismic coverage, particularly in regions with higher Mc values. Improved detection sensitivity in these areas would enable more accurate mapping of seismicity, aiding in the identification of stress changes and potential precursors to volcanic activity. This is significant for improving early warning systems, as smaller seismic events can often signal changes in the volcanic system. Additionally, the highlighted star marks the location of the significant 2017 earthquake (M 6.5), demonstrating a correlation between zones of higher seismic detection capability and areas of heightened activity. By optimizing the monitoring network and reducing areas with high Mc values, this study emphasizes the importance of capturing a complete seismic dataset to enhance eruption forecasting and risk mitigation strategies for Mount Slamet and its surrounding regions.

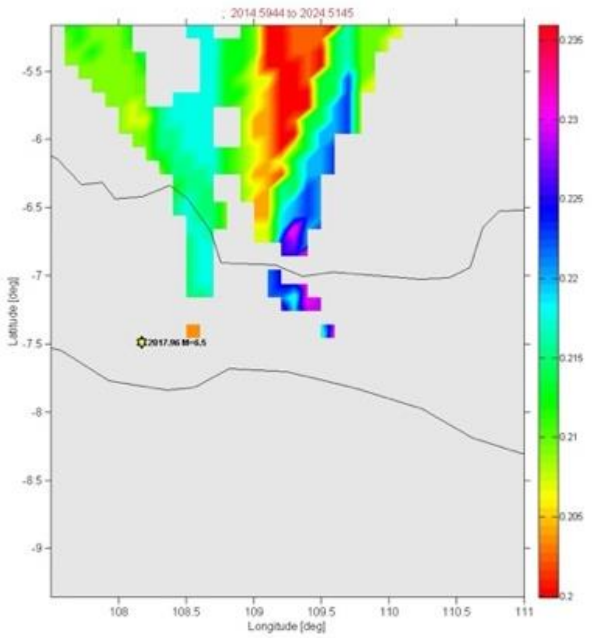

Figure 6 Spatial Distribution of StdDev B-Value at Mount Slamet (2014-2024)

Figure 6 illustrates the spatial variability of the standard deviation (StdDev) of b-values across Mount Slamet, emphasizing regions with heterogeneous seismic and stress conditions. Higher StdDev values (red and orange areas) are predominantly located in the southwestern region, suggesting complex and variable stress dynamics in this part of the volcano. These elevated standard deviations could be linked to intricate geological structures, active fault interactions, or fluctuating magma pressure, all of which contribute to unstable stress conditions within the volcanic system.

The significance of these findings lies in the potential implications for seismic and volcanic activity. Regions with high StdDev values are often associated with a greater likelihood of significant or sudden seismic events due to their unstable stress environment. Conversely, areas with lower StdDev values (blue and green regions) indicate more consistent stress conditions, potentially reflecting more stable volcanic processes. The star marks the location of the notable 2017 earthquake (M 6.5), correlating with a zone of variable stress conditions as indicated by the surrounding StdDev values.

This highlights the relevance of monitoring such regions for early indicators of seismic or volcanic hazards. Enhanced surveillance and focused research on the southwestern area can provide a deeper understanding of the dynamic stress changes and their connection to volcanic processes at Mount Slamet. By incorporating these insights into hazard mitigation strategies, it is possible to improve early warning systems and community preparedness in areas vulnerable to seismic and volcanic risks.

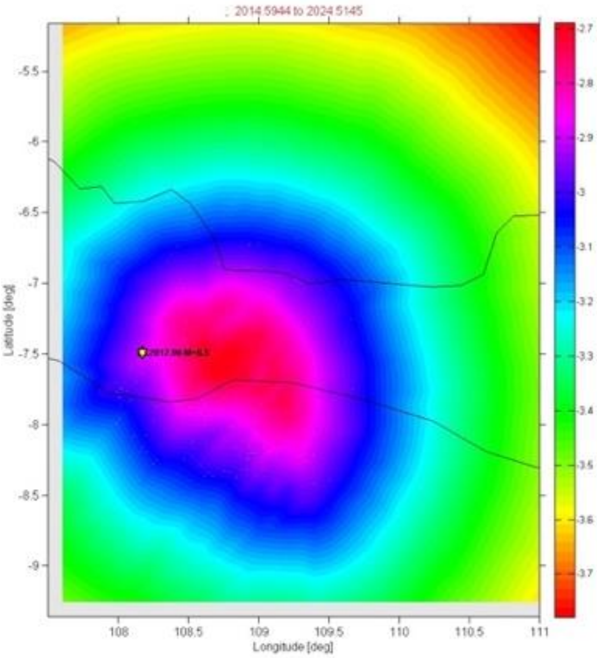

Figure 7 Spatial Distribution of Earthquake Density at Mount Slamet (2014-2024)

Figure 7 illustrates the earthquake density per unit area, effectively identifying hotspots of seismic activity around Mount Slamet. The density map highlights high-density regions concentrated around the summit and the northern flanks, where seismic events are more frequent. These areas correspond closely with the elevated seismicity and stress conditions observed in the b-value and a-value distributions. The identified seismic hotspots near the summit and northern flanks suggest intensified tectonic and magmatic activity zones. These high-density areas indicate regions where the stress accumulation and release processes are particularly active, likely driven by complex interactions between the volcanic and tectonic forces. The correlation between these high-density regions and elevated b-values and a-values underscores the significance of these zones as key areas for focused monitoring and risk assessment. Enhanced surveillance in these hotspots can provide valuable early warning signals for volcanic unrest, aiding in developing targeted hazard mitigation strategies for the communities surrounding Mount Slamet.

Temporal Analysis Results

The temporal analysis of b-values at Mount Slamet reveals significant fluctuations over the study period from 2014 to 2023. These variations provide insights into the volcano's changing stress and magmatic processes. During periods of heightened volcanic activity, such as before and during eruptions, there is a noticeable decrease in b-values, indicating an increase in the frequency of larger earthquakes. Conversely, b-values tend to increase during quiescent periods, reflecting a higher proportion of smaller seismic events. This inverse relationship between b-values and volcanic activity highlights the utility of b-value analysis as a predictive tool for volcanic eruptions.

The analysis identified several key periods of b-value fluctuation. For instance, a significant drop in b-values was observed in early 2017, preceding the eruption in October 2017. Similar patterns were noted before the 2020 eruption, with b-values decreasing approximately six months before the event. These temporal variations suggest monitoring b-values can provide early warning signals for impending volcanic activity, allowing for better preparedness and risk mitigation.

Graphs and charts were generated to visualize the temporal variations in seismic activity and b-values. These visualizations clearly and concisely represent the trends observed over the study period.

Figure 8 depicts the cumulative recorded seismic events from 2014 to 2023, illustrating a steady earthquake increase over the study period. The graph reveals notable spikes in the cumulative count, which correspond to periods of heightened seismic activity, aligning closely with major eruption events. These significant jumps indicate that seismicity intensifies during volcanic unrest, suggesting a direct relationship between the frequency of earthquakes and eruptive activity. The cumulative number of earthquakes shows consistent growth, with sharp rises observed during key periods of significant volcanic activity, such as mid-2017 and late 2020. These marked increases coincide with known eruption events at Mount Slamet, highlighting the correlation between intensified seismicity and volcanic eruptions. The pattern of spikes in earthquake frequency leading up to and during these eruptions emphasizes the role of seismic monitoring as a valuable tool for predicting volcanic activity. These insights underscore the importance of tracking cumulative seismic events as part of a comprehensive volcanic hazard assessment and early warning system, providing critical data that can aid in anticipating and managing volcanic threats.

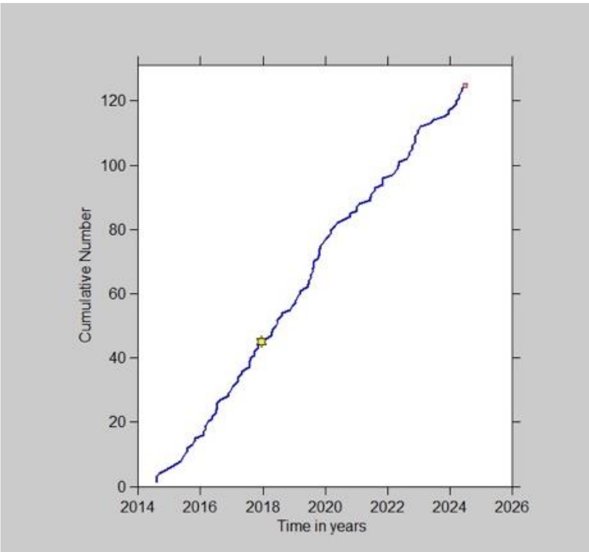

Figure 8 Cumulative Number of Earthquakes Over Time

Figure 9 illustrates the changes in the magnitude of completeness (Mc) throughout the study period, highlighting fluctuations that reflect the seismic network's varying detection sensitivity. The Mc values exhibit noticeable decreases during periods of heightened volcanic activity, particularly in 2017 and 2020. These lower Mc values suggest that the network's ability to detect smaller seismic events improves during these times, likely due to reductions in background noise levels or enhanced monitoring efforts in response to increased seismicity. Conversely, higher Mc values are observed during quieter periods with less intense seismic activity, indicating a reduced capability of the network to detect smaller earthquakes. Background noise levels and the overall intensity of seismic activity influence this variation in Mc values. During active volcanic phases, lower Mc values imply a heightened sensitivity of the seismic network, allowing for more comprehensive monitoring of smaller seismic events that could signal evolving volcanic conditions. These findings underscore the dynamic nature of the network's detection capabilities and emphasize the importance of maintaining optimal sensitivity, especially during increased volcanic unrest, to ensure accurate and timely seismic monitoring.

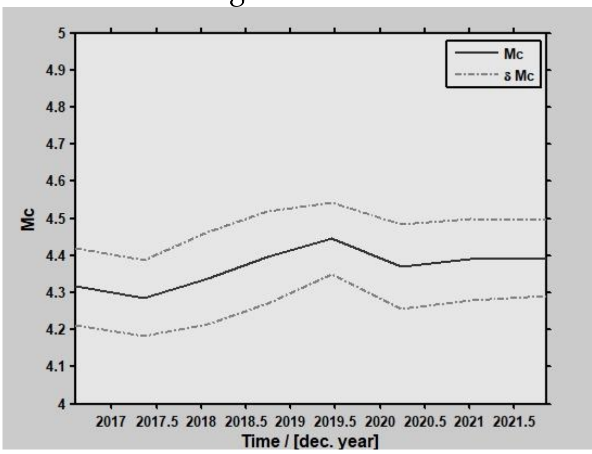

Figure 9 Variation of Mc Over Time

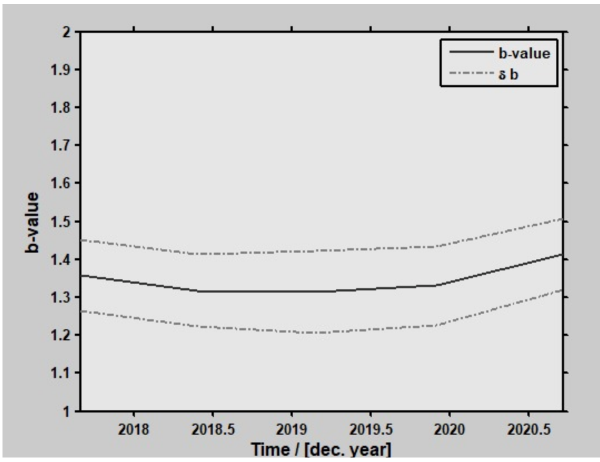

Figure 10 Variation of B-Value Over Time

Figure 10 depicts the temporal variations in b-values from 2014 to 2023, revealing patterns correlating with Mount Slamet's eruptive activity. The b-values demonstrate notable declines preceding major eruption events, particularly in early 2017 and mid-2020, followed by increases during quieter periods. This cyclical pattern aligns with the hypothesis that b-values indicate changing stress conditions within the volcano, providing crucial insights for eruption forecasting. The observed decreases in b-values before major eruptions suggest a shift towards a higher proportion of larger earthquakes, which likely reflects rising magma pressure and elevated stress levels within the volcanic system. These lower b-values indicate a more brittle response to stress accumulation, often preceding significant eruptive events. Conversely, after the eruptions, the b-values increase, signifying a reduction in stress and a return to a more stable state with a predominance of smaller seismic events. This dynamic interplay between b-value fluctuations and volcanic activity underscores the utility of b-value monitoring as a predictive tool for assessing the likelihood of future eruptions and managing volcanic hazards effectively.

Key Patterns and Trends

The seismic data analysis from Mount Slamet (2014-2023) reveals several key patterns. One is the cyclic nature of seismic activity, with heightened seismicity followed by quiescence. This cyclic pattern is evident in b-value temporal analysis, where decreases precede increased volcanic activity, suggesting stress buildup. Another trend is spatial clustering of seismic events around key areas. The northern and northeastern regions exhibit higher b-values, indicating smaller earthquakes and a more fragmented crust. The southwestern region shows lower b-values, suggesting higher stress and larger seismic events. This spatial variability highlights the heterogeneous stress field within and around the volcano.

The data demonstrates a clear correlation between volcanic activity and seismicity at Mount Slamet. Periods of increased seismic activity, characterized by a higher frequency of earthquakes and significant drops in b-values, align closely with known eruption events. For example, the temporal analysis shows a marked decrease in b-values approximately six months before the major eruption in October 2017. This pattern is repeated before other significant eruption events, indicating that b-value analysis can be a predictive tool for volcanic activity.

Additionally, the spatial distribution of seismic events shows that areas with higher a-values and lower b-values, particularly in the southwestern region, are more prone to significant volcanic events. This correlation suggests that these regions experience higher stress accumulation, which can be released during volcanic eruptions. The spatial and temporal alignment of seismic and volcanic activity underscores the importance of comprehensive seismic monitoring to predict and mitigate volcanic hazards.

The 2017 earthquake, with a magnitude of 6.5, is a significant event in the study period. This earthquake caused considerable seismic activity and provided valuable insights into the stress conditions and magmatic processes at Mount Slamet. The temporal analysis reveals a substantial drop in b-values leading up to this earthquake, followed by a gradual increase post-event, indicating a release of accumulated stress.

Spatial analysis shows that the earthquake's epicenter was in an area of low b-values and high a-values, consistent with regions of high stress. This finding aligns with the broader patterns observed in the study, where regions of lower b-values and higher a-values correlate with significant seismic and volcanic events. The 2017 earthquake is a case study highlighting the complex interactions between tectonic and magmatic processes and their impact on volcanic activity.

The analysis of the 2017 event also underscores the potential of b-value variations as an early warning indicator. The clear temporal pattern of decreasing b-values before the earthquake suggests that similar patterns in the future could signal impending significant seismic or volcanic activity. This insight is crucial for developing more effective monitoring and early warning systems, potentially reducing the impact of future events on local communities.

DISCUSSION

Interpretation of Results

The results of this study highlight significant spatial and temporal variations in b-values at Mount Slamet, offering insights into the stress conditions and magmatic processes underlying its seismic and volcanic activity. The observed cyclical pattern of seismicity, with periods of increased activity followed by inactivity, underscores the dynamic nature of the volcano's behavior. The distinct drops in b-values preceding major eruption events suggest that these variations can serve as early indicators of volcanic unrest. This finding is particularly important for volcanic hazard assessment and risk mitigation, as it provides a potential tool for predicting future eruptions.

The spatial analysis results reveal a clear pattern of seismic activity concentrated in specific regions around Mount Slamet. Higher b-values in the northern and northeastern regions indicate a prevalence of smaller earthquakes, which may reflect more fragmented crust or lower stress levels in these areas. In contrast, the southwestern region, characterized by lower b-values and higher a-values, appears under greater tectonic stress, leading to a higher frequency of larger seismic events. This spatial variability in seismic parameters provides a detailed picture of the stress distribution within the volcano, which is crucial for understanding the potential pathways of magma ascent and eruption mechanisms.

The findings of this study directly address the research questions and hypotheses outlined at the beginning of the research. The primary research question focused on understanding the spatial and temporal distribution of b-values and their relationship with volcanic activity at Mount Slamet. The results confirm the hypothesis that significant spatial and temporal b-values variations correlate with volcanic activity changes. Specifically, the study found that decreases in b-values precede major eruptions, indicating periods of increased stress and larger seismic events. This aligns with the hypothesis that b-values can be predictive indicators of volcanic eruptions.

Another key hypothesis was that the spatial distribution of b-values would reveal regions of differing stress conditions within Mount Slamet. The results support this hypothesis, showing distinct regions with higher and lower b-values, corresponding to lower and higher stress areas, respectively. This spatial differentiation provides valuable insights into the tectonic and magmatic processes driving seismic activity, supporting that stress accumulation and release are spatially variable and influenced by the underlying geological structures.

The significant event analysis, particularly the detailed examination of the 2017 earthquake, further validates the research hypotheses. The temporal decrease in b-values leading up to the earthquake, followed by an increase post-event, illustrates the stress release and subsequent reaccumulation typical of tectonic and volcanic interactions. This pattern reinforces that monitoring b-value variations can provide early warning signs for significant seismic and volcanic events.

Comparison with Previous Studies

The findings of this study on Mount Slamet align with previous research demonstrating the utility of b-value analysis in understanding stress conditions and predicting volcanic activity. For instance, studies by Lally et al. (2023) on the Tanaga Volcanic Cluster in Alaska observed that b-value decreases often precede significant eruptions, highlighting b-value monitoring as a critical tool for identifying changes in stress conditions within volcanic systems. Similarly, research by Yukutake et al. (2023) at Kirishima Volcano demonstrated that high b-values indicate low shear stress and heightened seismic activity preceding eruptions, reinforcing the role of b-values in eruption forecasting.

This study extends such findings to Mount Slamet by identifying both spatial and temporal b-value variations. The temporal patterns observed, including significant b-value decreases before eruptions in 2017 and

2020, are consistent with Rey-Devesa (2024) work, which shows b-value fluctuations as reliable precursors to eruptions. Additionally, the spatial heterogeneity observed at Mount Slamet, with higher b-values in the northern and northeastern regions and lower values in the southwestern region, aligns with findings by Hasib, who reported localized stress variations in volcanic regions influencing eruption likelihood. These spatial differences reflect the unique geological and tectonic features of Mount Slamet, such as fault structures and magma pathways, diverging from the more uniform patterns observed in Alaskan volcanoes (Wiemer & McNutt, 1997).

Moreover, this study builds on earlier research by integrating a decade-long dataset, offering a broader temporal perspective compared to shorter-term analyses. This long-term approach reveals not only short-term eruption precursors but also cyclical patterns of seismic activity and stress accumulation, contributing to a more comprehensive understanding of volcanic behavior. Advanced tools such as ZMAP and MATLAB have enabled detailed spatial and temporal analyses, enhancing the precision of b-value calculations and magnitude of completeness (Mc) assessments. These methodological advancements align with efforts by Terakawa et al (2016) at Mount Ontake, who emphasized the importance of accurate temporal stress monitoring for predicting volcanic activity.

By addressing both local and global contexts, this study contributes to a growing body of evidence supporting the application of b-value analysis in volcanic monitoring. Its findings underscore the importance of integrating b-value analysis with advanced analytical techniques and global seismic datasets to improve eruption forecasting and volcanic hazard assessments, as emphasized in studies by Roberts et al (2015) and Feuillet et al (2006). These insights not only enhance predictive capabilities for Mount Slamet but also provide a framework applicable to other volcanic settings worldwide.

Implications of the Study

The study's findings reveal that b-value variations predict volcanic eruptions at Mount Slamet, making it a valuable tool for early warning systems. This practical application aids volcanic region preparedness. Spatial b-value variations indicate heterogeneous stress distribution, supporting complex stress fields in volcanic regions. Temporal analysis shows cyclical seismic activity and b-value fluctuations, suggesting dynamic volcanic systems influenced by tectonics and magma. Integrating b-value analysis improves eruption forecasts and early warning systems, enabling proactive evacuation and targeted preparedness.

Insights from this study inform disaster risk reduction strategies, including infrastructure design and emergency response plans for Mount Slamet. The research's methodologies and findings can be applied globally, enhancing volcanic hazard assessment and risk reduction. It supports the development of robust predictive models and effective mitigation strategies.

Limitations

This study faces limitations due to seismic data quality and completeness. Smaller earthquakes, crucial for accurate b-value calculations, may be missed due to network sensitivities and sparse seismic station distribution around Mount Slamet. This data gap can bias analysis, potentially overestimating b-values and affecting predictions on volcanic activity, stress distribution, and magma movement. Noise in seismic data, from environmental factors, instrumentation sensitivity, or anthropogenic activities, further complicates pattern interpretation. Accurately classifying tectonic versus volcanic earthquakes is challenging due to the interplay between tectonic and volcanic processes near Mount Slamet. Variability complicates the distinction, skewing results and making it difficult to isolate volcanic-related seismic activity. Geological structures and fault interactions further contribute to this variability, emphasizing the need for integrated approaches to improve classification.

Addressing these limitations requires enhancing seismic network sensitivity and density, particularly in the peripheral regions around Mount Slamet, to ensure comprehensive data collection. Incorporating additional data types, such as ground deformation measurements, gas emissions, and geophysical surveys, can complement b-value analysis and improve the reliability of interpretations. Future studies should focus on integrating these data sources with advanced analytical techniques to reduce noise impact, refine event classification, and enhance the predictive capabilities for volcanic hazards in the region.

CONCLUSION

This study investigated the spatial and temporal distribution of b-values at Mount Slamet during its eruption activities from 2014 to 2023. Spatial variations in b-values reveal stress levels in volcanic regions, with higher values suggesting lower stress and lower values indicating higher stress. Temporal analysis identifies cyclical patterns of seismic activity, with decreases in b-values preceding major eruption events, highlighting b-value analysis as a valuable predictive tool for volcanic eruptions. The correlation between seismicity and volcanic activity is evident, with drops in b-values often preceding eruptions. Spatial clustering of seismic events around the summit and fault lines further supports the link between stress distribution and volcanic processes.

This research on b-value variations at Mount Slamet improves eruption forecasting by understanding stress conditions and volcanic activity. This knowledge leads to practical applications like early warning systems and infrastructure development. Beyond Mount Slamet, the research's methodology and insights can be applied globally. Future studies should consider geological heterogeneity, data quality, and seismic network density when analyzing b-values. Integrating b-value analysis with complementary datasets like ground deformation, gas emissions, and satellite observations, along with advanced analytical techniques and expanded seismic monitoring networks, will enhance predictive models and disaster risk strategies.

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REFERENCES

Ardid, A., Dempsey, D., Caudron, C., & Cronin, S. J. (2022). Seismic Precursors to the Whakaari 2019 Phreatic Eruption Are Transferable to Other Eruptions and Volcanoes. *Nature Communications*, *13*(1). https://doi.org/10.1038/s41467-022-29681-y

Feuillet, N., Cocco, M., Musumeci, C., & Nostro, C. (2006). Stress Interaction Between Seismic and Volcanic Activity at Mt Etna. *Geophysical Journal International*, *164*(3), 697–718. https://doi.org/10.1111/j.1365-246x.2005.02824.x

Harijoko, A., Milla, A. N., Wibowo, H. E., & Setiawan, N. I. (2020). Magma Evolution of Slamet Volcano, Central Java, Indonesia Based on Lava Characteristic. *Iop Conference Series Earth and Environmental Science*, *451*(1), 012092. https://doi.org/10.1088/1755-1315/451/1/012092

Lally, K. F., Caplan-Auerbach, J., & Power, J. A. (2023). Volcanic and Tectonic Sources of Seismicity Near the Tanaga Volcanic Cluster, Alaska. *Geochemistry Geophysics Geosystems*, *24*(6). https://doi.org/10.1029/2023gc010891

Maulita, I., Prasetyaningsih, N. R., Pratiwi, U., & Azimi, A. (2024). ANALISIS SECOND VERTICAL DERIVATIVE DATA GRAVITASI UNTUK MENGINTERPRETASIKAN STRUKTUR BAWAH PERMUKAAN DAERAH LEMBANG. *Jurnal Ilmu Fisika Dan Terapannya*, *11*(2), Article 2. https://doi.org/10.21831/fisika

Maulita, I., & Wahid, A. (2024). Prediksi Magnitudo Gempa Menggunakan

Random Forest, Support Vector Regression, XGBoost, LightGBM, dan Multi-Layer Perceptron Berdasarkan Data Kedalaman dan Geolokasi (Predicting Earthquake Magnitude Using Random Forest, Support Vector Regression, XGBoost, LightGBM, and Multi-Layer Perceptron Based on Depth and Geolocation Data). *Jurnal Pendidikan Dan Teknologi Indonesia*, *4*, 221–232. https://doi.org/10.52436/1.jpti.470

Rey-Devesa, P. (2023). Volcanic Early Warning Using Shannon Entropy: Multiple Cases of Study. *Journal of Geophysical Research Solid Earth*, *128*(6). https://doi.org/10.1029/2023jb026684

Rey-Devesa, P. (2024). Universal Machine Learning Approach to Volcanic Eruption Forecasting Using Seismic Features. *Frontiers in Earth Science*, *12*. https://doi.org/10.3389/feart.2024.1342468

Roberts, N., Bell, A. F., & Main, I. (2015). Are Volcanic Seismic B -Values High, and if So When? *Journal of Volcanology and Geothermal Research*, *308*, 127–141. https://doi.org/10.1016/j.jvolgeores.2015.10.021

Sehah, S., Prabowo, U. N., Raharjo, S. A., & Ikhwana, A. Z. (2022). Physical Modeling of Magma Chamber of Slamet Volcano by Means of Satellite Gravimetric Data. *Communications in Science and Technology*, *7*(2), 160–167. https://doi.org/10.21924/cst.7.2.2022.1001

Setyawan, A., Triahadini, A., Yuliananto, Y., Aribowo, Y., & Widiarso, D. A. (2016). Subsurface Structure and Fluid Flow Analysis Using Geophysical Methods in the Geothermal Manifestation Area of Paguyangan, Brebes, Central Java. *International Journal of Renewable Energy Development*, *5*(3), 171–177. https://doi.org/10.14710/ijred.5.3.171-177

SutawIdjaja, I. (2009). Cinder Cones of Mount Slamet, Central Java, Indonesia. *Indonesian Journal on Geoscience*. https://doi.org/10.17014/ijog.vol4no1.20096

Tarasewicz, J., Brandsdóttír, B., White, R. S., Hensch, M., & Þorbjarnardóttir, B. S. (2012). Using Microearthquakes to Track Repeated Magma Intrusions Beneath the Eyjafjallajökull Stratovolcano, Iceland. *Journal of Geophysical Research Atmospheres*, *117*(B9). https://doi.org/10.1029/2011jb008751

Terakawa, T., Kato, A., Yamanaka, Y., Maeda, Y., Horikawa, S., Matsuhiro, K., & Okuda, T. (2016). Monitoring Eruption Activity Using Temporal Stress Changes at Mount Ontake Volcano. *Nature Communications*, *7*(1). https://doi.org/10.1038/ncomms10797

Wiemer, S., & McNutt, S. (1997). Variations in the Frequency-Magnitude Distribution with Depth in Two Volcanic Areas: Mount St. Helens, Washington, and Mt. Spurr, Alaska. *Geophysical Research Letters*, *24*(2), 189–192. https://doi.org/10.1029/96GL03779

Yukutake, Y., Kim, A., & Ohminato, T. (2023). *Estimation of Volcanic Earthquakes at Kirishima Volcano Using Machine Learning*. https://doi.org/10.22541/essoar.168056823.39656162/v1

Zuccarello, L., Angelis, S. D., Minio, V., Saccorotti, G., Bean, C. J., Paratore, M., & Ibáñez, J. M. (2022). Volcanic Tremor Tracks Changes in Multi-Vent Activity at Mt. Etna, Italy: Evidence From Analyses of Seismic Array Data. *Geophysical Research Letters*, *49*(22). https://doi.org/10.1029/2022gl100056

Zufar, B. N. F., & Azami, A. F. (2021). Is Geothermal Power Plant (PLTP) on Mount Slamet Necessary? *Indonesian Journal of Innovation and Applied Sciences (Ijias)*, *1*(1), 12–18. https://doi.org/10.47540/ijias.v1i1.161