



Integrating Environmental Rehabilitation and Geoconservation in Manganese Geoheritage

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Abstract

Manganese mining can leave environmental degradation while also exposing geological features with scientific, educational, aesthetic, and tourism value. This study examines the integration of environmental rehabilitation and geoconservation at the Kliripan-Karangsari manganese geoheritage complex in Kulon Progo, Yogyakarta. The study used an integrated descriptive design based on systematic geological mapping of 78 observation points, field environmental assessment, petrographic, X-ray diffraction (XRD), and X-ray fluorescence (XRF) analyses, and community assessment through questionnaires and focus group discussions. The results identify four geomorphological units, three principal lithological units, two dominant structural orientations, and five manganese mineralisation styles. The principal manganese mineral identified is pyrolusite, while carbonate-hosted samples contain calcite and pyrolusite. Major environmental pressures include outcrop degradation, erosion, potential acid mine drainage (AMD), unlicensed excavation, specimen collection, vandalism, sedimentation, waterlogging, and restricted access to historical mine openings. The findings support geology-based zonation comprising core, buffer, and development zones, combined with selective rehabilitation, community participation, and five- to ten-year monitoring of water, soil, vegetation, slope stability, and geoheritage condition. The study provides a site-specific descriptive basis for integrating post-mining environmental management with geoconservation and community-based geotourism.

Keywords: *Geoheritage, Manganese, Post-Mining Environmental Management, Geoconservation, Acid Mine Drainage, Geotourism*

INTRODUCTION

Indonesia has exceptional geodiversity, including geological features formed by complex volcanic, tectonic, and sedimentary processes. Manganese deposits are important not only as mineral resources but also as records of geological processes and ancient depositional environments (Harjanto, 2021; Higasina et al., 1969). Former mining areas can therefore have a dual character: they may contain environmental degradation associated with excavation and abandonment, while the same disturbance can expose geological features with scientific, educational, aesthetic, and tourism value (Adrianda et al., 2025; Farsani et al., 2021).

This condition is evident in the Kliripan, Anjir, and Jonggol-Kalilingseng areas of Kulon Progo, Yogyakarta. These areas are included in the Kliripan-Karangsari geoheritage site, one of the recognised geological heritage sites of the Special Region of Yogyakarta under Ministerial Decree of the Ministry of Energy and Mineral Resources No. 13.K/HK.01/MEM.G/2021 (Surat Keputusan Menteri ESDM No. 13.K/HK.01/MEM.G/2021, 2021). The site is also considered important in the development of the proposed Yogyakarta National Geopark (Pandita et al., 2024). Historical manganese mining, together with the geological exposures produced and modified by mining activity, provides a basis for interpreting the relationship between geological heritage and post-mining environmental conditions.

From an environmental engineering perspective, conventional reclamation and

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geoconservation can create a practical management tension. Uniform backfilling or dense revegetation may conceal geological exposures that are important for scientific and educational interpretation. Conversely, leaving disturbed mine landscapes unmanaged may allow erosion, waterlogging, potential AMD, illegal excavation, and deterioration of geological features to continue. Rehabilitation and geoconservation therefore need to be considered as complementary management functions rather than separate objectives ([Awing et al., 2025](#); [Herrera-Franco et al., 2022](#); [Ocelli Pinheiro et al., 2023](#)).

The present study uses a descriptive approach to characterise geological and environmental conditions, identify management-relevant patterns, and formulate an integrated management and monitoring framework. The objectives are to: (1) document the geological and mineralogical characteristics that support geoheritage value; (2) describe environmental pressures affecting the site; (3) examine the social context for community participation; and (4) formulate a management approach that combines geoconservation, selective rehabilitation, and community-based geotourism. Because the research is site-based and descriptive, the results are interpreted as observed conditions and patterns rather than statistically generalisable estimates.

LITERATURE REVIEW

Geoheritage and Geoconservation

Geoheritage refers to geological features such as rocks, minerals, fossils, landforms, structures, and processes that have value beyond their role as economic resources because of scientific, educational, aesthetic, or tourism significance ([UNESCO, 2020](#)). In Indonesia, the verification and identification of geoheritage are administered through the Geological Agency of the Ministry of Energy and Mineral Resources and guided by Ministerial Regulation No. 01 of 2020 ([Peraturan Menteri ESDM No. 01 Tahun 2020, 2020](#)). Assessment commonly considers scientific, educational, aesthetic, and touristic values.

Geoconservation in mining landscapes requires consideration of both geological integrity and environmental safety. Mining may expose geological relationships that were previously inaccessible, but excavation can also create unstable slopes, disturbed drainage, exposed mineral surfaces, and abandoned openings. A management approach therefore needs to identify which geological features should remain visible and which disturbed areas require rehabilitation. The framework proposed by [Ocelli Pinheiro et al. \(2023\)](#) is relevant because it connects geoheritage assessment, environmental-pressure control, selective rehabilitation, and community benefit.

Manganese and the Kliripan-Karangsari Setting

Indonesian manganese deposits are generally associated with Tertiary sedimentary sequences and may reflect shallow-marine, diagenetic, hydrothermal, and weathering processes ([Harjanto, 2021](#); [Higasinaka et al., 1969](#)). Manganese mineral assemblages may include pyrolusite, manganite, psilomelane, and rhodochrosite ([Geoheritage DIY, 2017](#); [Islamadina & Warmada, 2022](#)). Their occurrence as veins, layers, replacement bodies, or fracture fillings can preserve evidence of geological processes and provide educational value.

At Kliripan-Karangsari, previous studies report manganese mineralisation associated with the Sentolo Formation limestone and indicate high MnO contents in some ores ([Geoheritage DIY, 2017](#); [Islamadina & Warmada, 2022](#)). Historical mining began in 1953, giving the landscape an additional industrial and cultural dimension ([Badan Geologi, Kementerian ESDM, 2021](#)). The combination of geological diversity, historical mining, and potential geotourism makes the site suitable for an integrated geoheritage-management approach. However, the present study focuses on descriptive field and laboratory evidence rather than attempting to establish a new genetic or resource-estimation model.

RESEARCH METHODOLOGY

Research Design

The study employed an integrated descriptive research design to characterise geological, environmental, and socio-economic conditions in the Kliripan-Karangsari manganese geoheritage area. The research forms part of a multidisciplinary programme concerning geological significance, environmental pressures, and community-based potential (Suharyadi et al., 2024). The methodology consisted of five stages: (1) geological inventory and documentation; (2) environmental-pressure assessment; (3) community and socio-economic assessment; (4) descriptive analysis and cross-site comparison; and (5) development of an integrated management and monitoring framework.

The descriptive design was selected because the main purpose was to document existing conditions and identify recurring patterns. Accordingly, the analysis emphasised frequencies, percentages, ranges and other descriptive summaries where appropriate, together with qualitative interpretation. No inferential statistical testing or claims of statistical significance were used.

Geological Inventory and Laboratory Analysis

Field investigations were conducted in Kliripan, Anjir, and Jonggol-Kalilingseng. A total of 78 systematic observation points were documented using handheld GPS, geological compass, geological hammer, and 0.1 M HCl testing. Geological characteristics, mineralisation features, outcrop condition, and surrounding environmental conditions were recorded photographically. Representative rock and ore samples were collected for laboratory characterisation.

Thin-section petrography, XRD, and XRF analyses were conducted at the Petrography Laboratory, Department of Geological Engineering, Universitas Pembangunan Nasional “Veteran” Yogyakarta and partner laboratories where required. The laboratory results were used to establish a descriptive mineralogical baseline and to support interpretation of geoheritage value.

Environmental and Community Assessment

Environmental pressures were assessed through direct field observations and secondary information. The main indicators were physical disturbance of outcrops, potential AMD, erosion and slope degradation, mining-related or potentially illegal activities, and accessibility of historical mine openings. Field pH measurements were used where accessible water or drainage features were present. Mineralogical observations and available published water-quality information were used to contextualise potential AMD risk.

ICP-MS analysis of trace and rare-earth elements was planned as an additional geochemical assessment. However, the analysis was delayed because of instrument malfunction at the primary partner laboratory. Consequently, ICP-MS results are not included in the present quantitative assessment, and potential AMD is discussed as an environmental risk requiring further monitoring rather than as a quantitatively established source signature.

Community information was collected through structured questionnaires and focus group discussions involving local communities and Pokdarwis Watu Jonggol. The questionnaire addressed knowledge and perceptions of geoheritage, environmental conditions, livelihood dependence, geotourism opportunities, and willingness to participate in conservation. FGD information concerned local experience, opportunities and constraints, institutional involvement, and possible community participation.

Descriptive Data Analysis and Integration

Categorical geological and environmental observations were summarised using

frequencies and percentages where applicable. Numerical observations were described using minimum, maximum, mean, median, or range when appropriate. The three study areas were compared descriptively in terms of geological characteristics, outcrop condition, environmental pressures, and community-related information. FGD findings were organised thematically.

The geological, environmental, and socio-economic information was then integrated through descriptive comparison. The purpose was to identify management-relevant relationships among geoheritage value, environmental vulnerability, accessibility, and community participation potential. A preliminary zonation and monitoring framework was developed from these observed patterns.

Methodological Limitations

The study is site-based and descriptive. Although 78 observation points were documented, no formal sampling-power calculation was performed. The available research material also does not provide sufficient numerical information on questionnaire respondents, respondent-selection procedures, questionnaire reliability coefficients, or formal FGD coding validation. These should be added from the original research records if available. Detailed laboratory QA/QC information should likewise be reported where applicable. The delayed ICP-MS analysis limits quantitative trace-element assessment. The findings should therefore be interpreted as a site-specific descriptive baseline rather than statistically generalisable estimates.

FINDING AND DISCUSSION

Geological and Geoheritage Baseline

The 78 observation points establish a site-specific geological baseline for Kliripan, Anjir, and Jonggol-Kalilingseng. The study area contains volcanic and carbonate geological settings, with manganese mineralisation associated mainly with volcanic breccia, andesite-related rocks, and Sentolo Limestone. The Sentolo Limestone occupies approximately 35% of the study area, while the Andesite Unit occupies approximately 15%. The Andesite Breccia Unit forms an important volcanic component.

Geomorphologically, the area includes Sermo Reservoir, Denuded Volcanic Hills, Fluvial Valley, and Denudational Limestone Hills. These units represent a transition from a volcanic-dominated landscape toward carbonate-dominated terrain and provide a useful basis for interpretation and geotrail planning. The geological diversity is important for geoheritage because visitors can observe relationships among lithology, landform, structures, mineralisation, and historical mining.

Structural Control

Field measurements of joints, veins, and faults indicate two principal structural orientations, approximately north-south and northwest-southeast. At LP 1-18, paired shear joints in andesite have strikes of approximately N80°E-N94°E and N301°E-N333°E, with an interpreted principal stress direction of approximately N106°E. At LP 2-10, paired shear joints occur at approximately N310°E-N330°E and N192°E-N206°E, while extension joints occur at N352°E-N355°E and release joints at N81°E-N101°E; the interpreted principal stress direction is approximately N348°E.

These observations indicate that fractures and structural openings provided pathways for mineral-bearing fluids. Structural information is therefore relevant to conservation planning. A zonation based only on administrative boundaries or visible surface features could omit structurally controlled mineralisation that is less conspicuous topographically. Structural trends should consequently be considered when identifying representative geological exposures and

defining core conservation areas.

Manganese Mineralisation

Five principal mineralisation styles were recognised: vein and matrix/infiltration mineralisation in volcanic rocks, and massive, stratiform, and dendritic mineralisation in carbonate rocks. In volcanic breccia, manganese veins occur along fractures and cavities. They are commonly black, submetallic, opaque, brittle, have a black streak, and show hardness of approximately 5.5-7 Mohs. Matrix mineralisation is softer, powdery to amorphous, and has hardness below 2 Mohs, consistent with wad-type material.

In the Sentolo Limestone, massive manganese replaces carbonate matrix and cement and also occupies intra- and interparticle pores. Stratiform mineralisation occurs as layers approximately 3-30 cm thick, while dendritic manganese follows fractures, bedding surfaces, and other discontinuities. The contrast among these styles demonstrates that manganese is expressed through several geological processes, including fracture filling, replacement, and precipitation within cavities or bedding-related openings. This diversity strengthens the scientific and educational value of the site.

Petrographic and XRD Results

Four representative manganese-ore samples were analysed: samples 2-9 and 3-15 from volcanic breccia vein mineralisation, sample 6-1 from massive limestone-hosted mineralisation, and sample 7-4 from stratiform limestone-hosted mineralisation.

XRD results indicate that samples 2-9 and 3-15 are dominated by pyrolusite (MnO_2), with no significant quartz, calcite, or feldspar gangue phases identified. Samples 6-1 and 7-4 contain calcite and pyrolusite, with calcite as the dominant carbonate phase and pyrolusite as the principal manganese mineral. Petrographic observation of sample 7-4 shows opaque manganese minerals occupying interparticle pores and cavities in bioclastic fragments and occurring with sparite.

The laboratory results therefore show a clear contrast between volcanic-hosted and carbonate-hosted mineralisation. Volcanic-hosted vein material is strongly dominated by manganese oxide, whereas carbonate-hosted material retains a pronounced calcite signature. This distinction is relevant to interpretation and conservation because different host-rock settings require different approaches to exposure management.

Table 1. Representative manganese-ore samples and analytical methods

Sample	Host lithology	Mineralisation	Petrography	XRD	XRF
2-9	Volcanic breccia	Vein	✓	✓	–
3-15	Volcanic breccia	Vein	✓	✓	–
6-1	Limestone	Massive	✓	✓	–
7-4	Limestone	Stratiform/layered	✓	✓	✓

Environmental Pressures

Environmental pressures occur simultaneously with geological heritage values. The main observed categories are physical degradation of outcrops, potential chemical pollution or AMD, erosion and slope instability, specimen collection and vandalism, and restricted access to historical mine openings.

The 2026 survey found that many historical mine openings were partly or substantially

obscured by sedimentation, slope collapse, vegetation, and standing water. These conditions reduce visibility of geological relationships and may create safety constraints for field observation. Continued disturbance from unlicensed artisanal mining can remove mineralised exposures, while erosion can bury or abrade geological surfaces. These processes affect both environmental quality and the integrity of the geological record.

Potential AMD requires continued attention. The present assessment is based on field observations, available pH measurements, mineralogical evidence, and published water-quality information. Because ICP-MS data are not yet available, the current evidence does not provide a quantitative trace-element source signature. The appropriate interpretation is therefore that AMD represents a potential environmental risk requiring monitoring and further geochemical verification.

Community and Institutional Context

Pokdarwis Watu Jonggol and local community members contributed to the field programme through access, guidance to historical mine openings and geological sites, field assistance, and support for rock and ore sampling. This contribution demonstrates the value of local knowledge in locating and interpreting sites where historical mine openings have become difficult to identify.

The available research material does not provide a sufficiently documented numerical questionnaire dataset to report respondent frequencies or percentages. Community findings are therefore interpreted qualitatively. The evidence supports community participation in access management, interpretation, surveillance, and future geotourism activities, but a complete quantitative community assessment should be added when the underlying survey records are available.

Integrated Management Implications

The combined geological and environmental findings support geology-based rather than purely administrative management. A three-zone framework is proposed. The **core geoheritage zone** should contain representative and scientifically important geological exposures, mineralisation features, and structural relationships and should receive strict protection and controlled access. The **buffer zone** should surround important exposures and accommodate selective rehabilitation that does not obscure geological features. The **development zone** should contain infrastructure, visitor facilities, community activities, and compatible land uses.

Rehabilitation should be selective rather than uniform. Complete backfilling or dense revegetation may remove the visibility of significant geological exposures. In areas requiring environmental control, measures such as sedimentation systems, constructed wetlands, or appropriate neutralisation treatments can be designed around conservation requirements ([Peraturan Pemerintah No. 22 Tahun 2021, 2021](#)). Safety, slope stability, drainage, and accessibility should be considered together with geological visibility.

The proposed monitoring framework should cover water quality, soil condition, ecological recovery, and physical geoheritage condition over approximately five to ten years. Field pH, manganese concentration when ICP-MS or equivalent laboratory data become available, photographic records, mine-opening accessibility, vegetation recovery, erosion, and outcrop condition can provide practical indicators. Monitoring should be adaptive so that additional geochemical information can refine the assessment.

The integrated approach also creates opportunities for community-based geotourism. Geological trails can connect volcanic and carbonate exposures, structural features, mineralisation

styles, and historical mining remains. Interpretation should explain geological processes while maintaining safety and conservation controls. Community participation can support guiding, site surveillance, interpretation, and compatible local services. The approach is consistent with the broader role of geoparks in linking geological conservation, education, and sustainable local development ([Awing et al., 2025](#); [Farsani et al., 2021](#); [Indrizal et al., 2024](#)).

Environmental Rehabilitation Compatible with Geoconservation

The environmental-management implications are not limited to protecting individual outcrops. Rehabilitation should consider the spatial relationship between geological exposures, drainage, slopes, vegetation, and access routes. Areas with unstable slopes or accumulated sediment may require engineering and ecological measures, but the treatment should be adjusted where geological features are part of the interpretive value. For example, drainage improvements can reduce waterlogging around historical mine openings while maintaining representative geological sections outside the hazardous area.

Selective rehabilitation also means distinguishing between areas that should be stabilised, areas that should remain accessible for interpretation, and areas where access should be restricted for safety. This approach can reduce unnecessary intervention. Photographic documentation before and after rehabilitation can provide a simple record of whether conservation objectives are maintained. Where erosion threatens an important exposure, control measures should be placed so that they reduce sediment movement without covering the geological relationship being conserved.

Potential AMD management requires the same principle. Water-management structures should be located and designed with reference to important outcrops and visitor movement. Constructed wetlands, sedimentation systems, or neutralisation measures may be considered where site conditions justify them, but their effectiveness should be verified through monitoring rather than assumed. The delayed ICP-MS dataset is particularly relevant because future trace-element information can help refine the identification of areas requiring chemical control.

Geotourism and Community Participation

The geological diversity identified by the survey provides a basis for educational interpretation. A geotrail can connect volcanic breccia exposures, structural features, manganese veins, limestone-hosted mineralisation, and historical mining remains. Such a trail should not simply present the site as a former mining area; it should explain how geological structures, host rocks, and mineralisation styles are related. The contrast between volcanic-hosted pyrolusite and carbonate-hosted calcite-pyrolusite assemblages is particularly suitable for field-based learning.

Community participation can strengthen this interpretation because local residents and Pokdarwis members have practical knowledge of access routes, historical mine locations, and changes in site condition. Their involvement can also support routine observation of vandalism, illegal excavation, vegetation changes, and access problems. However, participation should be supported by clear roles, safety procedures, and coordination with the institutions responsible for geoheritage and environmental management.

The proposed development zone should therefore be used to concentrate visitor infrastructure rather than distributing facilities across sensitive geological areas. Interpretation shelters, rest areas, signage, and community services can be located where they do not interfere with core exposures. This spatial arrangement can help separate conservation functions from visitor-support functions while keeping the overall landscape connected.

Monitoring as an Adaptive Management Tool

Monitoring should be understood as a mechanism for updating management decisions rather than simply collecting data. Initial observations provide a baseline against which changes in water condition, soil stability, vegetation recovery, erosion, accessibility, and outcrop condition can be compared. Repeated photography from selected fixed locations can complement numerical measurements and provide a practical record of physical change.

For water monitoring, field pH can be measured consistently at accessible drainage points, while future laboratory analyses can add manganese and other trace elements. Soil and vegetation observations can document recovery in rehabilitated areas. Geoheritage monitoring should record cracking, weathering, sediment burial, vandalism, specimen removal, and changes in accessibility. Historical mine openings require particular attention because sedimentation, slope collapse, and standing water can change both their interpretive value and safety status.

A five- to ten-year monitoring horizon is appropriate as a management proposal, but monitoring frequency within that period should be adapted to site conditions and available resources. Areas with active erosion, water movement, or continuing disturbance may require more frequent inspection than relatively stable exposures. The resulting information can be used to revise zonation, rehabilitation priorities, visitor access, and conservation measures. This adaptive approach is consistent with the descriptive character of the study because management is based on observed changes rather than on unsupported predictions.

CONCLUSION AND FURTHER RESEARCH

This study establishes a descriptive geological and environmental baseline for the Kliripan-Karangsari manganese geoheritage area from 78 systematic observation points. The site contains diverse volcanic and carbonate geological features, two dominant structural orientations, and five principal manganese mineralisation styles. Petrographic and XRD results identify pyrolusite as the principal manganese mineral, while carbonate-hosted samples show a calcite-pyrolusite assemblage.

The study also identifies simultaneous environmental and geoheritage pressures, including outcrop degradation, erosion, potential AMD, unlicensed excavation, specimen collection, vandalism, sedimentation, waterlogging, and restricted access to historical mine openings. These conditions indicate that post-mining rehabilitation should not be implemented as uniform land-cover restoration. Instead, geological exposures of high value should be protected through active geoconservation, while disturbed areas requiring environmental control should receive selective rehabilitation.

A management framework consisting of core, buffer, and development zones is proposed, supported by community participation and long-term monitoring. Monitoring should address water, soil, vegetation, slope stability, accessibility, and physical geoheritage condition over a five- to ten-year period. The participation of Pokdarwis Watu Jonggol demonstrates the practical value of local involvement, although a more complete quantitative community assessment requires the underlying survey records.

Further work should incorporate the pending ICP-MS analysis to strengthen trace-element and AMD assessment and should report the complete community-survey dataset and laboratory QA/QC information where available. Because the study uses a descriptive, site-specific design, its findings provide a management baseline rather than statistically generalisable estimates. The integrated approach nevertheless demonstrates how environmental rehabilitation and geoconservation can be planned together in a post-mining manganese landscape while supporting

education and community-based geotourism.

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