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DEVELOPMENT OF THE BONEN CAVE TOURISM AUGMENTED REALITY APPLICATION BASED ON WATERFALL ANALYSIS

Robertho Kadji*[1], Irene Augusta Boymau[2] , Lidia Paskalia Nipu[3] ,
Ika FitriKrisnasiwi[4] , Henda V. R. Taopan[5],
Frengky S. Banunaek[6] , Rizhard A. Ndolu[7]
Mining Engineering Study Program, Universitas Nusa Cendana, Kupang
E-mail: robertho_kadji@staf.undana.ac.id [1]*, irene_boymau@staf.undana.ac.id [2], lidia_nipu@staf.undana.ac.id[3], ikafitri.0102@staf.undana.ac.id[4] , henda.taopan@staf.undana.ac.id[5], banunaekfrengky@gmail.com[6], rizhardndolu@staf.undana.ac.id[7]

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Abstract

This study presents the application of an Augmented Reality (AR)–based digital interpretation system to enhance speleological geotourism experiences at Bonen Cave, Baumata Village, Kupang Regency, Indonesia. The research addresses limitations in conventional geotourism interpretation, including low interactivity, limited informational accessibility, and potential environmental disturbance in karst cave environments. The developed AR application integrates three-dimensional cave models, geological explanations, and historical narratives related to the use of the cave during the Japanese occupation period. Implementation was conducted through a community-based approach involving local tour guides and tourism stakeholders. The application was officially launched during the Fatusuba Festival on 17 October 2025 and publicly demonstrated to visitors. Field testing confirmed stable performance and compatibility across multiple Android devices, including Redmi Note 13 Pro, Redmi Note 9 Pro, and Samsung Galaxy A56. Results indicate that the AR application improves visitor engagement, supports knowledge transfer, and strengthens digital promotion of speleological geotourism while reducing the need for direct physical interaction with sensitive cave features. This study demonstrates that AR technology can serve as an effective and sustainable tool for enhancing geotourism experiences and empowering local communities in karst regions.

Keywords Augmented Reality; Geotourism; Digital Tourism; Karst Cave; Bonen Cave

INTRODUCTION

Karst landscapes represent important geoheritage resources due to their geological uniqueness, hydrological functions, and cultural significance. Speleological sites within karst areas offer high potential for geotourism development, combining scientific education, environmental conservation, and local economic opportunities. However, many speleological geosites in developing regions remain underutilized because of limited interpretive infrastructure, low accessibility of scientific information, and the risk of environmental degradation caused by uncontrolled visitor activities. Bonen Cave, located in Baumata Village, Kupang Regency, is a karst cave system that holds geological, historical, and cultural value. In addition to its speleothem formations and cave morphology, the site has historical significance related to its use during the Japanese occupation period (Banunaek et al., 2024). Despite this potential, tourism activities at the site have traditionally relied on verbal explanations and minimal physical signage. Such conventional interpretation methods are often monotonous, difficult to maintain in cave environments, and insufficient for conveying complex geological processes to a general audience. Furthermore, increased physical interaction with cave features poses a threat to the preservation of fragile karst ecosystems. Geotourism destinations rely on digital platforms to communicate their unique value propositions, showcase their geoheritage, and advocate for sustainable tourism practices (Mylonas et al., 2024; Marques et al., 2024; Williams et al., 2024). The most common problems frequently encountered at developing geological sites include lack of accessibility and infrastructure, promotion and marketing, financial and regulatory challenges, concerns about anthropogenic activities and conservation, and local community involvement (Matshusa et al., 2021).

Recent developments in digital technology, particularly Augmented Reality (AR), provide new opportunities for improving interpretation and visitor engagement in geotourism contexts. AR enables the overlay of digital information—such as three-dimensional models, animations, and audio narration into real-world environments through mobile devices. In tourism and heritage studies, AR has been shown to enhance experiential learning, increase visitor satisfaction, and support conservation by reducing reliance on physical interaction with sensitive sites. Nevertheless, the application of AR technology in speleological geotourism in Indonesia, especially in eastern karst regions, remains limited and underexplored.

This study addresses these challenges through the application of an AR-based digital interpretation system at Bonen Cave. The research focuses on the development, implementation, and public dissemination of a mobile AR application that integrates geological interpretation, historical narratives, and three-dimensional cave visualization. A community-based approach was adopted to involve local tour guides and tourism stakeholders in content validation, testing, and deployment of the application. The primary objective of this study is to enhance the speleological geotourism experience while supporting sustainable tourism practices and community empowerment. Specifically, the study aims to: (1) improve visitor understanding and engagement through interactive AR-based interpretation; (2) reduce physical disturbance to sensitive cave environments; and (3) strengthen the capacity of local communities to manage and promote geotourism using digital technology. The outcomes of this research contribute to applied knowledge on the use of Augmented Reality for sustainable geotourism development in karst regions and provide a practical model for similar destinations.

LITERATURE REVIEW

Augmented Reality in Tourism and Heritage Interpretation

Augmented Reality (AR) has been widely recognized as an effective digital technology for enhancing visitor experiences in tourism and cultural heritage contexts. AR enables the integration of digital information—such as three-dimensional (3D) models, animations, and audio narration—into real-world environments, allowing users to interact with additional layers of information through mobile devices. In tourism studies, AR has been shown to increase visitor engagement, improve learning outcomes, and create more memorable experiences compared to conventional interpretive media. Previous research indicates that AR applications are particularly effective in heritage and geotourism sites where physical interpretation is constrained by environmental sensitivity or spatial limitations. Studies conducted at archaeological sites and geological parks demonstrate that AR-based interpretation can visualize historical reconstructions and geological processes that are otherwise difficult for visitors to comprehend through static signage alone. By presenting abstract scientific concepts in visual and interactive formats, AR supports experiential learning while reducing dependence on physical infrastructure that may be vulnerable to weathering or vandalism.

AR Applications in Geotourism and Speleological Environments

In the context of geotourism, AR has been applied to enhance geological interpretation by visualizing stratigraphy, geomorphological evolution, and subsurface structures. Research in karst and cave environments highlights the potential of AR to address key challenges associated with speleological tourism, such as limited lighting, restricted access, and the need for conservation-oriented visitor management. Digital visualization allows visitors to understand cave formation processes and internal structures without extensive physical exploration, thereby reducing anthropogenic pressure on fragile cave ecosystems.

Augmented reality (AR) has rapidly become a prominent digital tool in tourism, overlaying digital content (text, 3D models, animation, sound) onto the physical environment through smartphones, tablets or head-mounted displays to create context-sensitive, interactive experiences (Cranmer et al., 2020; Jiang et al., 2022). In contrast to virtual reality, which substitutes the real world, AR maintains direct contact with real places while enriching them with additional interpretive, entertaining or practical layers (Yung & Khoo-Lattimore, 2019; Liang & Elliot, 2020).

Tourism sectors where AR is most visible include cultural heritage sites, museums, urban destinations, resorts, events and cruises (Yung & Khoo-Lattimore, 2019; Jiang et al., 2022; Cranmer et al., 2020). In heritage tourism, AR has been used to reconstruct past environments, animate ruined structures, and provide location-based narratives, helping preserve and communicate unique culture and heritage while modernising the visitor offer (Jiang et al., 2022; Cranmer et al., 2020). Museums and galleries deploy AR to add interactive interpretation to artworks and artefacts, increasing engagement and learning opportunities (Yung & Khoo-Lattimore, 2019; Cranmer et al., 2020). Destination marketing organisations adopt AR campaigns and apps to support pre-trip inspiration and on-site

exploration, integrating AR into broader experiential marketing strategies (Yung & Khoo-Lattimore, 2019; Cranmer et al., 2020).

Community-Based Digital Innovation in Geotourism

Community involvement is a critical factor in the sustainability of geotourism development. Community-based tourism models emphasize local participation, knowledge sharing, and economic empowerment while maintaining environmental conservation. Integrating digital technologies such as AR into community-based geotourism requires careful consideration of usability, accessibility, and local capacity building. Previous studies suggest that when local communities are actively involved in the development and deployment of digital tourism tools, technology adoption is more sustainable and socially impactful. Digital interpretation tools can support local tour guides by standardizing information delivery, enhancing interpretive accuracy, and increasing confidence in guiding activities. Nevertheless, empirical studies documenting the integration of AR technology within community-based speleological geotourism, remain limited.

Research Gap and Contribution

Based on the reviewed literature, it is evident that while AR technology has demonstrated strong potential in tourism and heritage interpretation, its application in speleological geotourism within developing regions is still underexplored. Systematic reviews show that AR tourism research is dominated by user acceptance studies applying technology acceptance models, focusing on perceived ease of use and usefulness, where ease of use strongly drives perceived usefulness (Liang & Elliot, 2020). Despite its promise, several challenges persist: low awareness of AR technologies, usability issues, time and effort costs for users, and managerial concerns in heritage contexts that AR may dilute perceived authenticity (Yung & Khoo-Lattimore, 2019; Cranmer et al., 2020). Research on in-situ visitor experiences, long-term impacts, gamification and potential negative consequences (e.g., distraction, crowding, over-mediation) remains limited, indicating significant opportunities for future work (Yung & Khoo-Lattimore, 2019; Jiang et al., 2022; Liang & Elliot, 2020). This study addresses these gaps by presenting a practical case of AR application development and implementation at Bonen Cave, Kupang Regency. By combining speleological interpretation, historical narratives, and community-based deployment, this research contributes applied evidence on how AR technology can enhance geotourism experiences, support conservation efforts, and empower local communities in karst environments.

METHOD

Research Design

This study employed an applied, descriptive-implementation research design with a community-based approach. The research focused on the development, implementation, and field testing of an Augmented Reality (AR) application to enhance speleological geotourism experiences at Bonen Cave, Kupang Regency. The design emphasized real-world application, public demonstration, and usability evaluation rather than controlled laboratory experimentation.

Study Area and Participants

The study was conducted at Bonen Cave, located in Baumata Village, Kupang Regency, Indonesia. The site was selected due to its geological significance as a karst cave system and its cultural–historical value. Participants involved in the implementation included local tour guides, members of the community tourism group, representatives of the local tourism authority, and festival visitors during the public launch event.

Development of the Augmented Reality Application Utilizing the Waterfall Model

This study utilized the Waterfall development paradigm for the creation of the Augmented Reality (AR) application to guarantee a controlled, systematic, and thoroughly documented approach. The Waterfall model is a linear software development process wherein each phase must be finalized prior to advancing to the subsequent phase. This methodology is especially appropriate for digital tourism applications characterized by well-defined objectives and stable requirements, as it facilitates regulated development, comprehensive documentation, and systematic assessment (Ariasa et al., 2022; Nurhuda & Putra, 2022; Buana et al., 2025; Pratama et al., 2022; Supriadi et al., 2022). The Waterfall approach was implemented via the subsequent stages.

1. Requirements Assessment and Strategic Planning

The development process commenced with requirements analysis and planning, involving important stakeholders such as local tourism officials, community leaders, and potential users. Data were gathered via interviews, field observations, and conversations to ascertain application objectives, target users, and functional requirements. Analytical instruments, including flowcharts and Data Flow Diagrams (DFD), were employed to delineate system operations and interaction logic. The primary needs listed encompassed AR-based depiction of cave elements, provision of geological and historical information, user-friendliness in on-site tourism contexts, and compatibility with widely utilized Android smartphones.

2. System and Application Architecture

The system and application design phase concentrated on structuring the architecture, user interface, and data organization of the AR application according to the specified criteria. Modeling instruments, including Entity Relationship Diagrams (ERD) and Unified Modeling Language (UML) diagrams, were employed to illustrate the links among application components, AR markers, multimedia content, and user interactions. Visual design components comprising three-dimensional cave models, high-resolution images, and interactive augmented reality content were devised to augment user engagement and bolster the digital branding of the Bonen Cave geotourism site (Nurhuda & Putra, 2022; Buana et al., 2025; Santyadiputra et al., 2019; Prasetyo & Suraya, 2023).

Image 1. (a) Main Page of AR Application (b) Main Menu of AR Application

3. Execution (Programming and Content Creation)

The implementation involved converting the sanctioned design into a functional AR application. Cave mapping and recording were executed by photogrammetry and direct field observation to produce three-dimensional (3D) models of cave pathways and significant speleothem features. The spatial data were converted into lightweight 3D representations appropriate for mobile devices. Interpretive information was subsequently created by amalgamating geological explanations of karst formation processes, speleological attributes, and historical accounts pertaining to the cave's utilization during the Japanese occupation. Content validation was performed via consultations with subject matter experts and local community leaders to guarantee scientific precision and cultural appropriateness. To guarantee dependable functionality in dimly lit cave settings, the application implemented a marker-based augmented reality system. Markers were affixed to information boards and portable AR cards, facilitating reliable scanning and interaction with conventional smartphone cameras. Principles of digital storytelling were utilized to convey scientific and historical information in an entertaining and accessible fashion (Nurhuda & Putra, 2022; Buana et al., 2025; Pratama et al., 2022; Santyadiputra et al., 2019).

4. Assessment and Appraisal

Testing and evaluation were performed to ascertain the application's functionality, usability, and performance. Black-box testing was utilized to evaluate system functioning, encompassing marker detection precision, content presentation, navigation sequence, and multimedia playing. The usability study was performed by direct observation and informal input from users and local tour guides during trial sessions. Documented shortcomings, including instability in marker recognition and usability concerns, were noted as inputs for refinement and future development (Ariasa et al., 2022; Nurhuda & Putra, 2022; Haryono & Madani, 2024).

5. Execution and Public Introduction

The augmented reality application was executed via guided demonstrations and direct audience engagement during the Fatusuba Festival on 17 October 2025. The festival functioned as a practical testing and distribution platform, enabling visitors to utilize and manage the application under supervision. This method facilitated concurrent public unveiling, usability assessment, and community involvement.

6. Testing for Device Compatibility

Device compatibility testing was performed during the public debut and ensuing field trials. The program underwent testing on various Android smartphones with differing hardware characteristics, including the Redmi Note 13 Pro, Redmi Note 9 Pro, and Samsung Galaxy A56. The observed performance metrics were marker recognition accuracy, stability of 3D object rendering, audio playback performance, and overall application responsiveness.

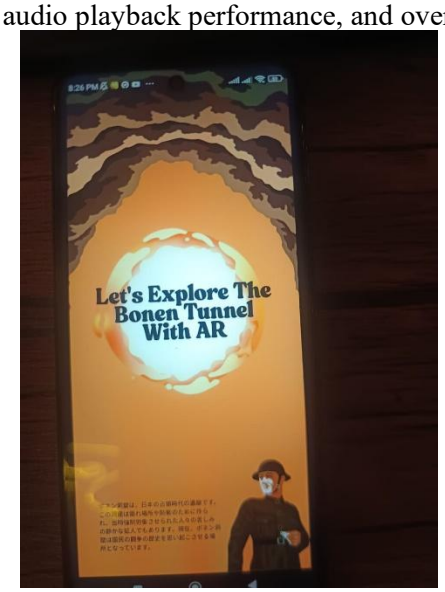

Image 2. Testing in Redmi Note 9 Pro Phone

7. Methods of Data Collection

Data gathering was executed utilizing qualitative and descriptive methodologies. Observational data were collected during public demos to evaluate user engagement patterns and technical performance. Unstructured user input was gathered from visitors and local tour guides concerning usability, clarity of information, and overall experience. Technical findings concerning device compatibility and application stability were documented throughout field testing.

8. Data Examination

Data analysis was conducted descriptively by integrating observational findings and user comments. The investigation concentrated on assessing the efficacy of the AR application in augmenting visitor engagement, facilitating interpretative activities, and guaranteeing accessibility across various devices. The results were analyzed for the enhancement of geotourism experiences, conservation factors, and community empowerment.

RESULTS AND DISCUSSION

Development and Implementation of the Augmented Reality Application

The Augmented Reality (AR) application developed in this study was designed as a digital interpretation tool for speleological geotourism at Bonen Cave. The application integrates three-dimensional (3D) cave models, geological explanations, and historical narratives into an interactive mobile-based platform. The 3D cave models

were generated from detailed cave mapping and photogrammetric documentation, allowing users to visualize cave morphology, passage orientation, and key speleothem features without the need for intensive physical exploration. Implementation of the application followed a community-based approach, involving local tour guides and tourism stakeholders in both content validation and field testing. Marker-based AR interaction was selected to ensure usability under low-light cave conditions and to minimize technical complexity for first-time users. This approach proved effective in enabling stable visualization of digital content when markers were scanned at designated points, such as information boards and portable AR cards. The integration of geological interpretation particularly karstification processes and cave formation into visual and audio narration enhanced the educational value of the geotourism experience. Rather than functioning solely as a promotional tool, the application also served as a medium for geo-education, supporting conservation-oriented tourism practices by reducing uncontrolled visitor movement within sensitive cave areas.

Public Launch and Device Compatibility Performance

The AR application was officially launched during the Fatusuba Festival on 17 October 2025, marking the first public dissemination of the technology to a broader audience. The festival setting provided a real-world testing environment involving diverse user backgrounds, ranging from local residents to visiting tourists. Live demonstrations were conducted at the festival venue, allowing visitors to directly interact with the application under guided supervision. Performance testing during the launch event demonstrated that the application operated reliably across multiple Android smartphone models, including Redmi Note 13 Pro, Redmi Note 9 Pro, and Samsung Galaxy A56. These devices represent different hardware generations and performance classes, indicating that the application does not require high-end specifications to function effectively. Marker detection, 3D object rendering, and audio narration operated smoothly without significant lag or application failure.

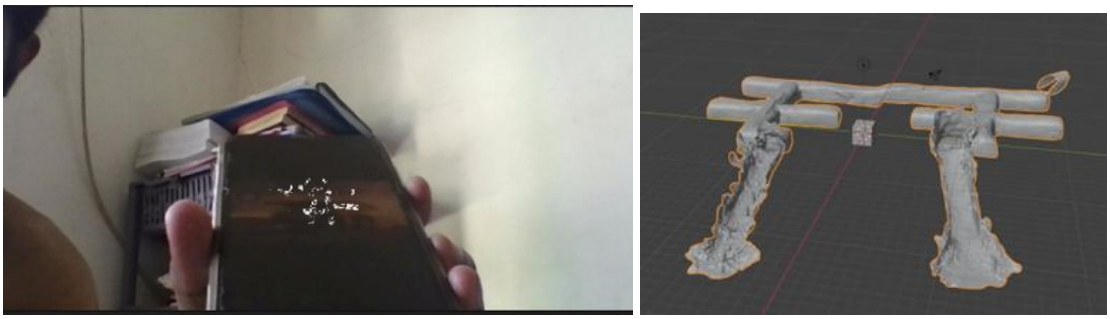

Image 3. Marker Based Application and 3D Object

This cross-device compatibility is a critical outcome, as it supports broader accessibility and scalability of the application for public use. In the context of community-based geotourism, ensuring that the application functions on commonly used mid-range smartphones increases the likelihood of adoption by both local tour guides and visitors. The successful public launch also strengthened digital promotion of the Bonen geosite, positioning it as an early example of AR-based geotourism innovation in karst areas of eastern Indonesia.

Implications for Geotourism Experience and Community Empowerment

The implementation of the AR application demonstrated tangible benefits for both visitor experience and local community involvement. From the visitor perspective, the application enhanced engagement by transforming passive observation into an interactive learning process. Users were able to access layered information (geological, historical, and cultural) through a single digital interface, improving comprehension without overwhelming physical signage. From a conservation standpoint, the AR-based interpretation reduced the need for visitors to approach fragile cave features directly. By visualizing geological processes and historical usage digitally, the application supports sustainable tourism practices aligned with karst ecosystem protection. This finding is particularly important for speleological sites, where uncontrolled tourism can lead to irreversible environmental damage. For the local community, especially tour guides, the application functioned as a digital assistance tool that strengthened interpretive capacity and confidence. Guides were no longer solely dependent on verbal explanations but could rely on standardized digital content to ensure accuracy and consistency. This contributes to professionalization of local guiding services and enhances the role of communities as active actors in technology-supported tourism development.

Overall, the results indicate that Augmented Reality technology can effectively bridge scientific knowledge, cultural heritage, and community-based tourism management. When implemented through participatory approaches and tested in real operational contexts, AR applications have strong potential to support sustainable geotourism development in karst regions.

CONCLUSION

This research demonstrates that the implementation of Augmented Reality (AR) technology can markedly enhance speleological geotourism experiences in karst regions when conducted through a community-oriented approach. The AR app made for Bonen Cave successfully put together 3D cave photography, geological analysis, and historical descriptions into an interactive digital platform that can be utilized on most mobile devices. The app's public debut at the Fatusuba Festival on October 17, 2025, proved that it was both technologically sound and useful. Field testing showed that the program worked well on many different Android smartphones. This means that it was compatible with a wide range of devices and made it easier for both visitors and local tour guides to use. Marker-based augmented reality worked well in caves with little light, making it possible to reliably share content in real-world situations.

From a geotourism point of view, the application made it easier for visitors to understand and participate with the material by turning traditional, passive interpretation into an interactive learning experience. At the same time, digital visualization made it less necessary to physically interact with fragile cave features, which encouraged tourism methods that focus on conservation. The AR app was a digital tool that helped the local community, especially tour guides, by improving their capacity to explain things, making sure that everyone got the same information, and making it easier for guiding services to become more professional. Augmented Reality technology can significantly and sustainably advance geotourism development in karst landscapes. The implementation strategy put out in this study is applicable to similar geosites, with future enhancements focused on offline functionality, broader dissemination, and ongoing evaluation of social, educational, and economic impacts.

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