https://rbgeomorfologia.org.br/
ISSN 2236-5664

Revista Brasileira de Geomorfologia

v. 26, nº 3 (2025)

http://dx.doi.org/10.20502/rbg.v26i3.2639

Research Paper

Technologies applied to Geomorphology teaching – Virtual Reality and digital models

Tecnologias aplicadas ao ensino de Geomorfologia – Realidade Virtual e modelos digitais

Anna Sabrina Vidal de Souza [1], Rubson Pinheiro Maia[2], Hudson Silva Rocha[3], Mariana Araújo[4] e Pedro Edson Face Moura[5]

[1] Universidade Federal do Ceará, Programa de Pós-Graduação em Geografia, Departamento de Geografia, Fortaleza, Brazil. annasabrinavidal@gmail.com
ORCID: https://orcid.org/0000-0001-5070-8208

[2] Universidade Federal do Ceará, Programa de Pós-Graduação em Geografia, Departamento de Geografia, Fortaleza, Brazil. rubsonpinheiro@yahoo.com.br
ORCID: https://orcid.org/0000-0002-1688-5187

[3] Universidade Federal do Ceará, Programa de Pós-Graduação em Geografia, Departamento de Geografia, Fortaleza, Brazil. hudsonsrocha@gmail.com
ORCID: https://orcid.org/0000-0001-5609-1042

[4] Universidade Federal do Ceará, Laboratório de Geomorfologia, Departamento de Geografia, Fortaleza, Brazil. mariana.araujo123@gmail.com
ORCID: https://orcid.org/0009-0007-1328-9236

[5] Universidade Federal do Ceará, Laboratório de Geomorfologia, Departamento de Geografia, Fortaleza, Brasil. pedroedson18@gmail.com
ORCID: https://orcid.org/0000-0003-3693-1280

Received: 01/11/2024; Accepted: 16/04/2025; Published: 28/07/2025

Abstract: The geomorphology teaching, which involves concepts about complex physical-natural processes, has traditionally adopted an approach based on methodologies of expository lessons aided by field excursions. However, the educational practices in modern society require the utilization of innovative technological resources subsidizing the learning process. Additionally, there is a growing demand for the inclusion of students with special educational needs (e.g. low vision and blinds) in different educational contexts. In view of this and considering the recent methodological advances in scientific research in Geomorphology with the use of geotechnologies, this work applied Virtual Reality and 3D digital and physical models' resources in education, aiming at shortening the distances between theory and practice. Through photogrammetry and digital modeling using the Structure from Motion algorithm and gamification in Virtual reality, it is possible to simulate, in an immersive environment, a multissensorial and practical experience, reproducing the fieldwork virtually. This was carried out by the computational reproduction of real scenarios, such as caves, inselbergs, canyons, and coastal cliffs. The digital and physical 3D models of these landforms were thus used in teaching activities in basic education (Middle and High School), with the objective to promote an interactive and inclusive pedagogical practice, contemplating the National Digital Education Policy in Brazil.

Keywords: Geotechnologies; Geosciences education; Virtual Reality; 3D Models; Inclusive education

Resumo: O ensino de geomorfologia, o qual envolve conceitos sobre processos físico-naturais complexos, foi tradicionalmente abordado com metodologias expositivas auxiliadas por excursões de campo. Entretanto, as práticas educacionais na sociedade atual requerem a utilização de recursos tecnológicos inovadores que subsidiem o processo de aprendizagem. Ademais, há crescente necessidade por inclusão de alunos com diversas necessidades educacionais especiais (e.g. baixa visão e cegos) em diferentes contextos educacionais. Diante disso, e considerando os avanços metodológicos na pesquisa científica em Geomorfologia no uso de geotecnologias, o presente trabalho aplicou tecnologias de Realidade virtual e modelos 3D físicos e digitais na educação, com o intuito de auxiliar no ensino e aprendizado, unindo teoria e prática. Através da fotogrametria e modelagem digital utilizando o algoritmo *Structure from motion* e da gamificação em realidade virtual, pode-se simular em ambiente imersivo uma experimentação prática multissensorial que reproduz o trabalho de campo virtualmente. Isso é feito através da reprodução computacional de cenários reais, como cavernas, *inselbergs*, cânions e falésias. Os modelos 3D do relevo digitais e impressos foram, portanto, levados à educação básica (Ensino Fundamental e Médio), a fim de promover uma prática pedagógica interativa e inclusiva, contemplando a Política Nacional de Educação Digital, no Brasil.

Palavras-chave: Geotecnologias; Ensino de Geociências; Realidade Virtual; Modelos 3D; Educação inclusiva.

1. Introduction

In Geosciences education, topics such as plate tectonics, the origin of mountain chains and oceans, the formation of morphoclimatic domains, and their associated landscapes are commonly addressed. Regarding Earth's geomorphological processes and landforms, there is a challenge not only in explaining but also in representing and making these topics comprehensible to students across different educational levels and contexts (SCHUCHARDT; BOWMAN, 2007; BEDAIR; SAYED; ALMETWALY, 2022). Despite the increasing use of digital educational resources (e.g., digital textbooks and tablets in classrooms), teaching remains largely reliant on oral explanations and the use of two-dimensional images and photographs. On the other hand, cutting-edge scientific research has increasingly incorporated diverse three-dimensional imaging technologies for landscape representation, using equipment such as drones, portable and fixed laser scanners, and other tools applied in (aero)photogrammetry techniques to generate three-dimensional terrain models at various scales, from caves to mountains (MOURA, 2022; SOUZA et al., 2023; MAIA; SOUZA, 2024). However, this technological and scientific advancement in Geosciences is neither widely accessible nor integrated into schools for Geography education, leading to a gap between higher education and basic education in the Brazilian educational system.

In both primary, secondary and higher education, Geoscience instruction primarily relies on field excursions as a method that enables students to engage with objects of study in the real world. However, it is essential to consider that students are part of an increasingly technology-driven society. By incorporating digital tools into curriculum, educational institutions not only expand the reach of learning but also foster the development of essential skills such as spatial interpretation and collaboration in virtual environments (BRASIL, 2018). Moreover, the understanding of landforms and processes in diverse natural landscapes is relatively limited for students with special educational needs, including those with mobility impairments as well as low-vision and blinds (CAKIR; KORKMAZ, 2019). In this regard, some studies in Brazil have explored the use of digital models and Virtual Reality (VR) to make Geoscience education more accessible and inclusive (VERGES et al., 2024). Despite that, these applications remain sporadic and are not yet widely disseminated or accessible to students in the Brazilian basic education system, notwithstanding the inclusion of competencies such as the use of digital information and communication technologies and access to information by the Brazilian National Common Curricular Base for primary and secondary education ., aiming at ensuring that students “understand the scientific-technological foundations of processes” (BRASIL, 2018).

To strengthen the integration of technologies in education, the development of the National Digital Education Policy (PNED – Law nº 14.533/2023) has the objective to facilitate public access to digital resources, prioritizing the most vulnerable populations, and to foster the incorporation of digital education in learning environments across all levels and modalities. It is believed that this can be achieved by the promotion of digital and informational literacy as well as by the development of various digital competencies (BRASIL, 2023).

The integration of advanced technologies in Geoscience education has the potential to foster a more interactive and inclusive learning experience. Through the manipulation of technological objects, students engage in immersion, interaction, and imagination via Virtual Reality (CONCANNON; ESMAIL; ROBERTS, 2019; ŠVEDOVÁ; KUBÍČEK, 2021; AZZURI et al., 2024). Technologies such as landscape visualization in VR using 3D immersion goggles and tactile models of landforms may serve as valuable tools for facilitating the understanding of complex concepts. These resources provide immersive and hands-on experiences, enabling students to explore and interact with representations of natural phenomena and environments in a more tangible manner (CAROLAN, 2007; FISHER et al., 2019; LAMPROPOULOS; KINSHUK, 2024).

Recent studies highlight the positive impact of technologies such as augmented and virtual reality, gamification and 3D landscape models on knowledge retention, student motivation, and inclusion of students with special educational needs (BOWER et al., 2014; MIKROPOULOS; NATSIS, 2011; PARSONS, 2016; SUBHASH; CUDNEY, 2018; KÖSE; GÜNER-YILDIZ, 2021; SILVA; MARTINS; ROCHA, 2025). This impact is particularly notable in Geography and Cartography teaching (CARRERA; ASENSIO, 2016; CARRERA et al., 2017; HRUBY, 2019; SHAKIROVA; SAID; KONYUSHENKO, 2020; QUOOS; FIGUERÓ, 2021; NIU et al., 2023; CARRUBA; CALCAGNO; COVARRUBIAS, 2023; HAYAKAWA et al., 2024).

In this context, the present study explores the application of these technologies in Geoscience education, with a particular focus on the teaching of Geomorphology. We explored technological applications using 3D printing and Virtual Reality as educational tools to support teaching in subjects related to Earth Sciences, using examples of various landforms in Brazil, including crystalline massifs, inselbergs, cliffs, and caves. The objective was to implement these resources by incorporating data visualization through 3D digital models of landforms in pedagogical activities across different educational contexts. This approach aimed to provide initial insights into the potential use of these technologies in Geosciences and to qualitatively assess their application, contributing to the research on innovative pedagogical practices in basic education by discussing their possibilities and limitations (AKÇAYIR; AKÇAYIR, 2017).

Moreover, the objective is to bridge the gap between different educational levels regarding the use and application of geotechnologies in teaching. Through these technologies, we aim at bringing seemingly distant topics closer to students, enabling them to visualize, manipulate, and understand concepts through immersive experiences.

For this purpose, this work presents the application of Virtual Reality (VR) technologies and digital 3D models as interactive and inclusive pedagogical practices to facilitate the understanding of complex geomorphological concepts in primary and secondary education.

2. Materials and Methods

2.1. Data Acquisition, Digital Processing of 3D Models, and Model Printing

The acquisition of visual data of natural objects (e.g., massifs, cliffs, rock outcrops) is performed using photogrammetric techniques, a traditional method that involves obtaining quantitative information and measuring real-world objects through the interpretation of photographs and their patterns based on the triangulation principle (ABER; MARZOLFE; RIES, 2010).

With technological advancements, the use of digital photography and the incorporation of aerial photogrammetry— a process of acquiring spatial and three-dimensional terrain data through aerial photographs— have been extensively developed for various applications. In Geosciences, aerial photogrammetry using Remotely Piloted Aircraft Systems (RPAS), or drones (BERTACCHINI et al., 2014; BARCELOS; DANELON; RODRIGUES, 2022; GROHMANN et al., 2023), enables data collection in large and difficult-to-access areas (e.g., small mountains). Photogrammetry using professional photographic cameras is typically employed in enclosed environments or areas with restricted drone usage (e.g., cave galleries).

The objective of (aerial) photogrammetric surveying is to generate three-dimensional virtual models of the imaged natural object, allowing for its manipulation, visualization, and data acquisition outside the field, using computers.

The data acquisition protocol initially involves fieldwork excursions. In this context, field surveys were conducted to acquire data in various distinct landscape contexts in Brazil: inselbergs in the semi-arid Northeast, coastal cliffs, and caves in tropical regions. For inselbergs and cliffs, aerial photogrammetric surveys were performed using an RPAS Phantom 4Pro DJIgo, equipped with a built-in camera. Imaging was conducted at submetric resolution and at an average altitude ranging from 80 m to 100 m above the takeoff base, depending on the size of the outcrop being imaged. The data acquisition method is manual, capturing approximately 300 photos per square kilometer with ~80% overlap, using both nadir and ~45° angle positions to ensure accuracy in lateral relief reconstruction for high-precision 3D digital modeling.

In caves, the employed technique was digital photogrammetry, which encompasses two main stages, the first being the field image survey (Figure 1). In this step, sequential photographs are taken following photogrammetric parameters of at least 60% lateral and vertical overlap. For this study, approximately 2000 photos were captured using a Sony DSC-Hx300 digital camera with a focal length of up to 215 mm. The photographs are taken sequentially and must provide a 360° coverage (acquisition globes, Figure 1A). Artificial white light illumination is an essential factor during photo acquisition in this case, and this procedure is repeated throughout the cave galleries surveyed. It is noteworthy that the camera’s light meter should be set to "Low Light" to maximize light capture by the sensor inside the cave. To assist in generating homologous points during point cloud processing (e.g., identifying texture differences in the object), control points with distinct geometric figures are positioned along the acquisition path.

The subsequent processing stages—similar for both photogrammetry and aerial photogrammetry—result in the construction of a three-dimensional model with submetric resolution. Processing is performed in the Agisoft Metashape Photoscan software (Laboratory of Geomorphology - UFC) through the Structure from Motion (SfM) algorithm, which creates a computational point model based on digital stereoscopic effects. The workflow comprises the following steps: addition of photos and definition of the geographic coordinate system (SIRGAS 2000); image alignment, and generation of a point cloud. Afterwards, three-dimensional models are generated through point cloud interpolation, giving a high-resolution texture appearance to the relief. This visualization can be merged with the aligned photos in the model (texture), providing a realistic representation of the outcrop in the 3D model (Mesh). Subsequently, the Digital Terrain Model (DTM) and georeferenced orthomosaic are exported from these models and can be manipulated in other 3D data visualization and Geographic Information System (GIS) software.

Figure 1. Representation of the photogrammetric data acquisition technique in a cave environment. The survey is based on the protocol for photogrammetric acquisition in caves, using 360° acquisition globe photographs.

These virtual models are adapted for three purposes: visualization using open-source software (Cloud Compare), which is also used for obtaining geometric data in research, generation of virtual reality scenarios, and 3D printing (Figure 2), aiming to enhance the didactic use of these tools in Geoscience education.

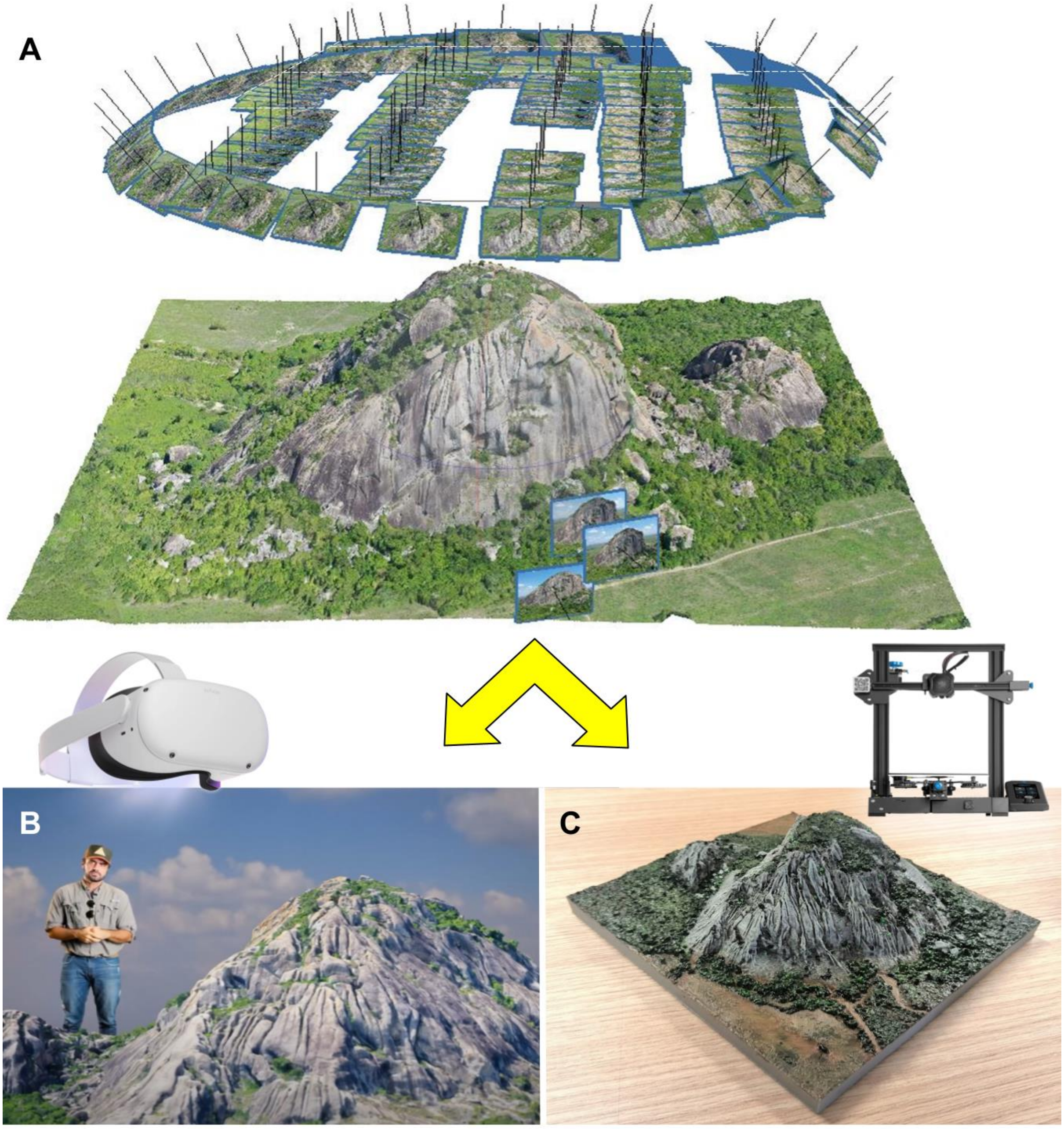

Figure 2. Representation of data acquisition and generation of educational products of the aerophotogrammetric survey, virtual reality and 3D printing of the imaged natural objects. (A) Representation of aerophotogrammetry in inselbergs using drones and generation of the digital model of the inselberg in Agisoft software. (B) Example of gamified models with human avatar in virtual reality. (C) Model printed from computer model on 3D printer and decorated.

After being generated in Agisoft Metashape, the models undergo a mesh and texture optimization process within the same software. This process involves applying an algorithm (Optimize Alignment), which interpolates faulty points to reduce the number of artifacts in the final product through kriging. This step is necessary to adapt the application to the graphical limitations of Meta Quest 2 (virtual reality headsets) without compromising the visual fidelity of the real model. The Unreal Engine software, a 3D graphics engine, is used to develop interactive applications, enabling real-time exploration of the models. To ensure a smooth experience, gamification features and graphical optimization techniques are employed, ensuring user interactivity and immersion (COSTA, 2020).

These techniques involve the renderizing of models and their textures through Nanite technology, which facilitates the manipulation of high-resolution and heavy models, also providing a more dynamic and realistic interface for visualizing immersive three-dimensional landscapes.

The virtual models, in addition to being manipulable on computers and in VR, were 3D printed using additive manufacturing through Fused Deposition Modeling (FDM) (VOLPATO, 2017) (Figure 2D). The process for generating physical models consists of extracting the file in ".stl" format, generated in Agisoft Photoscan. Finally, this file is sent to a 3D printer, model Ender-3 V2 (CReality), where the slicing process is performed using the Creality Slicer software. The models are then printed using PLA (polylactic acid), a biodegradable thermoplastic, resulting in prints with textures that accurately represent the real relief model. The models, printed in gray filament, are manually decorated using brushes (sizes 0, 0.5, and 1) and matte acrylic paint. The selected colors resemble the actual relief, employing the "layer upon layer" technique, where darker shades are painted underneath to create shading and depth effects, while lighter shades are applied to elevated portions.

Figure 3. Models printed from photogrammetric digital models. (A) Set of models generated by the Laboratory of Geomorphology - UFC.

2.2. Application of Technological Resources in Education

2.2.1. "Tactile Landscapes" Activity

To promote the teaching of Geomorphology to blind, visually impaired, and autistic students, lessons were organized using 3D models printed from the digital processing of landscape models (aerial photogrammetry). The tactile models made of PLA filaments are textured, allowing the perception of details in landform structures. Geography lessons were conducted with 7th and 9th-grade students from the Instituto dos Cegos (Institute for the Blind) in Fortaleza, Ceará, in a class of seven students.

The lesson topic, "Tactile Landscapes," addressed the diversity of landscapes and landforms in Brazil. For this purpose, ten models representing different Brazilian landforms were used (inselbergs, cliffs, caves, canyons, and waterfalls). Additionally, rock samples were incorporated to demonstrate different textures that contribute to landform development. The lesson was conducted interactively, with geomorphological concepts such as landforms and their formation processes being introduced through hands-on activities. Students were able to manipulate the models and were encouraged to reflect on the types of geographical events that shaped those landscapes (see Lesson plan in Table 1).

Table 1. Lesson plan followed in the activity "Tactile Landscapes"

Lesson plan "Tactile Landscapes"	
Subject: Geography / Class: Elementary School (Early Years) – Blind and Low Vision Students	
General Objective	Develop knowledge on geographical concepts through 3D physical models
Specific Objectives	● Understand the relationship between rocks and landforms (textures generating diverse shapes); ● Develop the concept of scale in landform formations in comparison to the human scale; ● Explore brazilian natural landscapes and their characteristics (landforms, vegetation, and associated sensations); ● Associate geographical concepts (e.g., place) with geomorphological diversity (landscape).
Materials	● 3D Models – Inselbergs [3]; Caves [2]; Cliff [1]; Waterfall [1]; Globe [1]. ● Rock samples – Granite [2]; Carbonate [1]; Sandstone [1].
Didactic Sequence/ Methodology	1. Begin with a discussion with students about the concepts of landscape and landforms, encouraging a dialogue about their experiences with natural landscapes. 2. Explore the diversity of natural environments and geomorphology by interacting with different types of materials (rocks) and the natural processes that shape the landscape. At this stage, introduce different types of rocks and associated textures, comparing natural and artificial textures. 3. Relate landform shapes to human anatomy analogies and present tactile models as examples of Earth's morphology. Demonstrate the difference between the human spatial scale and the scale of landforms. Explore each type of morphology separately—inselbergs, cliffs, caves, etc. 4. In the final moments, address the concept of "geographical place" in these natural spaces, discussing the relationship between society and the use of these environments, such as hinterlands, caves, and beaches.
Assessment	Encouraging self-assessment. Engaging in dialogue with students about their experiences with the models and the knowledge gained from this practice.

2.2.2. "Virtual Relief" Activity

The teaching activities utilizing Virtual Reality encompassed various educational levels, including interactive lessons with high school students (1st and 2nd year) and higher education students (Environmental Engineering undergraduates). This approach enabled the exploration of geomorphological concepts in different learning contexts. These activities were conducted during school visits to the Geomorphology Laboratory (Department of Geography – Federal University of Ceará, Fortaleza).

First of all, it is important to highlight the distinction between Virtual Reality (VR) and Augmented Reality (AR). VR immerses the user in a completely new digital environment, providing an interactive experience through the use of headsets and/or goggles. In contrast, AR enhances the real-world environment by overlaying digital objects, adding supplementary information, or improving its functionality (ÇOLTEKIN et al., 2020; RAUCHSNABEL, et al., 2022; AL-ANSI et al. 2023). In this study, we applied Virtual Reality resources in the learning environment.

The lessons were adapted to the context and level of each class, and the methodology involved active student participation in the use of technological resources, guided by the instructor's explanations on landforms in various environmental settings. The focus was on inselbergs and caves, covering fundamental concepts such as geological controls on landform evolution and the application of geotechnologies in Geography. The activities included virtual fieldwork and terrain visualization using (1) computational models (both digital and physical) and (2) virtual reality with VR headsets (see lesson plan in Table 2).

Table 2. Lesson plan followed in the activity "Virtual Relief"

Lesson Plan "Virtual Relief"	
Subject: Geography / Classes: High School (Tenth and Eleventh Grades) and Higher Education (Environmental Engineering)	
General Objective	Gain knowledge on geomorphological concepts through virtual models of landforms of different environments.
Specific Objectives	● Elucidate the relationship between rocks and landforms; ● Explore the diversity of landscapes and various morphologies that are difficult to access or remote and the novel techniques to map and represent them; ● Rationalize how natural processes shape landscapes (landforms).
Materials	● VR Glasses [2] ● Computers [2] with 3D models in Cloud Compare software ● 3D Models – Inselbergs [4]; Caves [2]; Cliff [1]; Waterfall [1]; Globe [1]
Didactic Sequence/ Methodology	1. Begin with a discussion with students about the concepts of landscape, landforms, and the processes that shape landforms, linking geology with geomorphology. 2. Discuss various types of landforms and the environments in which they occur (relation with climate, vegetation, etc.) and their importance for understanding Earth's history. 3. Explain the stages of model generation using geotechnologies (e.g., aerial photogrammetry), manipulated to obtain information about the landscape and used for societal applications (e.g., risk mapping, oil industry, etc.). 4. Manipulate virtual and physical landform models of Brazil and immerse students in virtual reality (using VR glasses), stimulating geomorphological reasoning about landforms and processes.
Assessment	Discussion circle with subjective questions: ● Have you ever heard of digital models of landscapes? ● Did you know about the applications of 3D models in society? ● Were you familiar with any location you viewed in VR? ● What stood out the most to you in the interactive landscape activity?

The first part of the lesson was divided into two main stages. Initially, students were introduced to the process of model generation through photogrammetric techniques. Subsequently, they were able to manipulate the virtual models using the open-source software Cloud Compare. These models were loaded onto computers and made available for student interaction, allowing them to explore previously unfamiliar landforms and topographic features in a virtual environment. The same virtual models were then presented as 3D-printed replicas, accompanied by explanations regarding the observed landforms, their specific formation processes, and the geomorphological dynamics involved in their evolution. Although these topics are generally covered in Geomorphology courses (Geography classes), direct interaction with such landforms is unusual.

The second part of the lesson consisted of virtual field immersion, allowing students to explore the actual locations where the data had been collected. Three VR headsets were provided, giving each student a few minutes to visualize and interact with the virtual landscape. The models presented included a cave (Cristal Cave, Bahia) and an inselberg (Serrote Muxió, Quixadá). One of the models featured an educational video in which a virtual avatar of the lead instructor appeared beside the landform model, providing explanations about its morphology and specific characteristics. In the cave model, the student controls the avatar navigating the cave interior, allowing them to explore a few meters within the virtual space.

3. Results and Discussion

3.1. Teaching Geomorphology using relief models for students with special educational needs

The teaching of Earth Sciences, particularly the discipline of Geomorphology, involves concepts such as landform types, the processes that shape them, and the features that characterize different landscape types. These concepts were addressed through an inclusive and technology-assisted teaching approach in classes with students with special educational needs, including blind and visually impaired students as well as autistic students.

The pedagogical practice aimed to make these Physical Geography topics—often perceived as distant or complex—more accessible to students living in urban environments, where direct contact with natural landforms is limited. Additionally, many students face challenges in learning and understanding the processes that shape landforms due to physical limitations.

Having this in mind, the didactic approach for middle school students (final years) consisted of an introduction to the relationship between different types of materials that compose the Earth's crust and the various landforms that can result from the interaction of numerous geological processes. This introduction was facilitated through direct contact with rock samples collected from different locations (including granite, limestone, sandstone, etc.), meaning rocks with different textures, which were compared to the textures of anthropic materials (such as the classroom table), which have a more uniform aspect due to human intervention. Students were able to handle igneous rocks (formed by crystals) and sedimentary rocks (composed of sand and calcium carbonate) and were guided to perceive the textural differences, such as roughness, the presence of fine or coarse grains, or more uniform surfaces. For blind and visually impaired students, tactile experience with natural materials was fundamental in developing an initial understanding of the vast diversity of materials that shape the Earth's relief. Building on this perception, students were introduced to various processes that these rocks can undergo (e.g., heavy rain and strong winds), which, over time, sculpt and erode them. This awareness of material differences allowed students to infer which materials might be more resistant or more susceptible to erosion and landform development. This reasoning became evident as students themselves proposed the types of processes that could modify or erode the rocks.

This fundamental understanding of how landforms (elevations) are created was reinforced during the handling of rock samples, based on the idea that some materials tend to be "stronger" and sustain higher elevations, whereas others may be easily eroded. The students' comprehension of this distinction was evaluated through their responses to explanations, such as recognizing that sand is weak and easily carried away by wind, making it incapable of forming large stable landforms.

In addition to this, the diversity of landforms and the variety of Earth's surface features resulting from different processes—such as temperature fluctuations, rainfall, and river flow—were discussed. This understanding is the foundation of geomorphological science, which investigates the interaction between Earth's physical substrate and the atmosphere. To help students recognize differences and similarities among landforms found in Brazil, they were given scaled models grouped by similar characteristics (Figure 4). At this stage, it is important to highlight that the concept of scale was also introduced to the students. Since the models represent miniaturized landforms, it was explained that these scaled-down representations corresponded to real landforms approximately 200 meters high. For comparison, the concept of landform scale was related to human scale, using their own height as a reference. Each student, measuring on average 1.60–1.70 meters, was over 100 times smaller than some of the landforms presented. This helped them grasp the vast dimensions that landscapes can reach.

Initially, students were given models representing typical semi-arid landforms, composed of highly resistant rocks such as granite (which they had previously examined through tactile interaction with rock samples). These landforms have distinct characteristics, including steep escarpments and smaller features such as grooves (channels formed by water flow), which were pointed out to the students as they touched and manipulated the models. These surface details could be perceived by the students as, during the mediation process, teachers guided the hands of blind and visually impaired students to specific features while providing explanations of their formation processes. In general, the students were curious and asked questions about the shapes they were feeling on the models, demonstrating a high level of physical interaction with the studied object—an uncommon practice in geomorphology, a field traditionally studied through visual observation of landforms.

Students with low vision were able not only to recognize textures but also to perceive some of the colors (on decorated models), which helped them understand what the landform looks like in reality. They also gained insight into how the surface color results from either rock weathering processes or the specific composition of the material.

Figure 4. Tactile landscape activities with blind and low-vision elementary school students using relief models generated by the Laboratory of Geomorphology - UFC.

Subsequently, models representing landforms such as waterfalls and caves were introduced, followed by an explanation of how each of these features tends to develop within the landscape. The students' engagement extended beyond simply handling the models individually; they actively participated by asking questions such as, "How are waterfalls formed?" and offering their own interpretations of landforms before receiving explanations. This hands-on interaction with the models, combined with subsequent geomorphological interpretation and abstraction of natural landscape evolution processes, highlights the potential of this technological tool in stimulating reasoning about the form-process relationship, which is fundamental to Earth Sciences.

Finally, models of coastal landforms, such as cliffs, were provided to the students, with particular attention given to their lived experiences, as they all reside in a coastal city. The discussion on cliff formation was thus enriched by the students' familiarity with their surroundings (MOTTA, 2003), since many recognized the beach from which the model was generated (Beberibe, CE), fostering a sense of identification with the activity. This connection enabled students to interact and discuss aspects of cliff formation in relation to social practices associated with coastal landscapes.

A fundamental aspect of the Tactile Landscapes activity is the unique opportunity for students to perceive detailed relief features through direct manipulation of the models—an experience that is nearly impossible through visual observation alone, whether in a virtual environment or in reality. This is because crucial aspects such as depth and the shape of fine-scale features, including erosional patterns on escarpments, cavities, and surface irregularities, could be detected by the students. This level of detail was made possible by the high-resolution models used in the 3D printing process.

A qualitative assessment of the activity can be outlined based on the observation that the models were explored by students with varying levels of engagement. Visually impaired students were able to explore, through tactile perception, different landforms and their detailed morphologies in the miniature reliefs. Those with low vision could distinguish colors, enhancing their perception of each relief and its environmental distinctions, such as the contrast between the "rocky surface" and "vegetation." Additionally, it was observed that students on the autism spectrum exhibited great curiosity about the technological processes involved in creating physical models, stimulating their skills and interests in the technological field. Thus, the potential of these technological tools in the practical and inclusive teaching of Geomorphology is evident, offering an equitable educational experience.

The models also provide an opportunity to promote autonomy and active participation of visually impaired students in the educational environment. Recent studies have demonstrated the effectiveness of digital models in education, highlighting positive experiences across different learning contexts. Fisher et al. (2019) conducted case study analyses in Australia, Mexico, and Canada, concluding that multisensory and multidimensional models have the potential to transform the manner we think, interact, and learn about geospatial information. By allowing students to manipulate and directly engage with the models, learning becomes less dependent on verbal descriptions or photographic slides. This hands-on approach also enhances the development of fine motor skills and the ability to interpret tactile information.

The use of 3D physical models was found to provide greater materiality to geomorphological and geoscientific concepts, facilitating the transformation of abstract ideas into concrete representations. In this sense, Quoos and Figueró (2021) applied this technique for educational purposes in conservation units. This demonstrates potential for inclusive adaptability. Additionally, Koehler, Wild & Tikkun (2018) conducted a comparative analysis focused on visually impaired students, investigating misconceptions related to plate tectonics and geoscience concepts. Their results indicated that students who used 3D-printed models demonstrated significantly better conceptual understanding compared to those who relied solely on traditional tactile graphics. These findings highlight the potential of digital models in promoting more effective and accessible learning, particularly in disciplines that require the visualization of complex concepts.

According to the Brazilian Common National Base, the new generation of students is involved in an increasingly digital and technological environment, immersed in mobile devices, social networks, and a vast array of digital resources. In this context, it is becoming increasingly urgent to rethink and innovate teaching strategies and methodologies, adopting approaches that are not only dynamic and engaging but also relevant to students' realities. It is essential to integrate practical experiences that stimulate curiosity and creativity, making the learning process more effective and inclusive (BRASIL, 2018).

In this regard, the elementary school curriculum includes thematic units related to forms of representation and spatial thinking (BRASIL, 2018). These forms of representation allow students to approach and decode the landscape in its various manifestations. Considering that landforms and landscapes are three-dimensional, geographic reasoning derived from engaging with physical relief models and exploring the textures of different Earth materials provides essential content for students' spatial thinking.

Based on the activities conducted, it can be affirmed that the innovation brought by 3D printing in education goes beyond simply adding more technology to educational resources; it holds great potential for the inclusion of students with diverse educational needs in the school environment, especially in subjects such as Geosciences. This perspective is supported by Article 3, Section V of the PNED (Law n° 14.533/2023), which emphasizes the application of assistive technologies, including products, resources, methodologies, strategies, practices, and services aimed at promoting functionality and learning, with a focus on the inclusion of individuals with disabilities or reduced mobility (BRASIL, 2023).

The use of tactile models tends to become more widespread due to the increasing use of Geographic Information Systems, including digital elevation data for the construction of 3D models, which are now freely available (FISHER et al., 2019), as well as the growing acquisition of 3D printers by schools (including the school visited in this study). The accessibility of this 3D printing technology allows many students to experience the materialization of theoretical concepts, transforming abstract ideas into something more concrete and accessible. This provides a more accurate understanding of the characteristics and processes of nature, as students can interact with and visualize land features in a more effective and meaningful way (HAYAKAWA et al., 2024).

Through these pedagogical practices, it is observed that the use of relief models represents an approach that not only integrates students but also makes them active participants in the learning process. In this way, 3D printing aligns with new educational demands, fostering a learning environment adapted to contemporary technological inclusion needs by transforming digital models into physical objects.

3D printing advances beyond commonly used resources in inclusive education, such as tactile maps, which, despite their significant role in learning, are limited to 2D representations of geographic concepts. Tactile 3D models allow for a highly detailed sensory experience and even enable students to manipulate and control the studied object (e.g., a cliff), enhancing their interaction with landforms, which exist in a three-dimensional space.

Given that the National Guidelines for Special Education in Basic Education emphasize the responsibility of educational systems and institutions in collectively building conditions that adequately address the diversity of their students, the use of 3D printing stands out as a valuable didactic tool. Both for the reasons already mentioned and for its connection to the technological advancement of science. Research sectors and universities are continuously employing and refining these resources; therefore, to bring these innovations into schools constitutes a crucial and necessary collaboration for progress in pedagogical practices (BRASIL, 2001).

The effort to integrate tactile models into the inclusive school curriculum promotes access to geoscience knowledge for visually impaired students as well as contributes to a more equitable educational environment adapted to the diverse needs of learners. However, there is a need for the updating and incorporation of these new teaching and learning methodologies in undergraduate programs, particularly concerning the development of skills that enable teachers to create appropriate and inclusive teaching materials for their students using geotechnologies. In addition to supporting teacher training, it is crucial to ensure other conditions, such as adequate time for planning and executing activities, as well as investments in technological infrastructure at both universities and schools. In this regard, the support of public policies that subsidize such practices is essential.

Finally, with regard to technological resources involving 3D models, it is observed that, despite the availability of 3D printers on the market with more affordable prices and better cost-effectiveness, the use of this technology is still not considered a priority in many schools, due to other internal demands that are often seen as more urgent. However, it is important to recognize the pedagogical potential that the use of these technologies can offer, even with unequal access to these resources (HAYAKAWA et al., 2024). Therefore, their implementation should be done in an inclusive and accessible manner, ensuring that all students have the opportunity to benefit equally.

3.2. Virtual field classes and relief visualization in Virtual Reality

High school and university students were introduced to the modern techniques used in Geomorphology for landscape imaging, particularly photogrammetry and aerial photogrammetry, which are responsible for generating three-dimensional models of landforms. Initially, during the activities, students had access to computational models generated from surveys conducted by the Geomorphology Laboratory at UFC using Agisoft Photoscan software (Figure 5).

Given that many students were already familiar with data visualization and modeling software from other contexts, it was possible to explain the various applications of this technology, such as the extraction of geological data from models and measurements in 3D models. For instance, the use of tools like the virtual compass (Compass) in Cloud Compare software was demonstrated, allowing students to explore functionalities relevant to geoscientific investigations.

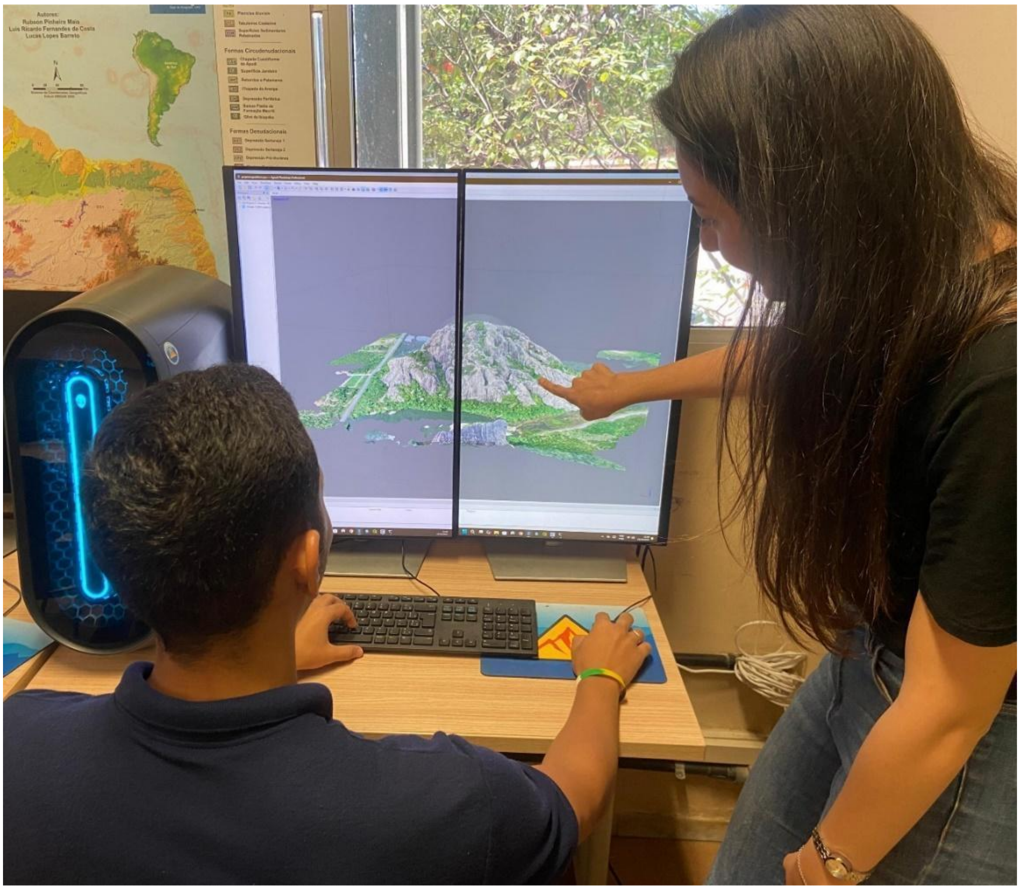

Figure 5. Digital manipulation of 3D models of inselbergs in the Agisoft Photoscan software under the tutelage of members of the Laboratory of Geomorphology. On this occasion, the students were introduced to aspects relating to the methodology of processing digital models and the characteristics of the relief that was imaged.

In parallel with the manipulation of computational models, students also had access to physical models (3D-printed relief models) generated from field data processing. This visualization allowed them to understand the step-by-step process of model generation up to its final printing. Additionally, the printed models were explored in terms of the morphological diversity of landforms in Brazil, which are studied based on geomorphological evolution point of view. Some students were already familiar with landforms in the Brazilian semi-arid region, such as inselbergs. However, discussions on their formation, processes involved in generating detailed features (observed in the models), and unique landforms such as tafoni (cavities in escarpments) introduced them to new geomorphological concepts. This knowledge about diverse landforms, beyond the traditional geomorphological classifications of plateaus, plains, and depressions, may contribute to a deeper understanding of landform diversity and the processes that shape them.

To enhance the learning objectives, virtual field classes were conducted in the final stage of the lesson. Given the natural limitations that prevent students from accessing remote or hazardous locations, such as caves, a virtual immersion experience was provided. Students explored 3D models of a cave (Furna Nova Cave, RN) and a canyon (Coqueirinhos Canyon, PB), developed through a collaboration between the Laboratory of Geomorphology and the Laboratory for Interactive Visualization and Simulations (LabVIS – UFC). Groups of three students at a time used virtual reality (VR) headsets, allowing them to navigate the cave as avatars and observe detailed features, such as sediments on the ground, variations and characteristics of sedimentary layers on the walls, and speleothems on the ceiling (Figure 6).

Figure 6. Scenario of a cave and canyon with an avatar that can be manipulated in virtual reality by gamifying the digital model generated by photogrammetry. This scenario is the user's view with MetaQuest 2 glasses, in which the user is the avatar represented by a man in blue overalls and a yellow helmet artificially inserted into the digital model for gamification. The avatar can move around the cavity and canyon using commands on the glasses control.

This immersion in the virtual field environment enhanced student interaction, as they frequently asked questions about the formation of the cave cavity, the reasons behind the varied morphology of the walls, and other inquiries that guided their geomorphological interpretations. This activity enabled the discussion of complex topics in karst geomorphology—such as how fractures control cave formation—in a more engaging and comprehensible manner, mediated by technology (Figure 7).

Studies indicate that virtual field lessons allow students to develop conceptualizations of the environments being explored (JITMAHANTAKUL; CHENRAI, 2019) by fostering mental models of the landscapes in which they immersed (ATCHISON; FEIG, 2011). Furthermore, it is stated that learning environments based on virtual reality (VRLE – Virtual Reality Learning Environments) (BRICKEN, 1991) facilitate immersion, interactivity, and imagination (HUANG; RAUCH; LIAW, 2010; CONCANNON; ESMAIL; ROBERTS, 2019). Since students actively move and interact with the virtual environment—using controllers in this case—the experience stimulates the formulation of concepts and interpretations related to the explored features.

Figure 7. Students in a Virtual Field activity in a cave using virtual reality, immersed in an interactive model. (A) External view of the student using VR goggles. (B) Illustrative image to represent the immersive view of the VR goggles user.

The students' immersion and engagement, as well as the questions that arose regarding geomorphology and adjacent topics related to technology—such as the application of these models in the industry—demonstrate the potential of this methodology in Geoscience education. Geosciences often deal with complex subjects that are challenging to understand, particularly when they have limited access to remote environments. One of the key learning outcomes, according to Atchison & Feig (2011), is the students' ability to formulate interpretations and present information based on observations and reasoning derived from their "newly constructed knowledge" acquired through the activity.

Virtual Reality (VR) and the use of Immersive Virtual Environments (IVEs) can have a transformative potential in education by providing spatial experiences that enhance the understanding and visualization of complex three-dimensional natural objects (SCHUCHARDT; BOWMAN, 2007). This technology has many applications in Geoscience education, allowing students to realistically experience processes such as volcanism and erosion. By creating three-dimensional virtual environments, VR enables students to explore and interact with content intuitively. For instance, in a geography lesson, students can "visit" caves and mountains, allowing them to engage in experiential learning within a safe and controlled environment.

The use of virtual reality with 3D immersive headsets in Geoscience education has demonstrated broad applications in the teaching process, as it provides a sensory experience of complex concepts such as landform evolution and climatic processes (JITMAHANTAKUL; CHENRAI, 2019; HARKNETT et al., 2022; VANDELLI et al., 2024). Studies show that virtual reality can share knowledge to students in a manner that closely resembles real-world experiences, given the immersive environment that facilitates the visualization and interaction with natural phenomena in ways that traditional methods cannot achieve (BOWER et al., 2014; TIBALDI et al., 2020; GRISEL; HALIM; KATJA, 2024).

One of the major potentials of using virtual reality (VR) in education is its ability to accommodate different learning styles and educational needs, fostering a more inclusive learning environment. Students with mobility impairments, for example, can benefit from VR-adapted educational experiences that overcome physical barriers and provide learning opportunities that might otherwise be inaccessible. In the field of Geosciences, individuals with reduced mobility face significant challenges in progressing both in basic and higher education, as well as in research, due to limitations in accessing remote locations and navigating uneven terrains. The application of virtual field lessons in caves (ATCHISON; FEIG, 2011), for instance, has been empirically proven as an adaptive technology for geomorphological visualization and interpretation, encompassing various educational levels and students with diverse physical conditions.

These virtual field lessons not only serve as complementary methodologies to traditional fieldwork but also emerge as powerful accessibility tools for students, educators, and researchers. Beyond VR immersion, technological resources such as Google Earth and Geographic Information Systems (GIS) platforms have been employed in virtual field lessons (BOSCH, 2021), highlighting the diversity of technological tools that can be leveraged to facilitate learning complex topics within Geosciences.

Challenges in utilizing these resources, which also should be considered, include the need for financial support for institutions to establish study and training laboratories, as well as teacher formation, in order to acquire knowledge on how to operate these technologies and integrate them into their teaching strategies (CONCANNON; ESMAIL; ROBERTS, 2019; HAYAKAWA et al., 2024). However, factors such as the availability of online learning platforms and the accessibility of these tools (e.g., low-cost VR headsets, open-source visualization software, and the availability of digital models on online platforms) contribute to their dissemination and implementation in educational settings. In this regard, Article 5 of the PNED (Law No. 14.533/2023) aims to develop and promote accessible and inclusive Information and Communication Technologies (Tecnologias da Informação e Comunicação – TIC) (BRASIL, 2023).

Overall, the integration of various technologies into education has shown promise in enhancing learning outcomes across different educational contexts (BOWER et al., 2014; CAKIR; KORKMAZ, 2019; WANG et al., 2023; VERGES et al., 2024).

4. Conclusions

The use of interactive technologies, such as virtual reality, digital landscape models, and physical models generated through 3D printing, serves as dynamic learning tools with significant potential for integration into educational environments across various academic levels.

The incorporation of technology into Geoscience education—traditionally reliant on fieldwork and access to remote locations—offers promising opportunities for inclusive pedagogical practices. Additionally, students with special educational needs and reduced mobility gain immersive experiences that facilitate the conceptualization of complex topics and the development of spatial reasoning in virtual environments. This approach enables the exploration of themes such as the geomorphology of karst and semi-arid regions, among other areas, which are often beyond the immediate reality of students.

The use of tactile models for visually impaired students provides a tangible and inclusive approach to learning, allowing them to explore and understand spatial and structural concepts through sensory interaction. These models enable students to touch and experience three-dimensional representations of landforms such as escarpments, valleys, and mountains, enhancing their comprehension of Earth's surface features.

These technological resources are promising across diverse educational contexts, particularly in the teaching of Geography and Geosciences, where spatial perception and the relationships between different environmental elements are fundamental to the learning process.

Contributions of the Authors: Conceptualization, A.S.V.S. e R.P.M.; Methodology, A.S.V.S.; R.P.M; H.S.R.; M.B.A.; P.E.F.M.; Validation, R.P.M.; Data preparation, A.S.V.S.; M.B.A.; Writing, A.S.V.S.; M.B.A.; Revision, A.S.V.S.; R.P.; H.S.R.; Supervision, R.P.M.; Funding acquisition, R.P.M.; R.P.M. All authors read and agreed with the published version.

Funding: The authors are thankful for the research funding provided by the project "Inselbergs of Quixadá- Ceará: Origin and Geomorpological evolution" and "Inselbergs of Brazil: Morphostructural aspects and associated erosion rates", both funded by CNPq (National Council for Scientific and Technological Development) of Brazil.

Acknowledgments: We appreciate the comments of both anonymous reviwers, which allowed the improvement of this work. We also thank the collaboration of the members of the Laboratory of Geomorphology (Fedreral University of Ceará) in the execution of the research activities.

Conflict of interest: The authors declare no conflict of interest.

References

1. ABER, J. S.; MARZOLFE, I.; RIES, J. B. Photogrammetry. In: ABER et al. **Small-Format Aerial Photography:** Principles, Techniques and Geoscience Applications. Amsterdam: Elsevier, 2010. p. 23-39. DOI: 10.1016/B978-0-444-53260-2.10003-1
2. AL-ANSI, A. M.; JABOOB, M.; GARAD, A.; AL-ANSI, A. Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. S**ocial Sciences & Humanities Open**, 8(1), 2023. DOI: 10.1016/j.ssaho.2023.100532
3. AKÇAYIR, M.; AKÇAYIR, G. Advantages and challenges associated with augmented reality for education: A systematic review of the literature. **Educational Research Review**, 20, p. 1–11, 2017. DOI: 10.1016/j.edurev.2016.11.002
4. ATCHISON, C. L.; FEIG, A. D. Theoretical perspectives on constructing experience through alternative field-based learning environments for students with mobility impairments. In: **Special Paper of the Geological Society of America**: v. 474, p. 11–21, 2011. DOI: 10.1130/2011.2474(02)
5. AZZURI, F.; DARFIANSA L. S.; BACHTIAR F. A.; TOLLE, H. The Development of Augmented Reality to Support Geomorphology Learning In Observing Landforms. In: **7th International Conference on Informatics and Computational Sciences** (ICICoS), Semarang, Indonesia, p. 538-544, 2024. DOI: 10.1109/ICICoS62600.2024.10636826
6. BARCELOS, A. C.; DANELON, J. R. B.; RODRIGUES, S. C. Uso de Aeronaves Remotamente Pilotadas (ARPS) na elaboração de modelos tridimensionais para auxiliar na cartografia geomorfológica. **William Morris Davis - Revista de Geomorfologia**, 3(2), p. 1–14, 2022. Disponível em: <https://williammorrisdavis.uvanet.br/index.php/revistageomorfologia/article/view/196>. Acesso em: Jan. 2025.
7. BEDAIR, S.; SAYED, S. A.; ALMETWALY, W. M. Enhancing Hybrid Learning using Open Source GIS-Based Maps Archiving System. **Egyptian Journal of Remote Sensing and Space Science**, 25(3), p. 779–793, 2022. DOI: 10.1016/j.ejrs.2022.07.003

8. BERTACCHINI, E.; CASTAGNETTI, C.; CORSINI, A.; CONO, S. Remotely piloted aircraft systems (RPAS) for high resolution topography and monitoring: civil protection purposes on hydrogeological contexts. **Earth Resources and Environmental Remote Sensing/GIS Applications V**, 924515, 2014. DOI: 10.1117/12.2067406
9. BOSCH, R. Development and implementation of virtual field teaching resources: Two karst geomorphology modules and three virtual capstone pathways. **Geoscience Communication**, 4(2), p. 329–349, 2021. DOI: https://doi.org/10.5194/gc-4-329-2021
10. BOWER, M.; HOWE, C.; MCCREDIE, N.; ROBINSON, A.; GROVER, D. Augmented Reality in education - cases, places and potentials. In: **Educational Media International**, v. 51, Issue 1, p. 1–15, 2014. DOI: 10.1080/09523987.2014.889400
11. BRASIL. **Lei N° 14.533, de 11 de janeiro de 2023**. Institui a Política Nacional de Educação Digital e altera as Leis [...]. Brasília: República Federativa do Brasil, 2023. Disponível em: <https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2023/lei/l14533.htm>. Acesso em: Jan. 2025.
12. BRASIL. Ministério da Educação. **Base Nacional Comum Curricular**. Brasília: MEC, 2018. Disponível: <http://portal.mec.gov.br/index.php?option=com_docman&view=download&alias=79611-anexo-texto-bncc-aprovado-em-15-12-17-pdf&category_slug=dezembro-2017-pdf&Itemid=30192>. Acesso em: Jun. 24.
13. BRASIL. Ministério da Educação. **Diretrizes Nacionais para a Educação Especial na Educação Básica.** Secretaria de Educação Especial - MEC; SEESP, 2001. 79 p. Disponível em: <http://portal.mec.gov.br/seesp/arquivos/pdf/diretrizes.pdf>. Acesso em: Out. 2024.
14. BRICKEN, M. Virtual Reality Learning Environments: Potentials and Challenges. **ACM SIGGRAPH Computer Graphics**, v. 25, n. 3, 1991. DOI: 10.1145/126640.126657
15. CAKIR; R.; KORKMAZ, O. (2019). The effectiveness of augmented reality environments on individuals with special education needs. **Education and Information Technologies**, 24(2), p. 1631–1659, 2019. DOI: 10.1007/s10639-018-9848-6
16. CAROLAN, M. S. Introducing the concept of tactile space: Creating lasting social and environmental commitments. **Geoforum**, v. 38, n. 6, p. 1264–1275, 2007. DOI: 10.1016/j.geoforum.2007.03.013
17. CARRERA, C. C.; AVARVAREI, B. V.; CHELARIU, E. L.; DRAGHIA, L.; AVARVAREI, S. C. Map-Reading Skill Development with 3D Technologies. **Journal of Geography**, 116(5), p. 197–205, 2017. DOI: 10.1080/00221341.2016.1248857
18. CARRERA, C. C.; ASENSIO, L. A. B. Augmented reality as a digital teaching environment to develop spatial thinking. **Cartography and Geographic Information Science**, 44(3), p. 259–270, 2016. DOI: 10.1080/15230406.2016.1145556
19. CARRUBA, M.C.; CALCAGNO, A.; COVARRUBIAS, M. Google Earth in VR, for Students with Special Needs. In: DE PAOLIS, L.T.; ARPAIA, P.; SACCO, M. (Eds.). **Extended Reality.** XR Salento 2023. Lecture Notes in Computer Science, vol 14219, 2023. DOI: 10.1007/978-3-031-43404-4_1
20. ÇÖLTEKIN, A.; LOCHHEAD, I.; MADDEN, M.; CHRISTOPHE, S.; DEVAUX, A.; PETTIT, C.; LOCK, O.; SHUKLA, S.; HERMAN, L.; STACHOŇ, Z.; KUBÍČEK, P., SNOPKOVÁ, D.; BERNARDES, S.; HEDLEY, N. Extended Reality in Spatial Sciences: A Review of Research Challenges and Future Directions. **ISPRS International Journal of Geo-Information**, 9(7), 439, 2020. DOI: 10.3390/ijgi9070439
21. CONCANNON, B. J.; ESMAIL, S.; ROBERTS, M. R. Head-Mounted Display Virtual Reality in Post-secondary Education and Skill Training. **Frontiers in Education**, v**.** 4 (80), 2019. DOI: 10.3389/feduc.2019.00080
22. COSTA, G. F. C. **Fotogrametria 3D no Design de Jogos Digitais**: estudo de caso da conceção de assets fotorrealistas em ambientes amadores. Dissertação (Mestrado em Design e Desenvolvimento de Jogos Digitais - 2º ciclo de estudos) - Faculdade de Artes e Letras, Universidade da Beira Interior, Covilhã (Portugal). 2020. 123 p.
23. FISHER, R.; HECKBERT; S.; MARIA, J.; SUTTON, S. Augmenting physical 3D models with projected information to support environmental knowledge exchange. **Applied Geography**, v. 112, 2019. DOI: 10.1016/j.apgeog.2019.102095
24. GRISEL, J.; HALIM, L. A.; KATJA, S. Subsurface Geosciences Learning in Virtual Reality: A Case Study in Central Luconia Province, Malaysia. **Earth Science, Systems and Society**, 4, 2024. DOI: 10.3389/esss.2024.10118
25. GROHMANN, C. H.; VIANA, C. D.; GARCIA, G. P. B.; ALBUQUERQUE, R. W. Remotely piloted aircraft-based automated vertical surface survey, **MethodsX**, v. 10, 2023. DOI: 10.1016/j.mex.2022.101982
26. HARKNETT, J.; WHITWORTH, M.; RUST, D.; KROKOS, M.; KEARL, M.; TIBALDI, A.; BONALI, F. L.; VAN WYK DE VRIES, B.; ANTONIOU, V.; NOMIKOU, P.; REITANO, D.; FALSAPERLA, S., VITELLO, F.; BECCIANI, U. The use of immersive virtual reality for teaching fieldwork skills in complex structural terrains. **Journal of Structural Geology**, 163, 104681, 2022. DOI: 10.1016/j.jsg.2022.104681
27. HAYAKAWA, E.; BALTAZAR, A. A.; BALTAZAR, S. A.; PIRES, M. M. Que rio é esse? A geografia escolar e o espaço vivido: impressão 3D e dados de sensoriamento remoto para o ensino de bacias hidrográficas. Revista Presença Geográfica, v. 11, n. 1, esp., 2024. Acesso em: <https://periodicos.unir.br/index.php/RPGeo/article/view/7785/1686>. Acesso em: Dez. 2025.
28. HRUBY, F. The Sound of Being There: Audiovisual Cartography with Immersive Virtual Environments. **KN Journal of Cartography and Geographic Information**, 69, p. 19–28, 2019. DOI: https://doi.org/10.1007/s42489-019-00003-5
29. HUANG, H. M.; RAUCH, U.; LIAW, S. S. Investigating learners' attitudes toward virtual reality learning environments: Based on a constructivist approach. **Computers and Education**, v. 55, n..3, p. 1171–1182, 2010. DOI: 10.1016/j.compedu.2010.05.014

30. JITMAHANTAKUL, S.; CHENRAI, P. Applying Virtual Reality Technology to Geoscience Classrooms. **Review of International Geographical Education Online** (RIGEO), 9(3), p, 577-590, 2019. DOI: 10.33403/rigeo.592771
31. KOEHLER, K.; WILD, T.; TIKKUN, S. Implications of 3-D printing for teaching geoscience concepts to students with visual impairments. **Journal of Science Education for Students with Disabilities**, v. 21, n. 1, p. 49-81, 2018. DOI: 10.14448/jsesd.10.0004
32. KÖSE, H.; GÜNER-YILDIZ, N. Augmented reality (AR) as a learning material in special needs education. **Education and Information Technologies**, 26, p. 1921–1936, 2021. DOI: 10.1007/s10639-020-10326-w
33. LAMPROPOULOS, G.; KINSHUK. Virtual reality and gamification in education: a systematic review. **Educational Technology Research and Development**, 72(3), p. 1691–1785, 2024. DOI: 10.1007/s11423-024-10351-3
34. MAIA, R. P.; SOUZA, A. S. V. Inselbergs shaped by collapse: considerations on the structural control on granitic scarps. **Revista Brasileira de Geomorfologia**, v. 25, n. 2, 2024. DOI: 10.20502/rbg.v25i2.2412
35. MIKROPOULOS, T. A.; NATSIS, A. Educational virtual environments: A ten-year review of empirical research (1999-2009). **Computers and Education**, 56(3), p. 769–780, 2011. DOI: 10.1016/j.compedu.2010.10.020
36. MOTTA, M. F. **Espaço vivido/Espaço pensado**: o lugar e o caminho. Dissertação (Mestrado em Geografia) – Universidade Federal do Rio Grande do Sul, Instituto de Geociências, Porto Alegre, 2003.
37. MOURA, P. E. F. **Aplicação de dados LIDAR na caracterização geomorfológica de cavernas na porção sul da bacia de Irêce-BA**. Tese (Doutorado em Geografia) - Programa de Pós-graduação em Geografia Universidade Federal do Ceará, 2022. 188p. Disponível em: <https://repositorio.ufc.br/handle/riufc/69727>. Acesso em: Ago. 2024.
38. NIU, T.; LI, Z.; HUANG, M.; YUAN, L. The Application of Virtual Reality Technology in Geography Teaching, p. 12-20, 2023. *In:* **Proceedings of the 2nd International Conference on Education, Language and Art (ICELA 2022)**. 2023. Atlantis Press SARL. DOI: 10.2991/978-2-38476-004-6_3
39. PARSONS, S. Authenticity in Virtual Reality for assessment and intervention in autism: A conceptual review. **Educational Research Review**, v. 19, p. 138–157, 2016. DOI: 10.1016/j.edurev.2016.08.001
40. QUOOS, J. H.; FIGUEIRÓ, A. S. A prototipagem da paisagem: a criação de geoprodutos como mapas físicos de relevo3D nas unidades de conservação para uso na gestão e educação. REDE - Revista Eletrônica do Prodema, v. 1, n. 15, p. 42-51, 2021. Disponível em: <http://www.revistarede.ufc.br/rede/article/view/712>. Acesso em: Dez. 2024.
41. RAUSCHNABEL, P. A.; FELIX, R.; HINSCH, C.; SHAHAB, H.; ALT, F. What is XR? Towards a Framework for Augmented and Virtual Reality. **Computers in Human Behavior**, 133, 2022. DOI: 10.1016/j.chb.2022.107289
42. SCHUCHARDT, P.; BOWMAN, D. A. The benefits of immersion for spatial understanding of complex underground cave systems. In: Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology, 2007, Newport Beach, California, USA. **Anais […].** New York: ACM, 2007. p. 121-124. DOI: 10.1145/1315184.1315205.
43. SHAKIROVA, N. D.; SAID, N. A.; KONYUSHENKO, S. M. Retracted Article: The Use of Virtual Reality in Geo-Education. **International Journal of Emerging Technologies in Learning (iJET)**, 15(20), p. 59–70, 2020. DOI: 10.3991/ijet.v15i20.15433
44. SILVA, R. M.; MARTINS, P.; ROCHA, T. Virtual reality educational scenarios for students with ASD: Instruments validation and design of STEM programmatic contents. **Research in Autism Spectrum Disorders**, 119, 102521, 2025. DOI: 10.1016/j.rasd.2024.102521
45. SOUZA, A. S. V.; MAIA, R. P., BEZERRA, F. H.; MIGOŃ, P.; SIAME, L. L. Granitic inselberg erosion controlled by dike swarm array in semiarid Brazil. **Geomorphology**, v.440, 2023. DOI: 10.1016/j.geomorph.2023.108865
46. SUBHASH, S.; CUDNEY, E. A. Gamified learning in higher education: A systematic review of the literature. **Computers in Human Behavior**, v. 87, p. 192–206, 2018. DOI: 10.1016/j.chb.2018.05.028
47. ŠVEDOVÁ, H.; KUBÍČEK, P. The Use of Virtual Environments in Geoscience Education. *In:* International Cartographic Conference, 30, 2021, Florencia, Itália (ICC 2021) **Anais [...]**. Abstracts of the International Cartographic Association, 3, p. 1–3, 2021. DOI: 10.5194/ica-abs-3-281-2021
48. TIBALDI, A; BONALI, F. L.; VITELLO, F.; DELAGE, E.; NOMIKOU, P.; ANTONIOU, V.; BECCIANI, U.; VAN WYK DE VRIES, B.; KROKOS, M.; WHITWORTH, M. Real world–based immersive Virtual Reality for research, teaching and communication in volcanology. **Bulletin of Volcanology**, 82(38), 2020. DOI: 10.1007/s00445-020-01376-6
49. VANDELLI, V.; MIGOŃ, P.; PALMGREN, Y.; SPYROU, E.; SAITIS, G.; ANDRIKOPOULOU, M. E.; CORATZA, P.; MEDJKANE, M.; PRIETO, C.; KALOVREKTIS, K.; LISSAK, C.; PAPADOPOULOS, A.; PAPASTAMATIOU, N.; EVELDIPOU, N.; MAQUAIRE, O.; PSYCHARIS, S.; STROEVEN, A. P.; SOLDATI, M. Towards enhanced understanding and experience of landforms, geohazards, and geoheritage through Virtual Reality Technologies in education: lessons from the GeoVT Project. **Geosciences**, 14(5), 127, 2024. DOI: 10.3390/geosciences14050127
50. VERGES, J.; COSTA, A.; MAIA, D.; VERGES, N. (2024). Os óculos de Realidade Virtual (RV) como ferramenta didática no ensino de Geografia: parâmetros a partir das percepções dos estudantes. **Revista Geográfica Acadêmica**, v. 18, Issue 1, 2024. Disponível em: <https://revista.ufrr.br/rga/article/view/7628/4024>. Acesso em: Set. 2024.
51. VOLPATO, N. (Org.). Manufatura Aditiva: Tecnologias e aplicações da impressão 3D. São Paulo: Edgard Blücher, 2017. ISBN: 9788521211501

52. WANG, X.; YOUNG, G. W.; PLECHATÁ, A.; MC GUCKIN, C.; MAKRANSKY, G. Utilizing virtual reality to assist social competence education and social support for children from under-represented backgrounds. **Computers and Education**, v. 201, 2023. DOI: 10.1016/j.compedu.2023.104815