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REVIEW ARTICLE

Why Geoheritage Matters in Geoconservation Strategies: A Case Study from the Khowai Badlands in West Bengal, India

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Abstract
This study investigates the integration of geoheritage into geoconservation strategies, with a specific emphasis on the Khowai Badlands in West Bengal, India. Recognizing the importance of preserving geological, ecological, and cultural heritage, this research aims to address the challenges and opportunities associated with holistic conservation approaches. Methodologically, the study employs a combination of literature review, case study analysis, and policy evaluations. The findings underscore the critical role of geological formations in supporting biodiversity and the cultural heritage embedded within these landscapes. Moreover, the study emphasizes the need for sustainable tourism practices and community involvement in conservation efforts, ensuring the long-term sustainability of our planet's natural and cultural heritage for future generations.

Keywords Geoheritage · Geoconservation · Khowai Badlands · Cultural preservation · India

Introduction

Geoheritage, encompassing geological features, landscapes, and processes of significant scientific, educational, and cultural value, is defined by Gray (2018a); Crofts et al. (2015), 2021). This includes iconic landforms, fossil-rich sites, and geological phenomena contributing to Earth's rich legacy (Reynard et al. 2016; Page 2018). The integration of geoheritage into wider geoconservation efforts is emphasized by Gordon (2018), Brakenhoff et al. (2015), and Matoussi Kort et al. (2023), highlighting its importance in comprehending natural systems and fostering sustainable practices (Higgs 2016). Amid environmental challenges like climate change and habitat degradation (Arora et al. 2018; Everard et al. 2020), safeguarding biodiversity remains paramount. However, recognizing the significance of geoheritage conservation is crucial (Mathews 2016; Volis 2016; Cave and Negussie 2017; Crofts 2018). Vereb (2020) and Nemeth (2021) stress the need to transcend the dichotomy between geological features and broader environmental protection, shedding light on Earth's historical trajectory and ongoing processes shaping the planet. Furthermore, Malik and Ali (2023) and Malik and Jamshed (2023) emphasize the intrinsic interdependence between geoheritage conservation and ecosystem vitality.

This study builds upon the theoretical groundwork laid out by scholars such as Gordon (2018), Brakenhoff et al. (2015), and Matoussi Kort et al. (2023), who underscore the importance of integrating geoheritage into wider geoconservation efforts. By evaluating the significance, challenges, and opportunities associated with this integration, this study contributes to theory building within fields such as environmental anthropology and cultural ecology (Baird 2022; Rozzi et al. 2023). It explores how acknowledging and incorporating geological features into conservation efforts enriches our understanding of natural systems and underscores the interconnectedness of geoheritage conservation, biodiversity, and ecosystem health, as discussed in the preceding paragraph. Through this analysis, this study aims to deepen the theoretical discourse on holistic conservation approaches and their role in fostering sustainable environmental stewardship.

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The Integration of Geoheritage into Geoconservation

The integration of geoheritage into geoconservation represents a holistic approach that acknowledges the significance of geological features alongside nature conservation and sustainability (Bennett et al. 2015; Gordon et al. 2018; Gordon 2018). Geoheritage sites, characterized by diverse geological features, landscapes, and processes, hold significant scientific, educational, and cultural value (Brilha 2016; Németh et al. 2021a and 2021b). These sites serve as educational hubs, facilitating research, education, and cultural appreciation (Henriques and Pena dos Reis 2019; Reynard and Giusti 2018), while also contributing to local economies through eco-tourism (Farabollini and Bendia 2022). Anderson and colleagues' "nature's sage" concept emphasizes the interconnectedness of geological processes and geoconservation, stressing the importance of understanding past and present dynamic processes in shaping biodiversity (Anderson et al. 2014). Integrating geoheritage into conservation efforts extends the conservation paradigm, recognizing the interplay between geological and biological factors (Brilha et al. 2018), thus leading to the development of advanced conservation strategies (Mathevet et al. 2018; Brocx and Semeniuk 2019). Examples like the Grand Canyon demonstrate successful integration, where both geological significance and biological diversity are prioritized (Migoń 2014). Successful integration of geoheritage in geoconservation can be observed globally, showcasing the benefits of acknowledging the interconnectedness of geological and biological heritage (Gonzalez-Tejada et al. 2017; Newsome and Dowling 2018; Reynard and Giusti 2018; Ríos et al. 2020; da Glória Garcia et al. 2022).

The successful integration of geoheritage into geoconservation requires a critical assessment of approaches, analyzing their impact on geoconservation and evaluating their effectiveness in preserving both geological and biological heritage. For instance, the Joggins Fossil Cliffs in Canada effectively combine geological heritage preservation with biodiversity research, paleontology, education, and public engagement (Carcavilla et al. 2009; Rygel et al. 2015; Calder 2017; Slaymaker et al. 2020). Similarly, conservation efforts at the Dorset and East Devon Coast in the United Kingdom safeguard geological features while promoting geoconservation and education (May 2015; Hose 2016, 2021; Comănescu and Nedelea 2020). Analyzing Table 1 and other examples reveals the critical link between geoheritage and geoconservation. However, challenges may arise in balancing the preservation of geological heritage with geoconservation, as seen in highly visited areas like the Iguaçu National Park in Brazil/Argentina (Siuki and Kowalczyk 2012; Ortega-Becerril et al. 2019).

Benefits and Challenges of Integrating Geoheritage into Geoconservation

The multitude of benefits offered by the integration of geoheritage into geoconservation extends beyond the mere preservation of geological features. Enhanced comprehension of the natural environment, encouragement of sustainable tourism, and assistance in safeguarding biodiversity are facilitated by this integration. In the Table 2, the primary advantages of incorporating geoheritage into geoconservation endeavors are delineated. These examples underscore how the fusion of geoheritage and geoconservation bolsters our grasp of Earth's geological past, stimulates local economies through sustainable tourism, and contributes to the protection of biodiversity. Moreover, the cultural and educational value of these locations is underscored, fostering public awareness and environmental stewardship for a more sustainable future.

The incorporation of geoheritage into geoconservation brings forth a range of advantages. However, it also introduces various challenges and potential conflicts that demand thoughtful attention and resolution. These issues can be categorized and are outlined in Table 3 for further exploration and analysis.

To address these challenges, a comprehensive and collaborative approach is crucial. This involves developing well-defined management plans that account for the diverse needs of geoheritage and ecological conservation. Impact assessments (Bruschi and Coratza 2018), active engagement of all stakeholders in decision-making (Halim and Ishak 2017), and fostering a shared commitment to the long-term sustainability (Chen et al. 2019; García-Sánchez et al. 2021) of these unique sites are essential. Recognizing the interconnectedness of geological and biological heritage (Naeem et al. 2016; Pásková et al. 2021) and seeking common ground for their preservation (Cave and Negussie 2017; Cigna et al. 2018) is vital for a harmonious integration of geoheritage into geoconservation.

Framework for Geoheritage Integration into Geoconservation

Integrating geoheritage in geoconservation can be structured within a comprehensive framework that draws from existing theories, models, and hypotheses from the fields of conservation biology, geology, and environmental science. This framework is designed to facilitate a systematic and holistic approach to the integration of geoheritage and geoconservation. It incorporates the following key elements:

Table 1 Global examples of successful geoheritage integration in geoconservation

Geoheritage Sites	Remarks	Geoheritage Components	Integration Successes	Sources/Authors
Joggins Fossil Cliffs, Canada	UNESCO World Heritage Site	An extensive fossil record dating back to the Pennsylvanian period, around 310 million years ago, includes early tetrapods, arthropods, and plants.	Successfully integrate geological heritage, biodiversity research, paleontology, education, and public engagement for enhanced scientific understanding.	Rygel et al. 2015; Slaymaker et al. 2020.
Galápagos Islands, Ecuador	UNESCO World Heritage Site	Volcanic landscapes, distinctive rock formations, and renowned biodiversity.	Conserves both geological and biological heritage, emphasizing geological context in island-wide preservation.	Kelley et al. 2019; Burbano and Meredith 2021.
Dorset and East Devon Coast, United Kingdom	UNESCO World Heritage Site	The "Jurassic Coast" boasts breathtaking rock formations, comprising fossils and distinctive landforms.	This site exemplifies successful geoheritage integration in conservation by safeguarding geological features and promoting geoconservation and education.	Hose 2016; Hose 2021.
Iguaçu National Park, Brazil/Argentina	UNESCO World Heritage Site	Renowned for the breathtaking Iguaçu Falls, the park also showcases a variety of geological formations.	Conservation efforts protect waterfalls and adjacent geological features, preserving both heritage and biodiversity.	Siuki and Kowalczyk 2012; Ortega-Becerril et al. 2019.
Burren, Ireland	UNESCO World Heritage Site	Karst landscape with unique geological features, including limestone pavements and underground caves	Burren conservation successfully protects geological and ecological aspects, preserving unique formations and thriving flora and fauna.	Ramazanova et al. 2018; Panzer-Krause 2019.
Uluru-Kata Tjuta National Park, Australia	UNESCO World Heritage Site	Uluru (Ayers Rock) and Kata Tjuta (the Olgas) are iconic geological formations.	Successfully integrates geological and cultural heritage, preserving indigenous traditions, knowledge, and formations.	Hueneke and Baker 2009; Palmer 2016; Dittmer et al. 2020.
Table Mountain National Park, South Africa	Part of the UNESCO Cape Floral Region World Heritage Site	The flat-topped mountain is an iconic geological landmark hosting a diverse array of plant species.	Successfully conserves geological formations and plant diversity, drawing tourists and scientists.	Thomas and Asrat 2018; Mabibibi et al. 2021.
Cappadocia, Turkey	UNESCO World Heritage Site	Unique geological landscape featuring fairy chimneys, cave dwellings, and underground cities.	Integration success involves conserving geological features, historical heritage, and the ecosystem, preserving unique formations and heritage.	Karakuş 2019; Akin et al. 2022.
Torngat Mountains National Park, Canada	UNESCO World Heritage Site	Boast a diverse range of geological features, including ancient rock formations, fjords, and glacial landscapes.	The park's strategy conserves geological heritage and Arctic ecosystems, preserving the unique landscape and ecological sensitivity.	Snook et al. 2018; Bélanger et al. 2019.
Santorini, Greece	Included in the first list of 100 World Geological Heritage Sites.	Famous for its volcanic caldera, cliffs, and unique geological formations.	Geological and ecological considerations are integral to the sustainable development and tourism management on the island.	Sigala 2019; Caetano and Ponciano 2021

Source: Completed by the author following an extensive review of the literature

- The Unified Conservation Theory (UCT) provides a foundational framework for comprehensive conservation efforts. It advocates for the simultaneous conservation of geological, biological, and cultural aspects of natural heritage, recognizing their interconnectedness (Kalamandeen and Gillson 2007). For instance, the Joggins Fossil Cliffs in Canada showcase how UCT integrates geoheritage conservation with biodiversity support and cultural value. In the Galápagos Islands, UCT guides conservation by considering the geological context alongside the renowned biodiversity. Similarly, Iguaçu National Park in Brazil and Argentina applies UCT principles to safeguard both geological wonders and the surrounding ecosystems. These examples illustrate the effectiveness of UCT in achieving holistic and sustainable conservation (Job et al. 2020; Kosters and Grey 2021).
- The Three-Pillar Model of Conservation emphasizes three equally vital components: geoconservation, geoheritage conservation, and cultural significance. This model recognizes their interconnectedness in maintaining natural and cultural heritage (Harrison 2015). For

Table 2 Key benefits of integrating geoheritage into geoconservation

Main benefit	Sub-benefit	Description	Examples
Educational significance (Xu 2013; Gajek et al. 2019; Tormey 2019; Giardino et al. 2022)	Scientific insights	Geoheritage sites offer valuable insights into Earth's geological history and processes, supporting geology education and research.	• Grand Canyon: Study of geological layers • La Brea Tar Pits: Fossil research
	Environmental education	Educational programs at these sites raise awareness of geological and ecological interconnections.	• Joggins Fossil Cliffs: Environmental programs • Burren: Environmental education
Cultural enrichment (Gavin et al. 2015; Szepesi et al. 2017)	Preservation of heritage	Many geoheritage sites hold cultural significance, preserving indigenous traditions and knowledge related to geological features.	• Uluru-Kata Tjuta National Park: Indigenous significance • Galápagos Islands: Cultural heritage
	Cultural awareness	Visitors learn about historical uses of geological features, indigenous beliefs, and local economies' dependence on geological formations.	• Mount Fuji: Cultural significance • Stonehenge: Cultural heritage
Scientific advancement (Pijet-Migoń and Migoń 2022)	Research opportunities	Geoheritage sites provide natural laboratories for geological research, contributing to scientific knowledge.	• Burgess Shale: Fossil research • Giant's Causeway: Geological research
	Climate change	Insights Geological features offer essential data on past climate changes, aiding the understanding of current climate patterns and long-term preservation strategies.	• White Cliffs of Dover: Climate change insights • Table Mountain: Climate studies
Tourism and economic benefits (Newsome and Dowling 2018; Girault 2019)	Eco-tourism opportunities	Geoheritage sites attract eco-tourists, generating income for local communities and supporting the regional economy.	• Azores Geopark: Sustainable tourism • Machu Picchu: Cultural tourism
	Job creation	The tourism industry around these sites creates various job opportunities, benefiting local livelihoods.	• Yellowstone National Park: Employment opportunities • Geoparks worldwide: Job creation
Geoconservation (Alemu 2016; Nemeth et al. 2021a and 2021b; Jaya et al. 2022; Kaur 2022)	Ecosystem health	Many geoheritage sites function as ecosystems, supporting diverse flora and fauna. The conservation of geological features preserves these ecosystems.	• Giant Arch in Wadi Rum: Desert ecosystems • Canaima National Park: Tepui biodiversity
	Habitat protection	The protection of geoheritage sites often extends to the surrounding areas, providing refuge for species and contributing to broader geoconservation efforts.	• Serengeti National Park: Wildlife habitat protection • Tubbataha Reefs Natural Park: Coral reef conservation
Public awareness (Hill et al. 2020; Coratza et al. 2023)	Environmental advocacy	Exposure to geoheritage sites raises public awareness about the importance of conservation and environmental protection.	• Jurassic Coast: Advocacy for geological and environmental protection • Iguazú Falls: Environmental awareness
	Stewardship education	Stewardship Education and experiences at these sites encourage individuals to become environmental stewards, actively participating in geoconservation.	• Cappadocia: Stewardship initiatives • Geoparks worldwide: Environmental education

Source: Compilation by the author derived from a literature survey

instance, Machu Picchu in Peru embodies this model by preserving both its iconic archaeological and geological features, contributing to cultural and geological heritage conservation (Margottini 2015; Bridgewater and Rotherham 2019). Australia's Great Barrier Reef Marine Park is another example, where conservation efforts target biodiversity, geological formations, and indigenous cultural values (Pratchett et al. 2019). The Three-Pillar Model ensures that these three aspects are given equal consideration, fostering a holistic approach to conservation that respects the interdependence of these pillars.

- The Hypothesis of Interconnectedness (HI) underscores the interdependence of geological heritage and biodiversity within ecosystems. Changes in geological features can have cascading effects on ecosystems (Clark et al. 2017). For instance, at Yellowstone National Park,

Table 3 Categorized challenges and conflicts arising from the introduction

Main problems	Sub-problems	Description
Resource allocation and prioritization (Harmon and Viles 2013)	• Resource allocation • Land use conflicts • Sustainability • Regulatory conflicts	Resource allocation and prioritization challenges involve balancing limited resources for geological and biological conservation. Land use conflicts deal with economic interests conflicting with conservation. Sustainability challenges balancing long-term health and immediate needs. Regulatory conflicts arise from differing mandates and regulations.
Visitor management and impact (Dowling and Newsome 2017, 2018)	• Visitor impact • Visitor education and compliance	Visitor management and impact challenges encompass addressing the consequences of tourism. Visitor impact pertains to managing and mitigating the effects of tourism on geological and ecological components. Visitor education and compliance involve educating visitors about responsible behavior while maintaining access to these sensitive sites.
Environmental considerations (Bruschi and Coratza 2018)	• Erosion and geological preservation • Climate change adaptation	Environmental considerations challenges involve safeguarding geological and ecological features in changing environments. Erosion and geological preservation focus on protecting sensitive sites from erosion, sometimes affecting ecosystems. Climate change adaptation addresses the impacts of climate change, including increased erosion and shifts in ecological dynamics.
Cultural and indigenous engagement (Gravis et al. 2020)	• Cultural and indigenous concerns	Cultural and indigenous engagement encompasses addressing the perspectives and participation of cultural and indigenous communities in conservation efforts, with a specific focus on cultural and indigenous concerns.
Scientific and research-related (Chandel et al. 2022)	• Data collection and research	Scientific and research-related challenges involve managing research activities and data collection, focusing on data collection and research.

Source: Compiled by author based on literature survey

the geothermal features impact the diversity of microbial life, showcasing the link between geological and biological components (Beam 2015). In the Galápagos Islands, volcanic landscapes influence the distribution and adaptation of species (Roell et al. 2021; Parkes et al. 2021). HI guides conservation by acknowledging these interconnected relationships. By understanding the ecological consequences of geological alterations, it promotes holistic management that safeguards both geological and biological diversity, ensuring the overall health and resilience of ecosystems in geoheritage sites (Selmi et al. 2022).

- The Adaptive Management Framework is a dynamic approach used to manage geoheritage sites, allowing for flexibility and responsiveness to changing conditions. This model involves continuous cycles of assessment, planning, implementation, and evaluation (Prosser et al. 2010). For example, the Grand Canyon in the United States employs this framework to adaptively manage geological and ecological aspects. When faced with erosion threats due to increased visitor numbers, the park implemented new visitor management strategies and monitored their effectiveness, ensuring the conservation of geoheritage and ecological health (Walters et al. 2000; Hughes et al. 2007; Mueller et al. 2017).
- The Holistic Site Assessment Model provides a comprehensive framework for assessing the significance of geoheritage sites, encompassing geological, ecological, cultural, and economic criteria (Zafeiropoulos and Drinia 2023). One such example is the Great Smoky Mountains National Park in the United States, which employs this model. The park's assessment integrates geological features, such as diverse rock types, with ecological diversity, including numerous plant and animal species. Cultural and historical significance is highlighted by the conservation of Appalachian culture (McGrath and Brennan 2020). Additionally, the economic benefits of eco-tourism contribute to its assessment. This holistic approach ensures that geoheritage sites like the Great Smoky Mountains are valued for their multidimensional contributions and managed accordingly (Gordon and Barron 2012; Nakarmi et al. 2023).
- The Cultural Landscape Conservation Approach views landscapes holistically, encompassing geological and ecological features. It emphasizes the integration of indigenous and local knowledge, recognizing the cultural value of geoheritage sites (Macdonald and King 2018). Uluru-Kata Tjuta National Park in Australia embodies this approach, where the conservation of the iconic geological formation, Uluru, is inseparable from its cultural significance to the Anangu people (Wallis and Gorman 2010; Boer 2023). Similarly, Mesa Verde National Park in the United States combines geological features with ancient Puebloan cliff dwellings, preserving both geological heritage and cultural landscapes (Palonka et al. 2023).
- The Triple-Bottom-Line (TBL) Sustainability Model assesses conservation efforts in terms of economic, environmental, and social factors (Majid and Koe 2012; Sala 2020). One example is the Great Barrier Reef Marine Park in Australia, which employs this model. It not only safeguards biodiversity and geological formations but also promotes sustainable tourism that benefits local economies (Pittman et al. 2019). Another example

is Mount Athos in Greece, where conservation efforts encompass both geological heritage and the cultural significance of monastic communities, supporting local livelihoods (Kitromilides 2020; Sarmiento et al. 2022).

- The Geotourism Development Model prioritizes responsible and sustainable tourism at geoheritage sites (Frey 2021; Zafeiropoulos et al. 2021). The Azores Geopark in Portugal exemplifies this model by embracing geotourism principles. It offers educational experiences focused on geological features and their ecological importance while involving local communities in tourism activities (Sadry 2020). Another example is the Burren and Cliffs of Moher Geopark in Ireland, which integrates geotourism into conservation efforts. It emphasizes responsible tourism practices, raising awareness about geological and ecological features and supporting the local economy (Ferraro et al. 2020; Wendt 2020; Doyle 2021).
- Resilience Theory assesses the adaptability of geoheritage sites to environmental and human-induced changes (Chikodzi et al. 2022). Yellowstone National Park in the United States is a prime example. This theory guides the park's strategies to enhance resilience. It addresses challenges like climate change by monitoring geothermal features and their impacts on ecosystems (Barrick 2010; Turner et al. 2016; Ray et al. 2022). The Serengeti National Park in Tanzania also employs Resilience Theory to manage geological and ecological aspects. It adapts to climate-driven shifts in wildlife distribution and habitats (Strauch et al. 2008; Kariuki et al. 2021).

Figure 1 presents a structured framework that synthesizes theories, models, and hypotheses from diverse disciplines to create a comprehensive strategy for integrating geoheritage into geoconservation. This framework acknowledges the intricate connections among geological, ecological, and cultural elements, prioritizing the conservation of these essential aspects of natural heritage. Embracing principles such as sustainability, resilience, and adaptive management, it aims to ensure the enduring protection of geoheritage sites. By incorporating approaches like the Unified Conservation Theory, Three-Pillar Model of Conservation, and Resilience Theory into strategic planning, managers can effectively safeguard geoheritage while promoting sustainability and resilience in conservation efforts.

Case Study on Khowai Badlands (West Bengal, India): A Paradigm of Integrated Geoheritage and Geoconservation

In Bengali, the term "Khowai" signifies a geological formation predominantly found in the Birbhum, Bardhaman, and Bankura districts of West Bengal, India, with additional occurrences in specific regions of Jharkhand, India. Khowai Badlands (Fig. 2), situated near Santiniketan in the Birbhum district of West Bengal, India, serves as an outstanding illustration of the seamless integration of geoheritage and geoconservation. From a geographical perspective, the Khowai Badlands extends across longitudes from 87°38′34.94″E to 87°40′23.44″E and latitudes from 23°40′08.71″N to 23°41′25.17″N, covering a total land area of approximately 1.85 square kilometers (Saha et al. 2020).

In the context of geoconservation, the selection of Khowai Badlands within the Ballavpur Wildlife Sanctuary is deemed significant for several reasons: Firstly, Khowai Badlands exemplify a unique geological formation characterized by laterite soil enriched with iron oxide, sculpted over millions of years by erosion processes driven by wind

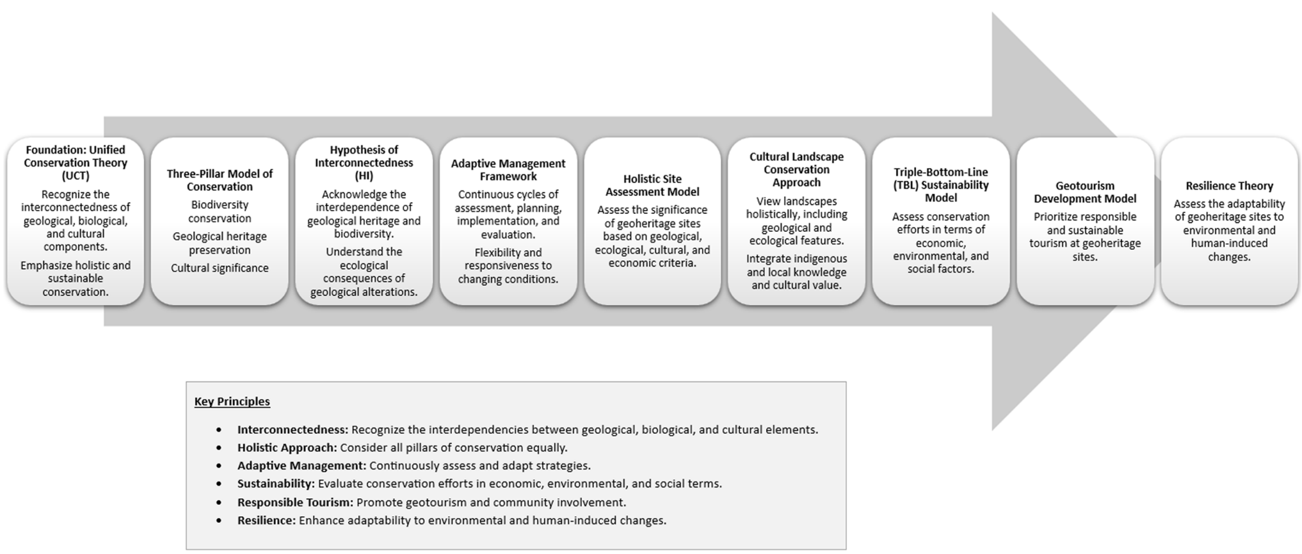

Fig. 1 Integrated geoheritage conservation framework for sustainable geoconservation. (Source: Prepared by author)

Fig. 2 Satellite view of the Khowai Badlands. (Source: Google Earth, 2023)

and water. This geoheritage is considered to hold immense scientific value, offering insights into past environmental conditions and geological processes. By conserving Khowai Badlands, a living record of Earth's geological history is preserved, contributing to our understanding of landscape evolution and geomorphological processes. Secondly, the integration of Khowai Badlands into the Ballavpur Wildlife Sanctuary emphasizes the interconnectedness between geological and biological elements. The sanctuary provides a habitat for diverse plant and animal species, many of which are dependent on the unique geological features of Khowai Badlands for their survival. For example, specific plant species may be adapted to the nutrient-rich laterite soil, while certain animal species may rely on the rock formations for shelter or nesting sites. Therefore, the conservation of Khowai Badlands is considered essential not only for preserving its geological heritage but also for maintaining the biodiversity of the surrounding ecosystem. Furthermore, Khowai Badlands serve as a focal point for promoting awareness and education about geoconservation. Its accessibility within the sanctuary allows researchers, educators, and visitors to learn about the importance of geological heritage and its role in shaping the natural environment. By incorporating Khowai Badlands into conservation efforts, public awareness about the value of geoheritage can be raised, and a sense of stewardship towards these unique geological landscapes can be fostered.

Table 4 provides a comprehensive overview of the various geological, ecological, and cultural components that contribute to the region's geoheritage significance. It details the geological processes and history, resulting landforms, and the geoheritage significance of each component found in the Khowai Badlands. The table is based on observations from a field visit conducted in 2023 and serves as a valuable resource for understanding the multifaceted nature of geoheritage in this region.

Integrating Geoheritage: Khowai Badlands in Geoconservation

Khowai Badlands, stands as an exemplar of integrating geoheritage into geoconservation. Its unique landforms, including intricately carved rock structures, small caves, and various erosion-related formations, not only captivate the eye but also serve as repositories of Earth's history. These features tell tales of millions of years, documenting sedimentary deposition, erosion, and climatic changes. Furthermore, fine-grained sediments, calcium carbonate deposits, sedimentary rock layers, alluvial fans, exposed rock layers, pediments, and arroyos collectively showcase the dynamic geological history. Integrating these geoheritage treasures into geoconservation enriches our understanding of the Earth's evolution. It highlights the interdependence between geological, ecological, and cultural dimensions. These invaluable insights underscore the importance of preserving these geoheritage features, fostering a holistic and sustainable approach to safeguarding both geological history and nature's abundant biodiversity.

Eco-Harmony: Integrating Geoheritage with Biodiversity at Khowai Badlands

In the context of integrating geoheritage within geoconservation, Khowai Badlands transcends its geological grandeur

Table 4 Geo-Ecological features and geoheritage significance in the Khowai Badlands

Component	Geological processes and history	Landform created	Geoheritage significance
Rock formations	Result from millions of years of sediment deposition, compaction, and uplift, followed by erosion sculpted by wind and water.	Intricately carved rock structures with unique shapes.	Showcase a geological history spanning millions of years, reflecting sedimentary deposition and later erosion.
Caves	Formed by the selective erosion of softer sedimentary rock layers over millennia, revealing the underlying hard rock.	Small caves or grottoes with cool and shaded interiors.	Provide windows into the region's deep geological history and the action of erosional forces.
Erosional features	Erosion, primarily by water and wind, has been a continuous process, shaping the landscape over geological epochs.	Gullies, hoodoos, unique erosion-related formations.	Offer a glimpse into the dynamic geological history, emphasizing the role of erosion and climatic changes.
Clay and silt deposits	Sedimentary layers tell the story of ancient environments where fine-grained sediments were deposited, compacted, and eventually exposed.	Fine-grained sediments shaping the landscape.	Serve as a record of changing environments and sedimentation processes throughout geological time.
Caliche deposits	Formed by the evaporation of groundwater carrying dissolved calcium carbonate, often during arid conditions.	Hard, white calcium carbonate deposits.	Indicate past arid climatic conditions and the processes of mineral precipitation in the geological record.
Alluvial fans	Developed as sediments were transported and deposited by flowing water, forming distinct fan-shaped landforms.	Fan-shaped sediment deposits at the slope's base.	Highlight the action of water in shaping the landscape and the geological history of sediment transport.
Exposed rock layers	Each layer represents a different geological period when sediments were deposited, compacted, and later exposed by erosion.	Distinct and colorful sedimentary rock layers.	Provide a visual record of geological history, with each layer preserving a unique era of sedimentation.
Pediments	Result from differential erosion where harder rock layers protect softer ones, forming characteristic, gently sloping surfaces.	Gentle, sloping bedrock surfaces extending from hills.	Showcase geological diversity, illustrating variations in rock hardness and erosion susceptibility over time.
Arroyos	Temporary stream channels carved by episodic heavy rainfall and flash floods, which reflect changing climate and erosion patterns.	Seasonal stream channels.	Indicate the region's vulnerability to flash floods and their impact on the geological landscape over time.
Surrounding flora and fauna	The presence of diverse plant life and potential wildlife species is integral to the area's ecological evolution.	Various plant species and possible wildlife.	Offer insights into the ecological and environmental changes that have occurred over geological time.
Cultural significance	The proximity to Shantiniketan, a town with a rich cultural and educational heritage, adds a cultural layer to the region's history.	-	Contributes to the holistic understanding of the region, encompassing both natural and cultural heritage.
Tourism	Attracts visitors for nature walks, photography, and geological exploration, promoting education and economic sustainability.	-	Enhances awareness of the region's geological history, supporting education and local economy.

Source: Prepared by the Author Following a Field Visit in 2023

to emerge as a haven for diverse ecosystems. Encompassed by dry deciduous forests, the Khowai site nurtures an array of flora and fauna, with unique geological formations significantly influencing the composition and adaptation of plant and animal species in the region. The coexistence of these ecological components is integral to the identity of Khowai Badlands. Adjacent to this geological treasure lies the Ballabhpur Wildlife Sanctuary, often referred to as the "Deer Park." Established in 1977, this sanctuary boasts a wooded area intertwined with the Khowai Badlands, forming a unique ecological mosaic. It is graced by three large water bodies (locally known as Jheels) that play host to both

Fig. 3 Hydro-geomorphological and pedo-geomorphological features of Khowai Badlands, showcasing its geoheritage and relevance to conservation. (**a**) Highlights gullies and erosion formations revealing geological and ecological history. (**b**) Includes escarpments, ravines, and caves supporting biodiversity. (**c**) and (**d**) Emphasize geological features vital for plant and animal habitats. (**e**) Showcases caves as wildlife refuges. (**f**) Underscores bioturbation structures preserving geomorphological heritage, reflecting geological and biological interconnectedness

Fig. 4 Biocultural integration into geoconservation: (**a**) Ballavpur Wildlife Sanctuary, (**b**) Sonajhuri Haat, (**c**) Sonajhuri Forest, and (**d**-**f**) local arts and crafts

migratory and resident birds, making it a thriving avian habitat. The sanctuary takes pride in its successful deer conservation programs, housing numerous Spotted Deer (locally known as Cheethals), Blackbuck, and other resident animals like jackals and foxes. The dense local vegetation, featuring species such as *Shorea robusta* (Sal), *Plumeria rubra* (Akashmoni), *Dalbergia sissoo* (Sissoo), *Anacardium occidentale* (Cashewnut), *Phyllanthus emblica* (Amlaki), *Terminalia bellirica* (Bahera), and *Terminalia chebula* (Haritaki), *Eucalyptus genus* (Eucalyptus) contributes to the ecological richness of the region. Integrating geoheritage with biodiversity in this manner emphasizes the harmonious relationship between the geological and ecological elements, demonstrating a holistic and sustainable approach to geoconservation at Khowai Badlands.

In Fig. 3, the hydro-geomorphological and pedo-geomorphological characteristics of the Khowai Badlands are depicted, with their significant geoheritage and relevance to geoconservation being highlighted. Gullies, hoodoos, and distinctive erosion-related formations observed in (a) not only showcase the area's geological history but also provide vital insights into the region's ecological heritage. (b) includes an escarpment, ravine, and flowing water, as well as small caves or grottoes with cool and shaded interiors, contributing to the biodiversity and habitat diversity of the area. These natural features are essential for the preservation of the local ecosystem. (c) reveals the importance of escarpments in maintaining geological diversity and supporting various plant and animal species, while (d) emphasizes the significance of ravine structures in providing unique habitats and geological diversity within the Khowai Badlands. (e) highlights the small caves, which not only serve as interesting geological formations but also as refuges for a variety of wildlife, playing a critical role in conserving both geological and biological diversity. (f) draws attention to bioturbation structures, underlining their role in preserving the area's geomorphological heritage. The interplay of geological processes and living organisms is deemed crucial for the overall health of the ecosystem, and these structures reflect that interconnectedness.

Cultural Heritage Integration in Geoconservation: The Synergy of Khowai and Santiniketan

Figure 4 provides an overview of how geoheritage is integrated into conservation efforts within the Khowai Badlands, with a particular focus on its cultural dimensions. (a) Highlights sections from the Ballavpur Wildlife Sanctuary, showcasing the synergistic relationship between conservation and biodiversity. The inclusion of sanctuary areas underscores the importance of preserving natural habitats alongside geological features, contributing to overall ecosystem health. (b) Sheds light on Sonajhuri Haat, a local arts and crafts market nestled within the conservation framework. This market serves as a nexus connecting the community's cultural heritage with efforts in geoconservation. By promoting local crafts and traditions, Sonajhuri Haat reinforces the link between cultural identity and environmental stewardship. (c) Showcases Sonajhuri Forest, a vital component in maintaining the area's ecological diversity. The forest serves as a refuge for various plant and animal species, contributing to the overall richness of the region's biodiversity. (d) and (e) Feature local arts, including traditional dances, and (f) highlights the craftsmanship involved in making traditional musical instruments. These cultural expressions not only celebrate local heritage but also foster a deeper appreciation for the natural environment, reinforcing the interconnectedness between culture and conservation efforts.

In the broader context of integrating geoheritage into conservation, Santiniketan Khowai emerges as a beacon of cultural heritage and education, rooted in the legacy of Noble Laurate Rabindranath Tagore. The site serves as a magnet for artists, scholars, and visitors, drawn by its rich cultural tapestry intertwined with literature, art, and heritage. Efforts in cultural preservation, including traditional dances, culinary traditions, and the vibrant presence of Sonajhuri Haat, play a crucial role in safeguarding local identity and indigenous knowledge. Furthermore, the presence of Visva-Bharati, a UNESCO cultural geoheritage site, adds a profound cultural layer to the region, enriching the connection between cultural heritage and geoconservation. Figure 5 depicts key institutions and initiatives supporting the integration of geoheritage into conservation practices. (a) Represents the Nature Interpretation Center situated within the Khowai Badlands, providing educational resources and interpretation services to visitors. The centre plays a crucial

Fig. 5 Integration of educational institutions into geoconservation efforts: (**a**) Nature Interpretation Center at Khowai Badlands and (**b**) Visva-Bharati (UNESCO living heritage university)

role in raising awareness about the significance of geoheritage and its conservation. (b) Showcases Visva-Bharati, a UNESCO living heritage university, emphasizing its pivotal role in advancing education and fostering scientific appreciation of geoheritage sites.

This integrated approach not only enhances the region's allure but also promotes geoheritage-cultural tourism, fostering a deeper appreciation for the interconnectedness of cultural and natural heritage within the realm of conservation. By recognizing the intrinsic link between cultural identity and environmental stewardship, Santiniketan Khowai exemplifies a holistic and sustainable approach to preserving the geological, ecological, and cultural treasures of the region.

Holistic Framework: Successful Integration of Geoheritage into Geoconservation at Khowai Badlands

At Khowai Badlands, the integration of geoheritage and geoconservation reflects a holistic approach, drawing from various conservation models and frameworks. Conservation efforts align with the Unified Conservation Theory, Three-Pillar Model of Conservation, and Hypothesis of Interconnectedness, recognizing the interconnectedness of geological, biological, and cultural aspects. Adaptive management strategies ensure flexibility in response to changing conditions, while holistic site assessment models inform conservation priorities. The cultural landscape conservation approach involves local communities, and initiatives align with the Triple-Bottom-Line Sustainability Model, promoting economic, environmental, and social sustainability. Geotourism principles foster responsible tourism, and resilience theory guides strategies to enhance ecosystem adaptability. Together, these approaches contribute to the seamless integration of geoheritage and geoconservation at Khowai Badlands. Conservation strategies that integrate geological and biological elements interact synergistically due to the interconnectedness of these components within ecosystems. In the case of Khowai, the geological formations, including rock structures, caves, and erosional features, provide critical habitats and niches for various plant and animal species. These formations offer shelter, nesting sites, and microclimatic conditions that support biodiversity.

For instance, the intricate rock formations and caves serve as refuges for species seeking protection from predators or extreme weather conditions. Additionally, erosion-induced features like gullies and hoodoos create diverse microhabitats that harbor specialized plant and animal communities. By conserving these geological features, conservationists inadvertently protect the habitats of numerous species, contributing to biodiversity conservation. Moreover, the geological attributes of the landscape influence soil properties, water availability, and nutrient cycling, all of which are essential for sustaining biological diversity. Different rock types and soil compositions provide varying substrates for plant growth, influencing the distribution of vegetation across the landscape. Additionally, geological features such as alluvial fans and exposed rock layers contribute to soil formation and nutrient availability, further shaping plant communities. Conversely, the conservation of biodiversity can also benefit geological conservation efforts. For example, the presence of vegetation can stabilize soil and prevent erosion, thereby protecting geological formations from degradation. Plant roots penetrate soil and rock, facilitating weathering processes that contribute to the breakdown of geological structures over time. Furthermore, the activities of animals, such as burrowing mammals, can influence soil composition and structure, indirectly impacting geological processes.

Cultural preservation initiatives, such as eco-tourism and support for local arts and crafts markets, play a crucial role in promoting both geological and biological conservation. By educating visitors and local communities about the importance of geoheritage sites and biodiversity, these initiatives foster a sense of stewardship and appreciation for the interconnectedness of geological and biological elements. As a result, there is increased support for conservation efforts aimed at protecting both natural and cultural heritage. Apart from, scientific research plays a pivotal role in informing and guiding conservation efforts at Khowai. Through interdisciplinary studies that explore the interconnections between geological, ecological, and cultural elements, researchers generate valuable insights that inform conservation strategies. By fostering collaboration between scientists, conservationists, and local communities, the conservation framework becomes more robust and adaptive to changing environmental conditions.

In the enchanting Khowai Badlands, this comprehensive framework is depicted as a profound testament to the seamless fusion of geoheritage with geoconservation (see Fig. 6). It is presented as an eloquent embodiment of profound wisdom that transcends the boundaries between geological marvels, cultural legacies, scientific inquiry, and ecological guardianship. In this harmonious blend, a fundamental truth is underlined — that the preservation of our planet's natural and cultural treasures is not a matter of isolated endeavors but rather a tapestry of interconnected stories. Here, geoheritage is recognized as an intrinsic thread woven into the broader narrative of geoconservation, emphasizing the profound interdependence of all facets of our world's heritage.

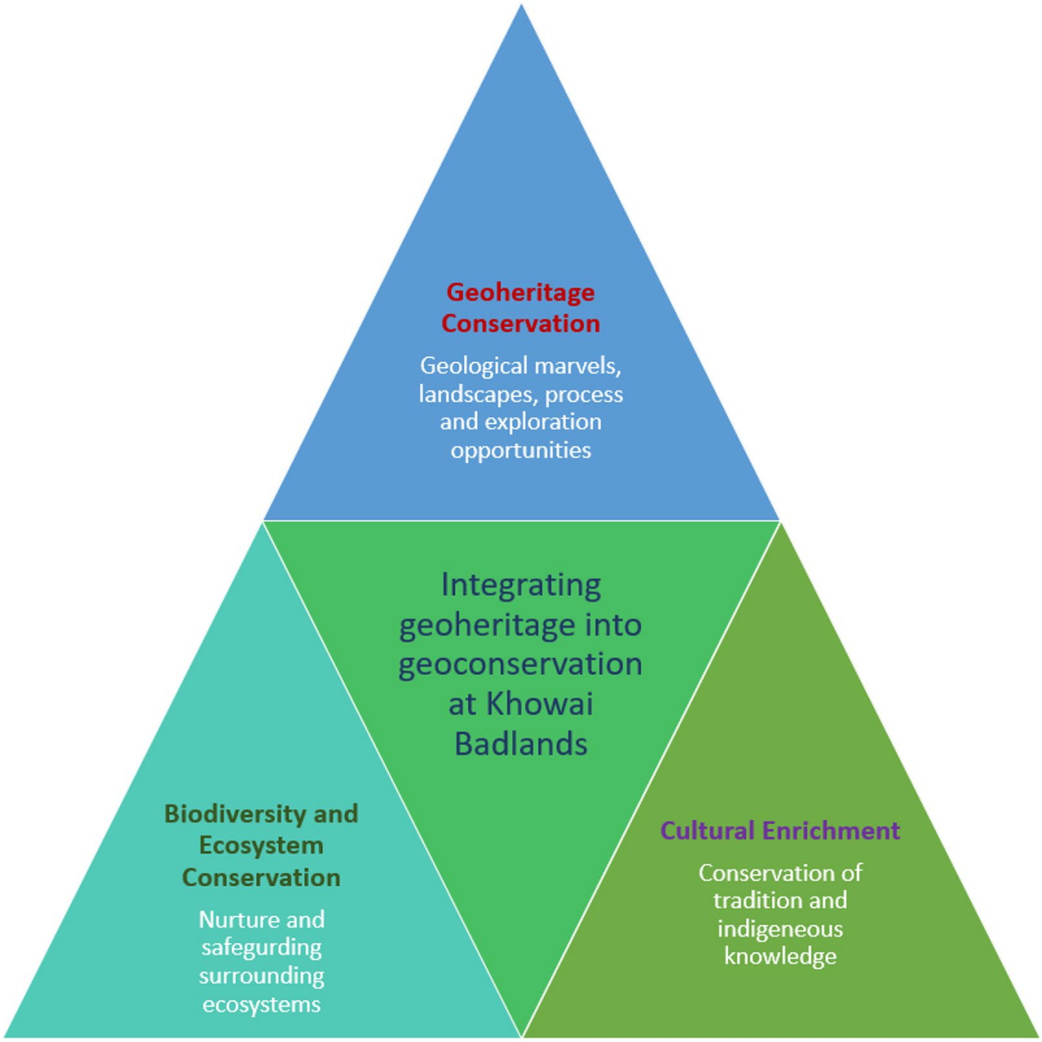

Fig. 6 A hypothetical model showcasing the integration of geoheritage with geoconservation efforts at the Khowai Badlands(Source: Prepared by author)

Policy Perspectives

Policy perspectives on geoheritage and geoconservation are evolving in response to emerging trends and prospects, as highlighted by Harmon (2007), Matthews (2014), and Harrison et al. (2020). A notable trend is the shift towards holistic conservation, which acknowledges the interconnectedness of geological, biological, and cultural heritage, as emphasized by Harrison et al. (2020). This integrated perspective is driving the development of more effective and sustainable conservation strategies. As climate change poses a significant threat to geoheritage sites, adaptation efforts will become crucial policy considerations, as noted by Pèlachs et al. (2017), Ferretti-Gallon et al. (2021) and Verma et al. (2022). Policy makers will need to explore innovative strategies to mitigate erosion and ecological shifts caused by climate change. Furthermore, leveraging technological advancements such as remote sensing and GIS, as discussed by Rocchini et al. (2017), Meini et al. (2018), and Shu et al. (2022), will be imperative for enhancing conservation efforts by providing precise data and analytical capabilities.

In the context of tourism, promoting sustainable practices and fostering geotourism initiatives are essential for advancing conservation goals (Leung et al. 2018; Edgell Sr 2019; Cheung and Li 2019; Singh et al. 2021). Geotourism emphasizes responsible travel to geological sites, aiming to cultivate appreciation for Earth's geological heritage while minimizing negative environmental impacts and supporting local communities (Monroe 2016; Bellos and Khoury 2022). Integrating geoheritage into ecotourism and geotourism experiences offers visitors educational opportunities to learn about the geological significance of sites, thereby promoting conservation and sustainability efforts (Monroe 2016; Bellos and Khoury 2022). By actively involving tourists in conservation initiatives and encouraging responsible behavior, ecotourism and geotourism play a vital role in safeguarding geoheritage sites and preserving their ecosystems (Healy et al. 2016; Gardener and Grenier 2011; Escorihuela 2018; Carvache-Franco et al. 2021; Vegas and Diez-Herrero 2021).

Research and scientific advancements will take precedence, focusing on geoheritage research within these sites to deepen our understanding of Earth's history and processes. Securing funding for geoheritage preservation will involve exploring innovative financing models and engaging in public-private partnerships (Whiteley and Browne 2013; Reynard and Brilha 2017; Mitchell et al. 2018; Hueso-Kortekaas and Iranzo-García 2022). Government policies will provide the legal framework for long-term preservation efforts (Worboys et al. 2015; Cresswell 2019; Costantini 2023). These trends underscore a growing commitment to protecting geoheritage alongside ecological and cultural conservation, ensuring a sustainable approach to geoheritage and geoconservation (Cave and Negussie 2017). Collaboration among stakeholders, including government agencies, conservation organizations, and local communities, is essential for effectively preserving these unique geological features for future generations (Prosser et al. 2011; Williams et al. 2020; Halder and Sarda 2021; de Luca et al. 2021).

Concluding Remarks

The integration of geoheritage into geoconservation, as demonstrated through the case study of Khowai Badlands in West Bengal, India, underscores the interconnectedness of geological, ecological, and cultural elements within conservation endeavors. The preservation of unique geological formations, such as rock structures, caves, and erosion-related features, is emphasized as vital habitats for diverse plant and animal species. Additionally, the significance of cultural heritage sites like Sonajhuri Haat and the involvement of local communities in fostering environmental stewardship are highlighted. However, it should be noted that the study's limitations, including its focus on a single geographical location and potential biases in data interpretation, must be acknowledged. To enhance future research, additional case studies from diverse regions, rigorous data collection methods, and broader stakeholder engagement, including indigenous communities and policymakers, should be considered. By addressing these limitations and expanding the scope of research, a deeper understanding of how to effectively integrate geoheritage into geoconservation practices can be achieved, ensuring the long-term sustainability of our planet's natural and cultural heritage.

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Author Contribution As the sole author, I conceived and designed the study, conducted the field visit, and meticulously reviewed and synthesized previous studies. I also bear full responsibility for editing and approving the final manuscript.

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Data Availability The references and data sources used in this study are publicly available from reputable internet sources.

Declarations

Ethical Approval and Consent to Participate This manuscript is based on a field visit and a comprehensive review of previous studies. Since it does not involve human participants, ethical approval and informed consent are not applicable to this study. As the sole author of the revised manuscript titled "Why Geoheritage matters in Geoconservation strategies: A case study from the Khowai Badlands in West Bengal, India" I affirm my commitment to upholding rigorous ethical standards, transparency, and integrity throughout the study.

Consent for Publication As the single author of this manuscript, I wholeheartedly grant my consent for the publication of this original review article in Geoheritage.

Competing Interests I declare that I have no potential conflicts of interest related to this research.

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