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ORIGINAL ARTICLE

New Workflow for Bridging the Gap Between Geology Knowledge and Society: The Example of the VIGEOCULT Project and the Orígens Geopark. South-Central Pyrenees

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Abstract
The effective dissemination of geological content in an engaging and easy-to-follow manner is challenging, especially because in most situations the general public has a limited geological background. This is particularly evident when considering dissemination outdoors. This study introduces a comprehensive workflow and methodology designed to transform complex geological research into accessible and engaging content for visitors to the Orígens UNESCO Global Geopark – hereinafter simply referred to as Orígens Geopark – in the southern Pyrenees. This workflow brings accurate geological research together with leading-edge graphical design techniques to create a set of outreach products such as virtual reality images, 3D models and 4D reconstructions of the past geological landscapes. Despite the potential of the workflow to create leading-edge dissemination products, some limitations have also been identified and are discussed here. This workflow developed for the project entitled "A natural open museum in the Pyrenees: virtual reality experience for dissemination and conservation of the geological and cultural heritage (VIGEOCULT) is applicable not only to Orígens Geopark but also in the tourism sector, educational (from elementary to university level) outreach in villages and schools, and public dissemination events.

Keywords Geological dissemination · Orígens Geopark · Pyrenees · Geological evolution · Geological reconstructions

Introduction

Geology, despite its fundamental role in shaping the world we live in, is not widely understood or appreciated within society. The general public often lacks geological knowledge, which can lead to misconceptions about natural processes and the environment. Such misconceptions may lead to wrong decision-making when considering resource and/or natural disaster management, and environmental and/or geoheritage conservation (Bach et al. 1988; Augustine 1998; Mooney and Kirshenbaum 2009; Stewart, and Nield, 2013; Stewart and Lewys, 2017)). Without a basic understanding of geology, people may not only struggle to appreciate how geological processes have shaped the landscape they observe but also find difficulties grasping the implications of significant natural phenomena like earthquakes, tsunamis, landslides, and volcanic eruptions. Furthermore, the beauty and significance of geological formations and structures and the Earth's history remain largely unappreciated, and only the consequences of the geological processes are the

Supplementary Material Geopark Youtube channel: https://www.youtube.com/c/GeoparcOr%C3%ADgens.
Link to the Inventari d'espais d'interès geològic: https://mediambient.gencat.cat/ca/05_ambits_dactuacio/patrimoni_natural/patrimoni-geologic/inventari_despais_dinteres_geologic/.

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ones being discussed (Bach et al. 1988). Education systems often do not emphasize geology as much as other sciences, contributing to this knowledge breach (García Yelo et al. 2022). Geologists excel in understanding complex geological processes, yet they often face challenges in creating simple and visually appealing sketches to explain these concepts (Fig. 1). Despite their deep expertise, translating technical knowledge into accessible information requires a different skill set. Bridging this gap through public education and outreach is crucial for fostering a society that is both, more informed and capable of making responsible decisions about the planet we live in. It also helps to develop appreciation for the beauty of the geological landscape and the importance of protecting relevant sites.

Recent technological advances, including more powerful smartphones and tablets, have revolutionized the way we access and share information. These devices, now equipped with high-speed processors and advanced graphics capabilities, offer users an unprecedented level of interactivity and connectivity. The emergence of new technologies, such as virtual reality (VR) goggles, further enhances this experience by immersing users in fully interactive digital environments. Current research on VR applications in education demonstrates significant advancements, particularly in fields such as archaeology, biology, medicine, and environmental sciences. In archaeology, VR has been used to virtually reproduce a broad variety of anthropological monuments and structures (Barceló et al. 2000 and references therein, Bruno et al. 2010; Unver and Taylor 2012; Lecari 2017). In biology, VR is used, among other things, to create immersive simulations of cellular processes and complex ecosystems, enhancing student understanding and engagement (Markowitz et al. 2018; Makransky and Mayer 2022; Majewska and Vereen 2023). In medicine, VR training modules provide realistic surgical practice environments, reducing the risk associated with real-life training (Moro et al. 2017; Dhar et al. 2021; Mao et al. 2021). Environmental science benefits from VR by offering virtual field trips to remote locations, enabling students to explore diverse ecosystems without physical constraints (Makransky and Mayer 2022). Virtual reality has also been used for aeronautical training and flight simulators, providing immersive environments for pilots to practice and refine their skills in realistic scenarios (Tadeja et al. 2020; (Pirker 2022). Finally, in geology, there have been several initiatives such as digital platforms to upload geological models (i.e., sketchfab, GeoVires or V3Geo) but also research and educational publications (Sutton et al. 2014; Harknett et al. 2022) and even dissemination in geoparks (Mir-Pellicer et al. 2022). These applications have shown to improve knowledge retention and practical skills, making VR a valuable tool for education. As technology continues to evolve, these tools will undoubtedly shape the future of communication and information sharing. These innovations have opened new avenues of dissemination, allowing geoscientists to explore novel ways to engaging with and sharing geological knowledge with wider audiences.

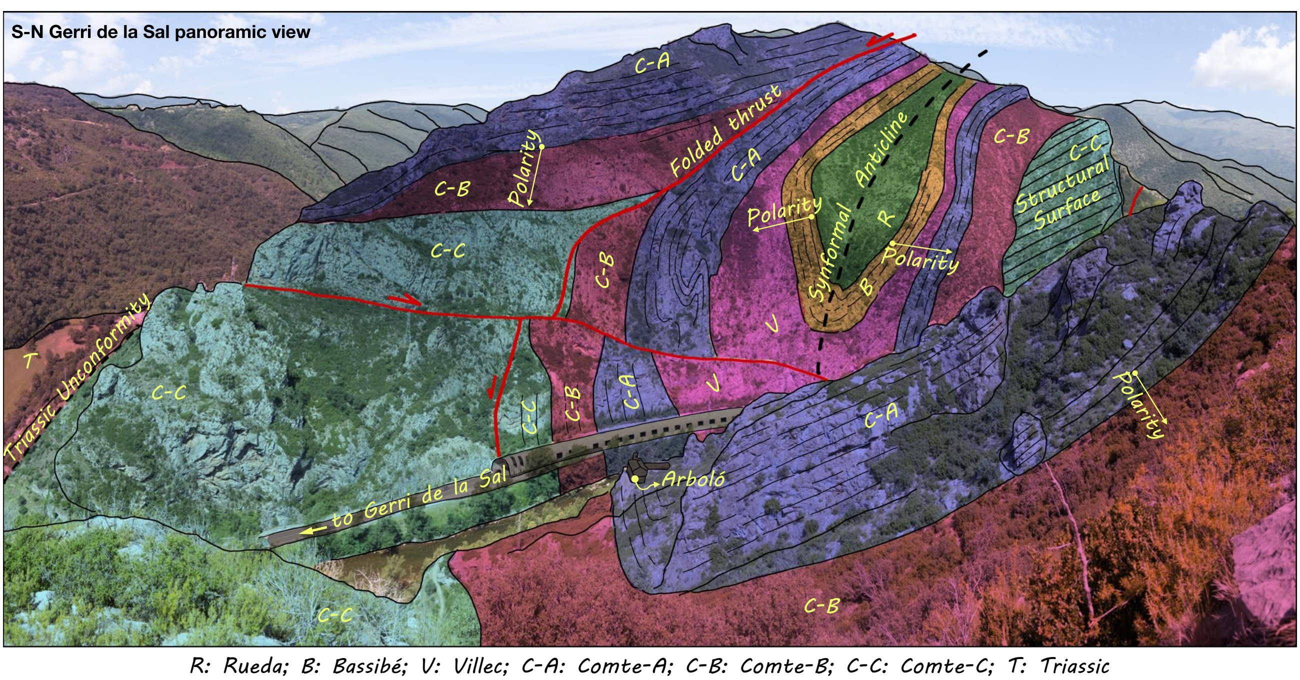


Fig. 1 Possible field sketch done by a geologist of an outcrop of interest highlighting the most relevant structures such as faults and folds as well as identifying the different geological formations and their polarity

On the other hand, migration into cities, coupled with the tendency to concentrate services and opportunities in major urban centres, often leads to the depopulation of certain regions, particularly those situated at a distance from main cities (Smith et al. 2020; Cole et al. 2024). This centralization pattern can drain smaller communities of their vitality, as residents migrate to urban areas in search of better economic prospects. However, this challenge also presents an opportunity to revitalize and attract more people to less populated regions. By redirecting resources and investments to these areas, it is possible to foster growth and development in communities that have been overlooked (Oncescu 2015; Zang et al. 2020). The distinctive geological landscape across various regions provides unique opportunities for industries like tourism and related services to further enhance potential economic revitalization. With strategic planning and investment, these underpopulated areas can be transformed into thriving hubs of activity, contributing to a more balanced and equitable distribution of population and resources. UNESCO Geoparks, gathered in the Global Geoparks Network (www.globalgeoparksnetwork.org), bring together all of the above.

The GGN is a legally constituted non-profit global organization that provides a platform for cooperation between Geoparks. It brings together government agencies, NGOs, scientists, and communities from around the world in a unique worldwide partnership. Operating under the regulations of UNESCO, the Global Geoparks Network fosters collaboration and knowledge exchange, promoting the conservation of geological heritage while supporting sustainable development in the regions where these Geoparks are located.

The Orígens Geopark (www.geoparcorigens.cat), recognized as a UNESCO Global Geopark in April 2018, has since become part of the Global Geoparks Network. Located in the southern sector of the Catalan Pyrenees, in the province of Lleida, Orígens Geopark encompasses a territory with exceptional geological heritage. The Orígens Geopark is regarded as an exceptional open-air natural laboratory visited by scientists from around the world that has been classically used for teaching geology. Its spectacular landscapes feature a wide variety of geological elements, making it a unique region for understanding the processes that shaped mountain systems. Such is the case that in the pioneering works of geological site protection developed by the Catalan Government, 16 out of the 158 geosites of the 2005 Geosite Inventory of Catalonia (see supplementary material for link to the website) are within the boundaries of the Orígens Geopark. This area was key in unraveling the formation of Pyrenees and has provided valuable insights into mountain range formation worldwide (Muñoz 1992, 2002, 2019; Mencos et al. 2015; Muñoz et al. 2018). Furthermore, the extensive fossil record within its area showcases 350 million years of evolutionary history, spanning from the Devonian trilobites and orthoceratids, to the exceptionally rich Cretaceous paleoecosystem with newly discovered Upper Cretaceous dinosaur species, and the modern mammal lineages from the Paleocene (Vela 2012; Marigó et al. 2013; Sellés et al. 2021; Vila et al. 2022; Prieto-Márquez and Sellés, 2022). The recognition as a UNESCO Global Geopark highlights the significance of this area for its geological importance and its potential to inspire and educate visitors from around the globe.

The geographical scope of Orígens Geopark, with its main reference town being Tremp (Fig. 2a), reflects its commitment to showcasing and preserving the unique geological heritage of this mountainous region, while also highlighting the cultural and natural diversity across this territory. This publication introduces a novel approach to create content aimed at helping the general public understand the geological processes that have shaped the present-day landscape of the area covering the Orígens Geopark. The need for improved communication tools, to help geologists convey their findings effectively to a broader audience, triggered the necessity to find new approaches to disseminate geological content. By leveraging advanced visualization techniques and accessible language, the proposed methodology translates complex geological concepts into engaging and comprehensible information. This approach includes the use of interactive virtual reality models, detailed diagrams, and clear explanations of key processes such as erosion, sedimentation, tectonic processes, paleontological and geological evolution. The goal is to bridge the knowledge gap between leading edge researchers and the general public, by fostering collaboration between geologists, graphic designers, 3D virtual reality developers, and animators. This synergy aims to promote a deeper appreciation and awareness of the Earth's dynamic history. Therefore, the approach taken by the VIGEOCULT project seeks to contribute to better-informed communities through the use of VR, specifically within the Orígens Geopark in the Catalan Pyrenees.

Geographical and Geological Setting

The Geopark Orígens is situated in the western sector of Catalunya, within the province of Lleida. This area encompasses several counties, including Pallars Jussà, Pallars Sobirà, Alt Urgell, and Noguera. Each of these contributing to the Geopark's diverse natural landscapes (Fig. 2a).

The Pyrenees is the east–west elongated doubly-vergent orogen between the Iberian Peninsula and the continental Europe. The orogen formed as the result of the collision between the Iberian and European plates from Late Cretaceous to Miocene times deforming the previously developed Late Jurassic-Early Cretaceous rift system

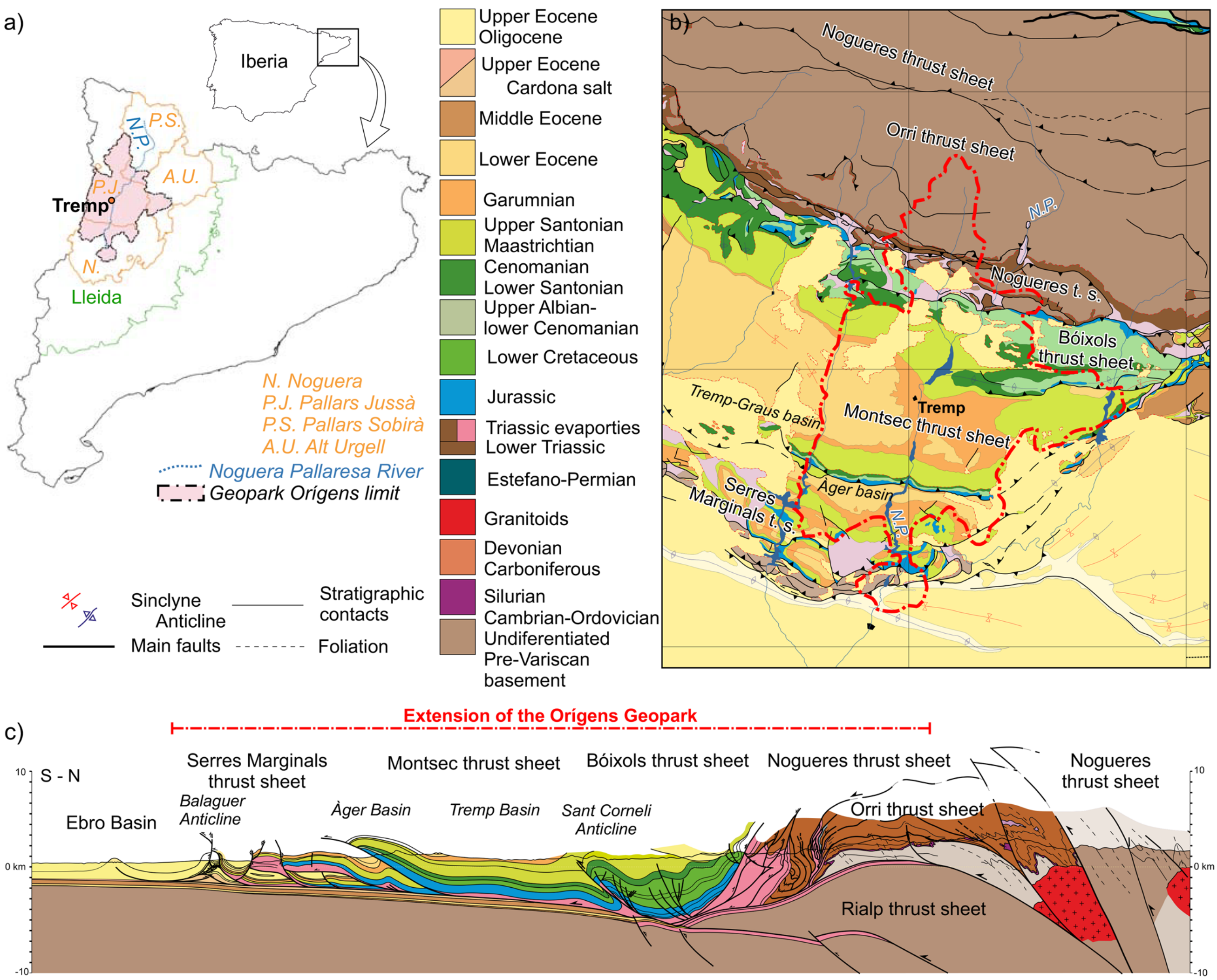


Fig. 2 **a**) Geographical map of Catalunya with the location of the province and counties in which the geopark is enclosed. **b**) Geological map of the Southern Pyrenees highlighting the limits of the Orígens Geopark. **c**) Geological cross-section of the Southern Pyrenees. (b and c share the same legend and they are modified from Muñoz et al. 2018)

along the northern Iberian plate (Le Pichon and Sibuet 1971; Choukroune and ECORS Team 1989; Roest and Srivastava 1991; Muñoz 1992, 2002, 2019; Beaumontet al. 2000; Rosenbaum et al. 2002; Vissers and Meijer 2012). In the core of the Pyrenees, the Axial Zone is characterized by pre-Mesozoic Variscan basement units organized in a south-verging antiformal stack, while the external domains of the orogen are constituted by cover thrust sheets that progressively climb up toward the Ebro and Aquitanian foreland basins to the south and north respectively (Muñoz 1992, 2002, 2019; Vergés et al. 1992; Biteau et al. 2006). The Geopark Orígens is located at the southern portion of the Pyrenean orogen (Fig. 2b). The Axial Zone basement antiformal stack is made up of three main thrusts that from top to bottom are: the Nogueres, the Orri and the Rialp thrusts. To the south and detached along the Upper Triassic evaporites the Serres Marginals, the Montsec and the Bóixols cover thrust sheets constitute the main structural features of this area of the Southern Pyrenees (Fig. 2c). Although the cover thrusts were emplaced during the Late Cretaceous to the Eocene in a piggy-back sequence from north to south, the late Eocene–Oligocene break-back reactivation of the thrust system was coeval with the displacement of all cover thrust sheets above the upper Eocene salt. Meanwhile, to the north, this reactivation significantly increased the uplift rate and denudation of the basement thrust sheets in the Axial Zone (Vergés and Muñoz 1990; Burbank et al. 1992; Coney et al. 1996; Meigs and Burbank 1997; Fitzgerald et al. 1999; McClay et al. 2004; Beamud et al. 2011; Fillon et al. 2013; López-Mir et al. 2015; Santolaria et al. 2015; Carola and Muñoz 2024).

Methodology

The workflow includes a screening phase that involves the entire team made of geologists, historians, graphical designers and animators, followed by two technical stages (geological and graphical) where various team members participate (Fig. 3). In the initial technical phase, geologists play a more prominent and direct role, providing knowledge, essential data, insights, and scientific accuracy to guide the foundation of the project. Once this groundwork is established, the second technical phase sees graphical designers and animators taking the lead, using the input from the geologists to craft visually compelling and scientifically accurate representations. Throughout this phase, geologists continue to provide support, ensuring that the final product honors the geological data and concepts while allowing the designers to focus on the aesthetic and technical aspects of the visualization.

Screening phase of the workflow

The first step of the workflow begins with an initial ranking of key geological sites within the geopark (Fig. 3a). This step is crucial to identify which locations have the most geological significance and should be prioritized for further exploration and explanation. The ranking is based on several factors, including how representative the geological features are, their historical importance, accessibility, and their potential to attract and engage visitors. This evaluation sets the foundation for developing a comprehensive educational experience around the geology of the Geopark.

Once the key sites are ranked, the next step involves assessing the geological features at each site to determine which are scientifically interesting and provide more educational value for the general public (Fig. 3b). This process requires careful consideration of what makes the geology at each location distinctive and how it can be communicated effectively to a non-expert audience while maintaining high scientific rigor. Class-leading examples are prioritized for

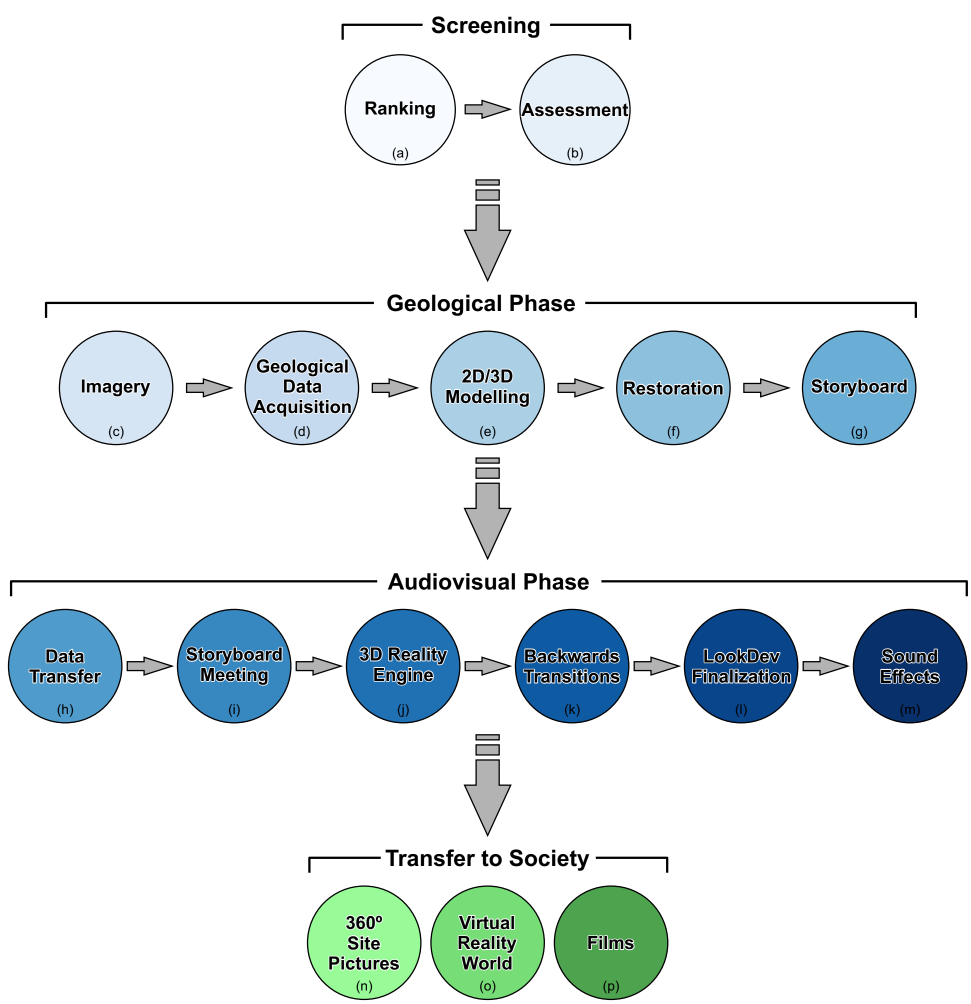


Fig. 3 Workflow of the project which contains 3 main phases which results in the dissemination material. The Screening Phase, containing the Ranking (**a**) and the Assessment (**b**) steps; the Geological Phase, containing the Imagery (**c**), the Geological Data Acquisition (**d**), the 2D/3D Modelling (**e**), the Restoration (**f**) and the Storyboard (**g**) steps; and finally, the Audiovisual Phase, containing the Data Transfer (**h**); the Storyboard Meeting (**i**), the Metaverse Generation (**j**), the Backwards Transitions (**k**), the LookDev and Finalization (**l**) and the Sound Effects (**m**) steps. The results can be of three different types which are 360º images of the selected sites (**n**), the 3D virtual reality environment (**o**) or films (**p**) (see main text for a detailed description of each step)

interpretation and further site development, since they help illustrate significant geological processes or contribute to understanding the geological evolution of the region. This ensures that the content presented to visitors is both scientifically relevant and engaging.

Geological phase of the workflow

Imagery, coming from drones as well as 360º cameras, was then employed to capture detailed visual data of the selected geological sites (Fig. 3c). Drones enable to capture images of the sites from angles and elevations that would be otherwise difficult or impossible to achieve, making it possible to visualize and analyze complex geological formations in greater detail. This imagery is needed to construct 3D digital versions of the sites and provides a high-resolution, accurate representation of the geological structures. These digital models serve as the basis for further geological research and interpretation. They also are used in the virtual reality experience and dissemination to the visitor of the geopark since they also allow to observe the landscape from a bird's eye view perspective.

Following the acquisition of drone imagery, data gathering and geological research are conducted (Fig. 3d). This stage involves compiling detailed geological data to create either a 2D geological cross-section or a 3D geological model, depending on the geological interest of the site (Fig. 3e) and the future use of such products. Researchers analyze the architecture of rock layers, structural features, and other key data to develop a geological interpretation of the area of interest. These models provide a framework for the next phase of the project.

Once the geological models are developed, the next step is to restore these 2D or 3D models to understand and explain the geological history and the processes that shaped the region (Fig. 3f). Restoration involves bringing models to a less deformed or non-deformed stage of evolution, effectively visualizing the backward evolution of an area. By using restoration techniques, geologists can recreate the sequence of events that led to the current landscape, illustrating the key processes that have occurred over millions of years. This restoration provides a dynamic and engaging way to communicate the geological history to visitors, highlighting significant changes in the environment over time.

The following step in the workflow involves creating a storyboard that outlines the environment and geological structures at each stage of the evolution of the region (Fig. 3g). This storyboard is complemented by sketches, photos and videos of current similar environments and geological processes. The goal is to provide visitors with a clear and engaging narrative of the geological history, making complex scientific concepts understandable and interesting to non-geologists. By integrating visuals with real-world examples, the storyboard helps visitors connect with the geological story in a meaningful and memorable way. This storyboard is also a key element for the next phase as will be demonstrated.

Audiovisual phase of the workflow

The initial step involves transferring the present-day digital outcrop model, along with all geological surfaces from the static geological model and restoration steps, to the graphical designers (Fig. 3h). This data enables the graphical designers to begin creating visual representations of the present-day geology of the site.

After delivering the digital models, the next phase is handing over the storyboard (Fig. 3i). During this phase, a series of meetings ensures that the geologists help the graphic designers fully understand the paleoenvironments and key geological processes that shaped the area over time. This conversation allows the graphical designers to grasp not just the static elements of the landscape, but the dynamic forces that led to its formation. The discussion helps clarify the evolution of the environment, ensuring the final visualizations are scientifically accurate and compelling.

Once graphical designers are familiar with the data and the geological narrative, the next step is to import the data into a 3D reality engine (Fig. 3j). This stage marks the beginning of the digital reconstruction, where the present-day environment is generated. By incorporating the geological data into the 3D reality engine, a highly immersive virtual space is created, allowing users to explore the geological features and landscapes in an interactive format. This stage lays the groundwork for the more complex, backwards reconstruction of the area's geological history.

Following the creation of the present-day environment, the graphical designers and animators collaborate with the geologists to reconstruct the geological processes that shaped the landscape (Fig. 3k). This step requires multiple iterations, with the geologists providing input on how to accurately represent the processes. Each iteration involves refining the representations based on feedback, scientifically maintaining the final result. This collaborative process helps bridge the gap between scientific understanding and visual storytelling. The resulting products of this stage are interpretative reconstructions of the topography as well as the Earth interior, i.e. the subsurface geology, of the past. This represents the blank canvas for the next step of the workflow.

Once the geological processes have been reconstructed accurately, the next step involves look development and finalization applying textures, materials and visual effects to the models (Fig. 3l). These steps add depth and realism to the reconstructed environments, helping to bring the geological story to life. Finalization responds to a deep and precise investigation of the past environments and climates.

By carefully selecting and applying highly detailed visual effects that mimic past landscape (rocks, vegetation, rivers, etc.), the designers can create immersive and visually appealing representations. At the end, such animations are not only scientifically accurate but also engaging for the audience.

The final step in the process is the addition of sound effects to enhance the appeal of the animation (Fig. 3m). Sound effects add an extra layer of immersion, making the reconstructed geological processes and environments more dynamic and engaging for viewers. From the sounds of landslides to the ambiance of ancient movement of faults shaping the landscapes, these auditory elements help create a more immersive experience. Additionally, some explanations are delivered to better understand either the process or evolution that is being transmitted to the visitor.

Following this workflow, the final transferable results to be shared with the public are available in three distinct formats. First, 360º images of the selected sites (Fig. 3n), captured from various fixed camera positions, highlighting key features visible from those viewpoints. Second, a 3D virtual reality environment (Fig. 3o), where users can either see a pre-defined representation or freely navigate and select their position within the 3D space. Lastly, short films (Fig. 3p), which provide explanations of processes or depict the evolution of certain phenomena. Since the digital character of all these products, the visitor does not require to be physically in a museum or dedicated space. The different reconstructions can be accessed online by using their mobile devices equipped with data plans together with the geolocation data within the park to activate the digital resource.

Results

The results obtained from the VIGEOCULT project significantly improved geological knowledge of the area covering the Geopark. This was due to the need for a detailed understanding of the geological processes, outcropping rock formations, tectonic structures, and history of the region. This knowledge was essential for generating accurate models and reconstructions of each key site, leading to a better understanding of the processes that shaped the landscape over millions of years. The knowledge gained not only completed the geological picture but also provided a strong base for future research and education initiatives.

The results of this study can be categorized into two main groups. The primary results directly address the core objectives of the project, including 3D geological digital models from the acquired site imagery and the creation of 360º panoramas, the development of VR materials for the virtual reality environment, and the production of the documentaries focused on geological outreach. In addition, secondary results emerged from the broader work conducted during the preparation of the dissemination materials. Although not directly related to the primary objective, these findings and additional research lines present potential for alternative applications and raised open questions that could be addressed in the future.

For the purposes of this publication and to make the results easier to follow and visualize, one of the top-ranked geological sites, Gerri de la Sal, will be used as example to depict the different steps followed during the geological phase of the workflow.

Primary results

As with the previous section, the following one is divided into the results obtained from the geological phase (3D digital models, 3D geological models and geological storyboards) as well as the results obtained from the graphical one (360º images, virtual reality environments and animations). It is important to mention that, since this project involves multiple steps utilizing different methodologies, the primary results also serve as input data for subsequent stages of the workflow, as will be demonstrated in the following paragraphs.

One of the initial outputs of the geological phase is the 3D digital outcrop model for each of the selected key sites (Fig. 4 and supplementary material). This model is generated from imagery acquired during the imagery step of the workflow (Fig. 3c). First, the initial imagery is imported into the Metashape Agisoft software (version 2.1.3) to locate the images within a 3D space (Fig. 4a). Following this, the alignment process is carried out, and an initial point cloud is extracted (Fig. 4b). The point cloud is then refined and errors are minimized by removing outliers and points with insufficient confidence. After this refinement, the filtered point cloud is densified (Fig. 4c). Next, a mesh is generated through triangulation of the point cloud (Fig. 4d). Finally, the orthophotograph is applied as a texture to the meshed model, completing the 3D digital outcrop model (Fig. 4e).

Another primary outcome of the project is the 3D geological model (Fig. 5 and supplementary material), which is created by integrating the 3D digital outcrop model (Fig. 5a) with conventional geological data collected in the field (Fig. 5b). Once both datasets are incorporated into 3D geomodelling software, the first step is to generate the geological mapping in 3D (Fig. 5c). This mapping, along with point-specific bedding data, serves as the main constraint for generating a series of cross-sections that illustrate the subsurface and the nowadays eroded parts which would be located above the ground. These cross-sections represent the foundation for the following 3D modelling (Fig. 5d). Depending on the final objective of the key site, these cross-sections can be restored to understand, illustrate and present

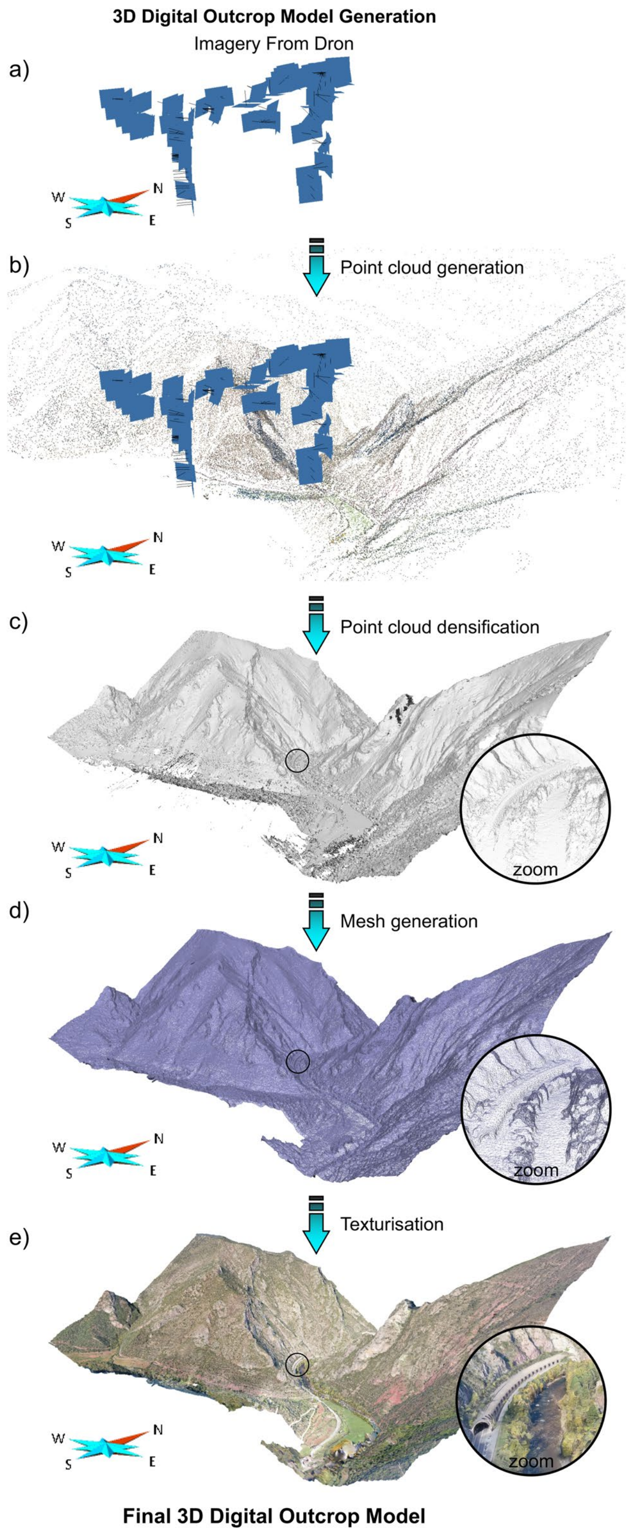


Fig. 4 Different steps followed to generate the final 3D digital outcrop model from the acquired drone imagery as initial input. **a**) 3D position of all the aerial images. **b**) generation of a point cloud. **c**) densification of the point cloud. **d**) Mesh generation based on the densified point cloud. **e**) Texture applied on the meshed surface. Notice the location of the zoom circle in the central part of the model and the detail and resolution obtained for each step

to the viewer how the area evolved through time. Once these cross-sections are completed, the various geological boundaries (e.g., stratigraphic contacts and faults) are interpolated to generate the 3D geological surfaces. The methodologies for this process, which is not straightforward and requires time and knowledge to interpolate the geological data, has been performed since the 2000's and proved to be successful in reconstructing the geological structures (Fernández et al. 2004; Mencos et al., 2011, among others). After careful refinement, this process results in the 3D geological model (Fig. 5e).

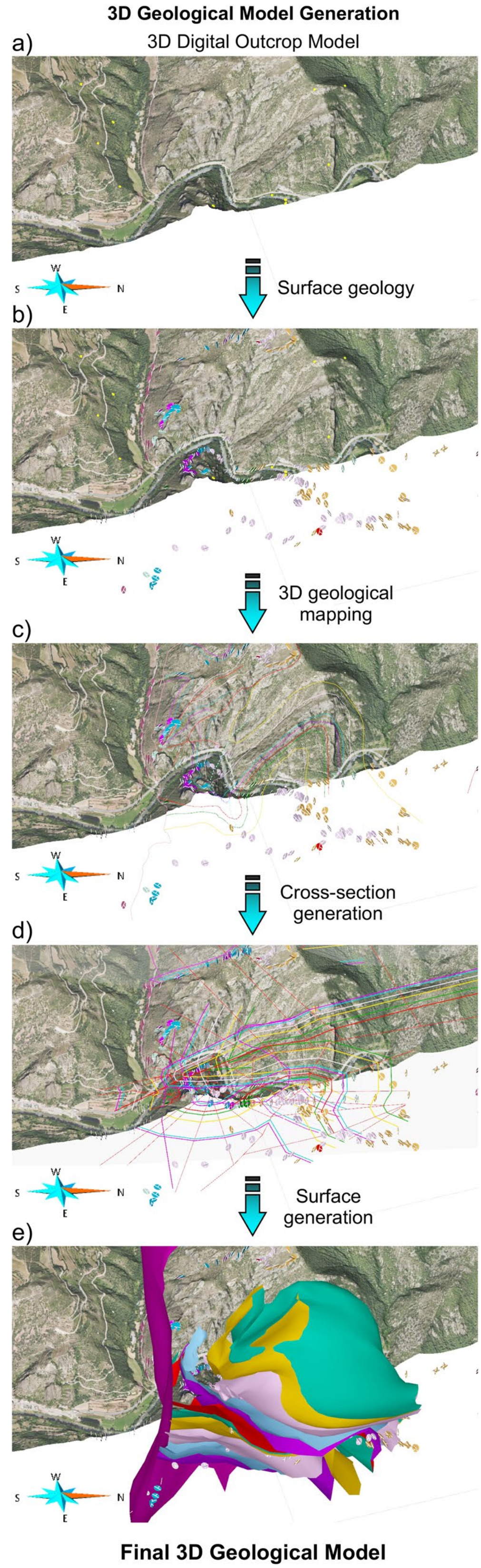
Finally, the last outcome of the geological phase is the storyboard, which illustrates the stepwise evolution of the site. For each step, a sketch of the topography as well as the deep portions of the area are accompanied with small texts describing various characteristics at each time step, such as the sedimentary environment, the type of fauna and flora and the tectonic regime, among others (Fig. 6).

On the other hand, from the audiovisual phase, one of the results obtained is the 360º images. These images can be used independently and displayed on mobile and/or tablets devices, or they can even be integrated into the virtual reality engine. These types of static images allow to either show the present-day landscape, transition to a reconstructed past and even display useful information which allows the user to better understand what is displayed and how it has been interpreted (Fig. 7a).

Another key result is the integration of geological elements (both present-day geology and restorations) with topographical elements (current relief and reconstructed past landscapes) into a virtual reality environment (Fig. 7b). This will be used to present the evolution of a key site or area through an immersive experience, allowing visitors to navigate into the 3D virtual past (Fig. 7c) and present-day world (Fig. 7d). They will be able to observe how geological structures develop and evolve over time, and how surface processes shape the landscape, ultimately leading to the present-day configuration (Fig. 7d).

A further outcome of the project during the graphical phase is the creation of videos. Among others, short videos that explain a variety of topics at the site level, such as the paleo-environment of a specific site, the activity of geological structures, or the evolution of topography over time. For instance, one of these videos demonstrates how present-day topography is shaped by long-term processes, such as river-induced erosion (Fig. 8). To reconstruct this, the current relief is derived either from a 3D digital outcrop model or a more regional digital elevation model provided by the Catalan Geological Survey. Using geological knowledge of the area, the streams are then reconstructed and modeled in reverse and so does the topography. By doing so, when the video is played, it illustrates the evolution of streams, landscape erosion, and sedimentation over time. In addition to

Fig. 5 Different steps followed to generate the final 3D geological model. **a**) import of the 3D digital outcrop model. **b**) import in the 3D space of all the geological data obtained from the fieldwork carried out in the area. **c**) 3D geological mapping based on surface data. **d**) Cross-section construction from the previous steps. **e**) 3D geological surfaces constrained by the outcropping geology as well as from the reconstructed deep portions of the area



short focused videos, longer format documentaries explaining the regional geology of the area integrating tectonics, sedimentary processes, paleoenvironment and topography evolution are expected to be created.

Secondary results

The materials produced as part of the project have also been adapted and repurposed to create a wide variety of dissemination tools aimed at different audiences. For instance, key findings and insights can be transformed into engaging infographics for use in presentations at local villages or schools, providing a visually appealing and easily digestible format for conveying complex information. Additionally, the content can be restructured into informative triptychs or brochures for distribution, as well as on-site information panels that enhance visitor understanding during tours or walks. Welcoming videos can also be produced for interpretive centers to introduce visitors to the topics in an accessible and captivating way.

Beyond the creation of these materials, the knowledge gained throughout the project can serve as the foundation for more interactive educational experiences. On-site talks and guided field trips can be organized, offering participants the opportunity to engage directly with the environment or subject matter in a hands-on manner (Fig. 9a). These talks, as can be seen on the YouTube and website of the Geopark Orígens (see supplementary material), are also another form of dissemination. Additionally, talks specifically aimed at engaging with local communities help them appreciate the geological wonders of their village, thus helping to protect endangered areas (Fig. 9b). Tour guides can also incorporate this knowledge into their narratives, allowing them to explain key processes and concepts to visitors in the context of other tourism activities. This not only deepens the learning experience but also enriches the overall visitor engagement by providing a broader understanding of the region, its history, and its natural processes.

Finally, the digital outcrop models obtained from the drone imagery and both, the 2D cross-sections or the 3D geological models that derived from the enhanced geological knowledge are suitable for potential application beyond educational (from elementary to university level) and scientific research, such as risk management, territorial planning and energy storage. 3D outcrop models can be invaluable tools for assessing landslide and flooding risks in vulnerable

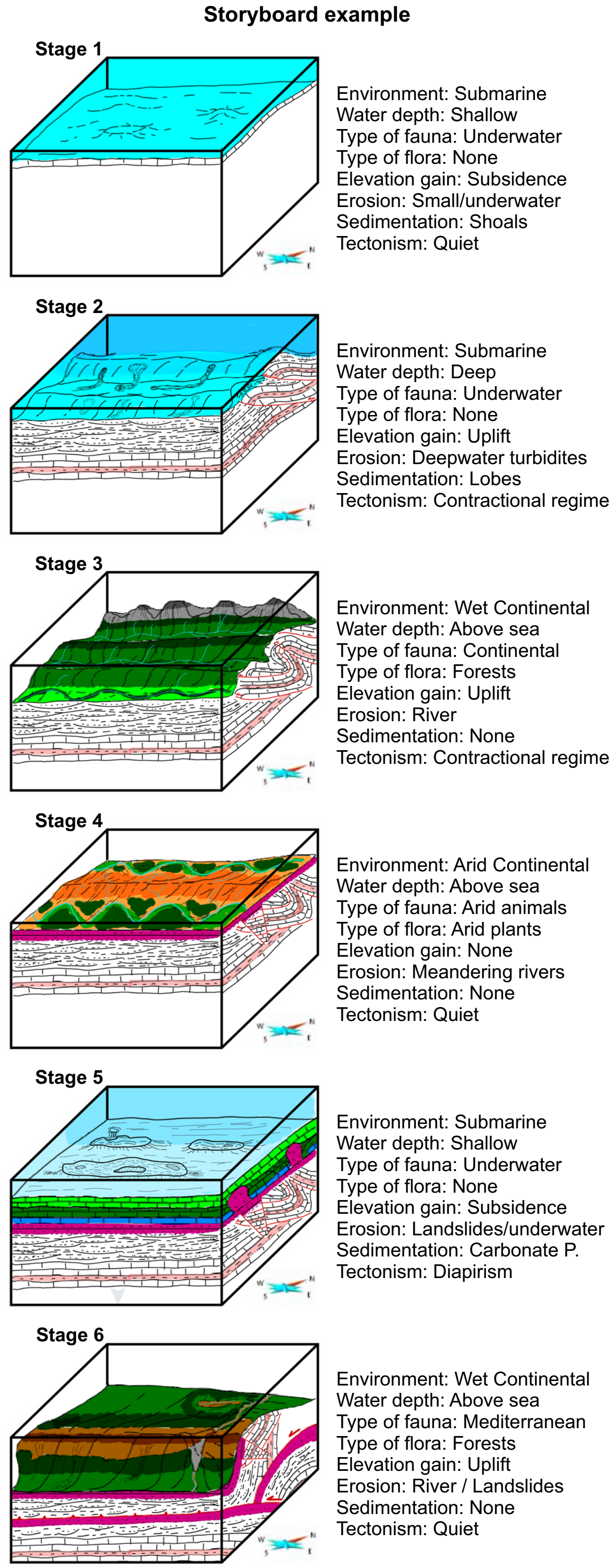


Fig. 6 Example of six steps extracted from the storyboard which allows to better understand all the characteristics and processes that took place for a determined step

areas. By providing highly detailed visualizations of geological features, these models allow scientists and planners to better understand terrain stability, water flow patterns, and potential hazard zones. This data can be used to predict the likelihood of future landslides or floods and to develop targeted action plans, such as reinforcing critical infrastructure or implementing early warning systems, ultimately reducing the impact of natural disasters on communities. On the other hand, the detailed cross-sections and 3D geological models, which accurately depict the subsurface structures and geological formations, can help on the characterization of groundwater aquifers and be used to assess the feasibility of storing or producing energy, such as hydrogen storage or geothermal, in suitable geological formations. By understanding the geology of the area, these models can help identify optimal locations for safe and efficient energy storage or contributing to the achievement of sustainable energy solutions for the region and, therefore, reducing its dependence on external sources or complement the already existing ones.

Discussion

This section has been organized into four distinct parts to provide a comprehensive evaluation of the proposed approach and methodology. The first part addresses the advantages of the approach of the project, highlighting the strengths of the methodology and its potential to achieve the desired outcomes. The second part examines the limitations of the methodology itself, offering a critical evaluation of its weaknesses and areas that require improvement. The third part discusses the challenges and limitations associated with applying this methodology specifically to the project, exploring potential barriers and constraints that may affect its broader implementation. Finally, the last part encloses several ideas and suggestions which cannot be included in the previous subsections.

Advantages of the methodology

After working with the proposed methodology, several advantages have been identified. These can be categorized into two groups: those that enhance the user experience and those that relate to the resulting dissemination materials.

It is often difficult to visualise or comprehend complex geological processes or geology-related concepts from static panels (Brusi 2024). Since this methodology is based on 3D technology and animation tools, one major advantage is the ability to provide more detailed and immersive and, above all, dynamic explanations for these geological processes. Among others, these might include the movement of tectonic faults, the development of geological folds, or natural processes like sedimentation and erosion. By leveraging 3D

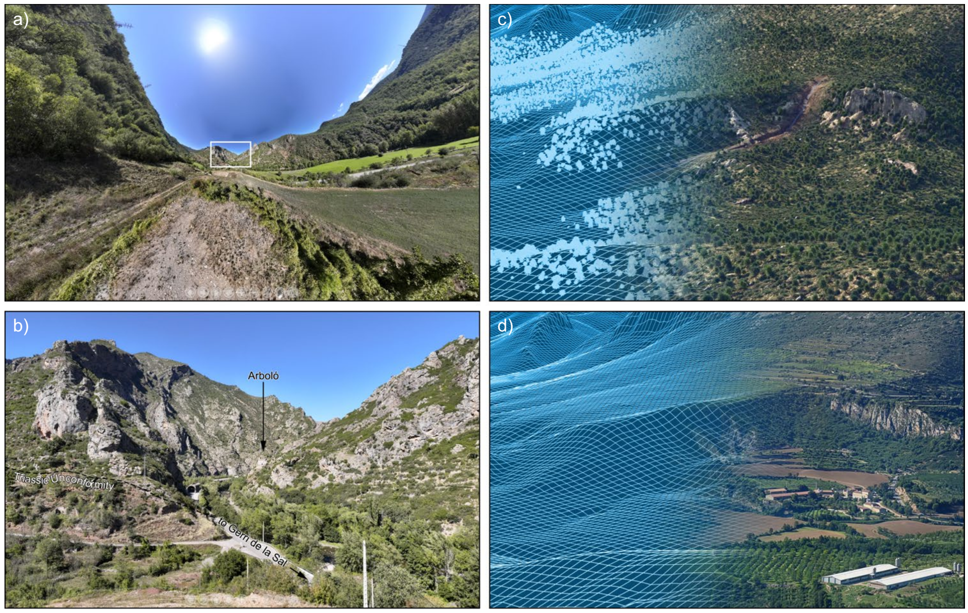


Fig. 7 **a**) example of a 360º image from the Gerri de la Sal site. **b**) detail of the previous image (see Fig. 1 for correlation with references) **c**) example of reconstructed past virtual reality world. **d**) examples of present-day virtual reality world

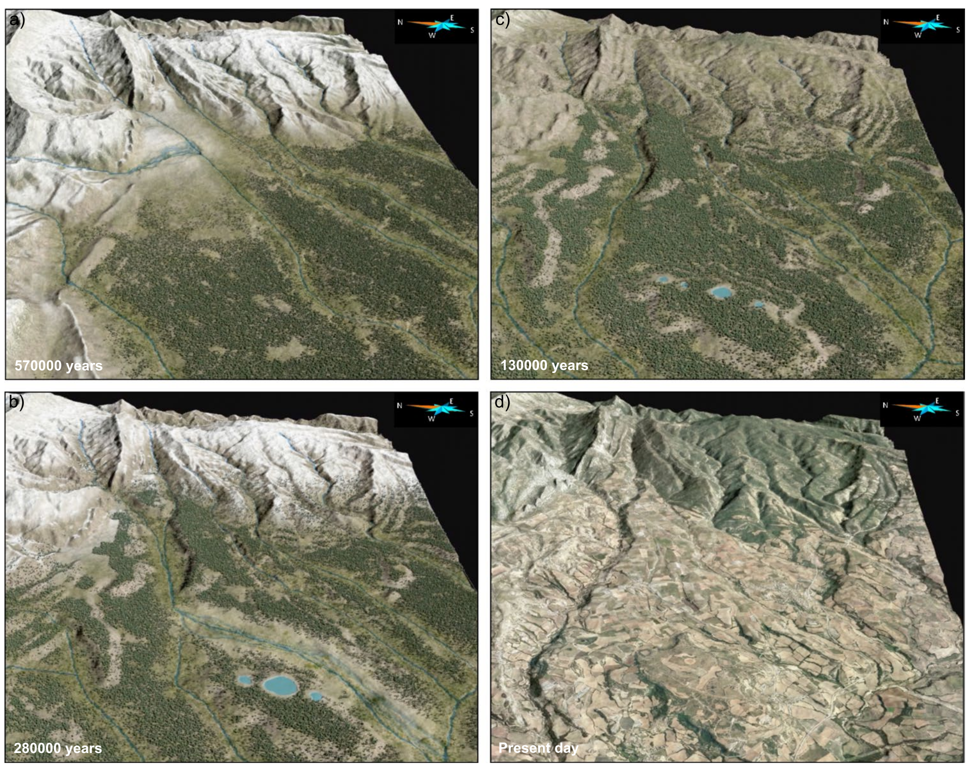


Fig. 8 Example of four key frames of a video explaining the evolution of the drainage network and how the topography changed through time. Time frames depicting the reconstruction at: **a**) 570000 years ago; **b**) 280000 years ago; **c**) 130000 years ago and; **d**) present day

technology, these explanations can be enriched through a variety of formats, including short videos, pinned annotations, or even modern analogue examples from different regions of the world. This allows users to engage more deeply with the content and understand challenging concepts more effectively (Petersen et al. 2022). The virtual reality approach has been successfully applied to teaching across various educational levels, yielding positive results (Radianti et al. 2020; Parong and Mayer 2021; Hamilton et al. 2021; Harknett et al. 2022; Mir-Pellicer et al. 2022; Won et al. 2023). Therefore, since the same technological devices can be utilized outdoors, similar results are expected.

One of the major drawbacks when trying to disseminate geological information is the scale of observation. As cleverly pointed out by Bach et al. (1988), one of the major problems is visualizing the size of elements. From a mineral

Fig. 9 **a**) Picture of one of the fieldtrips to disseminate the local geology to participants interested in learning more about the geological characteristics of the Gerri de la Sal area within the Geopark. **b**) Picture of one of the talks given to a local population about the beauty of the surroundings of the village from visual material generated resulted from the project

to a whole mountain range, the visitor must try to envisage the size by using from detailed sketches or microscope images to maps, which most of the times are compared with more mundane objects to understand the magnitude of the geological element in question. An additional key benefit of using 3D virtual reality that tackles the previous issue is the flexibility to alter the perspective from which visitors explore and observe key sites. For example, by using 3D virtual reality the user may be able to zoom out from an outcrop view (scale of tens of meters) to a landscape view (scale of hundreds to thousands of meters) which helps to frame the close by observation into a broader setting. Besides, in certain locations, physical access might be restricted due to safety concerns, lack of suitable viewpoints, or the feature being located underground. Not to mention the difficulties associated with envisaging geological time and how processes and structures evolve which is a factor most of the times visitors struggle to comprehend. In such cases, visitors are often limited to viewing and guessing these sites through interpretation panels or relying on their imagination. Despite this has partially been solved in static panels with the addition of photographs from helicopters, with the proposed 3D virtual reality methodology, users can seamlessly shift their point of view or time within the virtual environment. This can be done either through personal control or predefined site settings, allowing them to explore multiple angles and gain a deeper understanding of the site without the need to physically move. This enhanced flexibility helps contextualizing the same geological element at different scales of observation and steps of time thus transforming how people interact with and learn from these environments as already shown by other woks in archaeology (Bruno et al. 2010; Unver and Taylor 2012; Lecari 2017).

Focusing on the organizational aspects of how information is disseminated to visitors, the proposed methodology offers several clear advantages. One obvious benefit is that all material can be accessed digitally using VR goggles or a smart hand-held device, eliminating the need for physical materials. Visitors can store the information directly on their devices if desired, making it more convenient for later use. With the widespread availability of internet access, particularly in developed areas, and the increasing reliability of connections, dissemination materials can also be accessed on-demand via the internet, entirely removing the necessity for local storage.

A key advantage of this approach is the reduction in costs associated with traditional printed materials, which are not only prone to become outdated but also require continuous reprinting (Bruno and Wallace 2019; Brusi 2024). Furthermore, having all the materials in digital format enables continuous updates without disrupting the user experience. This flexibility allows content to be refreshed at a desired pace and even tailored to meet the needs of specific audiences, such as individuals with disabilities. It is well known that people with certain disabilities often face challenges in accessing parks that may not be fully adapted to their requirements. By implementing the proposed digital approach, this issue could be mitigated, providing a more inclusive experience for all visitors (Bruno and Wallace 2019; Bailey et al. 2022; Montoya-Rodríguez et al. 2023; Bryant and Hemsley 2024).

Additionally, this methodology allows to launch sites that may not yet be fully developed or not to promote them due to their fragility, while still offering an evolving user experience as new material is generated. This incremental approach could also provide valuable insights into user behaviour by monitoring which sites are most frequently visited, enabling park administrators to prioritize certain areas based on visitor demand or evaluate the interests from visitors as has been done in other places such as Brazil (Moreira 2012).

Another related benefit is the ability to minimize the need for physical information panels. Instead of relying on fixed displays that are subject to vandalism, natural degradation or organisational and institutional requirements in terms of size, materials colour palette (Brusi 2024), parks can use general information paired with QR codes such as the one recently used in the Cap de Creus area (Druguet et al. 2023) or geospatial technology to activate relevant content as visitors explore. This not only reduces the economic burden of maintaining and replacing physical panels but also ensures that information remains up-to-date without the associated costs of reprinting or installation.

Limitations of the methodology

The three main limitations identified so far in applying the proposed methodology are primarily related to time, with one issue stemming from the geological phase and two from the graphical phase.

In terms of geology, the primary limiting factor is the time required to complete the entire geological study, which includes creating the 3D digital outcrop model, the fieldwork, the construction and restoration of 2D cross-sections, and the generation of 3D geological models. As a reference, completing the 3D modeling of a specific geological structure, whose evolutionary history is only partially understood, can take up to a year. This timeframe accounts for all the previously mentioned necessary steps involved in producing the final 3D geological model.

Regarding the graphical phase, the main limiting factor in producing visual content is the lack of methodologies, workflows, and digital tools specifically designed to reproduce geological processes. Virtual reality has been widely applied across various research fields, including biology, archaeology, aviation, and medicine (Moro et al. 2017; Markowitz et al. 2018; Parong and Mayer 2021; Dhar et al. 2021; Hamilton et al. 2021; Mao et al. 2021). In these fields (among others), virtual tools have already been developed and implemented, making virtual reality a valuable asset for research, training, and dissemination. This contrasts with the lack of digital tools aimed at simulating geological processes, such as erosion or sedimentation influenced by tectonics, because they have yet to be developed, thus involving several sessions to merge synergies between geoscientists and graphical designers and developers. Derived from this, the second issue is that producing such animations becomes a time-consuming and labor-intensive task.

Despite this limitation, the lack of tools can be viewed as both a challenge and an opportunity for the graphic design community to make a valuable contribution, as it is envisaged that the demand for this type of content is expected to continue growing. So, as of today, the time needed for the geological research phase adds to a time-demanding generation 3D graphical content. As previously mentioned, reproducing geological processes at key sites demands extensive man-hours due to the significant time investment with several trial-and-error involved.

Limitations of the performance of the project

One of the current limiting factors of the project is the availability of virtual reality goggles. Although technological advancements are progressing rapidly, and several new models have been released recently, this remains a significant restricting point. However, similar to the exponential growth seen in smartphone adoption, it is anticipated that the availability and affordability of virtual reality goggles will increase significantly in the near future. As more manufacturers enter the market and refine the technology, these developments are expected to bridge the current gap and make virtual reality more accessible to a wider audience. Meanwhile, the approach adopted by Orígens Geopark involves owning a set of virtual reality goggles, which are available for visitors in key museums and interpretation centers. This initiative allows guests to begin exploring the immersive world of virtual reality. By providing these devices, the Orígens Geopark makes virtual reality technology more accessible, ensuring that even visitors without their own equipment can enjoy this cutting-edge experience.

However, while integrating heritage and cultural experiences into geological dissemination can significantly enhance the visitor experience, achieving this vision requires stable, well-supported working teams with sufficient budgets to fully develop such interdisciplinary projects. Unlike traditional geological education, which may rely on established curricula and resources, creating an enriched, multifaceted experience demands collaboration between geologists, historians, cultural experts, graphical designers, and educators. This collaborative approach requires time, resources, and a stable team structure to ensure continuity and coherence throughout the project. Without adequate funding and a committed team, the risk is that these initiatives may remain underdeveloped and undermaintained, lacking the depth and integration necessary to truly connect geology with cultural and heritage contexts. Therefore, a robust investment in both human and financial resources is essential to successfully realize the potential of these innovative educational projects.

Other appreciations and recommendations

To create a more holistic and engaging experience, the dissemination of geological knowledge must be complemented with heritage and cultural experiences, recognizing that visitors are often drawn to geological sites for reasons beyond just scientific interest (Hose 1995; Gordon 2012; Dowling and Newsome 2018; Duarte et al. 2020). While the geological features of a site may be the primary attraction, integrating stories of local history, past cultures, and the broader environmental context can enrich the visitor experience, making it more meaningful and memorable. This interdisciplinary approach not only appeals to a wider audience but also deepens the connection between people and the natural world, fostering a greater appreciation for the interplay between geology, biodiversity, human history, and culture. By weaving together these diverse narratives, we can transform geological sites into living classrooms that offer both educational value and cultural enrichment, ensuring that the knowledge gained is both comprehensive and accessible to all, thus mitigating one of the issues already identified when disseminating geological content (Bach et al. 1988). In addition, sites with a primary focus on disseminating heritage or culture can be enhanced by incorporating geological explanations. This approach can broaden the audience for geology, elevating it to its rightful place alongside other fields of interest, such as biology and history. By doing so, the economic growth of the region can be effectively leveraged to maximize its potential and long-term development as well as helping in the awareness of geo-conservation (Gordon 2012; Farsani et al. 2011; Oncescu 2015). The workflow presented here can easily be applied to characterize not just geological features of the geoparks but also cultural heritage. As for example, and using the same site as the one in previous sections, Gerri de la Sal town features an outstanding example of a folded thrust system but also keeps a well-preserved exploitation of salt, dating back to the VIII century, which was one of the main trading goods, thus helping to sustain the viability of the village through time. Such cultural sites can also be 3D modelled and presented to the viewer to better integrate all the geological and cultural elements of the region.

Conclusions

The proposed workflow, methodology and digital dissemination approach offers enhanced flexibility, a reduction in maintenance costs, and visitor inclusivity, all while improving the overall visitor experience and making tourism management more efficient. It is divided into three main steps: an initial screening phase, a geological phase, and a graphical phase. These steps are designed to produce geological dissemination materials for the Orígens Geopark in the Pyrenees but are applicable in other geoparks worldwide.

The screening phase starts by ranking key geological sites within the geopark based on their geological significance, accessibility, and potential to engage visitors. This helps prioritize locations within the area. Next, during the geological phase, 3D outcrop and geological models are developed using photogrammetry, along with geological data and insights gained from fieldwork conducted both regionally and at the site level. Once these models are completed and handed over to the graphic designers, the 3D virtual reality engine is developed, and 3D animations of the geological and topographical evolution are created and enhanced with textures and sound effects.

While the methodology shows significant potential for enhancing the communication of geological concepts and fostering innovation, it is essential to acknowledge both its strengths and limitations. One key advantage of using 3D virtual reality is its ability to provide more detailed and immersive explanations of geological processes which are non-visible at human scale. It allows users to explore and observe key sites from multiple perspectives, offering flexibility in how information is presented. This leads to a more engaging experience for visitors and enables more effective communication of complex geological concepts. From the perspective of park management, the methodology reduces the need for physical materials at observation sites and provides a means to monitor site demand and prioritize areas based on visitor interest. However, some challenges remain. Minor issues, such as the availability of virtual reality goggles, have been identified. The more significant limitations are related to the time required for both the geological and graphical phases of development. Acquiring the comprehensive geological knowledge needed to generate accurate 3D models and understanding the evolution of the region is time-consuming. Additionally, the graphical aspects of the project are slowed by the lack of semi-automated processes for reproducing geological events, which makes the production phase labour-intensive. Despite this, the implementation of this methodology not only yielded promising results in the dissemination of geological knowledge but also laid the foundation for the development of virtual reality tools focused on geological processes. Furthermore, some of the geological insights gained can be applied to other fields, such as risk management and territorial planning.

Finally, to fully develop the potential of Orígens Geopark and enhance the visitor experience, further research is essential. This includes refining virtual reality technologies tailored to geology, which can offer immersive simulations of complex geological processes and interpretative representations of the past. By testing virtual reality applications across various geological scenarios, we can create more accurate and engaging representations of all the features the geopark can offer. Additionally, integrating virtual reality with other educational tools, such as guided field trips, could provide a comprehensive learning experience that bridges virtual and real-world exploration. Such innovations would not only captivate visitors, encouraging repeat visits, but also elevate the status of the geopark as a premier destination. This enhanced engagement would, in turn, support the development of the area, fostering growth in tourism-related businesses and contributing to the local economy. By leveraging advanced technologies and general educational approaches, Orígens Geopark can achieve a more dynamic and impactful role in both education and regional development.

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Declarations

Competing interest The authors report no potential conflict of financial interests that could impart bias on the work submitted for publication such as professional interests, personal relationships or personal beliefs.

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