MORPHOLOGICAL ANATOMY OF MOUNT UNGARAN: REMOTE SENSING AND PETROLOGICAL APPROACH USING HIGH RESOLUTION DRONE TO REVEAL VOLCANIC STRATIGTRAPHY AND GEOLOGICAL STRUCTURE

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Abstract: *Mount Ungaran, a stratovolcano in Central Java, Indonesia, exhibits complex morphological and structural characteristics that remain relatively underexplored. Understanding its volcano stratigraphy and internal structure is crucial for reconstructing its eruptive history and assessing potential geological hazards. This study employs a high-resolution drone-based remote sensing approach integrated with petrological analysis to investigate the volcano's morphological anatomy, structural framework, and volcano stratigraphic evolution. High-resolution aerial imagery drone were generated to analyze topographic variations, volcanic landforms, and structural features such as faults, fractures, and lava flow distributions. The remote sensing data were complemented by field observations and petrographic analysis of rock samples to characterize lithological variations and identify key eruptive phases. Structural analysis focused on fault patterns and deformation features to understand the volcano's tectonic influences and potential instability zones. Preliminary results reveal distinct stratigraphic sequences that indicate multiple eruptive stages, with significant variations in lava composition and depositional environments. Fault structures and fractures suggest interplay between regional tectonics and volcanic activity, contributing to the formation of the current morphology. The integration of remote sensing and petrology provides a more comprehensive understanding of Mount Ungaran's geological evolution, allowing for improved hazard assessment and risk mitigation strategies. The remote sensing data were complemented by field observations and petrographic analysis of rock samples to characterize lithological variations and identify key eruptive phases. Structural analysis focused on fault patterns and deformation features to understand the volcano's tectonic influences and potential instability zones. Preliminary results reveal distinct stratigraphic sequences that indicate multiple eruptive stages.*

Keywords: Mount Ungaran, Volcanic stratigraphy, Remote sensing, High resolution drone, Fault

Introduction

Volcanic stratigraphic studies play a crucial role in geothermal exploration because they allow for the identification of the rock characteristics of a geothermal system, including reservoirs, overburden, and heat sources. Stratigraphic analysis provides an understanding of eruption history, volcanic deposition patterns, and subsurface structural changes that influence geothermal fluid distribution. Furthermore, stratigraphic studies also aid in predicting the presence of fractures or permeable zones that play a role in thermal fluid transport, thereby increasing the efficiency of sustainable geothermal resource exploitation (Utama et al, 2016). Mt.Ungaran, located in Semarang Regency, Central Java, is a stratovolcano that has undergone significant erosion and has a complex geological history. The mountain formed in three stages, with the youngest volcanic phase occurring during the Late Pleistocene and Holocene. This youngest phase formed three large structural blocks of Mt.Ungaran in the south (Suhandri, 2015). Furthermore, a cluster of pyroclastic cones also formed along the edges of the older volcanic phases. Although there is no historical record of eruptions, there are two active fumarole fields on its slopes.

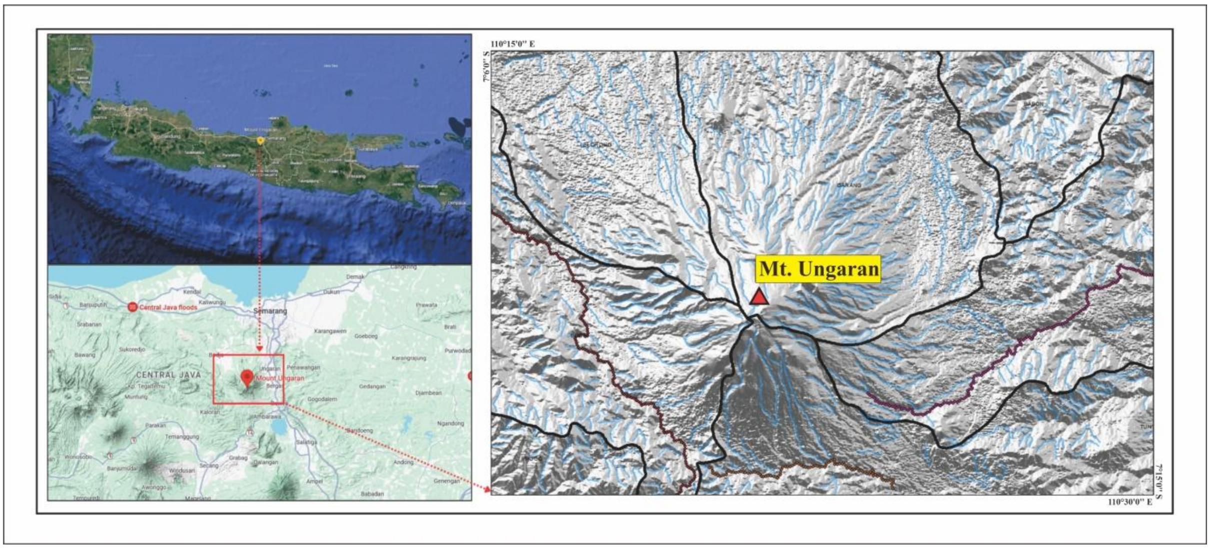

Figure 1: Location of research area

Mt.Ungaran is a volcano in Central Java, possessing complex morphology and geological history that are crucial for understanding the dynamics of volcanism in central Java (Figure 1). Access to the research area is still limited through the Gedongsongo temple tourist attraction and the Mawar route of Mt.Ungaran climbing post, making this area relatively isolated. Volcanic geomorphological studies have generally relied on conventional satellite imagery, but limited spatial resolution often makes it difficult to reveal detailed structures and stratigraphy. The development of high-resolution drone technology offers new opportunities for mapping volcanic geomorphology with greater precision, enabling the identification of micro-features such as fractures, lava domes, and young lava flows that were previously difficult to detect. Through a drone-based remote sensing approach combined with petrological analysis, a more detailed morphological study of Mt.Ungaran can be reconstructed, while linking it to the stratigraphic and structural geological context. These detailed mapping results not only contribute to the understanding of Mt.Ungaran's morphological evolution but also have implications for volcanic hazard mitigation efforts, environmental conservation strategies, and the development of geology-based ecotourism. Thus, this study aims to explore the extent to which the application of drone technology can improve mapping accuracy, reveal the relationship between geomorphology and stratigraphy and structure, and provide a scientific basis for the sustainable use of the Mt.Ungaran area.

Literature Review

Physiographically, this area is included in the northern Serayu Zone (van Bemelen, 1970). Research activities related to geomorphology and remote sensing in the vulkanik and Geothermal Prospect Area have been carried out by a number of previous researchers, including Saibi et al. (2012), Purwaningsih et al. (2020), Kurnianto et al. (2021), Mangopo & Suryantini (2025), and Kurnianto et al. (2025). The results of these studies provide a basis for the volcano stratigraphy and structural patterns of Mount Ungaran, and emphasize the importance of high-resolution drones/UAVs to monitor morphological changes, even with a low-cost approach in Claproth (1989). Mt. Ungaran has been studied partially through geophysics, geochemistry, stratigraphy, and remote sensing. However, no high-resolution drone mapping studies have been conducted specifically for Ungaran, while those for Mt.Merapi have been conducted (Grémion et al., 2023).

Several other studies involving geomorphology and remote sensing in their methodology in geothermal and volcanic areas, including studies in the Ulubelu geothermal area (Gentana et al, 2018; Gentana et al, 2019), geothermal prospect areas in Seulawah Agam Volcano (Siahaan et al, 2022; Siahaan et al, 2023), studies on the southern slopes of Mt.Merapi in the Special Region of Yogyakarta (Riswandi et al., 2020), and studies of active faults in the Mt.Lamongan complex in East Java (Nugroho et al, 2020). These research results confirm that remote sensing technology is very important in studies in geothermal and volcanic areas. By integrating petrological data and drone technology, researchers can map the geological structure and lithology distribution more accurately, thus providing a deeper understanding of Mt.Ungaran's volcanic history and stratigraphy.

Methodology

This study employed a high-resolution geomorphological mapping method utilizing drone technology. Drone-based photogrammetry was used to generate high-resolution Digital Surface Models (DSM) and ortho-photos, enabling detailed identification and analysis of geomorphological features in the volcanic field. This approach enabled high-accuracy mapping of difficult-to-reach and hazardous areas and provided data necessary for understanding the dynamics and evolution of volcanic morphology. The use of drone technology in this research proved effective in obtaining high-quality spatial data essential for detailed geomorphological analysis.

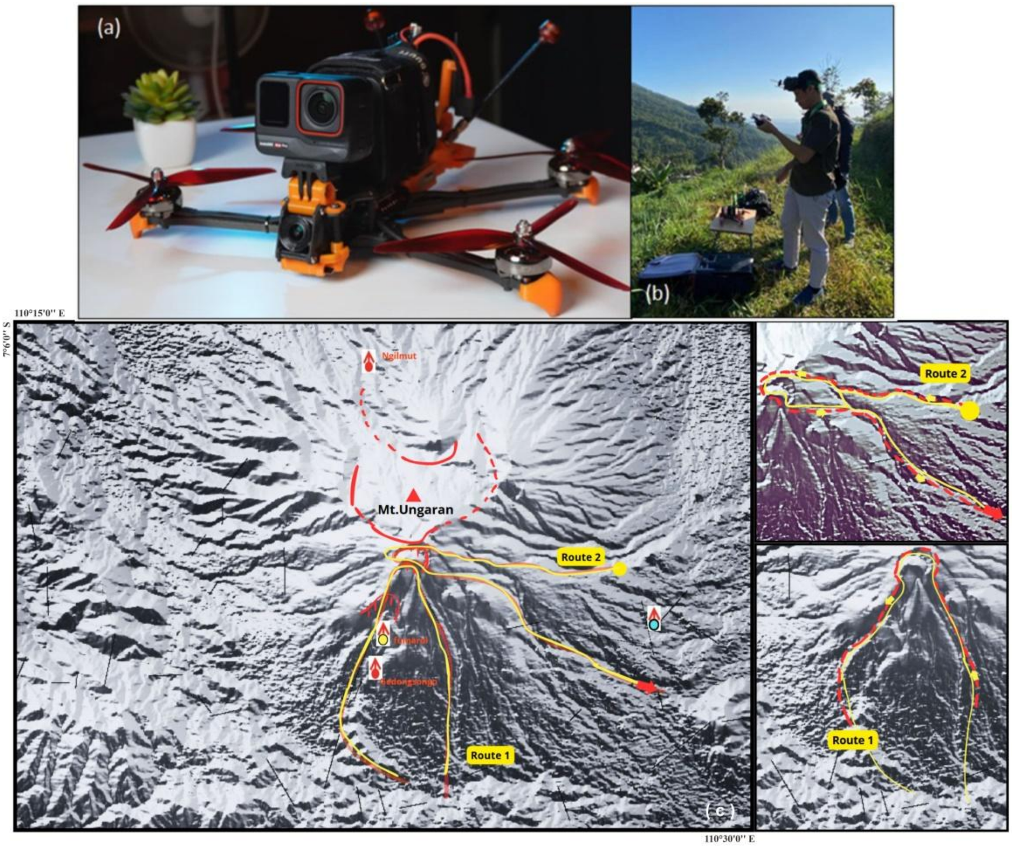

Figure 2: Krakatoa 7 Fixed-wing UAV drone (a), Drone transmitter settings (b), UAV drone route map from the foot of the mountain to the peak of Mt.Ungaran (c).

The drone used is the KRAKATOA-7 with the Rajawali type; the camera specifications and battery have high range so that it can fly up to an altitude of 3,500-4,000 meters above sea level (Figure 2ab). Data obtained from drone surveys allows for the creation of topographic maps and geological interpretations with high accuracy. Furthermore, the drone's ability to conduct repeated surveys facilitates the monitoring of geological changes such as erosion, landslides, or volcanic activity in real time. Thus, the use of drones has become an essential tool in geological research and natural disaster mitigation in the Mt.Ungaran area. Fixed-wing UAVs are suitable for large areas due to their high flight efficiency and longer operating time. Equipped with a multi-rotor drone (quadcopter or hexacopter), they are ideal for small areas with complex terrain due to their more flexible maneuverability and hovering capabilities.

The combination of supporting technologies used is a high-resolution photogrammetric camera, a camera capable of recording detailed images to produce ortho-photos and Digital

Surface Models (DSM). A real-time kinematic/post-processing kinematic (RTK/PPK) GPS device is used to obtain high-precision position and elevation data. Data processing software, such as Agisoft Metashape, Pix4D, or ArcGIS, is used to produce digital models and geomorphological analysis. Detailed specifications of the drone and equipment are provided in Table 1.

Component	**Drone Specifications**
Frame	Rajawali Krakatoa / Fold 7 inch
Motor	Emax Eco II 2807 1300KV
Flight Controller (FC)	MAMBA F722
ESC	Mamba F55 3-6S
VTX + FPV Camera	Caddx Vista + Nebula Pro Nano
Antenna FPV	ORT Pagoda Long LHCP
GPS & Receiver	Happymodel EP1 Dual Receiver Diversity
Battery 1	Li-ion GKA 6000mAh 6S2P
Battery 2	Li-ion GKA 9000mAh 6S3P
Camera	Insta360 Ace Pro
Radio Transmitter	Radiomaster Zorro ELRS 2.4GHz 250mW
TX Radio Antenna	Happymodel Moxon
FPV Goggles	DJI Goggles V2
Antenna Goggles 1	Lumenier AXII HD2
Antenna Goggles 2	ORT Digieyes V2

Table 1: UAV drone specifications

The research began with problem identification, namely the limitations of conventional geomorphological maps, and a literature review on geomorphological mapping techniques, drone use, and photogrammetry and DEM analysis methods. Next, research planning was conducted, including selecting a study location relevant to the research objectives. This location selection took into account topographic conditions, accessibility, and environmental factors that could affect the quality of the mapping results. This stage is crucial to ensure that the mapped area truly represents the phenomenon being studied while minimizing potential technical challenges in the field. Furthermore, planning also included designing the drone's flight path and determining the software used for data processing. The flight path was designed taking into account altitude, speed, and image overlap to produce accurate and consistent data. With careful planning, geomorphological mapping using drones is expected to produce high-quality data that can be used to support research interpretation.

The drone flight follows two routes, namely route 1: the drone flies from the base of Bandungan - Perantunan - Pos Watu Omah - Pos Watu Jajar - Puncak Bondolan - Puncak Botak - Puncak Tedeng - down to the Gedongsongo temple area - geothermal manifestations of fumaroles and hot springs; and route 2: the drone flies from the base of Umbul Sidomukti - climbing to Camping Mawar - Pos 2 Kinataran - Pos 3 Pronojiwo – Mt. Ungaran crater - Puncak Bald - down again to Pos Mawar (Figure 2c).

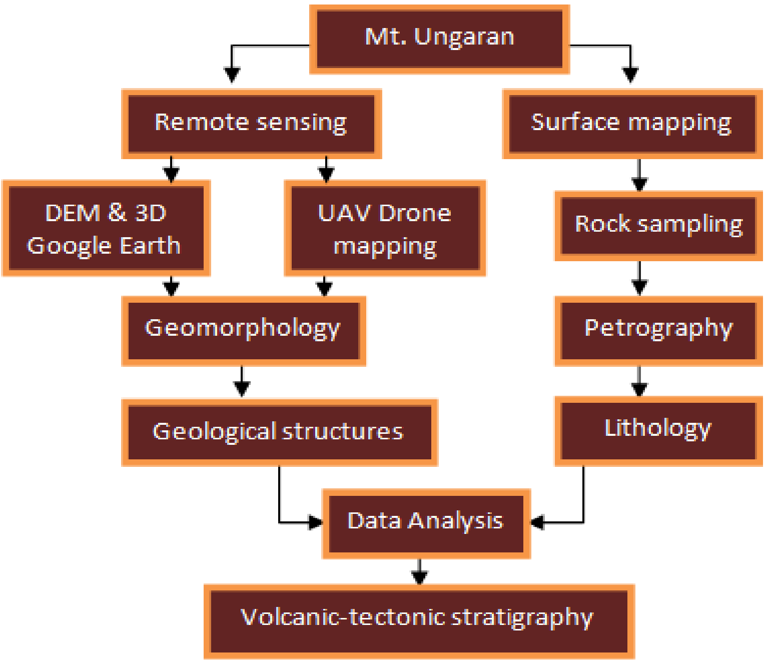

Figure 3: The mainframe of research

The next stage is data acquisition using drones to produce high-resolution aerial photographs supported by Ground Control Points (GCPs). The data is then processed through spatially corrected photogrammetry. The obtained data is analyzed to interpret landform structures and structural parameters, as well as to identify volcanic rocks in difficult-to-map areas.

The analysis results are then validated through ground checking and comparison with petrographic data. The research will produce high-resolution geomorphological images, a stratigraphic model of Mt.Ungaran, and applicable recommendations for geological purposes, disaster mitigation, and regional planning. The entire research process is outlined in a schematic (Figure 3).

Result and Discuss

1. Lithology features

The application of high-resolution drone technology to geological and geomorphological mapping of Mt.Ungaran provides a significant increase in accuracy compared to conventional satellite imagery. Drones are able to produce images with much more detailed spatial resolution and can be adjusted in altitude and flight paths according to research needs.

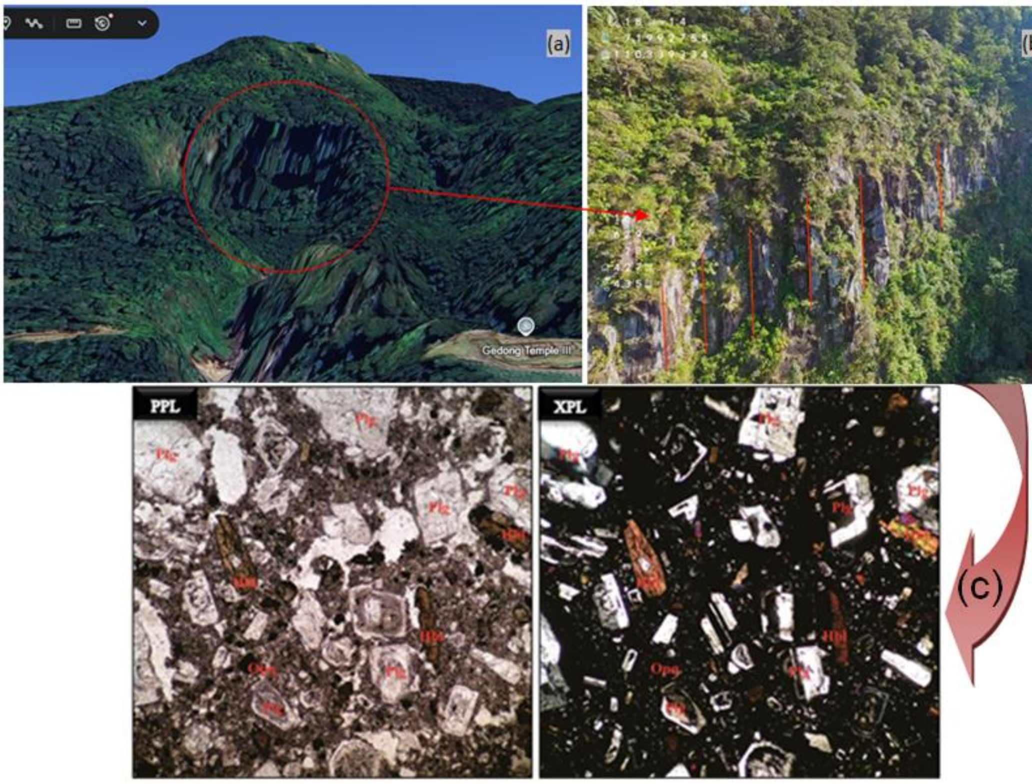

Figure 4: Comparison between high-resolution drone photograph (b) and Google Earth image (a) of the graben structure shows columnar intrusive rocks. Appearance of hornblende andesite in thin section observation (c)

Identification of small morphography units, geological structures, and rock cracks is now possible using drones. In addition, the use of drones also provides flexibility in data acquisition time without having to wait for satellite recording schedules, thus producing up-to-date data with high accuracy. This opportunity accelerates the process of stratigraphic analysis, interpretation of geological structures, and understanding the geomorphological dynamics of Mt.Ungaran.

The intrusive rocks found in the research area have macroscopic characteristics of gray, massive, holocrystalline, subhedral, porphyritic. The mineral composition is dominated by plagioclase, hornblende, and quartz. Petrographic observations were carried out at 10x magnification on the ocular lens and 4x on the objective lens; it is known that there are minerals, including plagioclase, hornblende, opaque minerals, and a glassy groundmass. The vitrophyric texture is where minerals are embedded in a glassy groundmass. The mineral composition is Plagioclase (44%), Hornblende (12%) and Opaque Minerals (magnetite) (3%). Based on the QAPF Classification for volcanic rocks (Streckeisen, 1976), the rock name is hornblende andesite (Figure 4).

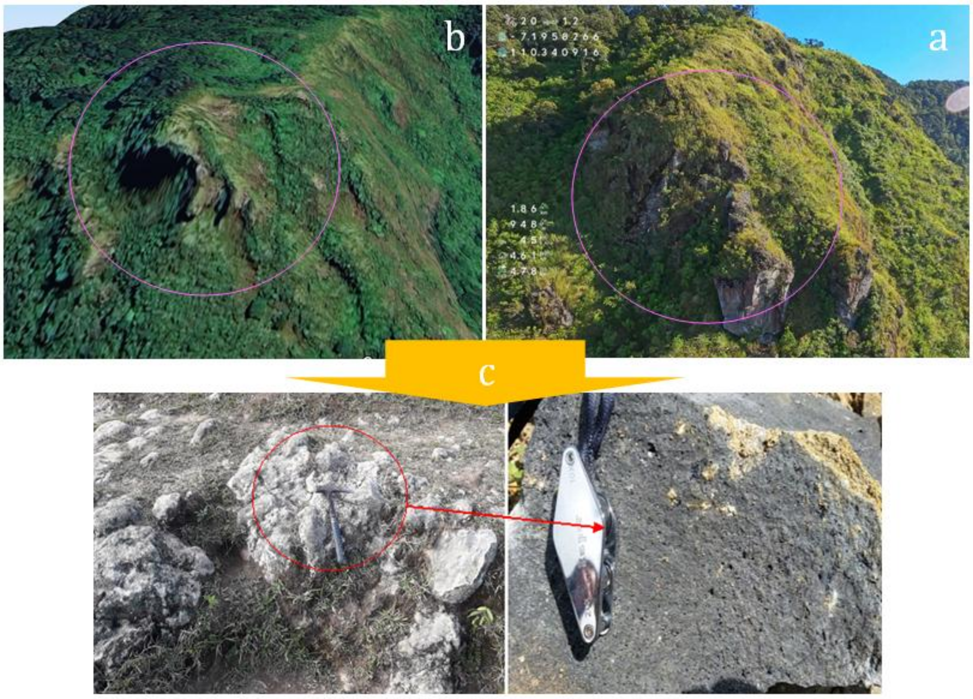

Figure 5: Comparison between high-resolution drone photograph (b), Google earth image (a) of lava (a), and andesite lava outcrop (c).

This extrusive lava rock represents the youngest lithological unit in the study area, located on the crater wall of Mt.Ungaran on the southern slope (Figure 5). It is located at an elevation of 1,100 meters and exposed off the hiking trail, making it unmapped by conventional geological mapping. For comparison, the same rocks are exposed at the bottom of the fumarole manifestation in the Gedongsongo temple area. Macroscopic observations of the rocks are gray, massive, hypocrystalline, medium phaneritic (1mm-5mm), subhedral, equigranular. The dominant mineral composition is pyroxene and plagioclase. This unit, when compared with the Geological Map of the Magelang and Semarang Sheet (Thanden et al., 1996), is included in the Mt.Ungaran Lava, which is of Quaternary age (Qls).

Petrographic analysis of the Mt.Ungaran rock samples shows a porphyritic texture, characterized by the presence of plagioclase phenocrysts (±42%) and hornblende (±37%) embedded in a finer-grained groundmass (±20%). The presence of opaque minerals in the form of magnetite (±3%) also enriches the rock's mineral composition. Based on the QAPF classification (Streckeisen, 1976), the composition indicates that the rock belongs to the andesite group.

The presence of plagioclase as the primary mineral reflects the early crystallization of intermediate magma, while hornblende as an amphibole mineral indicates that the resulting magma had a relatively high volatile content (especially H_2O). This condition is important because it is directly related to the nature of the eruption. Magma with high water content tends to produce more explosive eruptions due to the release of gas during decompression. Meanwhile, the porphyritic texture indicates a two-stage cooling process: crystallization of phenocrysts within a deeper magma chamber, followed by rapid solidification of the groundmass as the magma rises to the surface. This strengthens the indication of the presence of a shallow magma chamber beneath Mt.Ungaran, which plays a role in regulating the dynamics of volcanism.

2. Hydrothermal alteration and geothermal manifestations features

Research in the Mt.Ungaran area has identified several hydrothermal features and strong alteration zones, supporting the presence of volcanic activity that still exhibits thermal manifestations. Types of alteration found at the surface include argillitization and chloritization, which become stronger at depth (Listyani & Budiadi, 2017).

Figure 6: Drone image of fault indications in Kali Item with a strike/dip fault plane of N200ºE/50º, associated with alteration zone and up flow manifestations.

In the Mt.Ungaran area, several hydrothermal features and alteration zones have been identified, characterized by the presence of fumaroles and changes in vegetation hues, as recorded by UAV drone photography (Figure 6). Vegetation spots indicate that areas with changing vegetation hues or unique vegetation distributions correlate with hydrothermal alteration and geothermal manifestations. This zone shows soil discoloration and vegetation degradation, indicating intense hydrothermal alteration. This phenomenon is also related to the fault or fracture structure that serves as a pathway for the emergence of upwelling manifestations in the Ungaran volcanic geothermal system. Therefore, the observed vegetation changes, such as relatively sparse vegetation or varying leaf color, are likely caused by the effects of thermal or hydrothermal gases and fluids. This condition also supports geological and geochemical research that the Ungaran volcanic geothermal system still exhibits residual activity and fairly clear alteration zoning.

3. Geomorphology and fault features

Geomorphological mapping using UAV drone technology on Mt. Ungaran allows for detailed identification of the volcanic surface that was previously difficult to observe using conventional satellite imagery, such as fractures, lava domes, young lava flows, and small structures resulting from eruptions and deformation (Figure 7a). The high-resolution image not only facilitates the separation of stratigraphic units based on their shape, texture, and superposition, but also opens up opportunities to interpret the relationship between geomorphology and geological structures, such as fracture orientation, intrusion pathways, and weak zones that control volcanic activity. Thus, UAV drone mapping clarifies the relationship between volcanism, stratigraphy, and the geological structure of Mt.Ungaran.

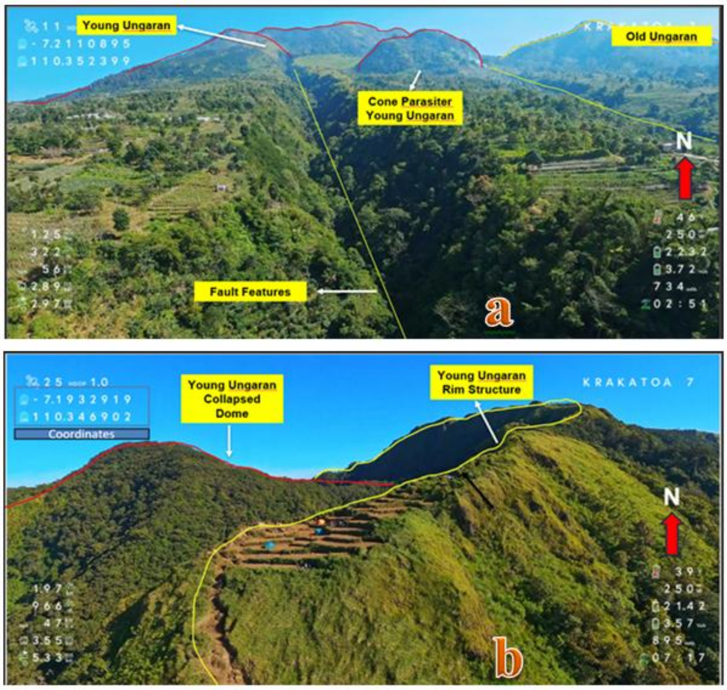

Figure 7: High resolution images show (a) fault features in the Bandungan River associated with parasitic cones from the young Mt.Ungaran and (b) collapsed dome and rim structure of young Mt.Ungaran .

The collapse structure on the dome of young Mt.Ungaran was formed due to the slope instability process triggered by the nature of the dome's constituent materials which are brittle and easily fragmented. The andesite to dacite lava that composes the dome of young Mt.Ungaran has high viscosity, so that the lava flow tends to accumulate around the eruption center and forms a steep dome morphography that can be traced in the eastern to southeastern sectors of the mountain body (Figure 7b). The dome collapse is controlled by radial and concentric fractures due to magmatic pressure from the eruption center resulting in a steep slope with a wide distribution of collapse blocks.

4. Volcanic stratigraphy

The appearance of young and old rocks from Mt.Ungaran in the field survey using drones is clearer than relying solely on available geological maps. The stratigraphic position from various observation directions, both vertically and in the lateral distribution of older and younger rocks, is more clearly visible, reflecting the actual conditions in the field.

Mt.Ungaran is a Quaternary composite volcano that developed gradually from older to younger phases. The younger phase formed at the end of the Pleistocene Epoch (approximately 0.3–0.27 million years ago), after part of the old Ungaran volcano collapsed northwest–southeast due to circular fault activity. This younger phase produced andesitic lava flows, pyroclastic breccia, and ash deposits that covered the middle to lower slopes. These volcanic products formed a young volcanic body with a rim that marks the natural boundary between the upper part of the mountain and the older outer slopes. The young Mt.Ungaran rim developed unevenly due to volcanic processes occurring above a weak zone and being cut by a fault system. The northwest–southeast (NW–SE) and northeast–southwest (NE–SW) trending geological structures influenced the direction of eruptions and the position of magma outflow, resulting in asymmetrical rims.

The use of high-resolution UAV drones provides significant advantages in studying the morphology of the Mt.Ungaran rim, especially in areas covered by vegetation and difficult to access. Interpreting field data and UAV image indicates that the young Mt.Ungaran rim is composed of a combination of dense andesitic lava, pyroclastic breccia, and overlapping lahar deposits. The southern and western rims exhibit sharp ridges with high relief. These areas are composed of hard, erosion-resistant lava. In contrast, the eastern and northern rims appear more gently sloping due to their composition of easily eroded breccia and volcanic ash. (Figure 8).

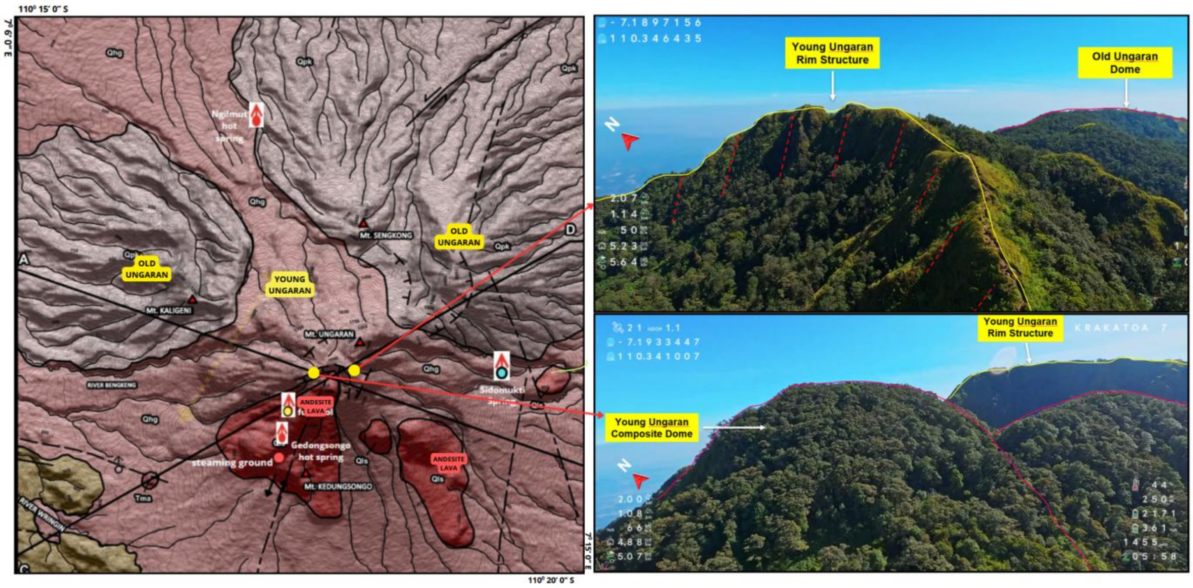

Figure 8: The morphological anatomy features of young Mt.Ungaran in drone images clarify the volcanic stratigraphy whose distribution is depicted in the geological map

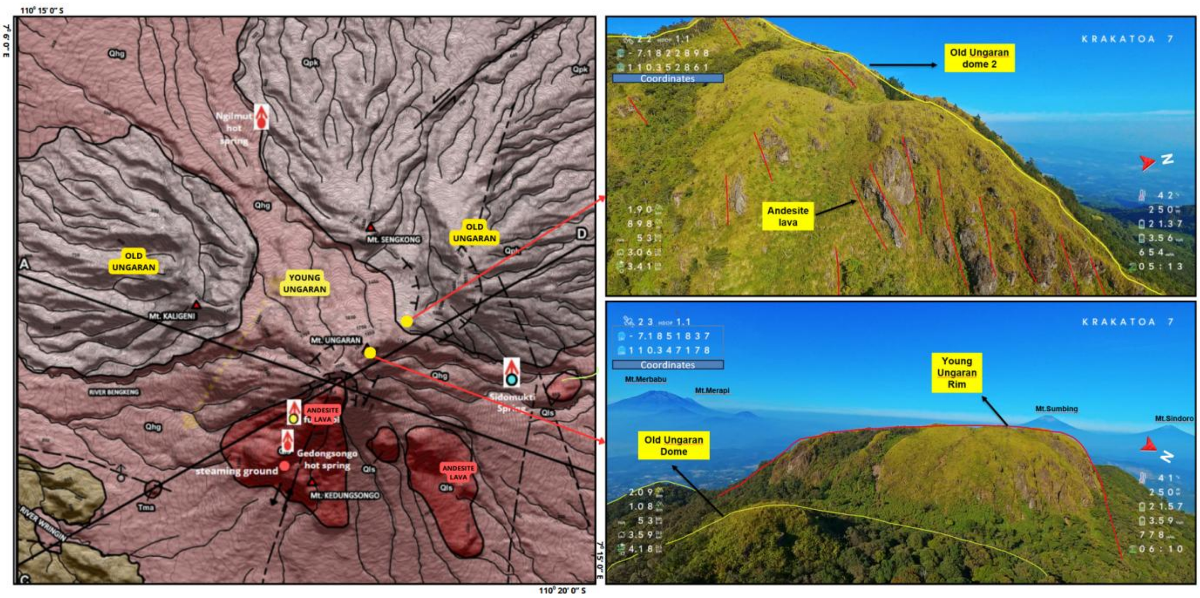

Figure 9: The dome anatomy features of old Mt.Ungaran in drone images clarify the volcanic stratigraphy whose distribution is depicted in the geological map.

The old Mt.Ungaran phase represents the initial stage in the formation of the Mt.Ungaran complex, estimated to have formed during the middle Pleistocene, approximately 0.7–0.4 million years ago. Based on research by Saibi et al. (2012), the old Mt.Ungaran body is composed of andesite-basaltic lava rocks, pyroclastic breccia, and lahar deposits that occupy the central to northwest portion of the mountain's edification.

Morphologically, old Mt.Ungaran now appears as a heavily eroded volcanic structure, forming a relic cone with ridges and valleys radiating radially from the old mountain's center. This structure indicates that the volcanic body underwent a long process of denudation before the young Ungaran phase of volcanic activity superimposed on its southeastern portion.

The interpretation of UAV drone image shows that the morphology of old Mt.Ungaran is characterized by relic peaks and caldera depressions (Figure 9). The old peak is located around the Gedong Songo Temple and Mt.Gajahmungkur, with a relative altitude of between 1,200–1,700 meters above sea level. This area is dominated by remnants of hardened lava that form a narrow ridge with steep slopes (35°–45°). The northwest part shows a broad, horseshoe-shaped basin morphology that opens to the west. Based on the elevation model from the UAV drone survey and detailed contour analysis, a basin is approximately 3 km in diameter and is likely the remains of a collapsed caldera resulting from the release of a large volume of magma before the formation of young Mt.Ungaran.

UAV drone interpretation results show a number of ring fractures around the northwest basin edge, indicating deformation due to post-eruption pressure. UAV-based morphology reveals small step faults on the south-southwest slope, which likely served as pathways for past hydrothermal fluid migration.

Conclusion and Recommendation

Integrated drone-based mapping and petrographic analysis of Mt.Ungaran reveal a complex volcanic and structural evolution from the middle to late Pleistocene. High-resolution UAV images enables precise identification of young and old volcanic units, fractures, lava domes, and caldera remnants, offering a clearer understanding of the volcano's stratigraphy and deformation patterns. Observations of fumaroles, soil discoloration, and vegetation anomalies indicate active hydrothermal alteration aligned with fault zones, confirming that Mt.Ungaran's geothermal system remains thermally active. Overall, these findings provide a comprehensive view of Mt.Ungaran's volcanic architecture, magmatic processes, and ongoing geothermal dynamics, contributing valuable insight into its geological framework and potential hazards.

Several recommendations for further development include:

- Increased high-resolution UAV mapping activities cover the entire Mt.Ungaran area.
- Integration of petrological and morphological studies using UAVs for more accurate evolutionary reconstructions
- Enhanced multi-method approach
- Optimized potential utilization of low-cost UAV technology

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