Spatiotemporal Modeling of Lava Dome Evolution of Mt. Mayon during its 2023 Eruption using Remote Sensing Data

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Keywords: 2023 Mayon eruption, lava dome, thermal images, Landsat, Sentinel-2

Abstract

Numerous lava dome construction and destruction processes were observed during the 2023 Mayon Volcano activity from 08 June until 08 December. Studying the lava dome development cycle of active volcanoes similar to Mayon Volcano is crucial because destruction phases of lava domes are associated with the generation of pyroclastic density currents (PDCs) and rockfalls. Since ground surveys to study the summit lava dome are dangerous, thermal satellite images were utilized to determine the evolution of the lava dome during the 2023 eruption. Bands 7-6-5 of Landsat 8/9 and bands 12-11-8A of Sentinel-2 were acquired to construct false-color images of Mayon during its 2023 eruption. Images with clear thermal anomalies were selected to illustrate and construct an imagery time-lapse of the lava dome processes during the eruption. From the selected satellite images as well as reports from the Philippine Institute of Volcanology and Seismology (PHIVOLCS), five constructive phases and four destructive phases were identified from 20 August 2022 to 08 December 2023. The constructive phases were marked by the slow growth of the lava dome, whereas the destructive phases were associated with lava flows and PDCs resulting from lava dome collapse. As the dome is completely shed, a new one emerges, repeating the cycle.

1. Introduction

1.1 Background of the Study

Pyroclastic density currents (PDCs) were generated from the lava dome at the summit of Mayon Volcano on 08 June 2023, signaling the beginning of another eruptive phase (Philippine Institute of Volcanology and Seismology [PHIVOLCS], 2023a). Before this eruption, PHIVOLCS had been monitoring the volcano for a possible eruption since 2022. On 20 August 2022, PHIVOLCS raised the alert status of Mayon to Alert Level 1 (No Eruption Imminent) as they were able to detect slow growth of the lava dome on the summit (PHIVOLCS, 2023b). Lava dome growth further progressed, leading to raising the alert level status to Alert Level 2 (Increasing Unrest) on 07 October 2022, which was eventually stepped down to Alert Level 1 on 16 March 2023. Between August 2022 and May 2023, the lava dome increased in volume by approximately 164,000 m^3. An increase in the number of rockfall events from an average of five events/day in May 2023 to 49 events/day prompted PHIVOLCS to raise the alert status to Alert Level 2 on 05 June 2023 (PHIVOLCS, 2023a). Three days after, an increase in the number of PDCs and rockfall events led to Alert Level 3 (Increased Tendency Towards Hazardous Eruption) being raised at noon on 08 June 2023 (PHIVOLCS, 2023a). PDCs and rockfall occurred primarily in the Mi-isi (south) and Bonga (southeastern) gullies of Mayon up to two kilometers from the summit. By 10 June 2023, the pre-eruption lava dome had completely collapsed and was replaced by a new dark lava dome (Figure 1). PDCs and rockfall induced by the lava dome collapse prevailed in the next few days. The peak of rockfall incidents occurred between 14 to 16 June 2023, with 300 events per day recorded, while the generation of PDCs peaked on 15 June 2023, with 13 recorded on that day (PHIVOLCS, 2023a). This activity of Mayon continued for the following months until 08 December 2023, when the alert status was lowered to Alert Level 2 (PHIVOLCS, 2023c).

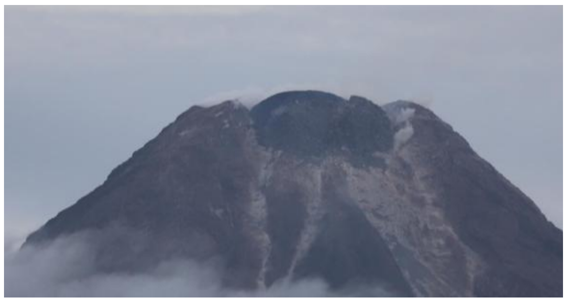

Figure 1. New Lava Dome Formation during the 2023 Mayon Eruption. Photo adapted from PHIVOLCS (2023d).

The 2023 Mayon Volcano activity is characterized as a cycle of lava dome construction and destruction. Slow lava extrusion caused the volume of the lava dome to rise. Eventually, the continuous influx of lava caused it to collapse, resulting in the generation of PDCs and rockfalls. Studying this cycle of lava dome construction and destruction can help in understanding the events of the 2023 Mayon eruption and prepare for possible hazards in future eruptions. However, the continuous volcanic activity at Mayon makes on-site assessment of lava dome development hazardous and challenging. As such, remote sensing provides a safe and effective means of monitoring these processes.

Similar volcanic activities of destructive and constructive processes were observed during the 2018-2019 activity of the Shiveluch volcano in Kamchatka, Russia, which were investigated using satellite and aerial images (Shevchenko et al., 2021). Utilizing remote sensing techniques, Digital Elevation Models (DEMs) were constructed to determine the increase or decrease in volume of the lava dome and other deposits in the area near the summit, material distribution was monitored using Synthetic Aperture Radar (SAR) data, and thermal anomalies were located using satellite infrared data. Observed thermal anomalies at volcanoes can indicate volcanic activity or a precursor to more explosive activity (Dehn and Harris, 2015). These thermal anomalies were reddish to yellowish gradients visible in thermal bands of satellite images of the volcano, which marked the emplacement of hot, volcanic deposits such as lava flows, PDCs, hot avalanches, gravity flows, and ashfall deposits. A conceptual model was then created to summarize the 2018-2019 Shiveluch eruption (Shevchenko et al., 2021).

For this study, the constructive and destructive processes during the 2023 Mayon eruption were investigated. Adapting the methods of Shevchenko et al. (2021) in identifying thermal anomalies, thermal images of Mayon during its pre-eruptive and eruptive phases from Sentinel and Landsat data were obtained and identified. From this, a time-lapse imagery and a conceptual model summarizing the 2023 Mayon activity were constructed. Photos obtained in this study were limited to the 2023 eruptive phase of Mayon Volcano, set between 20 August 2022 and 08 December 2023. Images used in this study were also limited to the acquisition dates of Landsat 8/9 and Sentinel-2, as well as the quality of images obtained on certain dates.

This study aims to answer the question, “How has the lava dome at the summit of Mt. Mayon evolved during its 2023 eruption?” Specifically, the study aims to detect the evolution of the lava dome formation and collapse of the 2023 Mayon Eruption from thermal imagery, create time-lapse imagery summarizing the evolution of the lava dome formation and collapse of the 2023 Mayon Eruption, and construct a conceptual model that shows the construction and destruction phases of the lava dome in Mayon during the 2023 activity.

Historically, the most devastating Mayon eruption in terms of casualties and hazard extent occurred in 1814 (Olan, 2015). While low Volcano Explosivity Index (VEI) eruptions (VEI 1-3) are expected in open-vent stratovolcanoes like Mayon, VEI 4 eruptions, such as the one in 1814, have a 1% chance of occurring every decade (Whelley et al., 2015). This suggests that events similar to the 1814 eruption may occur once every 100 years. If a similar eruption were to occur at Mayon, which is surrounded by densely populated municipalities, it would pose a significant threat to the lives of people living in the area would be at great danger. Therefore, the volcanic activity and behavior of Mayon require constant study and updates. Findings on the processes and deposits of Mayon will further expand the body of knowledge, benefiting the neighboring communities. Moreover, understanding the processes prior to its eruption (i.e., lava dome evolution) would also benefit in the monitoring of the active volcano.

1.2 Regional Tectonics and Geology

The Philippines is bounded by two oppositely dipping subduction zone systems comprising Manila, Negros-Sulu, and Cotabato trenches to the west, and the Philippine Trench to the east (Yumul et al., 2003) (Figure 1). Subduction processes produced magmatism, which eventually led to the formation of volcanoes across the country. Based on the recent volcano classification of PHIVOLCS, there are 24 active, 27 potentially active, and 355 inactive volcanoes in the Philippines (Delos Reyes et al., 2018; PHIVOLCS, 2023e). Active volcanoes are volcanoes with documented eruptions from the past 10,000 years. Potentially active volcanoes appear young geomorphologically but have no recorded historical eruptions. Inactive volcanoes are old, weathered volcanoes with no recorded historical eruptions (PHIVOLCS, 2023e). Given the high number of active volcanoes in the country, volcanic eruptions are very common. In recent times, some of the most active volcanoes in the Philippines have erupted. These volcanoes include Taal (active since January 2020) and Kanlaon (recently became active in June 2024).

Mayon is one of the most active volcanoes in the Philippines (PHIVOLCS, 2018). Located in Albay on Luzon island, Mayon (13°15′24″N 123°41′06″E) (Figure 4) is a stratovolcano standing 2,462 m above the Albay Gulf. The NW-SE trending San Vicente-Linao Fault cuts across the southern part of the volcano. Mayon is included in the Bicol Arc, a chain of volcanoes in the Bicol Peninsula formed from the subduction of the Philippine Sea Plate at the Philippine Trench (McDermott et al., 2005) (Figure 2). This arc also includes other active volcanoes such as Isarog and Iraya volcanoes in Camarines Sur and Bulusan volcano in Sorsogon.

Since 1616, Mayon has erupted at least 64 times with eruption styles ranging from Strombolian to basaltic Plinian, with cyclical activities beginning with basaltic eruptions followed by long-term andesitic lava flows (Global Volcanism Program [GVP], 2022). The most destructive eruption ever recorded from Mayon happened in 1814 with a VEI of 4 (Newhall & Self, 1982). The eruption buried the town of Cagsawa, killing approximately 1,200 people in the process (Hegina, 2014).

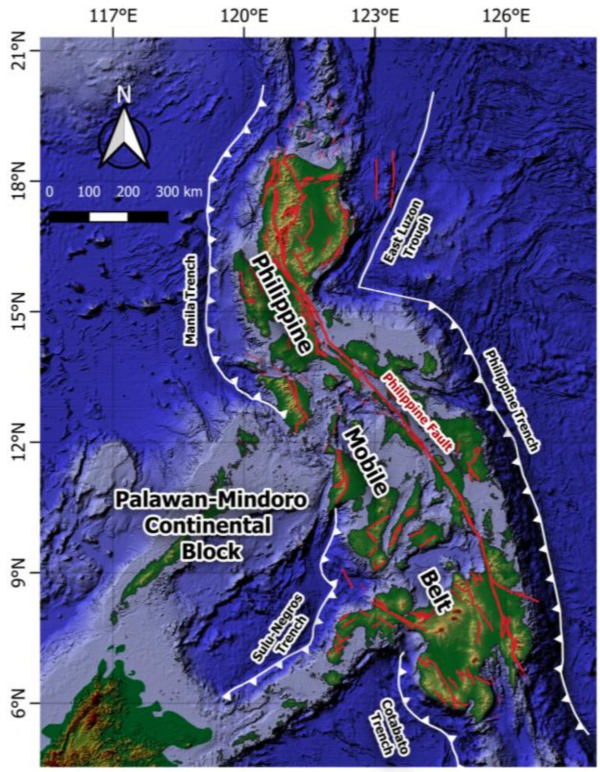

Figure 2. Tectonic setting and volcanic centers in the Philippines. Locations of trenches and volcanoes modified from PHIVOLCS (2016). The basemap is a shaded relief profile of the area generated from 3 arc-second Shuttle Radar Topography Mission (SRTM) elevation data obtained from EarthExplorer (USGS) and bathymetry from General Bathymetric Chart of the Oceans (GEBCO, 2023). Modified from Castro (2023).

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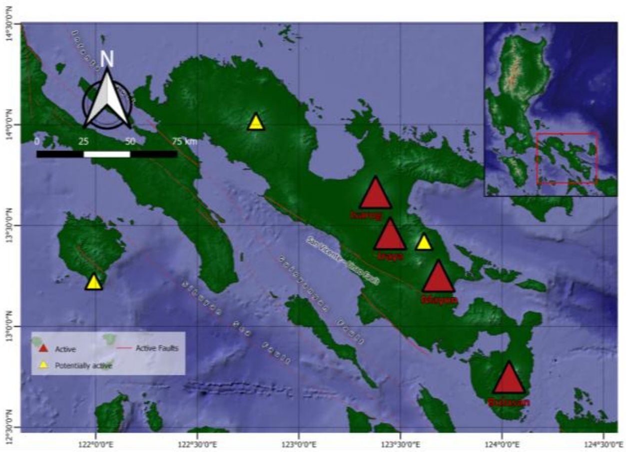

Figure 3. Map of the Bicol Arc. Locations of faults and volcanoes modified from PHIVOLCS (2016). The basemap is a shaded relief profile of the area generated from 3 arc-second SRTM elevation data obtained from EarthExplorer (USGS) and bathymetry from General Bathymetric Chart of the Oceans (GEBCO, 2023).

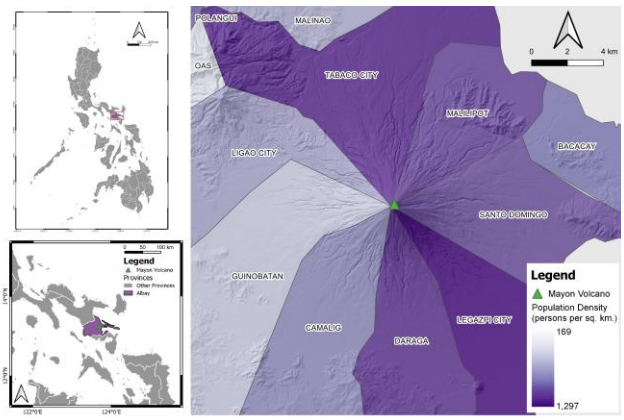

Figure 4. Location map of Mayon Volcano. DEM acquired from the National Mapping and Resource Information Authority (NAMRIA), through the University of the Philippines Resilience Institute (UPRI). Population density data from the Humanitarian Data Exchange (HDX). Adapted from Jatulan (2023)

2. Data and Methodology

This study utilized bands 7 (Shortwave Infrared (SWIR) 2), 5 (Near Infrared (NIR), and 6 (Shortwave Infrared (SWIR) 1) of Landsat 8/9 and bands 12 (SWIR 2), 11 (SWIR 1), and 8A (Vegetation Red Edge) of Sentinel-2 images acquired from EarthExplorer (U.S. Geological Survey [USGS]) and Copernicus Browser (European Space Agency [ESA]), respectively. Two sets of images were used to supplement each other, for instance, in cases where no image was available on certain dates or when an image was unusable (e.g., image noise present, or clouds and smoke of gases covering Mayon's crater). Images were filtered for dates starting 20 August 2022, when the slow dome growth was recorded and signaled the pre-2023 eruption. The end date for the search was set on 08 December 2023, when the alert level on Mayon was lowered. For the Landsat 8/9 images, the cloud cover range on the search criteria of EarthExplorer was set at 0-30%. A similar cloud cover range was set for the images acquired from the Copernicus Browser.

After the images had been acquired, they were loaded into QGIS, where they were processed to produce a false-color composite (FCC) using infrared bands 7-5-6 of Landsat 8/9 and bands 12-11-8A of Sentinel-2. The dates were then narrowed down based on the result of the processing. Only certain images were selected based on whether the anomalies were visible and those with no noise present. Table 1 shows the chosen dates and the corresponding satellite mission from which the images were acquired. The earliest satellite image is dated October 11, 2022. The pre-2023 eruption lava dome construction started on 20 August 2022. However, the satellite image on that day contained an obstructed view of the volcano's vent, and the earliest clear image of the volcano was on October 11.

Date of Acquisition mm/dd/yyyy	Satellite Mission	Date of Acquisition mm/dd/yyyy	Satellite Mission
10/11/2022	**Sentinel-2**	08/07/2023	Sentinel-2
11/30/2022	Sentinel-2	08/17/2023	Sentinel-2
02/13/2023	Sentinel-2	08/21/2023	Landsat 8/9
03/20/2023	**Sentinel-2**	09/11/2023	Sentinel-2
05/09/2023	**Sentinel-2**	**09/26/2023**	**Sentinel-2**
06/08/2023	**Sentinel-2**	10/06/2023	Sentinel-2
06/13/2023	**Sentinel-2**	**10/08/2023**	**Landsat 8/9**
06/18/2023	**Sentinel-2**	**10/11/2023**	**Sentinel-2**
06/23/2023	Sentinel-2	**10/26/2023**	**Sentinel-2**
06/28/2023	**Sentinel-2**	11/09/2023	Landsat 8/9
07/04/2023	**Landsat 8/9**	**11/10/2023**	**Sentinel-2**
07/08/2023	Sentinel-2	**11/30/2023**	**Sentinel-2**
07/13/2023	Sentinel-2	**12/05/2023**	**Sentinel-2**
08/05/2023	**Landsat 8/9**		

Table 1. Summary of dates of the selected satellite images with the corresponding satellite mission. Dates in bold are the images selected for the time-lapse imagery.

Selected satellite images were then imported into Adobe Photoshop to annotate and delineate the features pertinent to the discussion of the 2023 lava dome growth and collapse of Mayon Volcano. This was done based on classifying the thermal anomalies (based on the difference in colors in the images) qualitatively. If the anomalies are circular, they are identified as lava dome growth. If they appear to be flowing down the valleys of the volcano, they are identified as volcanic processes (e.g., lava flows, PDCs) caused by lava dome collapse. Images were further filtered, wherein those that best represented the events of the 2023 Mayon eruption were selected. Annotated images were then used to create a time-lapse imagery of the events. After analysis and interpretation of the satellite images, a conceptual model representing the 2023 Mayon eruption events was constructed.

Due to the continuous activity of Mayon volcano, ground-based validation was impossible. To compensate, observations from the false-color satellite images were compared with the official reports from PHIVOLCS. The bulletin posted by the institute provides information on the generation of PDCs produced by lava dome collapses. Through this, the observations from the satellite images can be validated.

3. Results and Discussion

This section presents the outputs of image interpretation of the false color composites of selected Sentinel-2 and Landsat 8/9 data (Figure 5). Specifically, the phases of the evolution of the lava dome in Mayon Volcano were identified as a result of the image interpretation.

3.1 Construction Phase I

As mentioned, the events leading up to the 2023 eruption started on 20 August 2022, when the slow growth of a lava dome was detected and Alert Level 1 was raised on Mayon. This marked the start of the pre-eruption phase, which lasted until 07 June 2023. On 11 October 2022, the alert level was raised again due to an increase in activity. A moderate emission of white, steam-laden plumes was observed drifting southwest of the volcano, as shown in Figure 5A, where blue smoke is visible facing southwest from the vent. A faint orange circle can be seen on the vent, representing the ongoing growth of the lava dome and the slow intrusion of magma underneath. On 20 March 2023, the alert level was lowered to 1, and a crater glow was observed, which can be seen as a circular orange anomaly (Figure 5B). The same anomaly was also delineated in the image on 09 May 2023. Volcanic activity in Mayon has decreased in April and May.

3.2 Destruction Phase I and Construction Phase II

This phase lasted from 08 to 10 June 2023. The start of the 2023 eruption was reported to have occurred on 08 June. Figure 4D shows smoke surrounding the volcano and coming from its vent. It was also reported that small-volume PDCs were generated from the volcano's summit lava dome, indicating the start of an effusive magmatic eruption and the destruction of the pre-eruption lava dome. Although a bit obscured in the photo because of the smoke, it can be slightly seen that a warm anomaly is moving SSE. On 10 June, the pre-eruption dome was completely shed and was replaced by a new one.

3.3 Destruction Phase II and Construction Phase III

After the destruction of the pre-eruption lava dome and the construction of a new one, very slow lava effusion from the summit crater was observed on 13 June, depositing lava flows and collapse debris on the Mi-isi and Bonga gullies, within around a kilometer from the crater. This indicates that the dome from 10 June began collapsing and continued until 18 June, when a new dome seemed to be forming again (Figure 5F).

3.4 Destruction Phase III

This phase lasted until October 11. In this phase, if new domes were being constructed, they collapsed immediately. There were dome collapse processes on 28 June, 04 July, 08 July, and 08 August (Figure 5G-I). On 26 September, the collapse continued, but the lava extrusions seemed to slow down. On 06 and 08 October, the collapse rate seemed to increase.

3.5 Construction Phase IV

A new dome formation may have occurred on 11 October. It was also reported that the dome collapse still occurred on the day, but it was not visible in the satellite image (Figure 5L).

3.6 Destruction Phase IV

A dome collapse was observed on 26 October and continued on 09 and 11 November. This phase lasted until 30 November, when the collapse slowed and a possible dome formation occurred.

3.7 Construction Phase V

Figure 5O shows a circular orange anomaly on the volcano vent in the image dated 30 November, indicating a possible dome formation. The same anomaly was seen on 05 December, and it was also reported that a lava dome construction occurred. No images were acquired on 08 December 2023, but PHIVOLCS lowered the alert level that day, signaling a decrease in Mayon's activity (PHIVOLCS, 2023c).

3.8 Conceptual Model of the 2024 Mayon Volcano Eruption

Observations from satellite images of Mayon are consistent with the reports and observations by PHIVOLCS during the volcanic activity from June to December 2023 (Figure 6). Prior to the 2023 eruption, Mayon Volcano's most recent activity occurred from June to October 2022, which consisted of lava dome growth and gas emission (GVP, 2023). This coincided with the Construction Phase I reported in this study. Volcanic activity of Mayon decreased in the following months before increasing activity once again, starting on 08 June 2023. PHIVOLCS recorded numerous lava flows, PDCs, crater incandescence and incandescent rockfall events, gas-and-steam emissions, and continued seismicity (GVP, 2023). PDCs, lava flows, and incandescent rockfall events were reported to have been deposited along the south (S) and southeast (SE) flanks of the volcano, specifically in the Mi-isi and Bonga gullies (PHIVOLCS, 2023a). These match the orange to yellow-orange lobes observed in the thermal images on 13 June 2023.

From 08 to 09 June and 11 to 30 June, 151 dome collapse PDCs travelling along the S (Mi-isi), SE (Bonga), and E (Basud) gullies of the volcano were recorded, coinciding with the Destruction Phase II and Construction Phase III of this study. This marks a period of high activity wherein the lava dome almost collapses immediately after being constructed due to continuous intrusion of fresh lava from the central vent. Similar activities were also observed in the succeeding months until the first weeks of October, when the intrusion rate appeared to slow down. Several lava domes were subsequently constructed and destroyed in succeeding months up until 08 December 2023, when the alert level of the volcano was lowered.

The 2023 Mayon eruption shows a series of construction and destruction lava dome growth phases. During constructive phases, magmatic intrusion along the central vent promotes the slow, gradual growth of the lava dome. Eventually, the lava dome reaches its maximum size and collapses, generating lava flows or PDCs. A fresh supply of lava then constructs a new lava dome, repeating the cycle (Figure 7).

4. Conclusions and Recommendations

A qualitative assessment of the thermal anomalies from multi-temporal satellite images and during the 2023 Mayon eruption was conducted. FCCs were generated utilizing bands 12-11-8A for Sentinel-2 and bands 7-6-5 for Landsat 8/9. These FCCs were used to produce a time-lapse imagery and a conceptual model summarizing the constructive and destructive processes involving the summit lava dome. Aside from the images acquired

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from EarthExplorer and Copernicus Browser, the Harmonized Landsat and Sentinel-2 (HLS) can also be used in future studies. It is also suggested to use Google Earth Engine (GEE) for more efficient data processing and analysis.

The time-lapse imagery of the 2023 Mayon eruption showed at least five constructive and four destructive phases. Construction Phase I occurred from 20 August 2022 to 07 June 2023. Satellite images correlate well with the volcano bulletin posted by PHIVOLCS for Mayon Volcano, reports of which are summarized (Figure 6).

FCCs were able to illustrate and detect constructive and destructive phases of the lava dome in the 2023 Mayon eruption. The satellite images were also helpful in providing remote monitoring of the volcano's activity since they correlate with the available reports on the eruption. However, the analysis is limited to the delineation of the thermal anomalies that could represent lava dome formation or collapse. Other datasets, such as Digital Elevation Models (DEMs) and Synthetic Aperture Radar (SAR), would be required to assess the movement of materials and quantitatively measure the volume increase and decrease throughout the recent eruptive phase of Mayon.

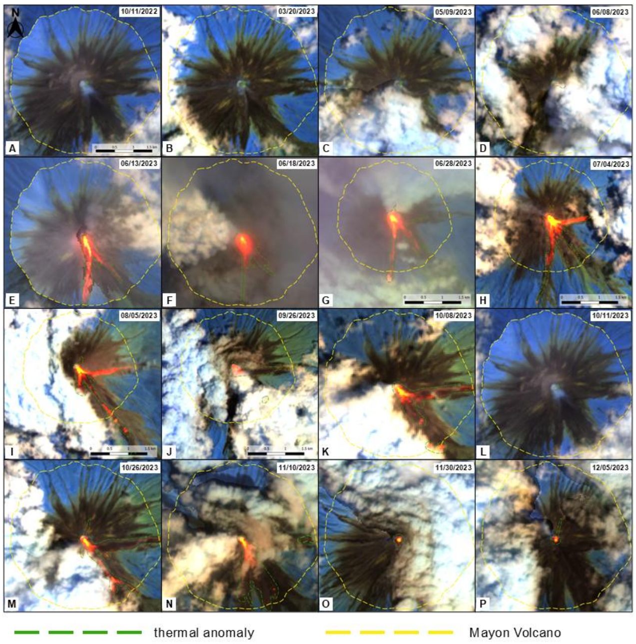

Figure 5. Time-lapse image of Mayon Volcano showing the evolution of the lava dome based on the image interpretation of processed Landsat 8/9 (A-G, J, L-P) and Sentinel-2 (H-I, K) thermal images using bands 7-5-6 and bands 12-11-8A, respectively. The band combinations produced false color images showing differences in surface temperatures of objects in the surveyed area.
A-C: Construction Phase I; D: Destruction Phase I and Construction Phase II; E-F: Destruction Phase II and Construction Phase III; G-K: Destruction Phase III; L: Construction Phase IV; M-O: Destruction Phase IV; P: Construction Phase V.

Additional methods are recommended to further understand the destructive and constructive phases of the summit lava dome of Mayon during its recent eruptive phase. Additional steps could be taken to quantify anomalies and assess thermal activity related to dome construction and destruction. Previous studies utilized machine learning techniques in quantifying the thermal activity of a volcano (Corradino et al., 2024). Moreover, it is also recommended to use other sources of thermal images aside from the ones derived from the satellite (Shevchenko et al, 2021) since data are limited by the date of acquisition of the sensors. It is also recommended to develop a methodology to automatically delineate thermal anomalies to improve the assessment of lava dome development.

DEMs can also be generated to quantify the changes in the volume of the lava dome and detect changes in the morphology of the summit during the eruption phase. Lastly, SAR data can also be utilized to measure the movement of materials during the eruption (Shevchenko et al., 2021).

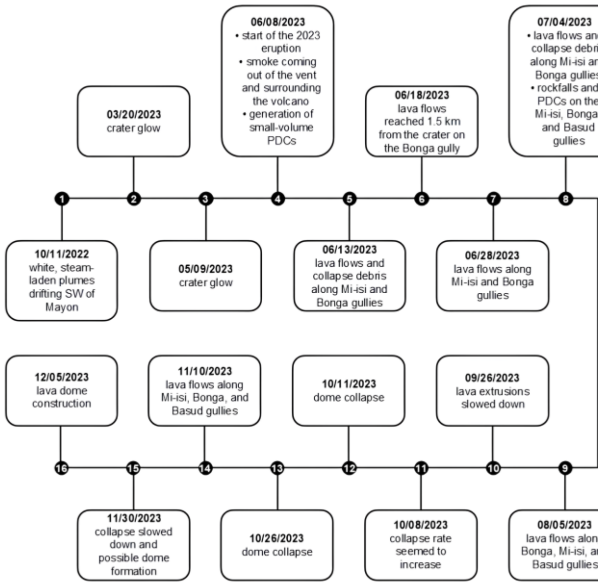

Figure 6. Timeline of events of the Mayon 2023 eruption according to reports from PHIVOLCS, with dates corresponding to the dates of selected satellite images for the time-lapse image.

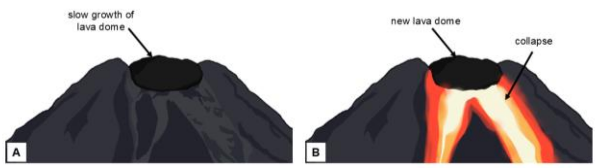

Figure 7. Conceptual model of the lava dome evolution of Mayon from its 2023 activity during its (a) constructive and (b) destructive phases.

https://doi.org/10.5194/isprs-annals-X-5-W4-2025-159-2026

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