Hydrothermal Alteration and Mineralization in the Grindulu River Segment, Pacitan, East Java: A Study of the Geotourism Potential of the River Area Mineralization

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Abstract

The Grindulu River in Pacitan is one of the areas that exhibits manifestations of hydrothermal alteration and metal mineralization. However, the valuable metals found are relatively low, making it less economical to produce. This condition opens up other opportunities by utilizing the area as a natural laboratory for geological education and sustainable geotourism development. This study evaluates the potential for hydrothermal mineralization-based geotourism through geosite assessment. The study area comprises the Watupatok Formation and the Arjosari Formation, which show silicic, argillic, and propylitic alteration zones. The research methods include geological mapping, rock sampling, petrographic analysis, XRD, FA-AAS, and geosite assessment using the Kubalikova method, covering scientific, educational, aesthetic, and value-added aspects. The results show the presence of mineralization in the form of pyrite, chalcopyrite, sphalerite, and galena, with low levels of valuable metals (Au, Ag, Cu, Pb, Zn). Nevertheless, all three segments of the Grindulu River possess significant geosite value for educational and conservation purposes, with segment 2 considered the most ideal due to its superior accessibility and educational value. This study concludes that the Grindulu River is more appropriate for development as a sustainable geotourism destination based on conservation and geological education rather than mining exploitation.

Keywords: *Geosite; Grindulu river; Hydrothermal alteration; Mineralization; Sustainable geotourism*

1. Introduction

Pacitan Regency in East Java is known for its comprehensive geological diversity, including karst morphology, geological structures, hydrothermal alteration, and well-exposed mineralization [1]. For example, quartz veins rich in sulfide minerals have been found along the Grindulu River (Pacitan), indicating potential precious metal deposits. This includes the magmatic belt of the Southern Java Mountains, known for its rich reserves of gold, copper, zinc, and other precious metals [2]. Therefore, the area along the Grindulu River, Pacitan (see Figure 1) has the potential to be an important part of Pacitan's geoheritage.

Geotourism (geological tourism) is an activity that utilizes earth phenomena as its primary attraction, combining geology, biodiversity, and cultural elements within a sustainable development framework [3]. This concept aims to reconcile geological resource conservation efforts with local economic development and create new jobs and prosperity for the community. Furthermore, Pacitan's geological heritage, with its high scientific value, can serve as a source of knowledge and a medium for geoscience education for residents and tourists [4]. The development of the Grindulu geotourism route is expected to also serve as a natural laboratory, where visitors can directly understand hydrothermal processes and mineralization.

Grindulu's hydrothermal mineralization potential is more suitable for conservation and education than mining exploitation. Previous studies have shown that the alteration zone in Grindulu is uneconomical for large-scale mining, but ideal as a conservation area and geological laboratory [2]. Accordingly, a recent study recommends developing educational geotourism based on gold mineralization in Grindulu to increase regional potential income and enhance community geological understanding. However, no comprehensive study has yet been conducted to inventory the geological sites in Grindulu and create an integrated geotourism route [1]. This highlights the need for geosite assessment and thorough geotourism planning.

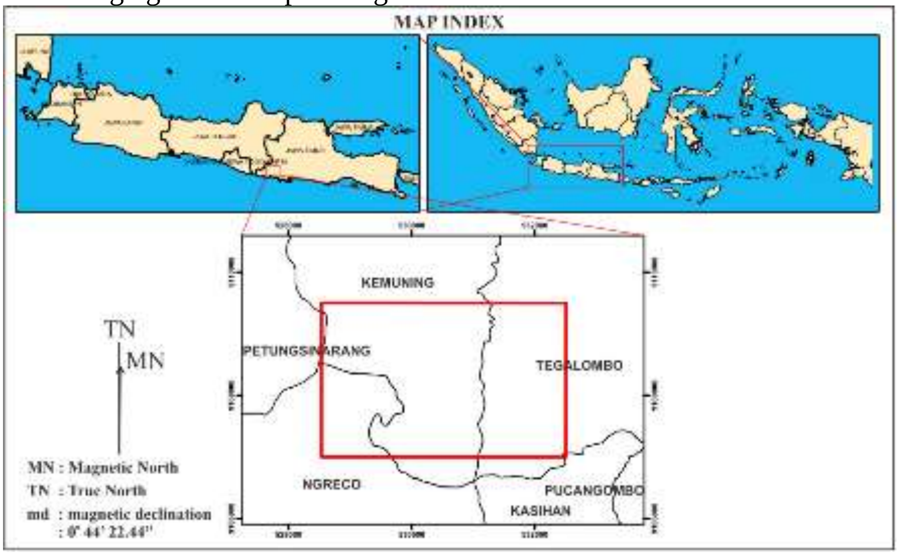

Figure 1. Research Location Map (Research area is marked with a red box)

Based on the explanation above, the purpose of this study, in addition to mapping the geological conditions, alteration, and mineralization, is also to assess the potential for geotourism and evaluate the status of geosites along three segments of the Grindulu River related to hydrothermal alteration and mineralization. The study results are expected to provide a scientific basis for sustainable management, conservation, and geoscience education in the Pacitan region. Meanwhile, strengthening geological conservation and education is a primary focus so that Grindulu's mineralization potential can be utilized sustainably and effectively for the community.

2. Method

This research methodology was developed using a descriptive-qualitative approach that combines applied geological studies and geosite assessments. The research was directed at understanding the geological conditions, hydrothermal alteration, and mineralization along the Grindulu River, while also assessing the potential for mineralization-based geotourism using geosite assessment methods. The research was conducted in three main river segments, namely Gamping, Tosari, and Krajan, which were selected because they showed rock outcrops, quartz veins, and indications of sulfide mineralization. Field data were collected through detailed geological mapping referencing the Pacitan Geological Map Sheet at a scale of 1:100,000 [5]. Observations were made on lithology, geological structure, quartz veins, and alteration zones, and they were documented using a geological compass, handheld GPS, and a digital camera. Rock samples were collected purposively from locations showing indications of alteration and mineralization, including lava, tuff, and altered breccia, as well as quartz veins containing sulfide minerals such as pyrite, chalcopyrite, sphalerite, and galena. Laboratory analyses were conducted to collaborate the field data. Petrographic examinations used a polarizing microscope to identify textures and alteration minerals. In contrast, X-ray diffraction (XRD) analysis was used to determine the clay and altered minerals types. The metal content of Au, Ag, Cu, Pb, and Zn was analyzed using the Fire Assay-Atomic Absorption Spectrophotometry (FA-AAS) method.

In addition to the geological study, this study also assessed geotourism potential using the method of Kubaliková (2013) [6], which encompasses scientific, educational, aesthetic, and additional value. The application of Kubaliková’s (2013) method in this study is consistent with other quantitative geosite assessment frameworks in Indonesia, such as the M-GAM method applied in Sawahlunto [7]. Scientific value is assessed by the uniqueness of the mineralization and alteration processes, while educational value relates to the location's potential as a learning medium for geosciences. Aesthetic value is assessed by the visual quality of the river landscape and rock outcrops, while additional values include accessibility, infrastructure, economic potential, and socio-cultural values. The results of the geosite assessments were used to determine the suitability of each river segment as a geotourism destination. All these results are interpreted by considering the principles of geological conservation and educational objectives, so that the research not only produces a scientific picture of the geological conditions and mineralization in the Grindulu River, but also provides a basis for the development of sustainable geotourism that contributes to conservation and increasing community knowledge of the earth.

3. Results and Discussion

3.1. Geology of the Research Area

Based on the regional stratigraphy of the Pacitan Geological Map [5], the research area is included in the Watupatok (Tomw) and Arjosari (Toma) Formations. Field observations and physical analysis of lithology, geological structure, rock orientation, and geological cross-sections indicate that the stratigraphy of the research area can be divided into two units: the Lava Unit of Watupatok Formation and the Tuff Unit of Arjosari Formation.

Lava Unit of Watupatok Formation

This unit is well exposed in riverbeds and roadside cliffs. Its lithology is dominated by andesite lava, small andesite breccias, and locally occurring basalt lava (Figure 2). Hydrothermal alteration in this unit varies from strong to unaltered, with quartz veins found at several observation locations. Geologically, this unit is classified as Late Oligocene to Early Miocene [5]. The stratigraphic relationship between this lava unit and the Tuff Unit of Arjosari Formation is interfingering.

Figure 2. (A) Outcrop of andesite lava with sheeted joints from the Lava Unit of Watupatok Formation at location LP 27, photo direction N 057° E, and (B) close-up view of andesite lava from the Lava Unit of Watupatok Formation.

Tuff Unit of Arjosari Formation

This tuff unit exhibits field characteristics of gray in fresh conditions and yellowish-reddish gray in weathered conditions, with a layered to massive structure (Figure 3). Its grain size ranges from ash to lapilli, with poor sorting, angular grain shapes, and an open-pit texture. The primary mineral composition consists of felsic minerals (quartz and K-feldspar), mafic minerals in hornblende, and accessory minerals in fine ash. Like the lava unit, hydrothermal alteration in this unit varies from strong to unaltered, and mineralized veins have been found at several observation locations. Based on stratigraphic data, this unit is also Late Oligocene to Early Miocene in age [5], with a stratigraphic relationship that interfingered with the Lava Unit of Watupatok Formation.

Figure 3. (A) Tuff outcrop with massive layers from the Tuff Unit of Arjosari Formation at location LP 6, with the photo taking direction N 350° E, and (B) close-up view of the tuff with massive structures from the Tuff Unit of Arjosari Formation.

3.2. Alteration and Mineralization of the Research Area

Hydrothermal alteration is a complex process involving changes in rocks' mineralogy, texture, and chemical composition. This process occurs due to the interaction between hydrothermal solutions and the rocks they pass through under specific physical and chemical conditions [8]. The distribution of alteration zones along the Grindulu River reflects the structural control of faults and fractures, similar to observations where fracture density strongly influenced hydrothermal fluid pathways [9][10]. Alteration zoning has distinctive characteristics and patterns that can be identified. The zoning pattern usually begins in the zone closest to the ore deposit. Outcrop identification, petrographic, and XRD analyses of several altered rock samples in the field indicate three alteration zones:

1. Silicic zone (characterized by Quartz ± Illite ± Calcite ± Pyrite)
2. Argillic zone (characterized by Smectite ± Kaolinite ± Quartz ± Pyrite ± Albite)
3. Propylitic zone (characterized by Chlorite ± Albite ± Quartz ± Dolomite ± Pyrite ± Smectite ± Illite).

Silicic Zone (Quartz ± Illite ± Calcite ± Pyrite)

The silicic alteration zone is characterized by a mineral association of Quartz ± Illite ± Calcite ± Pyrite. This zone experiences pervasive alteration patterns and strong intensities (61–85% secondary minerals), characterized by secondary quartz. This alteration forms in the final phase when volatile-rich hydrothermal fluids escape through post-magmatic fractures. After the fluid-rich phase, this alteration undergoes leaching, producing a vuggy texture, and can even undergo brecciation, thus creating a precipitation space for metals carried by hydrothermal solutions. Silicic alteration forms under hydrothermal fluid conditions with a pH <2 and relatively low temperatures <100–150°C [11]. XRD analysis of altered silicic rock samples at LP 3 showed the presence of quartz, Illite, calcite, and pyrite minerals (Figure 4).

Petrographically analyzed silicified rock samples from LP 9 showed gray, holocrystalline, fine-phaneritic grains (<1 mm), anhedral crystal form, crystal size of 0.05–0.2 mm, and an inequigranular relationship. They consisted of quartz (60%), clay minerals (30%), and opaque minerals (10%). Meanwhile, petrographic analysis of silicified rock samples from LP 19 showed characteristics of intermediate silicified volcanic rocks: gray, holocrystalline, fine-phaneritic grains (<1 mm), subhedral–anhedral crystal form, crystal size of 0.05–0.8 mm, and an inequigranular relationship. This rock is composed of plagioclase (labradorite) (5%), quartz (70%), carbonate (15%), oxide minerals (5%), and opaque minerals (5%) (Figure 4). The distribution of this alteration only occupies a small part, approximately 4% of the study area, and is commonly found in epithermal mineralization systems. Silicic alteration in the study area has experienced vigorous intensity and is found in andesite lava lithology. The distribution pattern of this zone is influenced by the presence of geological structures that develop in the study area.

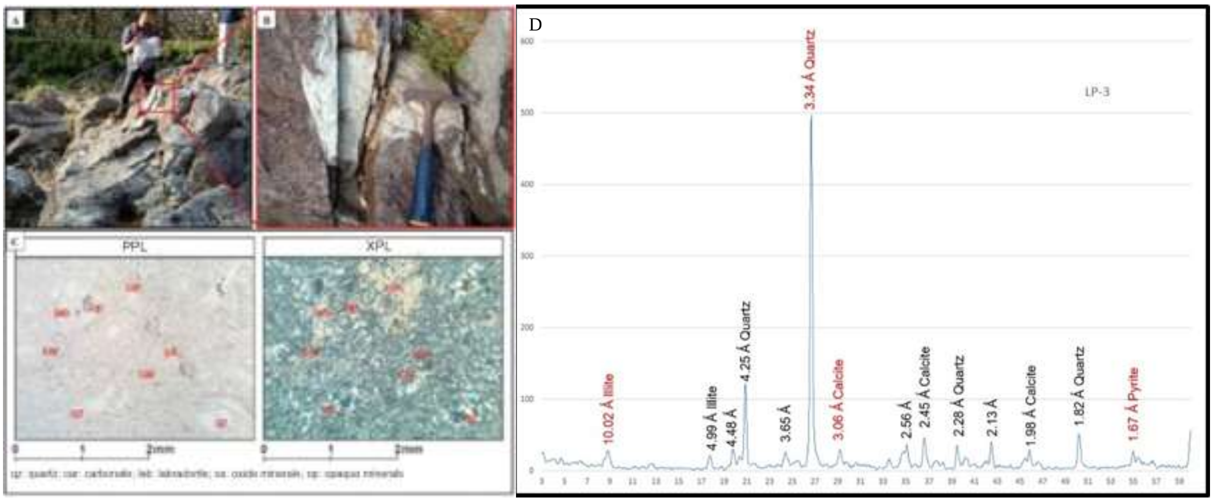

Figure 4. (A) Outcrop of lava rocks from the Lava Unit of Watupatok Formation that has undergone silicification alteration at LP 19 Sungai Grindulu (photo direction N 040° E). (B) Close-up view of lava rocks outcropping from the Lava Unit of Watupatok Formation that has undergone silicification alteration. (C) Petrographic view of the altered silicified sample LP 19. (D) XRD analysis results from sample LP 3 show the presence of quartz, illite, calcite, and pyrite minerals.

Argillic Zone (Smectite ± Illite ± Kaolinite ± Quartz ± Pyrite ± Feldspar)

This zone is characterized by a primary mineral association of Smectite ± Illite ± Kaolinite ± Quartz ± Pyrite ± Feldspar. Alteration in this zone develops with a pervasive pattern and vigorous intensity (approximately 61% secondary minerals), characterized by a white to reddish-white color and a dominance of Smectite–Illite–Kaolinite clay minerals. This zone influences the andesite lava units of the Watupatok Formation and the tuff units of the Arjosari Formation. XRD analysis of argillic altered rock samples in LP 2 indicates the presence of Smectite, Illite, Kaolinite, Quartz, Pyrite, and Feldspar minerals (Figure 5).

This alteration zone occupies approximately 10% of the study area, with a distribution surrounding the silicic zone. The distribution pattern is interpreted to be vertically controlled by geological structures in the form of faults. Argillic alteration forms after the propylitic alteration stage, at pH 4–5 and temperatures of 200–250°C [11]. In general, this alteration zone is located close to the heat source and surrounds the silicic zone due to the decrease in temperature away from the hydrothermal fluid outlet path on the fault plane.

Figure 5. (A) Argillic alteration outcrop in the Tuff Unit of Arjosari Formation at LP 2 location. (B) Close-up view of argillic alteration outcrop in the Tuff Unit of Arjosari Formation at LP 2 location (photo direction N 290° E). (C) XRD analysis results of LP 2 samples show the presence of smectite, illite, kaolinite, quartz, pyrite, and feldspar minerals.

Propylitic Type (Chlorite ± Kaolin ± Calcite ± Quartz ± Pyrite)

Prophylitic alteration is characterized by the presence of chlorite ± kaolin ± calcite ± quartz ± pyrite minerals. Propylitic zones exhibit alteration with non-pervasive to pervasive patterns, with weak to very strong intensities (24–78% secondary minerals). This alteration generally retains the rock's original texture in the field, but green chlorite minerals begin to appear locally (Figure 6). The alteration is so intense in some sections that the rock appears strikingly green. Propylitic alteration forms in the early phase when hot, volatile-rich hydrothermal fluids escape through fractures at temperatures >250°C and pH >6 [11].

The petrographic analysis of propylitic alteration rock samples from LP 27 showed the characteristics of basic volcanic rocks with a greenish-gray color, a color index of 60%, a holocrystalline texture, fine phaneritic grains (<1 mm), euhedral–anhedral crystal forms, a crystal size of 0.05–0.5 mm, and an inequigranular relationship. These rocks are composed of plagioclase (bytownite) (46%), quartz (4%), K-feldspar (sanidine) (10%), carbonate (10%), chlorite (20%), and opaque minerals (10%). The distribution pattern of propylitic alteration in the study area is controlled by the geological structures that develop in the region. Propylitic alteration occupies approximately 64% of the total area of the study area. Its presence covers other alteration zones and is found in several study locations.

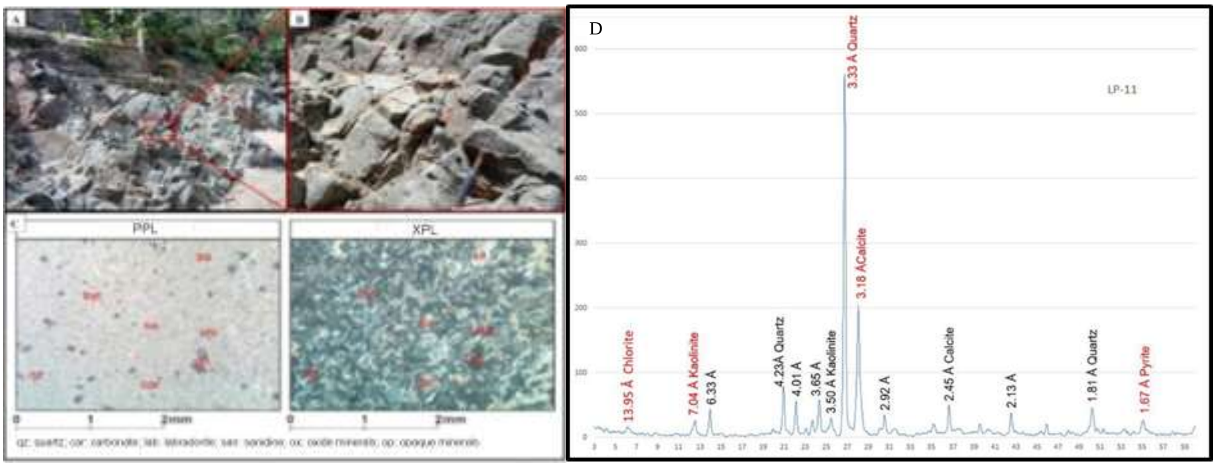

Figure 6. (A) Basalt outcrop from the Lava Unit of Watupatok Formation has undergone propylitic alteration at LP 27 Sungai Grindulu (photo direction N 057° E). (B) Close-up view of basalt outcrop from the Lava Unit of Watupatok Formation that has undergone propylitic alteration at LP 27. (C) Petrographic view of the propylitic alteration sample of LP 27. (D) XRD analysis results from sample LP 11 show the presence of Chlorite, Kaolin, Calcite, Quartz, and Pyrite minerals.

Mineralization in the Research Area

Several outcrop shows the presence of mineralization in the form of pyrite, chalcopyrite, sphalerite, and galena, in silicic and argillic alteration zone. To identify ore minerals that have the potential to carry valuable elements (gold, silver, copper, lead, and zinc), as shown and explained in the previous chapter, geochemical analysis using the Fire Assay-Atomic Absorption Spectrophotometry (FA-AAS) method was also conducted to determine the levels of valuable elements, particularly along the Grindulu River. The results of the AAS analysis of eight samples in the research area provided concentration values for each sample, as presented in Table 1.

Table 1. Levels of valuable elements in the research area based on AAS analysis

No	Sample Code	Au (ppm)	Ag (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
1	LP 1	0.01	1.6	158	15	19
2	LP 13	0.03	2.3	656	72	52
3	LP 15	0.3	<0.5	22	60	33
4	LP 20	0.01	<0.5	55	18	162
5	LP 23	0.13	20.7	1104	92969	15770
6	LP 24	0.01	<0.5	7	54	22

7	LP 26	0.22	2.6	8918	50	27
8	LP 30	0.06	<0.5	15	33	7

Based on the AAS geochemical analysis, the research area showed no valuable metal deposits (gold, silver, copper, lead, and zinc) promising for mining. The geochemical results from the Grindulu River area indicate gold contents ranging from 0.01 to 0.30 ppm and copper concentrations between 7 and 8,918 ppm. However, when placed in the context of global economic thresholds, these values clearly fall within the uneconomic category. For comparison, open-pit gold operations are generally only viable at grades of ~1–5 ppm Au, while underground mines typically require ≥3 ppm Au to remain profitable [12]. Even the highest value recorded at Grindulu (0.30 ppm Au) is only about one-fifth of the minimum cut-off typically used for economic open-pit deposits. Similarly, for copper, large-scale porphyry systems are considered viable when average grades approach 0.5–1% Cu (5,000–10,000 ppm), with some mega-deposits operating at cut-offs as low as ~0.2% Cu due to their scale [12]. In contrast, although one sample (LP-26) yielded 0.89% Cu (8,918 ppm), most other samples contain significantly lower concentrations, far below what would be required for sustainable ore extraction. However, the presence of mineralization in the research area, particularly along the Grindulu River, has potential beyond mining: it can serve as a geological tourism site (geotourism), which can provide educational opportunities about mineralization by directly observing the conditions and characteristics of the field related to the presence of gold and other valuable metal mineralization.

3.3. Geosite Assessment in the Research Area

A detailed review of the potential for educational gold mineralization-based geotourism in the research area is proposed as recommendations for geotourism management. The educational mineralization geotourism potential along the Grindulu River in the research area is divided into three river segments (see Figure 7), which will be explained in detail in the following section. Furthermore, to provide a more measurable basis for evaluation, the potential of each river segment will be assessed using the Kubalikova (2013) method [6], which assesses scientific value, educational value, aesthetic value, and additional value. Thus, the assessment results can provide a comprehensive overview of the suitability of each segment as a mineralization-based geotourism geosite.

Figure 7. Map of the location of the Grindulu River segments, divided into three segments (source: Google Earth, 2025). Segment 1, colored orange, is located in the western part of the Grindulu River flow; segment 2, colored red, is in the middle part of the Grindulu River flow; and segment 3, colored yellow, is located in the eastern part of the Grindulu River flow.

Segment 1 (Gamping, Ngreco Village)

Approximately 700 meters long, Segment 1, located in Gamping Hamlet, Ngreco Village, is particularly noteworthy for the presence of mineralized quartz veins found downstream of this segment. These mineralized quartz veins contain pyrite, sphalerite, and manganese (Figure 8a), which may contribute to the presence of valuable elements such as gold, silver, copper, and zinc. This is demonstrated by AAS geochemical analysis of samples from LP 1, LP 23, and LP 24 (Figures 8b-c, 8e-f), revealing the presence of valuable elements. The analysis revealed Au levels of 0.01 ppm in LP 1, 0.13 ppm in LP 23, and 0.01 ppm in LP 24 (Figures 8b-f) (see Table 1).

These mineralized quartz veins are also associated with geological structures such as faults and joints, confirming that the mineralization is controlled by geological structures such as faults, joints, or fractures (Figure 8d). Altered rocks are also found in this segment, which can be explained to visitors as having undergone hydrothermal processes that altered the previously present minerals. This explanation can provide new insights into the fact that mineralization results from hydrothermal processes that occurred during the final phase of magmatism at the site (Figure 8c and 8f).

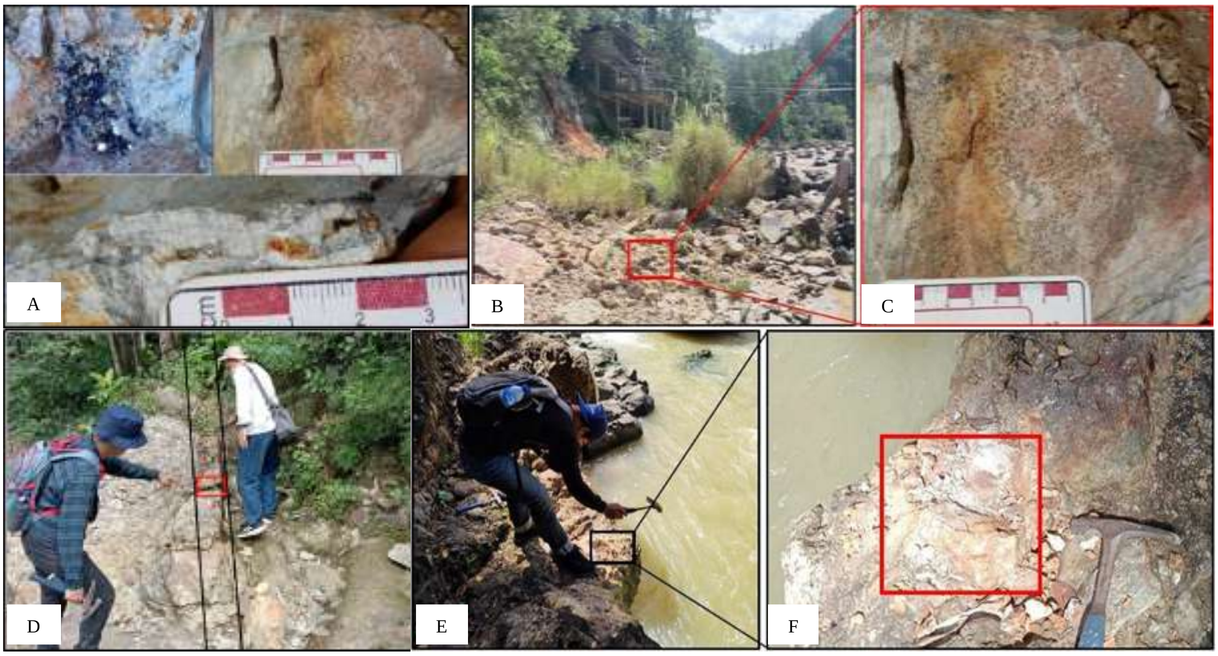

Figure 8. (A) Minerals resulting from the hydrothermal mineralization process in river segment 1 are pyrite (golden yellow), sphalerite (gray), and manganese (black). (B-C) Mineralized quartz veins in LP 1. The red box indicates the AAS sampling point of LP 1. Photo direction N305°E. (D) Mineralized quartz veins in LP 23 are associated with faults as evidence that mineralization is controlled by geological structures. The red box indicates the AAS sampling point of LP 23. Photo direction N255°E. (E-F) Mineralized quartz veins in LP 24 are also associated with faults as evidence that mineralization is controlled by geological structures. The red box indicates the AAS sampling point of LP 24. Photo direction N051°E.

The Segment 1 observation site is on the Pacitan-Ponorogo highway, with adequate parking available. However, access to the observation site in Segment 1 remains difficult because there is no road or stairs leading to the observation point in the river below the roadside. The site can only be reached through residents' yards and gardens filled with plants. In the middle of the segment, access down to the river is limited to a steep roadside ramp.

Segment 2 (Tosari, Kemuning Village)

The second segment is located in Tosari Hamlet, Kemuning Village, approximately 180 meters long. The primary focus of Segment 2 is the presence of mineralized quartz veins found downstream of this segment (Figures 9a and b). These mineralized quartz veins contain pyrite, chalcopyrite, and sphalerite, as indicated by field observations and mineragraphic analysis of sample LP 26. The presence of these minerals suggests the presence of valuable elements such as gold, silver, copper, and zinc. This is evidenced by the results of AAS geochemical analysis of samples LP 26 and LP 13 (Figures 9a and b), which indicated valuable element contents of 0.22 ppm Au in LP 26 and 0.03 ppm Au in LP 13 (see Table 1).

These mineralized quartz veins are also associated with geological structures such as faults and joints, indicating that the presence of these structures controls mineralization. In this segment, intersecting mineralized veins are also found, resulting from more than one tectonic period, indicating the presence of more than one tectonic phase (Figure 9b). Furthermore, traces of alteration or altered rocks are also found in this segment, which can be explained to visitors as having undergone hydrothermal processes, altering the previously present minerals. This additional insight is that the mineralization results from hydrothermal processes during the final phase of magmatism.

The observation site in Segment 2 is located right on the Pacitan-Ponorogo highway, with adequate vehicle parking located on the side of the road near the suspension bridge in Tosari Hamlet or across from SMPN 1 Tegalombo in Kemuning Village (Figure 9c). Access to the observation site in Segment 2 is relatively easy because the path to the river is a concrete road and not too steep. The road is next to the Tosari Hamlet suspension bridge, which local people often use to transport sand from the river (Figure 9d).

Figure 9. (A) Hydrothermal mineralized quartz veins found in river segment 2, sampling point LP 13. (B) Mineralized quartz veins in LP 26 intersect due to more than one fault or fracture, indicating the presence of more than one tectonic period. (C) The location of the vehicle parking area for river segment 2 is right on the side of the road near the Tosari Hamlet suspension bridge in Kemuning Village, Tegalombo. (D) The road to the riverbank in segment 2 is next to the Tosari Hamlet suspension bridge in the form of a concrete road that residents usually use to get to the Grindulu River.

Segment 3 (Krajan, Tegalombo Village)

The third segment is located in Krajan Hamlet, Tegalombo Village, approximately 800 meters long. The primary focus of this segment is the presence of mineralized quartz veins found in the downstream (Figure 25), middle, and upstream sections of the segment. These mineralized quartz veins contain pyrite, chalcopyrite, and sphalerite, as indicated by field manifestations and mineragraphic analysis of samples LP 16 and LP 30. The presence of these minerals suggests the presence of valuable elements such as gold, silver, copper, and zinc. This is confirmed by AAS geochemical analysis of samples LP 30, LP 15, and LP 20, which showed valuable element contents with Au levels of 0.06 ppm in LP 30, 0.03 ppm in LP 15, and 0.01 ppm in LP 20 (Table 1).

These mineralized quartz veins are also associated with geological structures such as faults and joints, indicating that the mineralization is controlled by geological structures in the form of faults, joints, or fractures. Altered rocks can also be found in this segment, which can be explained to visitors as having undergone hydrothermal processes that have altered the previously present minerals (Figure 10a). This knowledge can provide visitors with new insights into the mineralization resulting from hydrothermal processes that occur during the final phase of magmatism.

Figure 10. (A) Hydrothermal mineralized quartz vein with a width of approximately 25 cm found in LP 14, downstream of river segment 3. (B) The location of the vehicle parking area in river segment 3 is on the side of the road right next to the concrete bridge in Krajan Hamlet, Tegalombo Village.

The observation site in river segment three is located right on the Pacitan-Ponorogo highway, with adequate vehicle parking on the road's side, right next to the Krajan Hamlet Bridge in Tegalombo Village (Figure 10b). However, access to the observation site downstream of river segment 3 remains difficult, requiring a descent from the highway via a steep roadbed and only a decaying wooden staircase.

To assess the potential for mineralization-based geotourism along the Grindulu River, a geosite assessment was conducted using the Kubalikova (2013) method [6], which emphasizes four main aspects: scientific value, educational value, aesthetic value, and additional value. This assessment was applied to the three study river segments (Segment 1, Segment 2, and Segment 3) to obtain an overview of the suitability of each segment as a geotourism geosite. The assessment results are presented in the following table.

Table 2. Geosite Assessment of the Grindulu River Segment Based on the Kubalikova Method (2013) [6]

Assessment Aspects	**Segment 1 (Gamping, Ngreco Village)**	**Segment 2 (Tosari, Kemuning Village)**	**Segment 3 (Krajan, Tegalombo Village)**
Scientific Value	Mineralized quartz veins are associated with pyrite, sphalerite, and manganese. AAS results indicate Au content (0.01–0.13 ppm). The location clearly links mineralization and geological structures (faults, joints).	Quartz veins are mineralized with pyrite, chalcopyrite, and sphalerite. AAS results indicate Au (0.03–0.22 ppm). Evidence of more than one tectonic period (intersecting veins) strengthens the scientific value.	Quartz veins are found with pyrite, chalcopyrite, and sphalerite at several locations (LP 15; LP 20; LP 30). AAS indicates Au (0.01–0.06 ppm). This indicates a close relationship between mineralized veins and fault systems.
Educational Value	Suitable as a learning location on hydrothermal processes, alteration, and the relationship of mineralization to geological structures. It can be used as an example of simple silicic and argillic alteration.	The location highly represents epithermal mineralization education, demonstrating quartz veins cut across more than one tectonic period. Easy access makes it a suitable location for student field experiments.	Potential as a learning medium on the relationship between mineralization and tectonics and broader propylitic alteration. Suitable for explaining the evolution of mineralization in several river segments.
Aesthetic Value	The quartz vein outcrop along the roadside offers a striking visual contrast, although access to the river is steep and limited.	The view of the quartz vein below the Tosari suspension bridge, with concrete road access, adds to the aesthetic value. Combining the river, cliff, and mineralization adds to the aesthetic value.	The large quartz vein outcrop (approximately 25 cm) blends well with the natural river landscape. The visual appeal is strong, although access is more difficult and requires road improvements.

Added Value	The location is close to the main Pacitan-Ponorogo highway, but access down to the river is limited (passing through residents' gardens and a steep path). Low economic potential without improved access.	Excellent access, close to the Tosari suspension bridge and a school. Potential as a local educational tourist attraction is relatively high.	Near the Krajan concrete bridge, but access to the riverbed is difficult (steep path, rotting wooden stairs)—limited economic potential without infrastructure support.

Similar to karst aquifers and geothermal manifestations elsewhere in Java that have been successfully utilized as geoheritage-based tourism destinations [13][14], the Grindulu hydrothermal alteration features could be positioned as an outdoor classroom for sustainable geotourism. Their accessibility and clear mineralization patterns allow visitors to directly observe hydrothermal processes, thereby enhancing public geological literacy, fostering conservation values, and creating added socio-economic benefits for local communities.

3.4. Sustainable Geotourism Development Efforts

Geotourism development in the Grindulu River area encounters several obstacles, particularly limited infrastructure (road access, bridges, and basic facilities), low geological literacy among local communities, and inadequate human resource capacity (guides, managers) [15][16]. Funding constraints and weak coordination between institutions (village government, tourism office, academics) further hinder effective implementation. To overcome these challenges, community-based education and training—such as the establishment of Pokdarwis—are essential to emphasize that geotourism is both a business opportunity and a conservation effort. Lessons from Gulamo Geopark in Riau show that destination management training, digital promotion, and sustainable infrastructure improvements (road maintenance, sanitation, interpretation boards) can enhance visitor comfort while supporting environmental protection [16]. Equally important is multi-stakeholder collaboration: local governments, academics, and communities must jointly develop long-term strategies, supported by policy recognition of geosites as protected areas or geoparks to safeguard them from illegal exploitation.

The significance of Grindulu's geosite potential becomes clearer when compared with regional best practices. In Indonesia, Sawahlunto (West Sumatra) successfully transformed its abandoned coal mining heritage into a UNESCO World Heritage site through integrated geosite inventory, conservation, and community-based tourism [7][17]. Gulamo Geopark illustrates how non-exploitable geological features can be revitalized through local empowerment, infrastructure provision, and digital promotion [18]. Beyond Indonesia, Satun UNESCO Global Geopark in Thailand demonstrates how diverse geosites—including hydrothermal and mineralization features—can be sustainably managed using quantitative assessments and adaptive strategies [19]. Likewise, volcanic and geothermal tourism in Java (e.g., Dieng Plateau, Kawah Ijen) highlights the strong educational and aesthetic appeal of hydrothermal manifestations, even in the absence of economic mining potential [20].

In short, this solution aligns with UNESCO's geotourism principles: building cross-sector networks, promoting local geoproducts (geology-based educational souvenirs), and involving stakeholders in monitoring (citizen science) [21][22]. This way, challenges such as low literacy or limited funding can be addressed through synergy. At the same time, Grindulu geotourism can grow into an innovative destination that combines nature conservation, education, and community economics.

4. Conclussion

Research along the Grindulu River segment in Pacitan indicates that the study area comprises the Watupatok and Arjosari Formations, with hydrothermal alteration occurring in three zones: silicic, argillic, and propylitic. Petrographic, XRD, and FA-AAS analyses indicate sulfide mineralization in the form of pyrite, chalcopyrite, sphalerite, galena, and small amounts of precious metals (Au, Ag, Cu, Pb, and Zn). Geochemical results indicate low levels of precious metals, making them uneconomical to mine, but they have high scientific value as natural laboratories for understanding hydrothermal processes and mineralization.

Geosite assessment using the Kubalikova method indicates that the three river segments have geotourism potential with distinct characteristics. Segment 1 stands out for its scientific value, Segment 2 excels in educational aspects and accessibility, while Segment 3 has unique aesthetics but faces access constraints. Overall, the Grindulu River has great potential to be developed as an education and conservation-based geotourism destination that can support the preservation of geological heritage while increasing public awareness of the earth.

The sustainable development of the Grindulu geowisata requires improving accessibility to key geosites (especially Segments 1 and 3) through environmentally friendly infrastructure, empowering local communities via Pokdarwis formation, guide training, and geologically inspired tourism products, as well as strengthening conservation and education with interpretive boards, educational trails, and academic visits. Multi-stakeholder collaboration among local governments, academics, communities, and the private sector is crucial for creating a comprehensive master plan. At the same time, further research on geochemistry, mineralization–structure relationships, and spatial-based geosite potential modeling will provide a stronger foundation for future geotourism development.

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