Narrating Deep Time in the Digital Era Through a Multi-Platform 3D Environment for Geotourism and Geological Outreach

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Abstract

The effective communication of the concept of Deep Time and the history of the Earth to non-expert audiences remains a paramount challenge in geological outreach. As angular unconformities serve as exceptional manifestations of geological time gaps, this research aims to demonstrate their potential as assets for public education and the creation of concrete geotourism products. This study presents the ongoing development of an interactive web-based platform designed for the visual translation of angular unconformities through lightweight three-dimensional (3D) Virtual Outcrops. As initial implementation cases, two strategic geosites within the MurGEopark (recently recognised as the first UNESCO Global Geopark in Puglia, Italy) were integrated into the project. The first is the historic urban centre of Gravina in Puglia, showcasing the sub-horizontal Plio-Pleistocene calcarenites resting upon tilted Cretaceous limestones. The second consists of the former open-cast bauxite mines of Murgetta Rossa near Spinazzola, now integrated into the region's industrial geoheritage, where karst-filling deposits evidence the significant stratigraphic hiatus between two Cretaceous limestones Formations. Digital datasets were acquired via Unmanned Aerial Vehicle (UAV) and processed using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) workflows, generating high-fidelity dense point clouds and high-resolution textured meshes. These models were semantically segmented and labelled to highlight different deposits separated by a discontinuity surface recording a significant gap of time, and sometimes showing an angular unconformity. The platform employs an interactive multi-device digital ecosystem to implement user-centred edutainment dynamics. The architecture incorporates colour-coded visualisations aligned with the International Commission on Stratigraphy (ICS) standards alongside multi-layered virtual rendering modes. The system is structured for future on-site deployment as outdoor interactive digital panels placed facing the outcrops. This configuration caters to a broad and diverse, non-specialised target audience, ranging from casual tourists to dedicated geotourists and residents, allowing them to visually deconstruct the present-day landscape and re-enact the local Deep Time narratives on the spot.

Keywords: *Geological outreach, Deep Time, Geoheritage, Geotourism, Unconformity*

1. Introduction

Geology operates across immense temporal scales that transcend direct human perception, which is calibrated by evolutionary design for historical and lived time rather than millions or billions of years. This cognitive barrier often triggers a communicative paradox: whilst science has successfully calculated the planet's estimated 4.6-billion-year history, the broader public struggles to conceptualise this vast antiquity, with the frequent result of relegating geoscience communication to a self-referential or inaccessible domain. The very term "Deep Time", coined by John McPhee in 1981 to articulate James Hutton's 1788 foundational geological intuition, highlights a two-century cultural lag in assimilating the temporal dimension of our planet into collective awareness [1, 2].

Given this conceptual impasse, and since humanity implicitly occupies this temporal continuum, geotourism emerges as a strategic vehicle to deploy innovative frameworks for transmitting and perceiving this core geological dimension. Nowadays, fostering public geological literacy has transcended purely academic discourse, as it now constitutes a profound geoethical imperative, essential for cultivating planetary stewardship and navigating global environmental emergencies, from anthropogenic climate shifts to escalating geohazards [3]. In this context, UNESCO Global Geoparks (UGGps) hold an explicit mandate to bridge this educational divide through targeted dissemination programmes designed to highlight regional geological uniqueness [4–6]. However, translating Deep Time remains problematic even for geoscientists accustomed to such abstract scales. A viable solution lies in treating the natural landscape as an active educational archive, utilising specific outcrops to make the physical presence, or structural absence, of geological time visually palpable. As a direct result, modern geoeducation must shift towards experiential and direct modes of dissemination where the geological heritage serves as an active, legible narrative space.

Immersive digital technologies and three-dimensional (3D) surveying techniques, such as photogrammetry, offer a promising cognitive bridge to reconcile scientific terminology with public spatial perception [7, 8]. While 3D modelling has been widely integrated into university-level geological training [9, 10], its systemic application as an interactive tool for heterogeneous, non-technical audiences remains vastly underexplored [11, 12].

When integrated into cutting-edge geotourism assets, this digital paradigm yields reciprocal benefits for both visitors and host

communities. It satisfies the specialised intellectual curiosity of dedicated geotourists whilst at the same time engaging casual visitors, fostering the active embedding of the local geoheritage into the socio-economic fabric of the territory so that geological diversity becomes a shared cultural asset. Furthermore, interactive engagement with digital environments has a substantial impact on cognitive retention and public interest [13, 14], especially when the virtualised assets reflect the users' local territorial heritage. At the same time, and in alignment with the core principles of Universal Design, this approach ensures that geoheritage becomes inclusive and accessible, transforming complex field localities into barrier-free educational assets for individuals facing mobility constraints or geographical limitations.

To investigate this potential, this ongoing research focuses on angular unconformities as ideal interpretative keys to demonstrate Deep Time to non-specialised audiences. Ever since James Hutton's 1788 observations at Siccar Point, Scotland, the angular unconformity has stood as a powerful "narrative pause" in the stratigraphic record, marking both physical contacts and immense temporal gaps where missing rock sequences bear silent witness to millions of years of active Earth processes.

Digitally reconstructed within a multi-platform 3D environment, this unique geological feature serves as the core conceptual thread of this study. The project establishes an interactive digital itinerary that connects spectacular, highly representative geosites within the MurGEopark (recently designated as the first UNESCO Global Geopark in Apulia, Southern Italy [15]) transforming regional geodiversity into an immersive, accessible, and user-centred educational asset.

2. Geological framework and case studies

With a view to assessing the practical application of the system, this project introduces two strategic geosites within the MurGEopark [16, 17]. The first case study is the historic urban cliff of Gravina in Puglia, where a spectacular lithostratigraphic contact exposes sub-horizontal Plio-Pleistocene calcarenites resting on tilted Cretaceous limestones, revealing a silent temporal abyss of tens of millions of years. At this outcrop, the angular unconformity bounds Cretaceous limestones of the "Calcare di Altamura" Formation, with a local depositional age dating back at least 85 million years (according to the most recent age obtained from a succession in the vicinity of Gravina in Puglia by Petti et al.[18]), to the overlying Plio-Pleistocene "Calcarenite di Gravina" Formation, deposited approximately between 3 and 2 million years ago [19, 20]. The pronounced structural inclination of the older Mesozoic unit bears witness to significant tectonic deformation and subsequent subaerial erosion prior to the horizontal deposition of the younger Cenozoic sediments (Fig. 1).

Fig. 1. Panoramic view of the angular unconformity in Gravina in Puglia: the chromatic distinction highlights the stratigraphic contact (in yellow) between the Cretaceous limestones (in green) and the Plio-Pleistocene calcarenites (in red).

The second case study consists of the decommissioned open-cast bauxite mines of Murgetta Rossa near Spinazzola, where karst-filling deposits evidence the significant stratigraphic hiatus between the "Calcare di Bari" and "Calcare di Altamura" Formations [21], as shown in Fig. 2. This discontinuity within the Cretaceous limestones of the Apulia Carbonate Platform succession truncates upper Cenomanian strata (about 95 million years) and is capped by upper Turonian (?) - lower Coniacian strata (about 90 million years), with a time gap of about 5 million years [22].

Fig. 2. Disused bauxite mines at Murgetta Rossa, near Spinazzola. Note the position of the bauxite layer within the Cretaceous limestone succession, highlighting a significant stratigraphic discontinuity between the underlying Calcare di Bari Fm and the overlying Calcare di Altamura Fm. The bauxite layer testifies a time gap of about 5 million years between the two Cretaceous formations.

The selection of these specific localities responds to a dual strategic logic. From a geoscience perspective, both outcrops possess superb scientific and educational value, serving as ideal field laboratories to illustrate structural geology and principles of stratigraphy. From a geotouristic viewpoint, they offer powerful interpretative keys, acting as iconic landmarks of the regional geological evolution. Furthermore, this rich geological history is intrinsically intertwined with the human and anthropological development of this territory. The unconformity of Gravina in Puglia forms the literal bedrock of the ancient historical centre, anchoring a unique rock-cut civilisation. The morphological features generated by erosion and karst processes facilitated the excavation of both epigean and hypogean cave dwellings, rendering this geosite an outstanding example of combined archaeological, architectural, and geological heritage. In contrast to the urban setting, the Murgetta Rossa geosite chronicles a different chapter of human interaction with the Apulian environment, rooted in industrial geoheritage. As one of the most productive bauxite extraction sites in Italian history, these now inactive open-cast mines have left an indelible mark on the landscape, providing an exceptional open-air archive for industrial archaeology and mining geoconservation in Southern Italy.

3. Methodology

This section delineates the multi-stage digital workflow and technical implementation developed to create the interactive, web-native geoscience communication tool. The methodology moves from high-resolution aerial data acquisition and image-based reconstruction to semantic segmentation and chronostratigraphic partitioning of the resulting meshes. It then covers the downstream 3D geometric optimisation strategies required for web deployment, concluding with the user-centred design of the cross-device prototype platform.

3.1. UAV Data Acquisition and 3D Reconstruction

The creation of high-fidelity virtual outcrops involves a structured digital workflow designed to translate physical topography into lightweight web assets while preserving metric accuracy. Field surveys at both sites utilised as Unmanned Aerial Vehicle (UAV) platform a DJI Mavic 3 system, equipped with a Hasselblad camera featuring a 4/3 CMOS sensor capable of capturing 20 MP images with a native resolution of 5280x3956 pixels and a 24 mm equivalent focal length.

For the Gravina in Puglia geosite, the aerial survey covered a localised surface area of 9441 m^2, capturing 528 photographic frames at an altitude of 28.0 metres with a Ground Sampling Distance (GSD) of 9.27 mm/pixel. In comparison, the survey at the Spinazzola bauxite mines encompassed a broader territorial footprint of 119.000 m^2, collecting 628 frames at an altitude of 30.8 metres with a GSD of 1.02 cm/pixel. Both data acquisition campaigns combined automated flight missions and manual piloting modes, incorporating a mixture of nadir, 45° oblique, and horizontal frontal camera orientations.

To ensure strict comparability between the two case studies, a standardised processing pipeline was adopted, based on Structure-from-Motion (SfM) and Multi-View Stereo (MVS) techniques within Agisoft Metashape Professional. Photographic frames were aligned to generate a sparse point cloud, followed by outlier removal. The three-dimensional structure was then reconstructed directly from depth maps: this specific workflow bypasses the heavy computational demand of intermediate dataset management, thereby reducing processing times while maintaining geometric accuracy.

For the initial high-quality outputs, the models were textured using four 8192x8192 pixel maps, while a dense point cloud was generated in parallel to serve as a qualitative benchmark for reconstruction validation. To achieve compatibility with real-time web visualisation, this framework underwent mesh decimation to a threshold of approximately 200,000 faces, paired with the consolidation of the surface texturing into a single 8K map. This optimisation sequence achieves a substantial reduction in deployment weight while preserving geometric integrity and visual realism. Both executions were performed on a single high-performance workstation equipped with 32 GB of RAM, an Intel Core Ultra 9 285H processor, and an NVIDIA GeForce RTX 5070 GPU.

3.2. Semantic Segmentation, Labelling and Chronostratigraphic Colour-Coded Visualisation

To transform these datasets into efficient educational mediums for integration into the final digital platform, the models were subjected to semantic segmentation to isolate discrete geological units. This phase was conducted within CloudCompare, where the spatial boundaries of the outcrop were partitioned and labelled based on stratigraphical limits and colour-coded visualisations aligned with the International Commission on Stratigraphy (ICS) standards for the respective geological Periods or Epochs of each chronostratigraphic unit. Thus, for instance, regarding the angular unconformity exposed at Gravina in Puglia, the thematic colours correspond to the green for the Cretaceous Period and the yellow for the Plio-Pleistocene Epochs. For the unconformity visible at Murgetta Rossa, the thematic palette features the specific green hues characteristic of the Upper Cretaceous Ages.

The 3D mesh datasets from both case studies were segmented into thematic layers – separating, for instance, the geological features from the stratigraphic architectures in the Gravina in Puglia model: the resulting layers were designated as *Calcarenite_Plio-Pleistocene*, *Limestone_Cretaceous*, *Bridge-aqueduct*, and *Bell-tower* (Fig. 3).

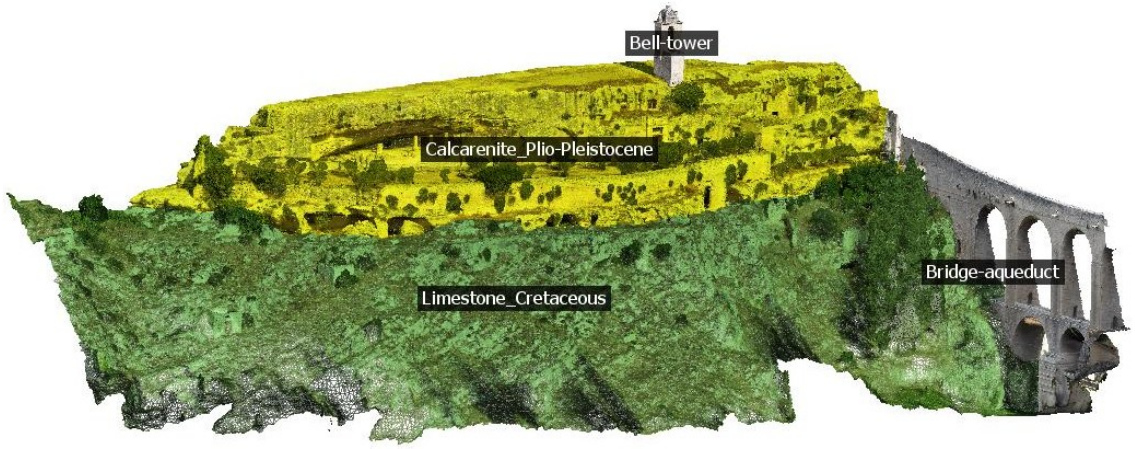

Fig. 3. Example of semantic labelling applied to the segmented 3D unconformity model of Gravina in Puglia within the CloudCompare environment.

3.3. Web-Oriented Optimisation

Models were exported in binary glTF (.glb) format using local coordinate mapping and managed within the open-source software Blender to ensure coherent spatial interactions alongside accurate alignment and rotation pivots within the web-based environment. Utilising a single .glb file represents a substantial performance advantage over legacy formats such as .obj, which require separate, fragmented external dependencies for material definitions (.mtl) and texture maps (.jpg).

Although compressed into a single deployment asset, the internal structural hierarchy of the segmented layers remains intact, allowing the web visualiser to read and render each component as a discrete, independent entity.

To achieve this structural autonomy, each segmented mesh underwent geometric bounding box analysis to relocate individual transform origins to localised centres of mass. Through the execution of a uniform spatial normalisation protocol, the global coordinate system of the composite meshes was aligned and centred with the absolute origin (0,0,0). This technical constraint guarantees absolute synchronisation during web deployment: hence, when layers are toggled, disassembled, or rotated within the cross-device application, their relative spatial transformations remain perfectly locked.

Following the completion of this geometric refinement and asset compilation stage, a quantitative evaluation was conducted to demonstrate the definitive impact of the data reduction pipeline on both repositories. For the Gravina dataset, the raw, unclipped original mesh of 34,482,348 faces (4.44 GB across standard .obj, .mtl, and .jpg formats) was compressed to a fixed threshold of 200,000 faces (62.4 MB in a single .glb format), achieving a 99.42% reduction in geometric complexity and a 98.63% data contraction. In the same way, the Spinazzola mines dataset was decimated from an initial density of 54,913,948 faces (7.16 GB) to

the identical uniform 200,000-face limit (31.33 MB), yielding a 99.64% reduction in face count and a 99.57% total size reduction.

This final size variation stems from a reversal in processing order: the larger Spinazzola asset features a more streamlined data weight than the Gravina file because its massive geometric scale required preliminary mesh decimation prior to semantic segmentation, whereas the Gravina framework underwent labelling and partitioning before data reduction, embedding a heavier metadata hierarchy into the final output.

3.4. Development of the Web-Based Prototype

Prototype development began with the construction of a dedicated Python script engineered for the three-dimensional visualisation of the geological models, establishing a foundational framework to test core system functionalities. Following this preliminary phase, the architecture evolved into a native web environment developed through an iterative, user-centred design pipeline. This optimisation stage focused on cross-device interface refinement to enhance real-time rendering performance, coordinate asset management for high-resolution textured models, and maximise navigation interactivity. The resulting production platform leverages TypeScript alongside advanced 3D graphics technologies to ensure progressive user experience enhancement, optimal graphic realism, and universal content accessibility.

Through accurate geometry decimation and efficient digital resource management, the platform maintains a lightweight computational demand while ensuring high visual fidelity and fluid navigation. This web architecture guarantees multi-device compatibility, delivering synchronised, high-performance interactions across desktop computers, tablets, and smartphones (Fig. 4).

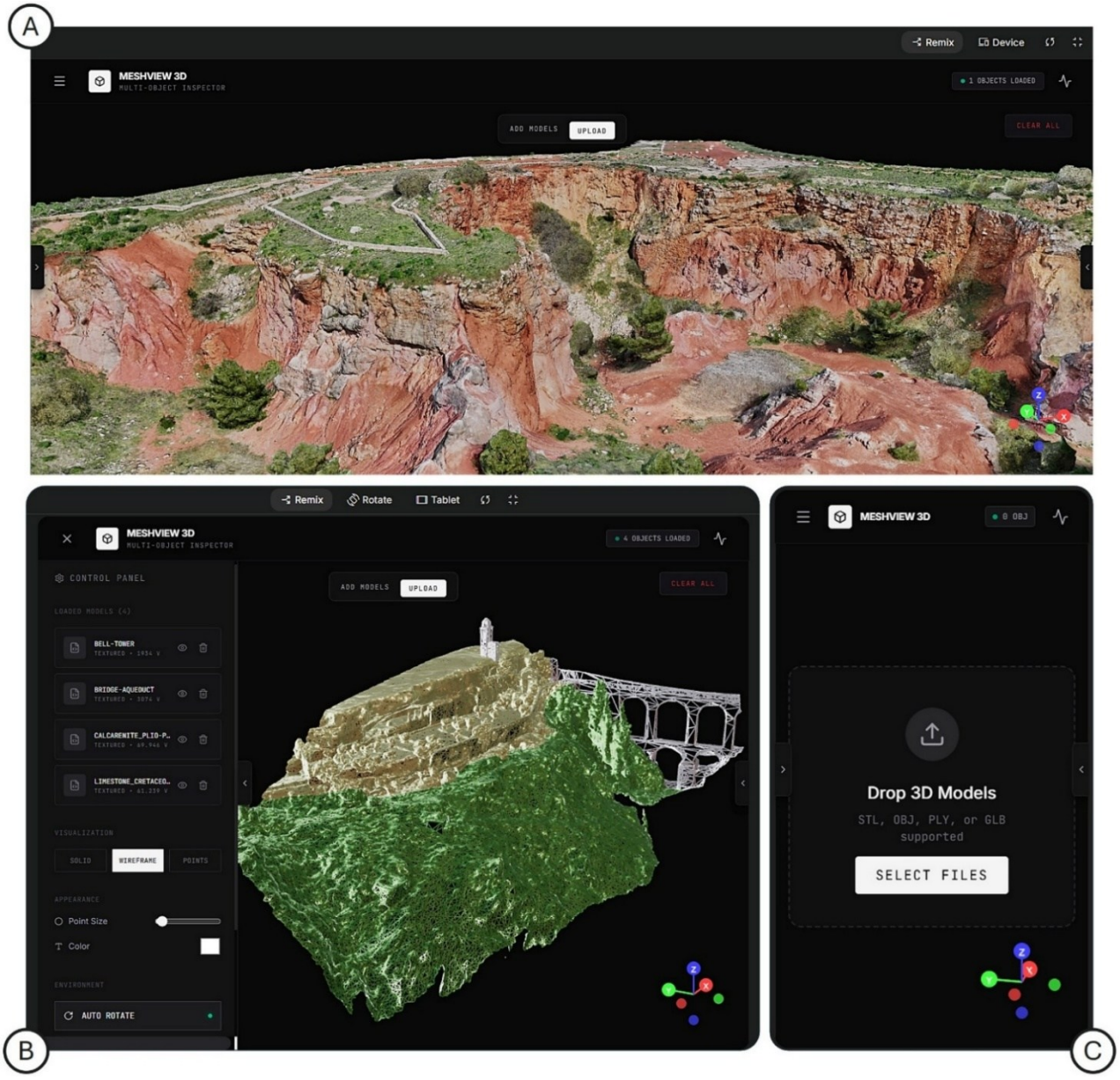

Fig. 4. Responsive interface layout of the cross-device digital platform displayed across different hardware viewports: a) Real-time 3D visualisation of the virtual outcrop within standard desktop environments; b) Dynamic multi-layer interaction, semantic asset management, and wireframe rendering mode on a tablet interface; c) Lightweight file upload interface and automated drop-zone configuration optimised for smartphone browsers.

The application enables three-dimensional visualisation directly within standard web browsers without requiring dedicated software installation. The platform supports standard photogrammetric formats (including .glb, .glTF, .obj, .stl, and .ply) and integrates automated centring and orientation procedures to optimise asset placement within the virtual scene. The system

facilitates simultaneous multi-model management and offers distinct rendering modes: textured meshes, wireframes, and point clouds. The rendering engine employs advanced illumination models to enhance the perception of morphological details and surface topography, governed by intuitive navigation controls for orbital rotation, pan, and zoom. Built-in interface features include direct asset uploads, layer visibility toggles, and display mode customisation. Furthermore, the specific colour-coded visualisations aligned with the ICS standards highlight distinct geological units, chronostratigraphic intervals, and angular unconformities, facilitating the interpretation of Deep Time for non-specialist audiences.

Current development focuses on integrating interactive text labels and descriptive annotations that users can toggle to display targeted data regarding each chronostratigraphic unit. In parallel, a comprehensive narrative script is under production for platform integration, designed as both readable text and an audio voiceover. This dual-modality commentary aims to guide users through the geological history of the Apulia region and its specific Deep Time intervals while they freely explore the angular unconformities and geotouristic milestones. Upon completion of these implementation phases, subsequent updates will introduce gamification dynamics and edutainment features to maximise user engagement and deliver a fully articulated virtual environment.

4. Conclusions and future perspectives

In a context where geoscience culture remains restricted to academic circles and peer-to-peer discourse, this study addresses a fundamental geoethical imperative: democratising expert knowledge and fostering public awareness of regional geodiversity and geoheritage without compromising scientific accuracy. By integrating systematic UAV photogrammetry, semantic optimisation, and web-native interactive deployment, this research establishes a scalable framework for public geoscience communication.

The multi-phase pipeline has proven effective in translating heavy desktop-restricted scientific datasets into high-performance, cross-device digital ecosystems, bridging the gap between Deep Time perception and understanding and public landscape awareness. The two case studies of Gravina in Puglia and Murgetta Rossa geosites demonstrate that the workflow provides local sustainable geotourism initiatives with an accessible, high-impact tool for geological outreach empowerment, geoheritage valorisation, and active geoconservation.

The work completed thus far validates the feasibility of an integrated approach designed to transform complex geological features into immersive edutainment assets. Outcrops of strong scientific significance, with a visual identity rooted in the very Apulian landscape, are reconstructed into three-dimensional photogrammetric models, establishing a digital information space tailored for non-expert audiences. Building upon the technical implementation described above, current development prioritises expanding this digital environment into a multimodal learning ecosystem. By deploying interactive audio-narratives and knowledge-evaluation loops, this digital infrastructure contextualises the graphic realism of the models by giving a structured voice to the geological record through accessible scientific storytelling. This further integration fosters active public engagement, allowing users to consolidate their comprehension of Deep Time processes during autonomous exploration.

Future milestones involve expanding this repository by integrating additional regional case studies into a comprehensive geotouristic itinerary dedicated to the angular unconformities of the MurGEopark. Should ongoing validation confirm initial testing expectations, this methodology will be extended to analogous nationwide outcrops eligible as “Italian Siccar Points”. Furthermore, this digital archive constitutes a barrier-free collective heritage, accessible remotely to users unable to experience physical geotourism. Future project iterations will expand this Universal Design component to guarantee complete inclusivity for visitors facing physical limitations or structural fragilities.

These primary outcomes indicate that the current platform possesses substantial potential to enhance geoheritage visibility, stimulate sustainable destination management, and guide targeted geotourism interventions within the MurGEopark. Once fully deployed via onsite interactive panels and dedicated web portals, the digital infrastructure is projected to strengthen regional geodiversity branding, catalyse community-led geotourism products, and facilitate international UGGp networking.

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