The Earthquake-Volcano Nexus: A Geophysical Interplay Analysis

College of Computing and Technology, Drexel University
Arielle Marinduque, Ayagoz Smagulova, Kelsey Selvaggi, Likhita Nallapati, Shriya Rawal

Abstract - This study investigates the complex relationship between earthquake swarms and volcanic eruptions by analyzing global seismic and volcanic activity data from 2000 to 2023. By examining earthquake magnitudes, locations, and timings in conjunction with volcanic eruption records from the NOAA, we aim to identify potential correlations and causal links between these phenomena. The research focuses on regions characterized by significant tectonic activity, like subduction zones and volcanic hotspots. Through spatial and temporal analysis, we explore the extent to which earthquake swarms can serve as precursors to volcanic eruptions, with the goal of improving early warning systems and disaster preparedness.

1 INTRODUCTION

The interrelationship between earthquakes and volcanic eruptions has long intrigued scientists, as seismic activity often precedes eruptions in many regions. This study investigates the potential connection between earthquake swarms and volcanic eruptions from 2000 to 2023, aiming to determine whether earthquake activity can reliably predict eruptions. The analysis will focus on earthquake magnitudes, locations, and timings in relation to volcanic events to identify potential patterns that may improve eruption predictions.

Both earthquakes and volcanic eruptions are driven by tectonic processes within the Earth's crust, yet they are often geographically and temporally linked, especially in regions like the Pacific Ring of Fire. Despite many studies, a consistent predictive pattern remains elusive. This research aims to assess to what extent earthquake swarms impact volcanic eruptions, contributing to the development of early warning systems and risk mitigation strategies for areas vulnerable to both seismic and volcanic hazards.

2 LITERATURE REVIEW

I. How Earthquakes and Volcanic Eruptions occur

To understand the interrelationship between earthquakes and volcanic eruptions, we first need to examine how these geophysical events occur. According to Kanamori and Brodsky (2004)[1], Earth's tectonic plates are constantly sliding past each other with only millimeters of movement per year. However, when the edges of two plates contain enough strain, this strain sends waves in the form of earthquakes. Earthquakes do not occur in regular intervals.

A critical factor for volcano eruption, according to Cashman and Sparks (2013)[2], depends on how magma is stored in the volcano, but magma is generally stored in small chambers and is constantly created by melting the Earth's crust and mantle. An eruption can be triggered when a volcano mobilizes its stored and crystallized magma and/or transports the melted magma into higher parts of the volcano via pressure and gas buildup. Finally, other triggers for volcanic eruption include the buildup of pressure in crystallized magma or tectonic triggering. These tectonic triggers occur primarily around subduction zones, where the stress from plate movements causes a ripple effect.

II. Subduction Zones and Hotspots

To understand how subduction zones can affect volcanic activity around hotspots, we should first discuss what these terms mean. According to Encyclopædia Britannica[9], a subduction zone is an area where two tectonic plates meet. Specifically, the term "subduction" refers to how the older, denser material of a seabed tectonic plate is pushed underneath the newer, less dense material of a continental plate. These zones are usually formed between continental plates and seabed plates, but they can occur when any two plates meet convergently.

A hotspot, or a hotspot volcano, is formed by rising heat within the Earth's mantle. According to NOAA[10], plumes of mantle magma rise from the depths of the Earth's mantle to the surface, partially melting on its way. The pressure created by this rising and melting of molten rock can cause volcanic eruptions, called hotspot volcanoes.

3 METHODS AND TOOLS

I. Data Gathering and Cleaning

The National Oceanic and Atmospheric Administration (NOAA) has a sub-organization called the National Centers for Environmental Information (NCEI) that houses datasets for natural hazards. We accessed the earthquake and volcanic eruption datasets through their website[1], filtered the dataset for data between 2000 - 2023, and downloaded the datasets as two tsv files.

After the datasets were downloaded on the NOAA website, the datasets were loaded into a Jupyter Notebook. From there, the "Year", "Dy", and "Mo" were combined into one Date column. The "Location" column was split into "Location", "Name", and "Country" to follow the other dataset. Only columns that described the features of the geophysical event were selected for the dataset. Finally, both datasets were merged for further analysis. Once the dataset was loaded into Excel, the subregion table from Wikipedia[2] was used to VLOOKUP the country between datasets and the subregion table to create another column for the subregion.

I. Geographical maps via Tableau and ArcGis

To investigate regions with potential geophysical activities we used ArcGis map viewer to visualize tectonic boundaries on the world map to see divergent and convergent areas. Color was used to differentiate the two types of boundaries to enhance visual understanding. We also implemented two geographic maps using Tableau for each phenomenon. The goal is to explore potential correlations between volcanic hotspots and seismic activity. We analyzed earthquake data using latitude and longitude for accuracy, layering country boundaries to identify regions of seismic activity over the past 23 years. Similarly, volcanic eruptions were analyzed by country, with precise location data from latitude and longitude. To deepen the analysis, we also considered the average elevation and types of volcanoes to assess whether these factors influenced the relationship between volcanic and seismic events.

Geographical maps are ideal for visualizing spatial patterns, providing an overview of regions that warrant further analysis. We used maps for both volcanoes and earthquakes to directly compare their locations and identify similarities or disparities. An alternative, such as a choropleth map, would have limited our ability to add layers like volcano types or outline tectonic boundaries, as it focuses more on broad regions like countries.

II. Time-series Analysis (line chart) in Tableau

To demonstrate the timeline of earthquakes and volcanic activity, two line graphs were used in Tableau: one for earthquakes and one for volcanic activity. The earthquake graph measured magnitude and the volcanic activity graph measured the number of volcanic activity. Both graphs used color to distinguish sub-regions and used a month-year timeline as the x-axis. The alternatives included a scatter plot or area chart, but the line graph was the best option to visualize the magnitude of an earthquake. The scatter plot would focus on the count of earthquakes or volcanic activity, which was not the objective of this graph, and the area chart may make it difficult to distinguish the magnitude of earthquakes.

Additionally, a stacked bar chart was used to display the count of volcanic activity and earthquakes that occurred during the year. The graph contained the y-axis for count of activity and the x-axis for year, and color was used to distinguish the type of geophysical event. Alternatives included a line graph and scatter plot. The line graph did not make it easy to compare years together without interactivity, and a scatter plot would have too much white space.

III. Network chart with Python

To investigate the relationship between earthquake activities and/or swarms that are related to volcanic eruptions globally, Python, networkx, Pandas, Matplotlib and Plotly libraries were used [6]. Networkx was used to create and manipulate networks by providing tools to manage nodes (countries, earthquake events, and volcanic events) and respective edges (relationships between the nodes). Colors and labels were added to aid the understanding within the chart and make it easier to understand the overview differences in densities in relation to countries and events. Pandas was used to manipulate and clean the dataset collected from NOAA to reduce noise within the dataset. Overall, this form of visualization provides a clear dynamic image of key connections, clusters and any hidden patterns that may not otherwise be prominent with a general map visualizations.

IV. Scatter plot in Orange

To further investigate the interrelations, Orange data mining tool was utilized to generate a scatter plot

[1] https://www.ngdc.noaa.gov/ngdc.html

[2] https://en.wikipedia.org/wiki/List_of_countries_and_territories_by_the_United_Nations_geoscheme

visualization. The scatterplot allows for comparison between the strength of the earthquake's magnitude (MMI) to volcanic's intensity (VEI), using a filtered dataset from NOAA that showed specific volcanic and earthquake activities that were recorded and studied to be linked. This provides a more straightforward understanding of the relationship between the two event's intensities in relation to each other. Points on the plot were color coded according to MMI and VEI intensities and the size represented the VEI to allow for immediate understanding of the correlation. Jittering was also applied to spread out the points and reduce overlap of similar values, as well as labels were added to provide a temporal perspective to the graph.

4 DISCUSSION

I. Spatial Correlation

This visualization from ArcGis Map viewer shows the locations and types of tectonic plate boundaries, such as convergent, divergent, and transform. Blue lines show convergent boundaries (earthquakes) and red lines show divergent boundaries (volcanic activities).

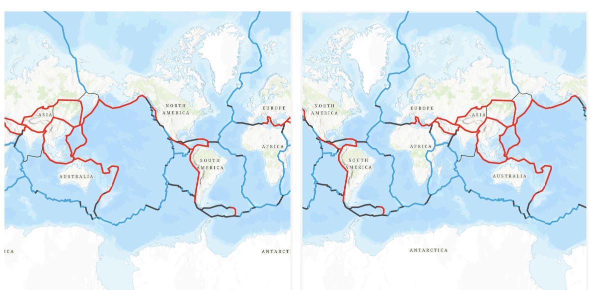

Figure 1: Locations and types of tectonic plate boundaries

The Figure 2 map created in Tableau shows that earthquakes have a clear alignment with tectonic boundaries, while volcanic eruptions had a more scattered distribution. This suggests that volcanic activity depends on additional factors beyond tectonic stress, such as magma composition and crustal properties. By combining datasets and visualizing them on geospatial maps, it highlighted regions of high geophysical risk and provided insights into the complex interactions between tectonic movements and volcanic activity.

II. Subduction Zones

To better understand how these events are linked, we looked at tectonic subduction zones and volcanic hotspots. Using data from the NCEI division of NOAA to place the locations of earthquakes and volcanoes in the years 2000-2023 on a map of the world, seen in Figure 1, below, we can see how the locations of these events correlate with each other as well as with subduction zones and volcanic hotspots.

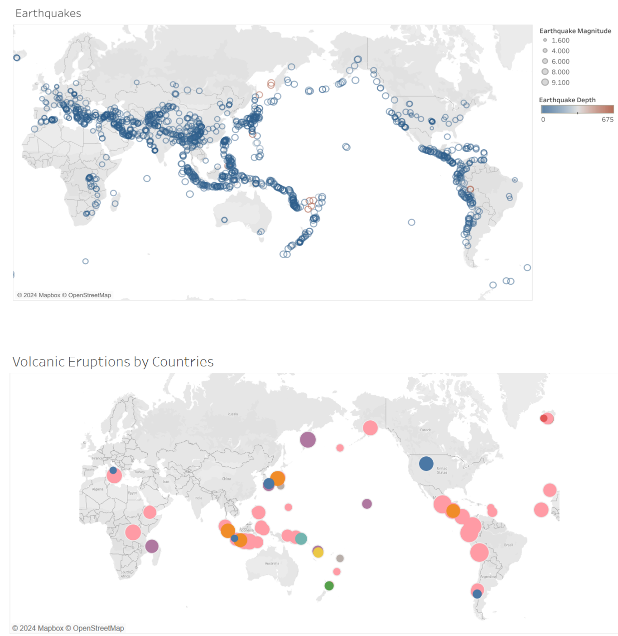

Figure 2: The top map shows earthquake locations. Earthquake magnitude is represented by the size of the points and depth is represented by color. The bottom map shows volcanic eruptions by country, categorized by type

This data shows that geophysical events can occur in a wide range of areas, but they do follow some obvious trends. The locations of earthquakes almost exactly mirror the locations of subduction zones and tectonic plates as seen in figure 1. The pattern seen here around the Pacific Ocean on the east coast of Asia and Australia and the west coast of the Americas is famously known as the Ring of Fire. However, there is also a significant subduction zone through the center of the Asian continent, southern Europe, and Northern Africa. The frequency of earthquakes along these zones is much higher than anywhere else in the world.

Interestingly, no correlation was found between the location of the earthquake and the depth nor between the depth and the magnitude. Most earthquakes register around 5 on the Richter scale, which is why we see so many similarly sized points on the map. Likewise, most earthquakes occur at depths less than a couple hundred feet. While, when it comes to volcanoes along the subduction zones, we can see that they do not perfectly trace the subduction zones like the earthquakes do. However, they are close enough that the tectonic activity causes a ripple effect that can cause magma movement and potentially trigger volcanic eruptions.

III. Hotspot Activities

At first glance at the maps in figure 2, a direct correlation is not immediately evident between volcanic hotspots and earthquake occurrences. This is evident in North America, where seismic activity is widespread compared to the relatively few volcanic eruptions, such as those at Yellowstone Caldera and Redoubt Volcano in Alaska. Both volcanoes are known to have an indirect relationship with seismic activity, primarily due to magma movement and tectonic shifts that precede eruptions, causing tremors. For instance, seismicity at Redoubt Volcano remained elevated during its 2009 eruption, signaling magma movement and lava dome growth[7]. Similarly, Yellowstone's seismic activity, tracked via tomography, reveals magma and heat flow beneath the surface, contributing to its geothermal features and periodic tremors[8].

Interestingly, stratovolcanoes, such as Mount Redoubt, seem to be more frequently associated with seismic activity, as seen in the map's pink circles. A similar pattern is evident in Mexico and Central America (Costa Rica, Guatemala, El Salvador, and Colombia), where the concentration of volcanic activity corresponds with higher seismic occurrences. However, this pattern does not hold everywhere. For example, despite the high concentration of volcanoes in Indonesia, there is a striking lack of earthquake activity in the region. To better understand these dynamics, it would be valuable to track how seismic activity and volcanic behavior evolve over time.

IV. Temporal Patterns

To investigate the temporal patterns between the geophysical phenomena, we first must discuss the timeline of volcanic activity and earthquakes between 2000 - 2023.

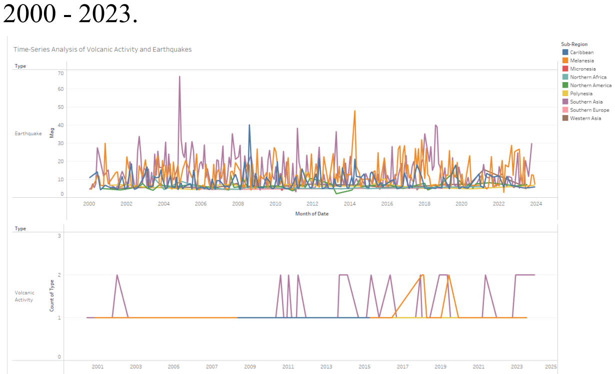

Figure 3: General Timeline of Earthquake and Volcanic Activity

The above figure demonstrates the timeline of earthquakes and various volcanic activity with respect to subregion and earthquake magnitude. Following the data cleanup, the dataset was loaded into Tableau for a timeline. For the timeline, color represents a subregion, size represents the earthquake magnitude, and the timeline is on a yearly basis. Interestingly, volcanic activity does not seem associated with the subregion nor magnitude of earthquakes.

Additionally, we wanted to display the number of earthquakes in comparison to the number of volcanic activity. Figure 4 demonstrates the timeline of earthquakes and various volcanic activity with respect to the number of earthquakes and volcanic activity within a given year. Volcanic activity does not seem associated with the number of earthquakes that occurred during the year. Although there is no direct temporal relationship, there seems to be some evidence of an overlap between the two events. It may be valuable to also examine the interconnectivity between volcanic activities and earthquakes through shared location features.

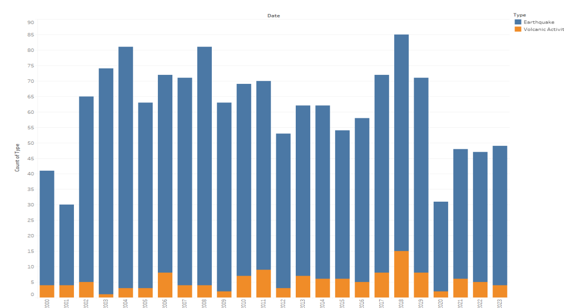

Figure 4: Stacked Bar Chart of Volcanic Activity and Earthquake

V. Interrelationship between Earthquakes and Volcanic activities

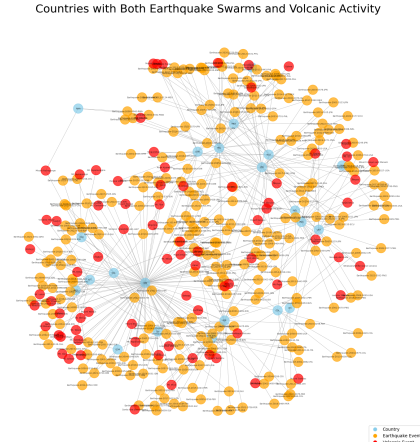

Figure 5: Network Graph showing the relationship between Countries and their Earthquake swarms and Volcanic activities

To dive further into how these two phenomena interrelate, figure 5 represents an undirected network visualization graph that shows the relationship between countries and their respective connections to earthquake and volcanic activity events. Each node represents countries (sky blue), earthquakes (orange), and volcanoes (red), while the edges represent the proximity relationship. Network analysis was used because it provides a more dynamic way of extrapolating the interrelationship globally. Figure 5 further highlights the specific relationship between the geophysical events that link the two activities together, as the proximity of the nodes indicates how many volcanic eruptions are preceded by earthquake swarms.

Countries with high centralities, like Japan, Hawaii, and Chile, represent regions with frequent activities due to their spatial relationship to tectonic plates. The graph further shows dense clustering in areas related to the Pacific Ring of Fire, an area where earthquake swarms and volcanic eruptions occur frequently due to increasing tectonic stress. This ties into the findings mentioned in figure 2, above that show an overlap of some location in the subduction zones with volcanic activities. Hence, it can be deduced that subduction zones are more likely to be related to earthquake activities that potentially lead to volcanic eruptions [3].

Following that, there are nodes like Alaska, Indonesia, and Iceland that are isolated, potentially due to the dynamics of being in hotspot areas versus regions where tectonic stress is greater. However, some other isolated nodes may indicate that there are no clear relationships between the events. This again, may relate to external factors that result in the two geophysical events acting independently. A reason for this may be due to the differences in geological conditions, such as magma-driven eruptions in hotspot regions caused by fault slips [4]. This potentially explains why there is not a strong correlation between the locations of earthquake activities and volcanic activities in some regions as opposed to others.

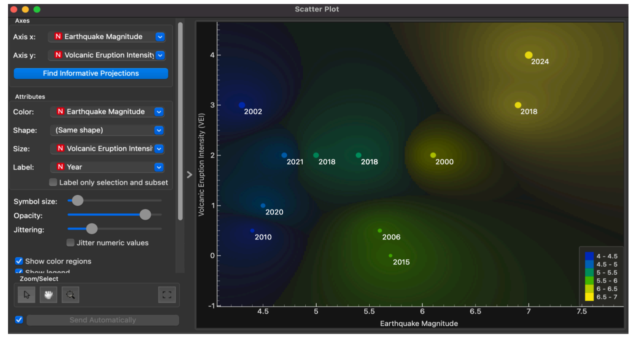

Figure 6: Scatter Plot of Earthquake Magnitude vs. Volcanic Eruption Intensity (VEI) from 2000-2024

In further trying to understand the interrelationship from a different perspective, we used a scatter plot to compare the MMIs and VEIs. Figure 6 shows the interrelationship between the magnitude of earthquakes and the intensity of volcanic eruptions according to the data collected from NOAA. This scatter plot indicates that the higher the magnitude of the earthquake, the volcanic eruption intensity subsequently increased. The highest for both is in 2024. According to the dataset and interactive scatterplot, this point represents the event that occurred in Kamchatka Peninsula, Russia [5], where a 7.2 magnitude earthquake resulted in an eruption of the Shiveluch volcano in Ust-Kamchatsk with a VEI score of 4.2. Although spatial locations of these events do not always overlap, the behavior of some volcanic eruptions are dependent on the seismic activities in the respective area. This suggests that there is some correlation in terms of the strength between them, coupled with other geophysical factors, that may aid in more accurate monitoring and warning systems for volcanic activities.

5 LIMITATIONS

I. Data gaps and Geological complexities

Datasets obtained from NOAA may have contained some gaps in information regarding remote regions, which reduces the accuracy of global interactions between earthquake activities and volcanic activities. Also, the lack of reporting of events in some regions could lead to the gaps within the data quality. The dataset from NOAA also contained null data in the month column, which had to be dropped in the time-series analysis. Also, due to the dynamic nature of volcanoes and earthquakes, it should be noted that various external factors impact their intensities, trends, and occurrences that could not be captured in the dataset or discussed. This complexity in nature limits the generalizability of the findings.

II. Visualization Limitations

For visualization methods like network analysis and scatter plots, the results may be oversimplified due to the data filtering process that is needed. This could potentially overlook the details of the relationship between the two activities. For the time-series analysis, the earthquake line chart may look crowded because of the number of subregions included, which may affect obtaining precise data points from other subregions. Color on both line charts may be changed to a range, but to avoid color confusion with the number of subregions used, this was not implemented. Finally, the stacked bar chart may make it difficult to properly compare with numbers, but we believe using the size of each category should suffice. For the maps generated with Tableau, due to the number of events and similarities in regions, there is quite an overlap of points, which may make it a little difficult to distinguish certain regional points.

III. Future Considerations and Improvements to Dataset

To improve the reliability of volcanic-earthquake predictions, future researchers should aim to fill in the gaps in the dataset for smaller regions. This can be done by potentially gathering and merging datasets from different earthquake/volcanic regional centers, instead of using a global dataset. As well as explore more geophysical variables that impact the occurrences of these activities, to ensure a more holistic understanding of their relationship. Additionally, future researchers may also gather data points for a longer period of study to ensure that they have a lot of earthquakes and volcanic eruptions associated with each other.

6 CONCLUSION

Overall, this project demonstrates promising insights into the interplay between earthquakes and volcanic activities. The spatial and temporal analysis revealed that while there is some correlation between the two events that could help disaster preparedness, there are some inconsistencies across regions where other geophysical factors should be explored. Our findings further suggest that subduction zones, for example, the Pacific Ring of Fire, are linked with higher frequencies of earthquakes and volcanoes due to tectonic stresses, as opposed to regions like Indonesia and Alaska which are located more in hotspot regions. Furthermore, although earthquake swarms show a potential indicator of volcanic activity, more factors and datasets are required for further investigation into the trends.

For practical use, this analysis can contribute to real-world applications of disaster risk management, develop predictive models to improve predictions of volcanic eruptions following seismic events and implement evacuation plans accordingly. This is particularly helpful for communities located near tectonic boundaries and subduction zones, as there is a stronger correlation and predictability nature between seismic events and volcanic activities.

7 REFERENCES

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