Augmented and Virtual Reality in STEAM: Virtual Field Trips

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This article explores an approach to science, technology, engineering, arts, and mathematics (STEAM) education by integrating augmented reality and virtual reality into geoscience, addressing challenges in STEAM education while preparing teachers and students for a digitally connected world.

Augmented reality (AR) and virtual reality (VR) technologies have emerged as transformative tools in education, providing immersive and interactive experiences that bridge physical and digital realms.[1] These technologies are increasingly being integrated into science, technology, engineering, arts, and mathematics (STEAM) education to foster interdisciplinary learning and critical thinking.[2, 3]

The integration of AR and VR into STEAM education draws upon foundational pedagogical and technological frameworks that underscore the importance of

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interdisciplinary learning and experiential engagement. One such foundational framework was Yakman's model of integrative STEAM education, which outlined a structured approach through meaningful real-world problem-solving experiences. Yakman emphasized that STEAM education should not merely compare disciplines but interweave them to mirror the complexity and interdisciplinarity of real-world challenges, fostering critical thinking, creativity, and innovation in students.[15]

In the context of immersive learning, AR and VR technologies align well with this integrated pedagogical model by providing environments where learners can explore complex systems and concepts through multiple sensory modalities. For example, virtual field trips (VFTs) allow learners to traverse geographically and physically inaccessible sites while engaging in inquiry-based learning, thus supporting the cognitive and experiential dimensions of STEAM.

The pedagogical efficacy of AR/VR technologies in educational settings is well documented. Wu et.al.[16] identified several core advantages in education: enhanced interactivity, visualization of abstract concepts, improved learner motivation, and opportunities for contextualized learning experiences. These technologies facilitate embodied cognition by enabling learners to engage with digital content in spatially situated and physically interactive ways, aligning with constructivist and experiential learning theories.

Furthermore, Wu et.al. highlighted that when AR and VR are combined with a pedagogical model, such as problem-based learning or inquiry-based tasks, learning outcomes are significantly enhanced.[16]

Building upon these foundational studies, this article leverages AR and VR tools to construct educational environments that embody these principles.

The developed scenarios under in this article—focused on lightning phenomena, the Samaria Gorge, and Pentelikon marble (Figure 1)—illustrate how immersive technologies can be purposefully aligned with pedagogical objectives. The technology transforms learners from passive recipients of information to active explorers in simulated environments that are grounded in authentic geoscientific and cultural contexts.

Among the innovative applications of AR and VR tools in education is the concept of VFTs, which offer learners the opportunity to explore and interact with distant or inaccessible environments without leaving their classrooms or personal place. By incorporating AR and VR tools, VFTs enable dynamic and engaging learning experiences, allowing students to observe geoscience phenomena, simulate processes, and develop transversal competencies. These digital tools provide solutions to challenges, such as logistical constraints, accessibility issues, and financial barriers, traditionally associated with field-based learning.[4]

The selection of these three geoscience scenarios was based on the pedagogical and technical approaches.

Pedagogically, the scenarios were aligned with geoscience curricula and STEAM competencies, supporting inquiry-based interdisciplinary learning while fostering critical thinking and environmental awareness. The use of VFTs transforms traditional learning into immersive engaging experiences that allow students to explore real-world phenomena despite barriers like weather or cost.

Technically, the scenarios are feasible due to the use of an existing AR platform with an inventor module and viewer app as well as the development of interconnected high-quality 360° VR environments. These tools

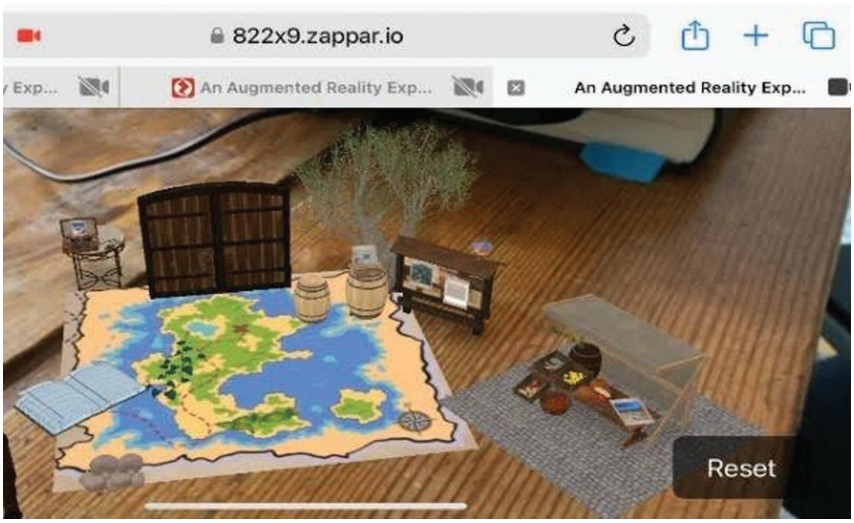

FIGURE 1. The Pentelikon marble scenario.

are integrated into an open scalable platform enriched with story maps, a geographic information system, multimedia, and user-generated content, enabling authentic hands-on digital learning while ensuring sustainability and the potential for expansion beyond the project's lifetime.

The purpose of this article is to integrate three different scenarios in VFTs in AR and VR environments. The article aims to examine the role of these two tools in enhancing learning outcomes fostering critical analysis, interdisciplinary connections, and environmental awareness. The current approach adds value by combining AR and VR to create immersive interactive learning experiences that enhance engagement, critical thinking, and accessibility in STEAM education.

The article begins with a detailed description of the three scenarios. This is followed by two sections that address the integration of these scenarios and the development of the AR and VR environments. The three educational scenarios exemplify a cohesive integration of both AR and VR technologies, thereby illustrating their complementary strengths and the broad spectrum of immersive learning experiences they can collectively support.

SCENARIOS

Lightning scenario

Lightning poses significant danger to life, animals, forests, and infrastructure. Data from the Meteo Unit of the National Observatory of Athens[5] show an average of two lightning-related deaths per year in Greece over the past 20 years. Providing either general information or information for Europe, the Mediterranean area, or, particularly, Greece, the lightning scenario educational material includes five modules: learning about lightning, weather conditions and lightning, awareness and protection, risk identification, and vulnerability.

The module on learning about lightning provides an educational video detailing lightning formation, emphasizing atmospheric parameters like temperature and humidity. The video explains physical processes, such as frictional charging, charge separation, inductive charging, electric field generation, and electric current.

> VIRTUAL FIELD TRIPS ALLOW LEARNERS TO TRAVERSE GEOGRAPHICALLY AND PHYSICALLY INACCESSIBLE SITES WHILE ENGAGING IN INQUIRY-BASED LEARNING.

The section on weather conditions and lightning covers the spatial distribution of lightning in Greece and the Mediterranean under different weather conditions, such as cold fronts and summer instability. It includes observed and forecast lightning activity, aiding in increased vigilance and protection.

The "I Am Aware and Protected" module presents a map of Greece with recorded lightning fatalities over the past 20 years, providing details like victim demographics and incident specifics. Users classify locations as safe or unsafe by navigating virtual environments like forests or houses.

Students explore a map of Europe to understand the vulnerability of different countries to catastrophic weather-related phenomena. The data, sourced from the EM-DAT international disaster database,[6] are analyzed and presented through statistical charts illustrating the distribution and annual change in the number of events, economic losses, and vulnerability characteristics. Students view these charts at European and country levels, gaining insights into the frequency and impact of weather-related events, such as floods and storms, phenomena closely related to lightning activity.

The scenario of Samaria Gorge

The Samaria Gorge, located in southwestern Crete (Greece), spans 13 km, with a width ranging from 40 to less than 2 m and a maximum depth of 600 m.[7] It is traversed by a seasonal stream and surrounded by steep mountains exceeding 2,000 m. Tectonic activity (that is, the processes occurring in Earth's interior, related to the movement of lithospheric plates, earthquakes, and so on), meteorological conditions, and geological structure (that is, the rocks that are present as well as their characteristics) have shaped the island's modern relief as well as the Samaria Gorge itself.[8]

The proposed scenario involves crossing the gorge from its entrance at Xyloskalos to its exit at Aghia Roumeli. This route showcases diverse geological formations and landforms, making it an ideal location for exploring geoscience concepts. The objective is to introduce significant geological processes, emphasizing how gorges are formed and the role of fluvial erosion in shaping Earth's surface. The interplay between endogenous and exogenous processes (that is, processes occurring in Earth's interior and at its surface, respectively) is also highlighted, demonstrating their influence on the local and regional landscape.

> **THE TECHNOLOGY TRANSFORMS LEARNERS FROM PASSIVE RECIPIENTS OF INFORMATION TO ACTIVE EXPLORERS IN SIMULATED ENVIRONMENTS.**

Users can virtually navigate the gorge through successive stops. The first and last stops provide panoramic views of the gorge at its entrance and exit, respectively, to help users understand the geological processes behind the gorge's formation. Intermediate stops allow close observation of various geological formations and landforms, such as folds, conglomerates, and chert intercalations, alongside fluvial features like alluvial deposits, step-and-pool sequences, and slot canyons. Karstic formations, including caves and stalactites, are also examined. When the user comes across each of these formations, a brief explanation is also offered (in both English and Greek) to help them understand what these formations are.

Explanatory signs and tools foster understanding of natural processes, their interrelationships, and their impacts on landscape evolution. The scenario also highlights human activities, such as the creation of agricultural terraces, and their effects on the gorge's landscape.

Key geoscientific aspects covered include the following:

- *Landscape evolution*: Gorge formation and the interaction of different processes
- *Rocks and geological formations*: Metamorphic limestones, bedding, chert intercalations, folds, and conglomerates
- *Fluvial landforms*: Alluvial and slack water deposits as well as slot canyons
- *Karstic landforms*: Caves and stalactites
- *Human impacts*: Human activities and their impact on the landscape.

This integrated approach offers a holistic understanding of natural and anthropogenic processes shaping the environment.

The Pentelic marble scenario

Pentelicus Mount, or Penteli, is a Greek mountain with a peak, Pyrgari, reaching 1,109 m. Situated in the north of Athens, it stretches between the Attica Basin and Marathon. Its southern slopes overlook Penteli and Melissia, while the northern slopes reach Nea Makri. Known for its ancient marble quarries and scenic pine forests, the area is rich in cultural and natural heritage, featuring settlements like Nea Penteli and Dionysos.[9]

In antiquity, the mountain was called Brilessos or Brilettos, meaning "strong stone," as cited by Herodotus and Thucydides. In the third century BC, it was renamed Penteli after the establishment of a settlement on its southwestern hill.[9] The scenario explores Pentelic marble's history, from its ancient use in monumental art to modern construction.

Derived from *marmaro*, meaning "to shine," marble was revered in ancient Greek architecture and sculpture. Pentelic marble, renowned for its white color with a golden hue, was central to Classical Age monuments, including the Parthenon. Quarrying in ancient times was arduous, requiring significant manpower and primitive tools. Today, modern environmentally friendly techniques have replaced these traditional methods, with mining continuing at Dionyssovouni.[9,10,12]

This educational scenario highlights Mount Pentelicus' geological and cultural heritage, blending geology, history, and art. Students learn marble extraction methods and the industry's evolution. Visitors traverse a georoute beginning at Davelis Cave, following the ancient Marble Transport Road, and passing landmarks like Saint Panteleimon Monastery and the Open-Air Museum of Quarry Art, culminating at the modern Dionyssovouni quarry. Each point emphasizes Pentelic marble's timeless role in civilization's history and architecture. The ultimate goal of the scenario is to contribute to the preservation of Penteli's unique geological and cultural heritage, ensuring that its legacy is passed on to future generations in the digital age.

By integrating geology, chemistry, geography, and history, this scenario connects participants to Pentelic marble's legacy, from antiquity to its role in reconstructing the Greek state, according to relevance to geoscience curricula in European Union schools.[9, 10, 12]

AR ENVIRONMENT

The School of Pedagogical and Technological Education (ASPETE) developed five AR applications using Zapworks Designer as examples to inspire and educate students. These applications demonstrate the diverse possibilities of AR in interactive and educational environments. Students are encouraged to explore these examples and use Zapworks Designer to create their own unique AR experiences, fostering creativity and technical skills in designing immersive applications.[13]

AR applications overview: Faults

The Faults app offers interactive educational experience about geological faults. Users can explore photos, 3D models, and video showcasing fault morphology. Each of the three scenes includes fault photos, geological tools, an information card, and interactive navigation to enhance understanding.[13]

Understanding thunderstorms

This app educates students about thunderstorm formation through an interactive Q&A game. Users answer questions about humidity and temperature, leading to outcomes like no storm and small, medium, or large storms. Storm formation is visualized in an AR environment with clouds, rain, and lightning.

Samaria Gorge Trip

This app educates students about thunderstorm formation through an interactive Q&A game. Users answer questions about humidity and temperature, leading to outcomes like no storm and small, medium, or large storms. Storm formation is visualized in an AR environment with clouds, rain, and lightning.

Treasure Hunt for Pentelic Marble

This AR game combines education and entertainment. Playing with trigger cards, students explore an AR environment to find elements and hidden codes related to Pentelic marble. Collecting and assembling the codes solves the treasure hunt, fostering an engaging learning experience.

Climatic conditions and lightning

The visualization of lightning activity in AR provides videos showing sequential lightning maps for specific weather cases by scanning trigger cards. Different colors represent hourly activity, and lightning strikes are displayed for easy interpretation.

Description of the AR environment

Zapworks Designer is an online application that runs directly from a browser.[13]

Installation and system requirements

The recommended specifications for optimal system performance include a Windows 10 or macOS 10.15 (or later) operating system, paired with an Intel Core i7 processor or its equivalent. A minimum of 16 GB of random-access memory is advised to ensure smooth multitasking and efficient processing of demanding applications. Additionally, at least 4 GB of available storage space is required, alongside a graphics card that supports DirectX 12 to handle graphical tasks effectively. These specifications collectively provide a robust foundation for running advanced software and maintaining system reliability in academic and professional environments.

The basic navigation and setup of the design interface encompass four key components that facilitate the creation and editing of AR content. The design canvas serves as the primary workspace where users construct and modify their AR projects. The toolbar provides essential tools for incorporating and adjusting various elements, including 3D models, images, videos, and interactive features. The components palette offers a comprehensive collection of elements that can be easily dragged and dropped onto the canvas, streamlining the design process. Finally, the properties panel displays the attributes of the selected element, enabling precise customization to align with the project's requirements. Together, these components create an intuitive and efficient environment for AR content development.

Basic navigation

Zapworks Designer consists of several panels, each essential for developing experiences. The main elements of the Zapworks Designer user interface (UI) are as follows.

Components panel. The components panel displays the digital elements you can add to your scene. Here, you can find the following:

- *Button*: Select from a range of basic buttons to add to your scene.
- *Text*: Choose from preset text templates.
- *Image*: Add an image from your media library to your scene or upload a new image from your device.

- *Video*: Add a video from your media library to your scene or upload a new video from your device.
- *3D*: Import a 3D model to your project to create a 3D experience.

Scene manager panel. The scene manager panel allows you to change the properties of the scenes in your project, as follows:

- *Scene selector*: Select which scene is currently visible in the view window.
- *Rename scene*: Change the name of your scene by selecting the scene name or through the menu burger in the scene selection menu.
- *Add scene*: Add an additional scene to your project.
- *Duplicate scene*: Duplicate the current scene.

Global properties. The global properties section provides a comprehensive set of tools to enhance the functionality and customization of a project. Users can upload a target image, which serves as the anchor for detection within the project. The AR web embed feature enables seamless integration of ZapWorks Designer projects into websites, expanding accessibility and reach. For enhanced realism, the shadow settings allow users to enable shadows for 3D elements. A background sound option lets creators add audio that enriches the immersive experience when users engage with the project. The scene properties section facilitates editing scene names and accessing scene content, while scene transitions enable smooth navigation among scenes. Additional features, such as the photo UI, activate camera functionality for capturing and sharing scenes, and the zoom tool adjusts the scene's viewing distance. Finally, the 2D/3D switch allows users to toggle between 2D and 3D perspectives, providing flexibility in how content is visualized. These tools collectively empower creators to design dynamic, interactive, and engaging AR experiences.

Scene properties. The scene properties section pertains to changes in the specific scene you are currently in. Here, you can find the following:

- *Name*: Edit the name of the current scene.
- *Transition effects*: Add a transition that plays when moving between scenes.
- *Snapshot and video sharing*: Enable camera controls for saving and sharing your scene.

Scene objects panel. When selected, the scene objects panel displays a list of all objects in your active scene. You can rename, lock, and manipulate the objects here.

Context bar. The context bar provides essential functionality for managing elements and toggling between the AR mode and screen UI mode, facilitating seamless interaction within the interface. Users can manipulate selected elements through various transformation operations, such as the following:

- *Move*: Adjusts an element's position along the *x*-, *y*-, or *z*-axis
- *Scale*: Modifies the element's dimensions along these axes
- *Rotate*: Alters the element's orientation.

Additionally, the duplicate option creates copies of elements, while the lock/unlock feature restricts or permits transformations. The delete function removes unwanted elements, and the recenter option resets the canvas view to its default position. For iterative work, undo/redo enables reversal or reinstatement of changes. Finally, the AR/screen UI mode toggle allows users to switch between immersive AR experiences and standard UI interaction, enhancing versatility and user experience.

Zapworks UI: Action bar. The action bar contains the following project management functions:

- *Rename*: Rename the project in your workspace by double-clicking on the current name.
- *Project*: Replace the current project with a template.
- *Help*: Open a drop-down menu with links to view shortcuts, see what is new, find useful documentation, and provide feedback.
- *Collaborators*: See users currently working on the project.
- *Preview*: Create a temporary QR code for scanning and viewing the current version.
- *Publish*: Publish your project so that anyone with the project activation code can access it.

The Zapworks Designer environment offers an intuitive platform for developing engaging and educational AR experiences. Utilizing features such as the design canvas, components palette, and scene manager, users effectively design interactive AR applications that seamlessly blend creativity with functionality. Within this framework, ASPETE created three demonstrative AR applications: Learning About Lightning, Samaria Gorge Trip, and Treasure Hunt for Pentelic

Marble. These applications function as practical learning tools, equipping students with technical skills while showcasing the educational potential of AR technology.

Each demonstration highlights a distinct application of AR in education and entertainment. The Samaria Gorge Trip app offers an exploration of geological formations, Learning About Lightning simulates meteorological phenomena through interactive Q&As, and Treasure Hunt for Pentelic Marble integrates gamification with cultural education. These examples are accessible via the links provided in this collection, enabling users to explore each application and inspiring the development of customized AR experiences.

Table 1 summarizes key differences across platforms, focusing on ease of use, interactivity, 3D supports, and educational suitability.

In comparison to other AR platforms, Zapworks Designer stands out for its simplicity and accessibility. While many AR development tools require coding knowledge or advanced technical skills, Zapworks enables users to build highly interactive and animated scenes through an intuitive drag-and-drop interface. This allows students with no programming background to create sophisticated AR experiences involving animations, 3D models, and interactive triggers. The platform lowers the technical barrier significantly, promoting creative exploration and broader participation in AR content creation within educational settings.

Students highlight increased interest, ease of use, and improved understanding of geological phenomena, especially in scenarios like the Pentelic marble treasure hunt and the thunderstorm simulation. Teachers from both Greece and other European countries note that the cognitive content is closely aligned with their curricula, and many emphasize the added value of using immersive tools to simulate real-world exploration without logistical constraints. Reported benefits include higher student engagement, support for experiential learning, and the ability to address curriculum topics that are otherwise difficult to teach due to geographical or safety limitations.

VR ENVIRONMENT

The VR environment implementation combines many web technologies. In all VFTs, the user moves around with their computer keyboard and mouse. With the computer keys, they can go left, right, forward, and backward, and with their mouse, they can change their point of view. The functionalities of the tool and UIs were implemented using HTML5, Cascading Style Sheets (CSS) 3, and JavaScript (JS). For styling purposes, the implementation also includes Bootstrap Library for flexibility and responsiveness.

The VR functionality is implemented through the use of the A-Frame web VR framework.[14] This framework includes various 3D models, animations, responsive designs, and reusable components that are helpful and easy to use. It also includes a 3D inspector that was mainly used for testing before deployment. Some of its components are 2D images, 360° images, 2D videos, 3D videos, simple text, and ready-made or custom 3D models.

Front-end architecture

Figure 2 displays the integration of all front-end technologies used and described, the main focus being on A-Frame, where the whole VR environment is hosted.

Thunder scenario overview

The thunder scenario is divided into two chapters, "Learn and Get Protected" and "Find the Danger," along with a

TABLE 1. A comparison of AR educational platforms for geoscience and science, technology, engineering, and mathematics (STEM) integration.

AR platform comparison
Zapworks Designer • Coding required: **No** • UI: **Intuitive drag and drop** • Animation and interactivity: **Advanced (triggers, timelines)** • 3D model support: **Yes** • Best suited for: **Kindergarten–12th grade educators and students**
Unity, with Vuforia • Coding required: **Yes (C# scripting)** • UI: **Complex, steep learning curve** • Animation and interactivity: **Highly advanced** • 3D model support: **Yes** • Best suited for: **Developers, higher education**
CoSpaces Edu • Coding required: **Optional (blocks)** • UI: **Kid friendly, simplified** • Animation and interactivity: **Moderate** • 3D model support: **Yes** • Best suited for: **Primary and secondary education**
Merge Cube • Coding required: **No** • UI: **Simple, tangible cube** • Animation and interactivity: **Limited** • 3D model support: **Yes** • Best suited for: **Interactive STEM activities**
Google Expeditions • Coding required: **No** • UI: **Guided but fixed** • Animation and interactivity: **None** • 3D model support: **No** • Best suited for: **Passive virtual tours**

gallery option. Users begin by choosing between viewing a gallery, exploring a map of Greece, or engaging in the "Find the Danger" minigame. The map option connects to the first chapter, offering an educational experience about lightning incidents in Greece.

"Learn and Get Protected." Users explore a map of Greece with thunderbolt pins marking locations of severe lightning events. Clicking on a pin provides detailed information about each incident, available in both English and Greek. An additional statistics option offers further insights, also bilingual, fostering awareness of lightning patterns and risks across the country.

"Find the Danger." This chapter transforms learning into an interactive minigame. Users are placed in a simulated environment with thunder sounds and a warning of imminent lightning. They must choose the safest location to stand, receiving immediate feedback and educational tips on lightning safety. The scenario concludes with a gallery, where users can browse striking images of lightning, complementing the educational content with visual engagement.

Pentelikon marble scenario

The Pentelikon marble scenario offers an immersive educational experience through a 360° video, three virtual galleries, and a gallery of educational videos. These functionalities aim to provide an in-depth understanding of Penteli's historical, cultural, and geological significance.

The 360° view feature allows users to explore Penteli as it is today through an interactive video. Users can change perspectives using their computer mouse, gaining a dynamic view of the area. The scenario also includes three virtual galleries: the Ancient Times Gallery, focusing on the ancient quarries of Penteli; the Recent Times Gallery, which highlights the Aloula area; and the Today Gallery, showcasing modern Penteli. Each gallery features informative blocks with bilingual content (English and Greek), offering historical and visual insights.

The educational videos section provides three informative videos accessible via interactive thumbnails. Users click on a picture to view a video, with credits available through an information button in the top-left corner of the interface. This scenario seamlessly integrates multimedia elements to engage users while teaching them about Penteli marble's heritage across time periods.

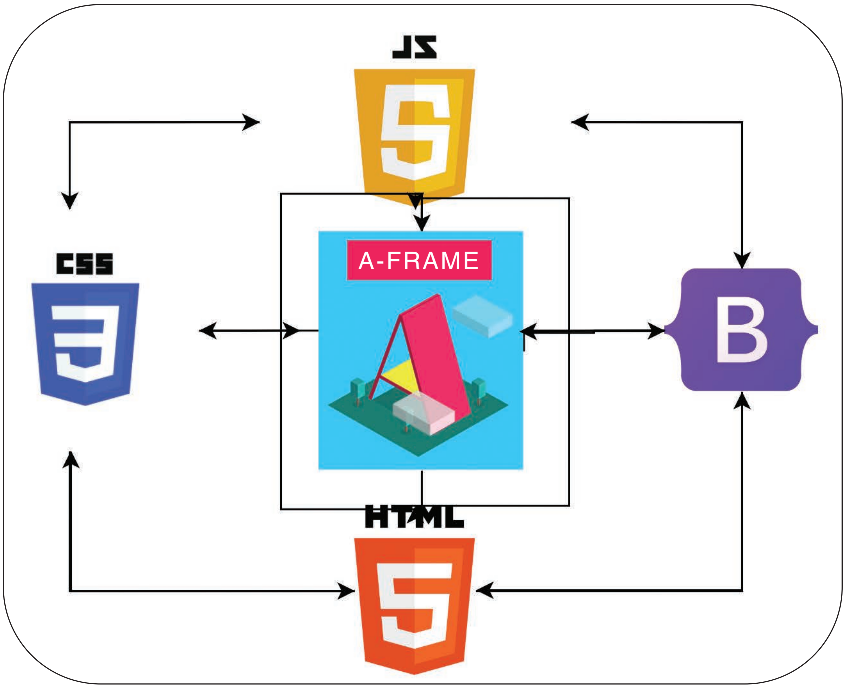

FIGURE 2. The front-end technologies used.

Samaria Gorge scenario

The Samaria Gorge scenario begins with a home page map featuring 11 chapters, each presenting a unique perspective of the gorge as users progress through it. A consistent feature across all chapters is the toolkit, which offers interactive tools to enhance educational experience.

The magnifying glass tool allows users to zoom in and out, revealing intricate details of the scenery. The hammer tool introduces an interactive element, where a hammer appears within the scenery. Users can locate it on a specific stone to access detailed information about the stone.

Additional tools include the compass, which provides real-time directional guidance (north, south, east, and west) and aligns with the user's movements, and the measuring tape, which measures distances between points in the scenery. Users activate the tape by pressing color-coded pins in sequence, with matching pin colors revealing accurate measurements. Together, these tools create a rich hands-on exploration of Samaria Gorge.

TripGift scenarios' architectures

The architecture describes how the user can navigate through the platform. Each scenario has its own architecture since the scenarios are completely different both functionality and design wise.

Thunder scenario: Architecture. The current architecture includes four different components: the main menu (MM), the gallery, the map, and the find-the-danger component, each corresponding to one of the main functionalities of the scenario (Figure 3). The MM component is the one that navigates through all other components. From the gallery component, the user can navigate back to the MM or move to the map. The same is true for the map component: the user can go back to the MM or the gallery. The third component describes the find-the-danger part of the scenario where, as described in previous sections, five scenes apply, each shown as a circled item in the architecture, with a dashboard on top that includes all the scenes. The scenes start in a forest and end in a city. It can also be seen that all scenes can navigate back to the MM or the map.

Pentelikon marble scenario: Architecture. In this scenario, there are five different components, again representing a functionality of a specific scenario (Figure 4). The components are different time periods, each being a walk-in gallery, along with a component in the middle that shows pictures from today. It can be seen that from all the components, the user can navigate to any other since these options are presented in an all-time available toolkit.

Samaria Gorge scenario: Architecture. This is the architectural design of the third scenario (Figure 5), which explains the navigation among all the chapters.

The TripGift scenarios provide an immersive and educational experience through interactive tools and user-friendly navigation. In the thunder scenario, users explore a map marked with lightning bolts representing severe lightning events, with detailed case information accessible upon selection. In scenarios like "In the Forest," users receive real-time alerts of impending lightning, evaluate safe options, and make decisions, receiving instant feedback to enhance their learning. The Pentelikon marble scenario offers virtual galleries featuring bilingual information stands and three educational

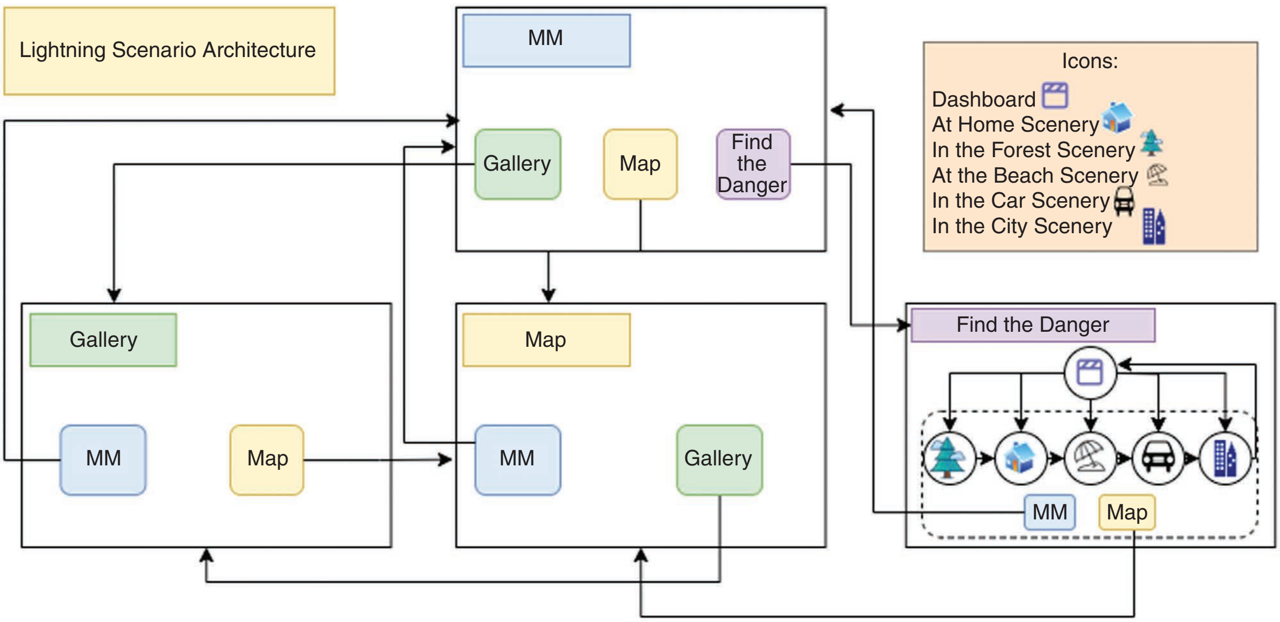

FIGURE 3. The architectural design of the thunder scenario.

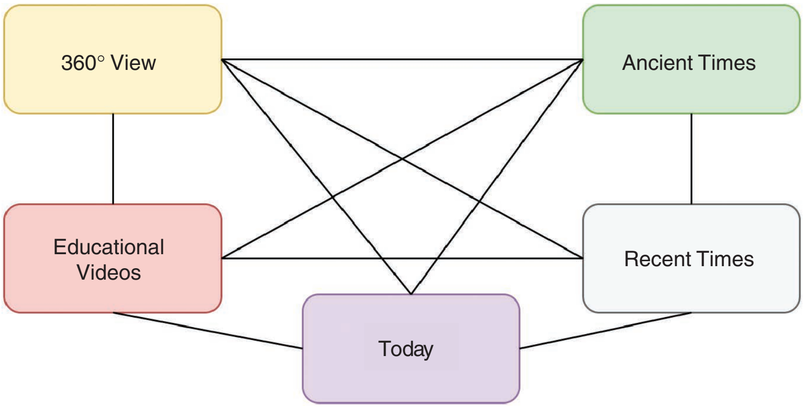

FIGURE 4. The architectural design of the Pentelikon marble scenario.

videos, allowing users to delve into the historical and geological significance of Penteli's marble. Finally, the Samaria Gorge scenario combines intuitive navigation with a versatile toolkit, enabling users to interact with features like the hammer, which provides geological insights, and the measuring tape, which calculates distances using color-coded pins. Together, these scenarios create a dynamic platform that blends education, history, and hands-on exploration.

The VR tool delivers immersive educational experiences through three distinct scenarios. In the thunder scenario, users are engaged with a map of Greece marked with lightning bolt icons indicating historic lightning events, play a safety-focused minigame, and explore a gallery of lightning images. The Pentelikon marble scenario offers a journey through time, with 360° videos and virtual galleries highlighting the ancient and modern history of the Penteli area, complemented by multilingual educational materials. Finally, the Samaria Gorge scenario takes students through an interactive exploration of the gorge, utilizing tools like the magnifying glass, compass, and measuring tape to provide detailed insights into the environment while fostering an engaging learning experience. Each scenario integrates responsive navigation, multilingual content, and interactivity for a rich user experience.

The most challenging principle to implement was responsiveness. Since the framework used (A-Frame)[14] is a different HTML library with custom elements, we had some difficulties integrating the Bootstrap Library, which ensures said principle. Due to this issue, we had to include an older version of this library to ensure the same user experience on all device screen sizes.

Since A-Frame is powered by Three.js, it has all benefits in terms of flexibility and extensibility. A-Frame is also very developer friendly since it runs in a browser with no obligatory

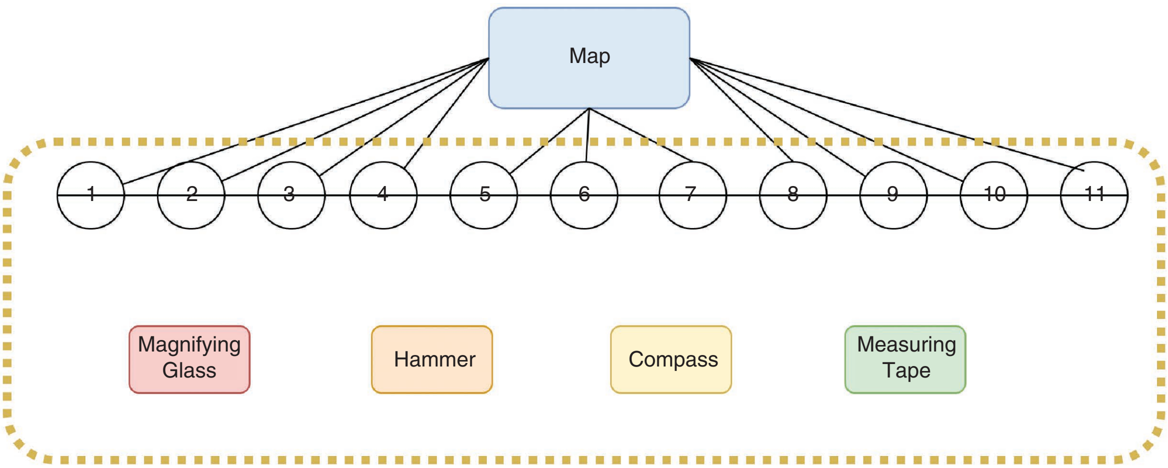

FIGURE 5. The architectural design of the Samaria Gorge scenario.

installations, and it uses simple HTML syntax (see Table 2).

USER TESTING

Following the completion of the AR/VR platform development, a short pilot implementation was conducted in a secondary school in Greece, involving both educators and students. During this phase, students were guided through the virtual environments as part of a structured geoscience lesson, facilitated by their teachers. Subsequently, focus group discussions were organized to gather qualitative feedback from both student and teacher participants, aimed at informing iterative improvements to the platforms with regard to both pedagogical content and technical functionality.

The pilot implementation yielded encouraging results. The majority of participating teachers observed a marked increase in student interest and engagement, with several expressing their intention to integrate VFTs into their future instructional practices.

Furthermore, educators highlighted the potential of VFTs as effective tools for differentiated instruction and flipped classroom methodologies. From an educational standpoint, the VFT applications demonstrated positive outcomes in fostering active participation, enhancing comprehension, and motivating learners. Despite minor technical limitations, the platforms, once refined, were considered highly promising as complementary, and in some cases, alternative, instructional tools to conventional teaching approaches.

Importantly, the integration of immersive technologies contributed to a more dynamic and interactive learning experience. Students exhibited heightened curiosity and involvement, particularly in subject areas such as geoscience, where the virtual representations supported deeper conceptual understanding through multimodal engagement (visual, auditory, and kinesthetic). Additionally, the use of digital tools and environments during the pilot enhanced students' digital literacy and technological fluency, further supporting the broader educational objective of cultivating 21st century skills.

DISCUSSION

What distinguishes this work is the development of a modular multiscenario AR/VR system that enables both guided exploration and learner-generated content through open customizable platforms.[17,18] The innovative integration of educational games, toolkits, and geospatial storytelling ensures sustained engagement and pedagogical depth across diverse learning contexts.

The integration of AR and VR in the lightning, Samaria Gorge, and Pentelikon marble scenarios represented a transformative approach to immersive education, offering accessible and interactive ways to explore complex geoscientific phenomena. By combining contextual enrichment with interactivity, these tools enhanced the engagement and deepened learners' understanding of natural processes.[19]

In the lightning scenario, AR and VR enabled students to visualize meteorological phenomena like lightning formation and storm dynamics, with AR modules highlighting factors such as susceptibility and protection while VR simulations provided immersive storm experiences.

Similarly, the Samaria Gorge scenario utilized AR to overlay geological data onto the landscape and VR for an in-depth exploration of the gorge, helping students understand the interplay of tectonic uplift, erosion, and weathering.[20]

TABLE 2. A comparison of VR educational platforms for geoscience and STEM integration.

VR platform comparison
A-Frame • Coding required: **Yes (HTML, JS)** • UI: Code **based** • Animation and interactivity: **Moderate to advanced (events, animations)** • 3D model support: **Yes (.glTF, .OBJ)** • Best suited for: **Web developers, educators with coding skills**
PlayCanvas • Coding required: **Yes (JS)** • UI: **Visual editor + scripting** • Animation and interactivity: **Advanced (physics, interactivity)** • 3D model support: **Yes** • Best suited for: **Game developers, interactive web experiences**
Three.js • Coding required: **Yes (JS)** • UI: **Code based, requires strong JS skills** • Animation and interactivity: **Highly advanced (custom interactions)** • 3D model support: **Yes** • Best suited for: **Experienced developers, custom VR apps**
JanusWeb • Coding required: **Yes (HTML, JS)** • UI: **Web based** • Animation and interactivity: **Moderate (supports avatars)** • 3D model support: **Yes** • Best suited for: **VR developers**

In the Pentelikon marble scenario, AR illustrated ancient quarrying techniques, and VR allowed learners to virtually explore Mount Pentelicus, showcasing its geological and cultural significance. Together, these scenarios demonstrated the power of AR and VR to combine interactivity, immersion, and contextual learning, offering a dynamic educational experience that connects students to the intricacies of natural and cultural heritage.[21, 22, 23]

Furthermore, through the pilot user testing, the use of immersive technologies not only increased student motivation and engagement but also improved conceptual understanding in geosciences. Teachers highlighted the tool's potential for differentiated instruction and noted that immersive learning environments aligned well with flipped classroom methodologies and digital competency goals.

From an educational standpoint, the AR/VR platform directly addressed key STEAM challenges, including limited accessibility, scalability, and curriculum relevance.[27] The dual-mode (AR and VR) architecture promotes equitable access for geographically isolated or economically constrained students, while modular bilingual content ensures inclusivity across diverse learning needs and contexts.[28]

In comparison with existing educational platforms, such as Google Expeditions or Merge Cube, which often deliver fixed passive content, our approach delivers highly interactive scenario-driven experiences. Features like real-time-feedback games, digital measuring tools, and customizable authoring environments allow users, both learners and educators, to cocreate and personalize content. This comparative innovation positions the platform as not only a learning resource but also a participatory student-driven educational environment.[29]

Together, these scenarios demonstrate the power of AR and VR to combine interactivity, immersion, and contextual learning, offering a dynamic educational experience that connects students to the intricacies of natural and cultural heritage.

The integration of AR and VR platforms in the lightning, Samaria Gorge, and Pentelikon marble scenarios revolutionizes education by blending immersive technology with interactive learning. AR overlays digital information onto real-world environments, deepening the understanding of geoscientific phenomena, while VR transports learners into lifelike settings, enhancing spatial awareness and experiential engagement. Together, they bridge theory and practice, making abstract concepts tangible and accessible. These technologies not only foster critical thinking and interdisciplinary connections but also promote environmental awareness, stimulating curiosity and active participation. Their versatility and effectiveness redefine how students interact with and comprehend the natural world, offering an innovative and impactful educational experience.

Future work

Future research on AR and VR tools should focus on piloting applications in schools, gathering quantitative and qualitative feedback to refine content and functionality, and diversifying scenarios to include geoscientific phenomena, such as glacial dynamics, volcanic activity, and coastal erosion. Expanding the application of these immersive tools to other disciplines, such as biology, archaeology, and environmental science, will further demonstrate their cross-disciplinary potential. To ensure broad adoption and curriculum integration, efforts must also prioritize affordability, device compatibility, and comprehensive teacher training. Finally, the development of robust assessment metrics to evaluate long-term educational outcomes, including knowledge retention, critical thinking, and digital literacy, will be key to measuring the sustained impact of these tools.

Both AR and VR technologies can be seamlessly integrated into learning management systems (LMSs), such as Moodle Classroom, to enhance course delivery. Within this framework, LMSs can serve complementary roles in facilitating user navigation and fostering learner engagement through interactive immersive experiences.

Future work will also prioritize enhancing accessibility for users with disabilities by aligning the platform with universal design and inclusive standards. Planned improvements include the integration of closed captions and audio descriptions for all multimedia content, screen reader compatibility, adjustable text sizes, and alternative navigation interfaces. These features aim to support diverse learning needs and ensure equitable inclusive participation in immersive learning environments for all students, regardless of ability. C

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REFERENCES

1. M. Asif, A. Mondal, S. Soumil, A. Das, and P. Sahoo, "Augmented reality and virtual reality in education: A transformative journey into immersive learning environments," in *Advances in Computational Solutions: Integrative Approaches and Applications*, R. Kumar, A. Dhar, A. Banerjee, and A. Mahapatra, Eds. New Delhi, India: Integrated Publications, 2024, pp. 185–204.
2. J. Jesionkowska, F. Wild, and Y. Deval, "Active learning augmented reality for STEAM education—A case study," *Educ. Sci.*, vol. 10, no. 8, 2020, Art. no. 198, doi: 10.3390/educsci10080198.
3. S. Belbase, B. R. Mainali, W. Kasemsukpipat, H. Tairab, M. Gochoo, and A. Jarrah, "At the dawn of science, technology, engineering, arts, and mathematics (STEAM) education: prospects, priorities, processes, and problems," *Int. J. Math. Educ. Sci. Technol.*, vol. 53, no. 11, pp. 2919–2955, 2022, doi: 10.1080/0020739X.2021.1922943.
4. X. Chen and Y. Zhang, "Virtual field trips in K-12 classroom teaching: A systematic review," *Int. J. Technol. Teaching Learn.*, vol. 19, no. 1, pp. 52–68, 2023.
5. K. Papagiannaki, K. Lagouvardos, and V. Kotroni, "A database of high-impact weather events in Greece: a descriptive impact analysis for the period 2001–2011," *Nat. Hazards Earth Syst. Sci.*, vol. 13, no. 3, pp. 727–736, 2013, doi: 10.5194/nhess-13-727-2013.
6. D. Guha-Sapir, R. Below, and P. Hoyois. "EM-DAT: The CRED/OFDA international disaster database." EM-DAT, 2021. [Online]. Available: https://www.emdat.be/

7. D. Vaiopoulos, A. Vassilopoulos, N. Evelpidou, and G. Skianis, "Geomorphological study of Samaria Gorge, Crete, using remote sensing techniques and GIS," in *Proc. Remote Sens. Environmental Monit., GIS Appl., Geol. II*, Bellingham, WA, USA: SPIE, 2003, pp. 408–416.
8. E. Manoutsoglou, I. Lazos, E. Steiakakis, and A. Vafeidis, "The geomorphological and geological structure of the Samaria Gorge, Crete, Greece—Geological models comprehensive review and the link with the geomorphological evolution," *Appl. Sci.*, vol. 12, no. 20, 2022, Art. no. 10670, doi: 10.3390/app122010670.
9. M. Korres, *From Penteli to the Parthenon*. Athens, Greece: Melissa, 1994.
10. T. Doutsos, *Geology: Principles and Applications*. Liberal Books, 2014.
11. European Union, *EU Principles for Sustainable Raw Materials*. Luxembourg: European Union, 2021.
12. "Exploitation methods." orykta.gr. [Online]. Available: https://www.orykta.gr/ekmetalleusi-emploutismos/20-methodoiekmetalleysis
13. "Zapworks: The most powerful all-in-one WebAR platform." Zapworks. [Online]. Available: https://zap.works/
14. "A-Frame: Hello WebVR." A-Frame. [Online]. Available: https://aframe.io/
15. G. Yakman, "STEAM education: An overview of creating a model of integrative education," in *Proc. Pupils Attitudes Towards Technol. Conf.*, 2008.
16. H. K. Wu, S. W. Y. Lee, H. Y. Chang, and J. C. Liang, "Current status, opportunities and challenges of augmented reality in education," *Comput. Educ.*, vol. 62, pp. 41–49, Mar. 2013, doi: 10.1016/j.compedu.2012.10.024.
17. T. W. C. Hilde et al., "TAMU - Texas A&M University topography and acoustic mapping undersea system," in *Proc. OCEANS 91*, 1991, pp. 750–755, doi: 10.1109/OCEANS.1991.627936.
18. J. Coffey, D. J. Beard, and D. A. Ryan, "Visualising coastal seabed characteristics: Using VRML models to present three-dimensional spatial data via the web," *J. Spatial Sci.*, vol. 52, no. 1, pp. 133–143, 2007.
19. L. Melelli, F. Silvani, M. Ercoli, C. Pauselli, G. Tosi, and F. Radicioni, "Urban geology for the enhancement of the hypogean geosites: The Perugia underground (Central Italy)," *Geoheritage*, vol. 13, no. 1, 2021, Art. no. 18, doi: 10.1007/s12371-021-00545-z.
20. A. Giardino, G. Santinelli, and V. Vuik, "Coastal state indicators to assess the morphological development of the Holland coast due to natural and anthropogenic pressure factors," *Ocean Coastal Manage.*, vol. 87, pp. 93–101, Jan. 2014, doi: 10.1016/j.ocecoaman.2013.09.015.
21. J.-R. Kim, S.-Y. Lin, J.-W. Hong, Y.-H. Kim, and C.-K. Park, "Implementation of Martian virtual reality environment using very high-resolution stereo topographic data," *Comput. Geosci.*, vol. 44, pp. 184–195, Jul. 2012, doi: 10.1016/j.cageo.2011.09.018.
22. G. Caravaca, S. L. Mouélic, N. Mangold, L. L. Deit, M. Massé, and L. Deit, "Using virtual reality to replicate 'in situ' field work on Mars," in *Proc. 4th Virtual Geosci. Conf.*, Sep. 2021. [Online]. Available: https://hal.archives-ouvertes.fr/hal-03922867
23. M. Hincapie, L. M. Cifuentes, A. Valencia-Arias, and J. Quiroz-Fabra, "Geoheritage and immersive technologies: Bibliometric analysis and literature review," *Episodes*, vol. 46, no. 1, pp. 101–115, 2023, doi: 10.18814/epiiugs/2022/022016.
24. F. Pasquaré Mariotto and F. L. Bonali, "Virtual geosites as innovative tools for geoheritage popularization: A case study from Eastern Iceland," *Geosciences*, vol. 11, no. 4, 2021, Art. no. 149, doi: 10.3390/geosciences11040149.
25. D. Tormey, "New approaches to communication and education through geoheritage," *Int. J. Geoheritage Parks*, vol. 7, no. 4, pp. 192–198, 2019, doi: 10.1016/j.ijgeop.2020.01.001.
26. C. Lansigu, V. Bosse-Lansigu, and F. Le Hebel, "Tools and methods used to represent geological processes and geosites: Graphic and animated media as a means to popularize the scientific content and value of geoheritage," *Geoheritage*, vol. 6, no. 2, pp. 159–168, 2014, doi: 10.1007/s12371-014-0101-4.
27. E. Giordano et al., "Multimedia and virtual reality for imaging the climate and environment changes through earth history: Examples from the Piemonte (NW Italy) Geoheritage (PROGEO-Piemonte project)," in *Engineering Geology for Society and Territory*, vol. 8, G. Lollino, D. Giordan, C. Marunteanu, B. Christaras, I. Yoshinori, and C. Margottini, Eds., Cham, Switzerland: Springer-Verlag, 2015, pp. 257–260, doi: 10.1007/978-3-319-09408-3.
28. L. Perotti et al., "Fieldtrips and virtual tours as geotourism resources: Examples from the Sesia Val Grande UNESCO Global Geopark (NW Italy)," *Resources*, vol. 9, no. 6, 2020, Art. no. 63, doi: 10.3390/RESOURCES9060063.
29. E. Spyrou et al., "Contribution of geological heritage to geoeducation: A case study from Samaria Gorge and Mount Pentelicus (marble quarries)," *Heritage*, vol. 8, no. 2, 2025, Art. no. 42, doi: 10.3390/heritage8020042.