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RESEARCH ARTICLE

Ancient Disaster, the Cause of the Burial of the Kumitir Archeological Site

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Abstract The Kumitir site, associated with the Majapahit Empire, is a significant archeological discovery. Archeologists from the East Java Cultural Heritage Preservation Center (BPCB), uncovered a structure at this site, buried beneath boulder-sized rocks. According to historical literature, the collapse of Majapahit was caused by volcanic eruptions from the Anjasmoro, Arjuno, or Welirang complexes. Therefore, this study aimed to recreate the gravity-driven mass flow covering the Kumitir Site. Geological surveys, including sediment structure analysis and grain orientation measurements, were conducted to provide new information on paleocurrent and ancient sedimentary processes at the site. Digital Elevation Map (DEM) and the Laharz simulation tool facilitated the creation of reconstructed lahar flow maps using open-source DEM data with an eight-meter resolution. The results of the boulder analysis showed that a paleochannel played a significant role in the burial site, with two sources identified, namely Mount Welirang (Welirang alluvial fan) and the Anjasmoro complex (Old Jatirejo alluvial fan). Meanwhile, the combination of methods applied signified the direction of the Welirang alluvial fan (ESE-NNW) and the Jatirejo Tua alluvial fan (SSW-NNE). Volumes of 9 million m^3 and 65 million m^3 were the most relevant parameters for estimating the lahar flows of the western and eastern craters, respectively.

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1. Introduction

Kumitir, situated in the Jatirejo District of Mojokerto, East Java, Indonesia, is geographically located at Latitude 7°34’15.45”S and Longitude 112°24’44.28”E (Figure 1). Furthermore, it has been recognized as a Majapahit Empire heritage site (Adrisijanti, 2014). A team of East Java Cultural Heritage Preservation Center (BPCB) archeologists discovered the brick construction during Phase 1 of excavations in 2019. The discovery is significant, as it offers a clue to locating the Majapahit palace complex or kedaton. According to the Negarakertagama Book, the outer side of the Majapahit kedaton complex is surrounded by the residences of the king’s palaces. As shown in Figure 2a, the dimensions of the Kumitir fortress area are approximately 300 x 200. Subsequent excavation operations in the second stage present a principal structure obscured by boulder-sized rocks, as detailed in Figures 2b, 2c, and 2d. The excavation results from the east side of the Kumitir site, are shown in Figure 2e. This raises the question of whether the rocks were purposely placed or resulted from a natural event. Sampurno (1983) and Satyana (2007) stated that volcanic eruption contributed to the collapse of the Majapahit Empire. According to Ricklefs (1999) and Satyana (2007), the “Guntur Pawatugunung” event, a catastrophic volcanic eruption that occurred around 14000 AD, was suggested to play a role in the collapse of the kingdom. These hypotheses propose that natural disasters, particularly volcanic eruptions in nearby volcano complexes, could have led to the demise of the Majapahit Empires. The Kumitir Site, located in Jatirejo in the central part of the Majapahit Kingdom, is possibly been affected by pyroclastic flows and lahars, as evidenced by the landscape and excavation results in the area (Sampurno, 1983; and Satyana, 2007).

Lahar, an Indonesian term for volcanic mudflows formed by rains on the steep sides of volcanic structures (Scott, 1988; Procter et al., 2020), can alternatively be defined as a high-speed flow of rock debris and water (Smit & Fritz, 1988; Procter et al., 2020). According to Nell (1976) and Syarifuddin et al. (2016), it refers to a rapid river comprising high quantities of sediment, mud, pyroclastic, water, and poorly sorted rock debris. Thouret et al. (2020) described lahar as a type of catastrophic flow specific to volcanoes. The distinction from other debris flows lies in differences in water saturation and sediment content. Pyroclastic flows have high sediment concentrations of dried volcanic material, while lahar flows consist of water-saturated sediment (Arifani and Siregar, 2018; Thouret et al., 2020).

Reconstruction is required to determine historical events that occurred in the past (Wirasanti and Murwanto, 2020). Flood modeling, as shown by Arumi et al (2022), is a widely used method for this purpose. Predictions of flow coverage and debris transfer resulting from volcanic activity contributed to reconstructing historical events. To achieve

Figure 1. Location of Kumitir Site in Jatirejo, Mojokerto, Indonesia

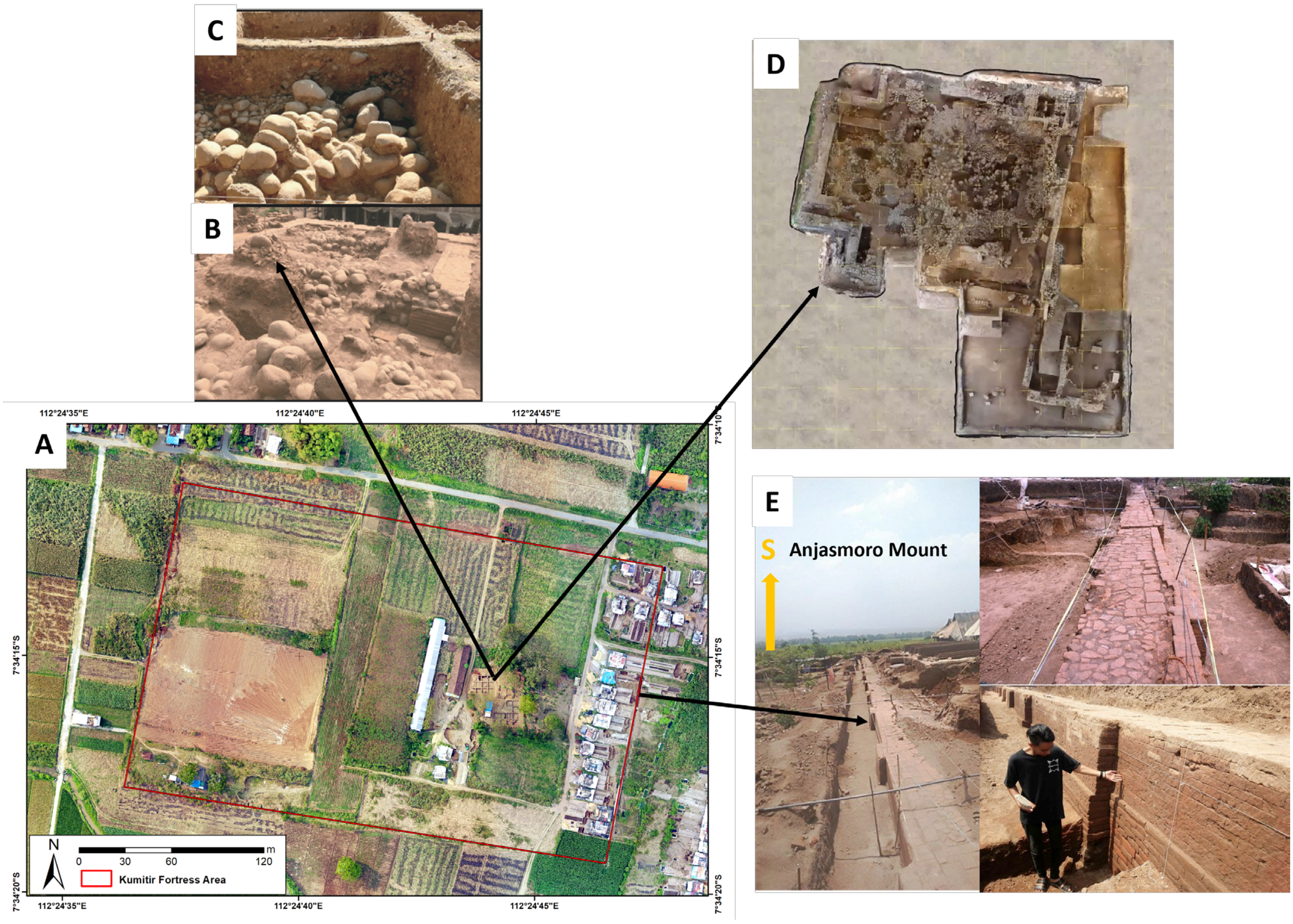
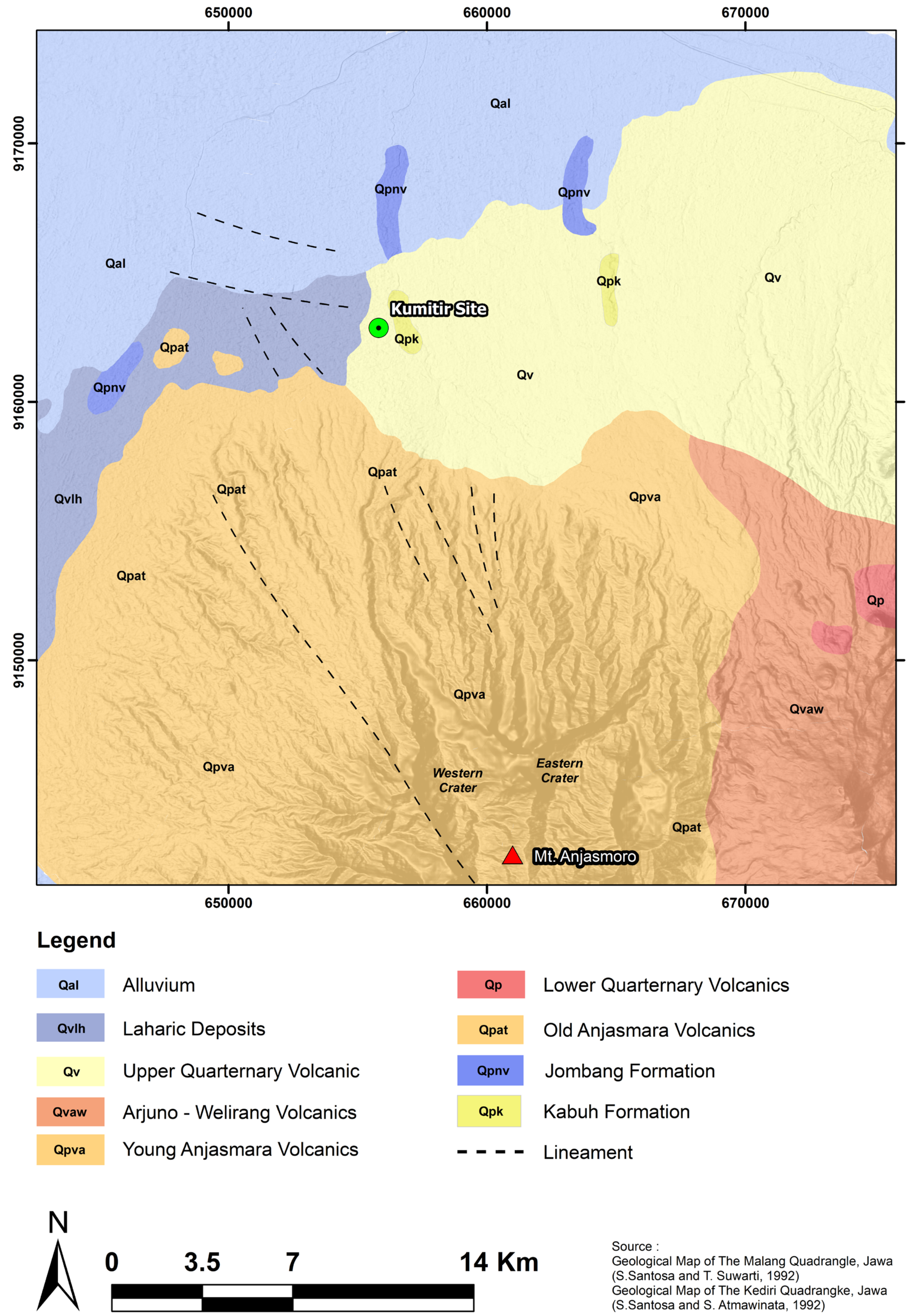


Figure 2. Some excavation results of the Kumitir site: a) Kumitir site with dimensions of 300m x 200m, b) some boulder-sized igneous rock (before the excavation process reaches 30 percent), and c) boulder-sized igneous rock (after the excavation process reaches 30 percent and some boulders have been moved), d) Total excavation (100%). e) The eastern side fortress of the Kumitir site (Photo taken by Widodo, 2020)

this, a gravity-based mass flow simulation model has been constructed, utilizing a digital elevation map (DEM) as the major data source. The simulation adopts an empirical method to map locations prone to gravity-driven mass flows, including debris flows, landslides, rockfalls, and mountainous flows such as snow avalanches and lahar flows. Among the programs used to simulate lahar flows is the Laharz simulation tool which applies a semi-empirical approach model based on 27 previous lahars (Schilling, 2014).



Source :
Geological Map of The Malang Quadrangle, Jawa (S.Santosa and T. Suwarti, 1992)
Geological Map of The Kediri Quadrangke, Jawa (S.Santosa and S. Atmawinata, 1992)

Figure 3. Regional geological map of the study area. The lower right map shows the insert map. The two main former eruption craters analyzed in this study are described as western and eastern craters (Santosa and Atmawinata, 1992; Santosa and Suwarti, 1992)

2. Geology Review

Based on regional physiography, the Kumitir Site is located within an alluvium zone adjacent to a quaternary volcanic zone on its southern side. The closest significant geological feature is Mount Anjasmoro, an inactive volcano located to the south. The map also shows that the site is positioned on the distal slope of Mount Anjasmoro. In addition to Anjasmoro, the area is surrounded by Mount Penanggungan (an inactive mountain) and Mount Arjuno-Welirang (an active volcano). However, the two mountains are situated more than 20 km away. According to Sutikno (1993), the Kumitir site is located on fluvial-volcanic fan deposits, specifically within the Jatirejo Alluvial Fan. This fan was formed by sedimentation processes originating from Mount Anjasmoro. Aerial photographs reveal that two major valleys at the summit of the volcano facilitate the flow of rivers that can transport lahars from the peak to the distal slopes, contributing to the formation of alluvial fans composed of fluvial-volcanic deposits.

Regional geological maps from the Kediri (Santoso and Atmawinata, 1992) and the Malang Sheets (Santosa and Suwarti, 1992) showed that the Kumitir Site is located within the Upper Quaternary Volcanic Rocks (Qv), composed of volcanic breccia, lava, and tuff. Surrounding the site were other volcaniclastic deposits, specifically lahar deposits (Qvlh). At higher elevations to the south, there is another volcanic formation known as the Anjasmoro Formation, which comprises the body of Mount Anjasmoro and consists of lahar, volcanic breccia, tuff, and lava.

Based on the average radius, average slope, surface roughness, rock compositions, mineralogy, and deposit characteristics, the geomorphology of Mount Anjasmoro is classified as Type III or extremely broad-dissected cones with caldera (Suhendro and Haryono, 2023). This type typically features a pyroclastic density currents (PDC) deposit, particularly evident in the flank region, and is associated with abundant lahars. Additionally, some type III volcanoes produce hummocky deposits (Suhendro and Haryono, 2023).

3. Methods

Sedimentary Structure Analysis

The direction of paleocurrents was determined through sedimentary and class structures. The study utilized existing cross-bedding structural patterns to evaluate the trend in sedimentary structure. Furthermore, the prevailing tendency of this structure was used to predict the direction of paleocurrents (Collinson, J.D. and Mountney, 2019). Given the relatively flat bedding pattern at the study site, this trend provided crucial data which were then plotted on a rose diagram to establish the main direction of the current sedimentary structure, as shown in Figure 4.

Clastic fabric analysis was adopted due to the presence of numerous rocks obscuring archeological sites in the main sector of the study area. The uniformity of these rocks facilitated the determination of the primary river direction. Data was collected by measuring the trend of the fabric's long axis and plotting it in a rose diagram. The dominant trend observed in the diagram reflected the direction of the paleocurrents that contributed to the burial of the site.

Laharz Simulation

Laharz, a Geographic Information Systems (GIS) tool developed by the United States Geological Survey (USGS) (Muñoz-Salinas et al., 2009; Schilling, 2014) was adopted to stimulate lahar flows using DEM (Park and Lee, 2018). The tool has been frequently applied in various studies such as (Huggel et al., 2008; Muoz-Salinas et al., 2009; Lee et al., 2015; Park and Lee, 2018). It utilizes a semi-empirical model based on 27 historical lahar flows from nine distinct mountains across the United States, Mexico, Colombia, Canada, and the Philippines (Muoz-Salinas et al., 2009; Park and Lee, 2018). As shown in Figure 5, the semi-empirical equation correlated the volume of lahar (V) with the cross-sectional area of the puddle (A) and the planimetric puddle area (B). The relationships are expressed in equations 1 and 2.

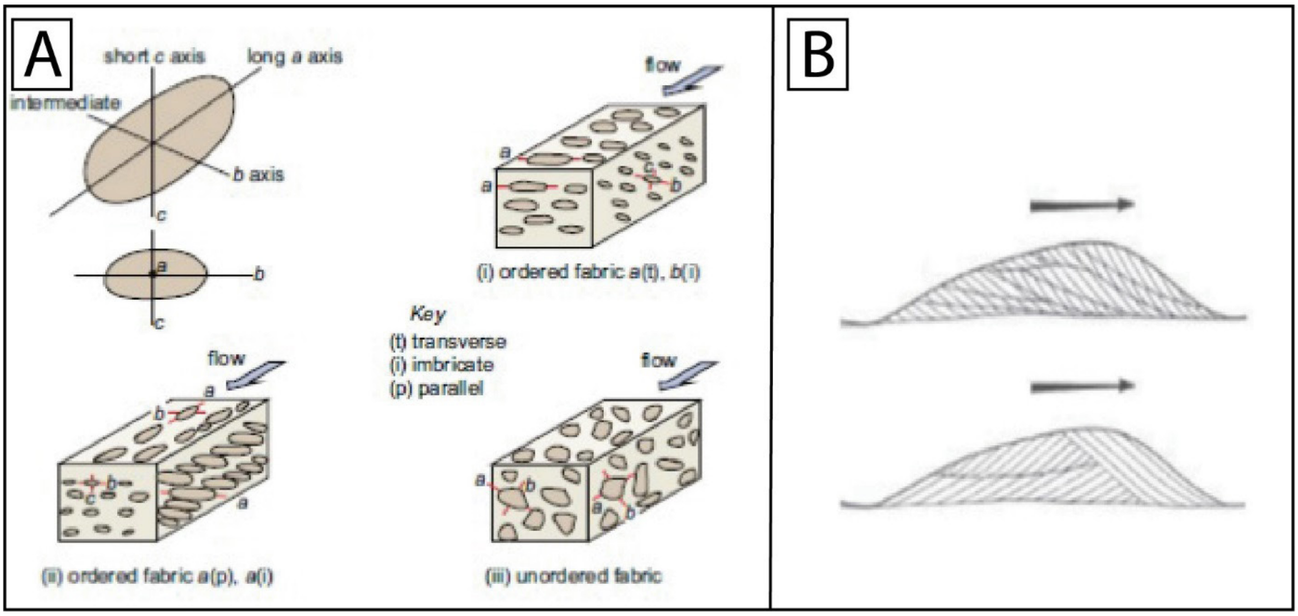


Figure 4. Sedimentary structure analysis concept. A) Axial nomenclature of a clast (taken from Collinson and Mountney, 2019): i) ordered fabric with the orientation of the long axis, ii) ordered fabric with the orientation of the long axis, iii) unordered fabric; B) Cross-stratification and its flow direction (Berg, 2010). The direction of the current parallel to the trend of the sedimentary structure

$$A = 0.05V^{2/3} \tag{1}$$

$$B = 200V^{2/3} \tag{2}$$

The ratio of H (vertical subsidence) to L (horizontal run-out distance) should be determined to define a proximal hazard zone, which is the area closest to the source of the lahar flow. The intersection of each hydrological delineation and the proximal zone was then used to establish the number of lahar flow pools in the distal zone (Schilling, 2014).

The Laharz program required DEM data in meters for X, Y, and Z coordinates (Schilling, 2014). The simulation utilized a regular grid-based model, which defines the surface of the earth as a matrix of elevation points with a continuous slope between the locations (Holmgren, 1994; Zhou, 2017). According to Peckham and Jordan (2007), Grid-based DEM was the most efficient structure for estimating and assessing topographic features. As a result, this study adopted an open-source grid-based DEM obtained from the DEMNAS website (https://tanahair.indonesia.go.id/demnas/#/). The data comprised four mosaic DEM covering the area, with a spatial resolution of 0.27 arc seconds, or approximately 8 meters.

The Laharz algorithm began with surface hydrological delineation, which includes defining flow networks, flow direction, accumulation algorithms, and user-defining threshold. According to O'Callaghan and Mark (1984), Jenson and Domingue (1988), Peckham and Jordan (2007), as well as Arisandy and Sukojo (2016), the flow direction algorithm calculated the flow path of neighboring pixels. Delineation rasters were typically detected when the flow accumulation exceeded the threshold value (Schilling, 2014). Consequently, a higher threshold number led to the identification of fewer rivers or streams. It was important to acknowledge that the initial stage of the Laharz simulation generated a flow network raster.

The results of the river flow network delineation are presented using blue lines superimposed on a terrain model of the study area, providing a clearer picture of the landform. Figure 6 shows that there is no direct flow channel from Mount Anjasmoro's northern slope to the Kumitir Site. However, this observation is constrained by the use of 2011 DEM data. The landform at the time of the lahar flow, which occurred approximately 1400 AD, was mostly different from the present-day topography.

Following the generation of the flow network, Laharz required H/L ratio values to create proximate hazard limits. As shown in Figure 5, H represented the vertical fall distance of the flow, while L denoted the horizontal runout distance. The H/L ratio estimates the potential energy of the pyroclastic flow before it reaches the main deposition place and continues downstream (Schilling, 2014). To establish proximal danger boundary polygons and starting locations, the proximal hazard zone procedure of Laharz was applied. The intersection of the proximal danger boundary with the river network was represented by the starting point. This is most the moment at which the lahar begins to overflow. Figure 7 presents a proximal hazard border that shows the possible area of origin of the lahar as well as 50 starting points.

The volume in cubic meters is an essential input for simulating-lahar flows in the distant Laharz zone. Due to the focus on the Kumitir Site, specific starting locations for the simulation were selected to reduce processing time and adjust the intended direction of lahar flow. In this case, 37 starting points were used to guide the flow northward and replicate the lahar flow to the Kumitir Site. The Laharz Toolbox allows up to seven volume variations in one simulation run. The process was repeated, assuming the applied volume failed to reconstruct the targeted flow. The volume used to process lahar pool areas depends on various sources (Thouret et al., 2007; Park and Lee, 2018). In the absence of historical records on volcanic material volume from Mount Anjasmoro, the simulation scheme considered the volcanic location and explosiveness index (VEI).

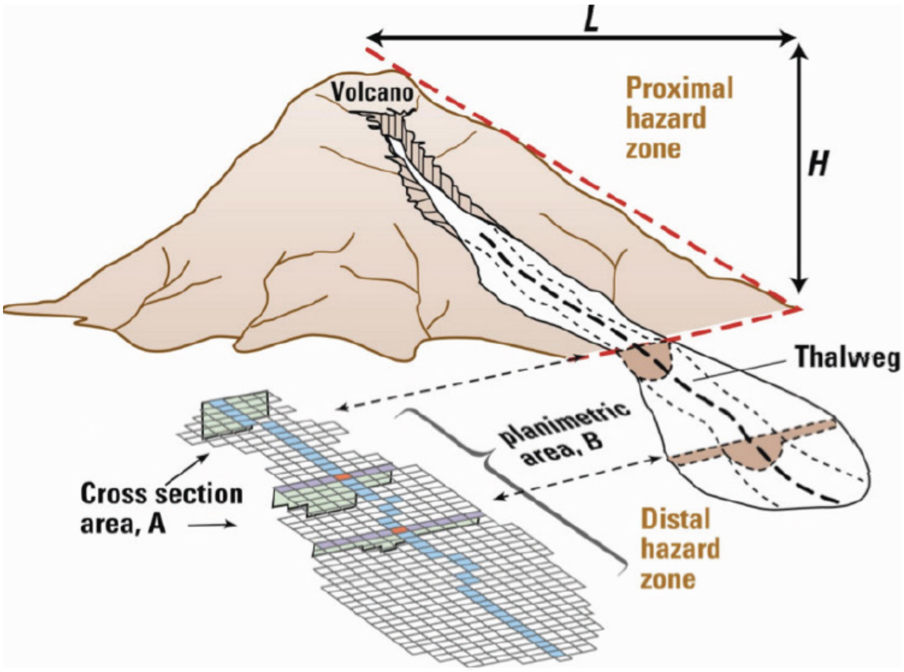


Figure 5. Illustration of cross-section (A) and planimetric area (B) based on DEM pixel. L defines the horizontal run-out distance, and H shows the vertical drop (Schilling, 2014)

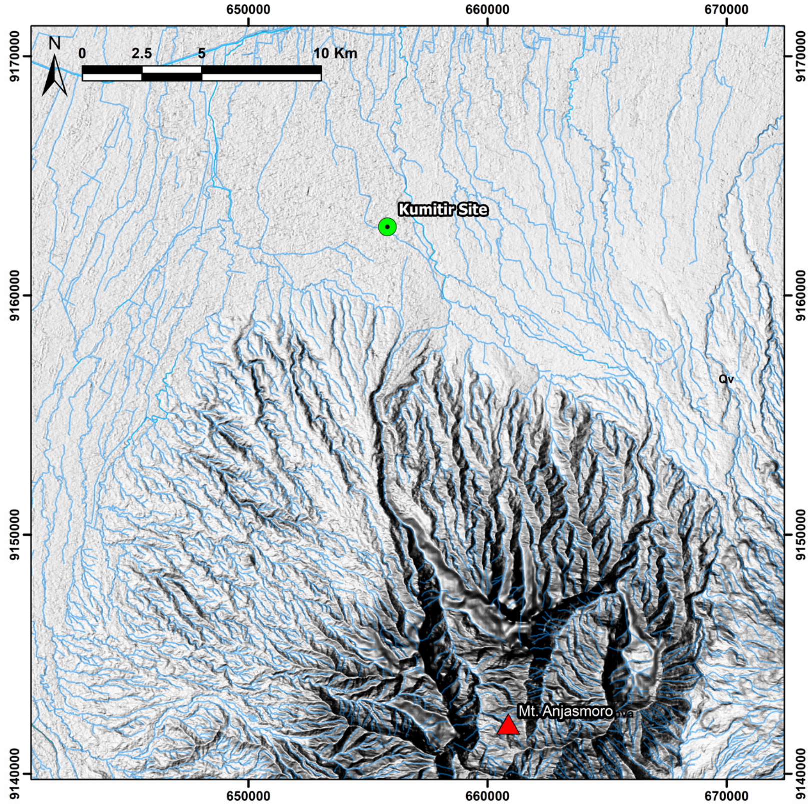


Figure 6 Surface hydrological raster results. The green circle symbol indicates the location of the Kumitir Site, and the blue line all over the map specifies the flow channel delineation.

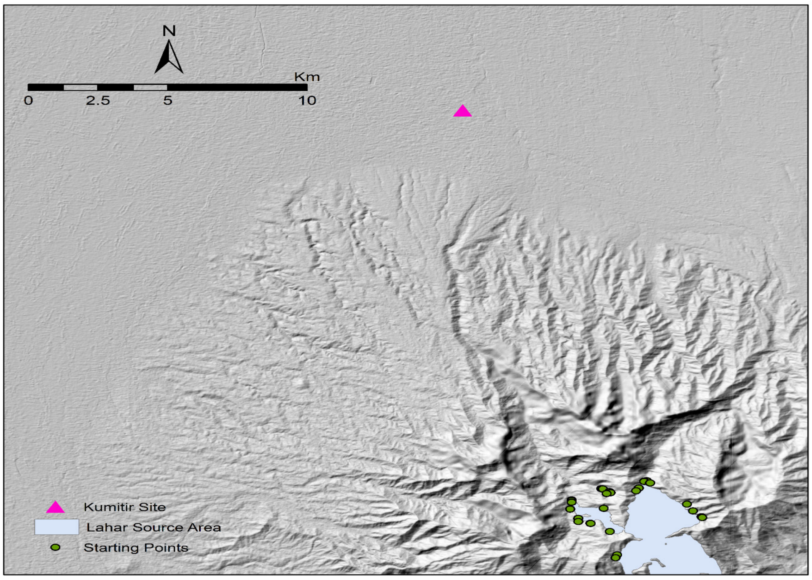


Figure 7. The result of the proximal zone boundary is the area lahar-originate indicated by a light blue polygon and the starting points are shown by green dots.

4. Result and Discussion

Sedimentary Structure Analysis

At the Kumitir archeological site, the field data collected from a limited 6 ha surrounding land, were categorized into boulder orientation and sediment structure. The structural data reflected geological occurrences that occurred after Kumitir's civilization existed. The data was organized into a rose diagram to establish the dominant direction, which was subsequently utilized as the foundation for paleocurrent analysis.

Data on boulder orientation suggested two main directions, namely ESE and SSW, as shown in Figures 8a and 8b. According to Collins and Mountney (2019), paleocurrents can flow parallel or transversely to the longest axis of the boulder. The dominant direction of the main current axis directions was identified as ESE-WNW and SSW-NNE. Furthermore, sediment structure data shown in Figure 8c, were analyzed to determine the active current. The orientation data for sedimentary structure showed a significant trend towards WNW, suggesting that the current direction possibly originated from the ESE.

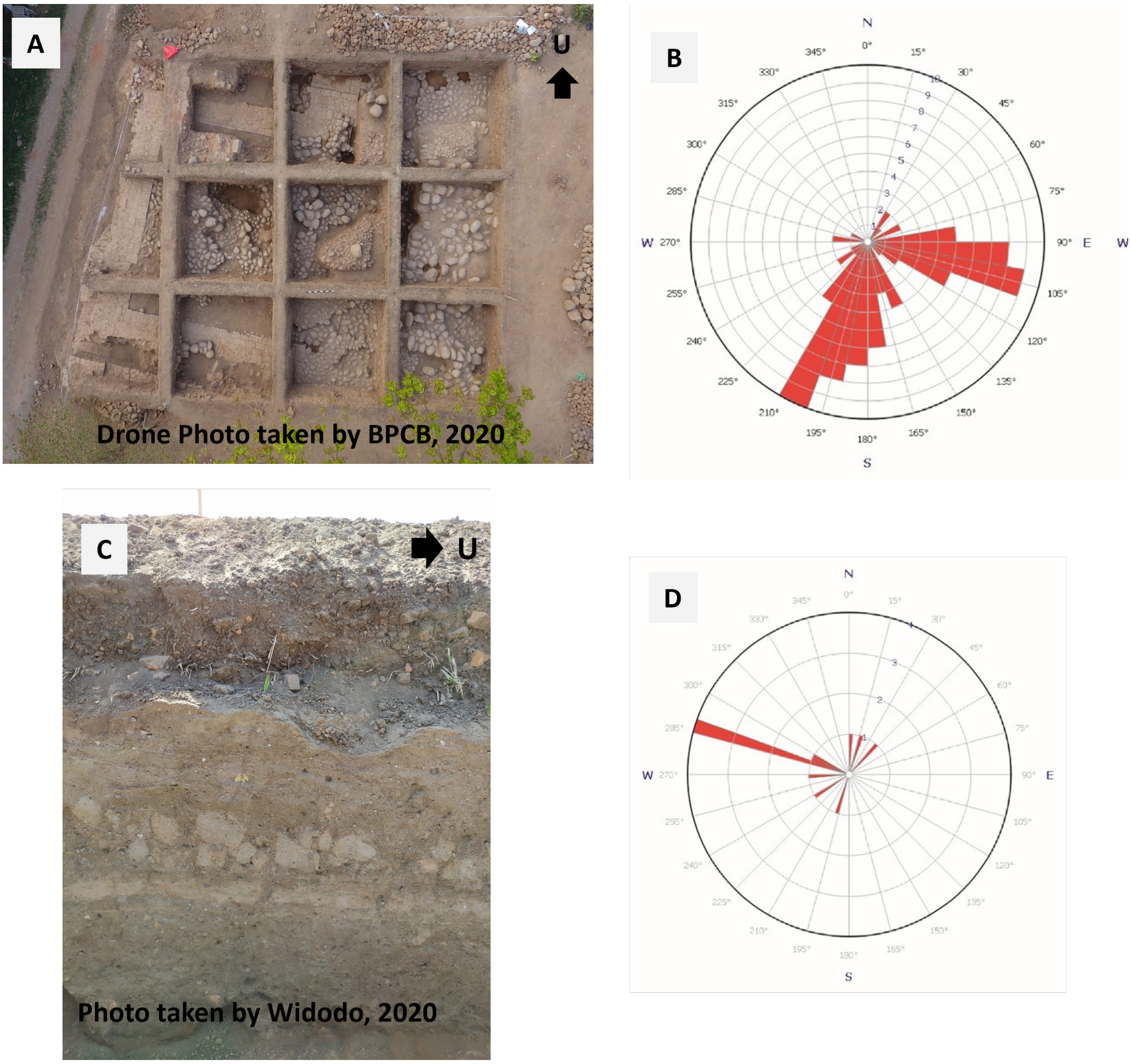


Figure 8. a) Drone photo showing boulder orientation and sediment structure at the Kumitir Site, b) Boulder orientation c) Fragment orientation of sedimentary structure. The direction of the current is parallel to the trend of the sedimentary structure. d) Sedimentary structure orientation by rose diagram

The earliest channel design is believed to have originated on the slopes of Mount Welirang. The channel pattern on Moint Welirang's slopes clearly shows a broad radial pattern, with a side heading northwest to the location of the Kumitir archeological site. Meanwhile, the second pattern originates from the southeast corner of the site, specifically from the channel formed by the former cladera of the Anjasmoro complex, leading north to the Jatirejo area. This second channel pattern represents the closest source to the archeological site.

Laharic Simulation

The initial simulation was aimed at replicating the flow of the 2010 Mount Sinabung eruption, which had a VEI of 2 and a volume greater than 1 million m3 (Park and Lee, 2018) Despite implementing 1, 3, and 6 million m^3, the eastern crater lahar did not reach the intended Kumitir Site. However, the lahar from the western crater nearly reached the site, covering an area of 6 million m^3. The following simulation adopted larger volumes from the 1981 Mount Semeru eruption (Thouret et al., 2007), namely 9 million m^3 and 12 million m^3. The flows from the western crater reached but did not entirely bury the Kumitir Site. The final calculation of lahar volume signified a flow that approaches and even passes through the site. It was discovered that the reconstructed lahar flows from both crater sources tended to approach the spot without accurate reproduction. This is because the DEM utilized was created in 2011, and land morphology may have changed throughout the Majapahit Empire. Historical material deposition could have changed elevation and covered river channels. According to simulations, the best volumes for recreating the flows covering the Kumitir Site are 9 million m^3 for the western aperture and 60 million m^3 for the eastern crater. It was important to acknowledge that the limitation of the existing DEM impacts the study.

Figure 10 presents a more thorough visual representation of the rebuilt–lahar flow in 3D, emphasizing topographic variables. The graphic signified the possibility of gravity-driven mass flow towards the north flank of Mount Anjasmoro. Therefore, lahar can be categorized as a type of flow that swamped the Kumitir Site.

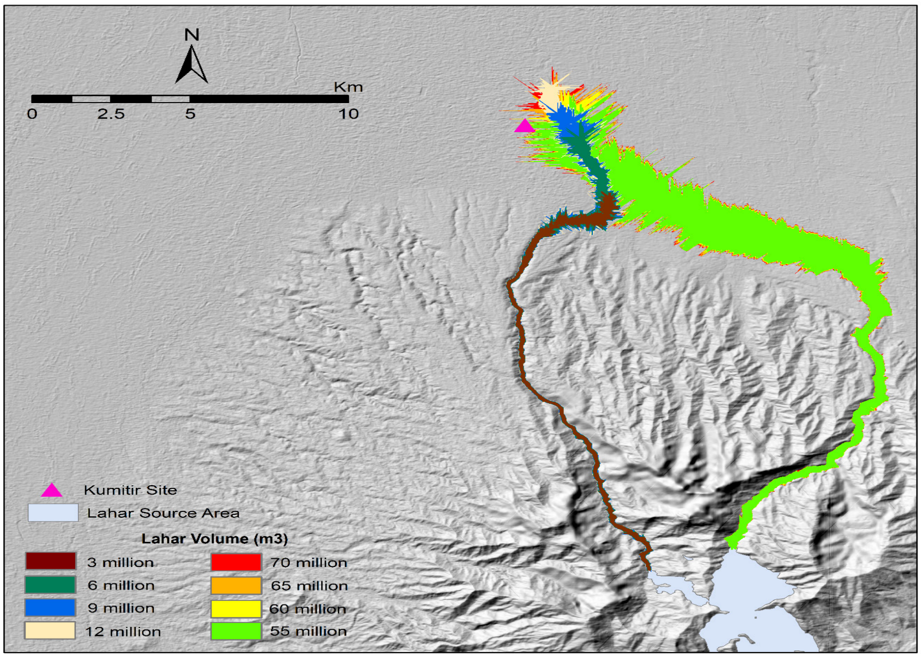


Figure 9. Map of simulated flows from Mount Anjasmoro, which is thought to have covered the Kumitir Site. The lahar is mapped to have flowed through the two large stream channels originating from the western and eastern craters.

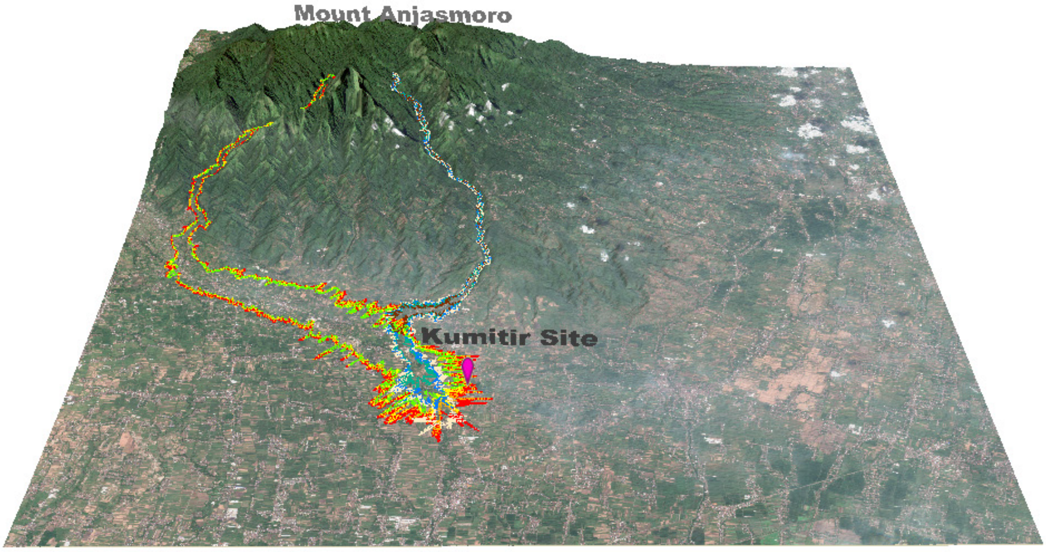


Figure 10. 3D map of lahar flow simulation based on 2D map. The 3D map shows the lahar flow from the former eruption-crater of Mount Anjasmoro flowing through stream channels toward the distal zone to approach the Kumitir Site.

5. Conclusion

In conclusion, excavations at the Kumitir Site uncovered a unique structural pattern of ancient stream barrier walls known as 'talud' in Indonesia, which were covered by massive rocks. The analysis of the boulder suggested the presence of a paleochannel that had a significant impact on the burial site. This channel appeared to have two sources, namely Mount Welirang (Welirang alluvial fan) and the Anjasmoro complex (Old Jatirejo alluvial fan). The combination of approaches showed the directions of Welirang alluvial (ESE-NNW) and the Jatirejo Tua alluvial fans (SSW-NNE). Simulation results signified the existence of two primary flow channels, which originated from the eastern and western craters. Due to the restricted accuracy of the DEM created in 2011, the lahar flow produced by the simulation only approximated but did not comprise the full Kumitir Site. Specifically, the simulation for the east and west rater flows was stopped at 70 million m^3 and 12 million m^3, respectively. Changes in geomorphology and variations in DEM over time, particularly 1400 AD, altered the flow patterns. A direct field study was required to confirm the lahar flow path and identify further geomorphological changes. The initial stage of this method included reconstructing landscapes to develop artificial river channel limits that could accurately guide the mass flow.

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