https://doi.org/10.5194/egusphere-2026-4843
Preprint. Discussion started: 30 September 2026
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Immersive 3D Virtual Reality for Field Geological Practice: A New Paradigm in Geoscience Education

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Abstract. Geology education, due to its deep reliance on the composition and evolution of the Earth's material, is in dire need of practical knowledge to strengthen theoretical understanding. However, traditional field geology teaching has long been limited by space-time constraints, irreversibility of phenomena and multi-scale characteristics of complex geological processes, and the existing digital teaching tools are mostly limited to two-dimensional displays or static three-dimensional models, which lacks immersive presentations of dynamic evolution and interactive operations of geological phenomena, making it difficult for students to establish systematic geological thinking. For this reason, this study integrates the realistic 3D modelling and virtual reality technology, builds a realistic 3D field geological practice virtual simulation platform, and constructs a platform teaching system covering the whole process of "Preparation-Teaching-Examination-Evaluation". By comparing the students' practical scores before and after the use of the platform and collecting feedback, it was found that the students' practical scores increased significantly after the application of the platform, and the proportion of high scores (90-100) increased from 13.8% to 27.4%, and more than 90% of the students recognized the functions of the platform and expressed their willingness to use it continuously. The study confirms that the virtual-reality integration teaching mode effectively improves the cognitive depth of geological phenomena and the efficiency of practical skills transformation through realistic 3D roaming, stratigraphic dynamic evolution simulation and standardized assessment system. This study not only provides a feasible solution to solve the bottleneck of traditional geology teaching, but also lays a practical foundation for promoting the transformation of geology education to the direction of intelligence.

1 Introduction

Geology, as a discipline focusing on the composition, structural evolution, and process mechanisms of the Earth, is inherently practical and spatial in nature (Walker, 2021; Yeon, 2021). Therefore, geological knowledge is best acquired through direct

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interaction with geological entities, and experiential understanding must be integrated with theoretical knowledge to achieve effective learning outcomes (Bond & Cawood, 2021). As a crucial bridge between theoretical instruction and geological cognition, field geological practice serves not only as an essential medium for cultivating students' geological thinking and enhancing their professional skills, but also as a key pathway for training innovative geoscientists (De Paor et al., 2016; Bond & Cawood, 2021).

However, traditional field-based geological practice teaching has long faced several challenges. First, spatiotemporal constraints often hinder the real-time observation of key geological phenomena. Second, the complexity and irreversibility of geological phenomena make it challenging for students to fully comprehend multi-scale processes within a limited fieldwork period. Furthermore, field courses are highly susceptible to disruptions from severe weather and public health emergencies, hindering the consistent development of students' practical skills (De Paor et al., 2016; Walker, 2021; Yeon, 2021; Tavani et al., 2022).

The rapid advancement of information technology offers innovative solutions for field geology instruction (Tavani et al., 2022). Early digital tools such as GPS, GIS, and UAVs have been progressively integrated into geological instruction for positioning, spatial analysis, and aerial surveying. These technologies have significantly enhanced the efficiency of field investigations by enabling high-precision data collection and visualization (Carver et al., 1995; Vasuki et al., 2014). However, these technologies remain largely confined to 2D or static 3D representations. This limitation hinders immersive interaction and dynamic process simulation, preventing students from exploring and thereby perceiving the spatiotemporal evolution of geological phenomena (Cayla, 2014).

Virtual Reality (VR) and realistic 3D modeling technologies are driving a paradigm shift in education (Carbonell Carrera & Bermejo Asensio, 2017). VR technology transcends the physical constraints of traditional teaching, enabling dynamic visualization and interactive exploration of geological phenomena. Realistic 3D modeling, in turn, enables the digital reconstruction of complex geological environments through high-precision laser scanning and multi-source data fusion, thereby providing an authentic spatial framework for virtual instruction (Cayla, 2014; Carbonell Carrera & Bermejo Asensio, 2017; Bond & Cawood, 2021).

Adopting the realistic 3D modelling and VR, this study constructed a virtual simulation platform by integrating realistic 3D modeling and virtual reality to visualize geological environments and manage teaching data. The platform offers simulation experiments, course exercise, and evaluations in a digital and immersive setting. The results from two student cohorts show

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improved practical scores and strong user approval. The study also explores future applications of live 3D, artificial intelligence, and robotics in geology education. A comparative analysis of student performance revealed a significant improvement in practical scores after using the platform, with the proportion of high scores (≥90%) increasing from 13.8% to 27.4%. Over 90% of students endorsed the platform and expressed interest in continued use. These findings facilitate the digital transformation of field geology teaching.

2 Literature review

2.1 Educational applications of VR technology

VR was first introduced as an academic term in the seminal paper "The Ultimate Display"(Sutherland, 1965). This work pioneered the concept of a virtual reality world by exploring advancements in computer display and human-computer interaction, and promotes the development of computer graphics and image technology and the research of human-computer interaction equipment such as helmet display and data glove. VR can generate a realistic three-dimensional multi-sensory environment through computers, graphic workstations and other related equipment, creating a sense of immersion for users. The environment also responds to user actions, enabling deep integration and interaction between the user and the virtual space, thus achieving the deep integration and interaction between people and the environment (Liu et al., 2016).

Recent research demonstrates the efficacy of virtual reality (VR) as an educational tool across diverse fields. In medical science, VR significantly enhances nursing and dental education by providing innovative and realistic training. It is also revolutionizing cardiovascular medicine through advanced interactive simulations (Liu et al., 2023; Skalidis et al., 2023). In physical education, VR has transitioned from a theoretical concept to practical, system-based applications that provide immersive and personalized learning experiences (Zhang & Liu, 2016; Ding et al., 2020).

The technology's versatility is further demonstrated in simulation-based and special education. For university and nuclear physics, VR enables flexible and effective lab experiments without spatiotemporal constraints (Šiđanin et al., 2020). In special education, VR combined with haptic feedback provides enhanced sensory experiences and individualized motor skill training, effectively facilitating learning for children with impairments (Irigoyen et al., 2024; Zhang et al., 2025).

2.2 Educational applications of realistic 3D technology

Realistic 3D technology is an emerging field focused on creating high-fidelity digital representations of real-world objects and environments (Tao et al., 2019). It employs techniques including high-precision laser scanning, drone photogrammetry, and ground surveying to collect spatial data. It then converts real-world objects and environments into high-precision 3D digital

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models, achieving a digital representation of their structure and appearance (Ahmed et al., 2019; Lin et al., 2008; Ming et al., 2008). Its applications are diverse, encompassing cultural heritage preservation (Ahmed et al., 2019), GIS-assisted urban planning (Lin et al., 2008), and urban traffic monitoring and management (Yao & Ci, 2015).

Realistic 3D technology can digitally capture real-world scenes, allowing complex geological and geographical phenomena to be accurately and intuitively reproduced in a virtual 3D space (Lv et al., 2017). In education, this technology enhances the realism and immersion of learning, thereby improving students' spatial cognition and practical skills. Through virtual roaming, manipulation, and analysis, students can gain a deeper understanding of complex subjects and engage in academic exploration. Its effectiveness has been demonstrated in applications such as virtual chemistry labs, 3D reservoir model teaching, and anatomy education (Zheng, 2014; Lin et al., 2008; Ming et al., 2008). However, the applicability of most existing 3D models in education is limited, as they are typically designed for specific projects or experiments and lack integrated display environments and systematic teaching content.

2.3 The evolution and digital transformation of field geological practice

Field geological practice is a core component of geological education, essential for developing students' professional interest, strengthening their theoretical understanding, and building practical skills (Barros et al., 2012). It is widely recognized in higher education, with field internships that include techniques like route surveying and sample collection forming a mandatory part of curricula worldwide (Barros et al., 2012; Shipley et al., 2013).

Digital tools are significantly changing how field geology is taught and practiced. The widespread adoption of 3D geological modeling, drone surveys, and Geographic Information Systems (GIS) has revolutionized fieldwork, facilitating a shift from traditional “pen and paper” methods to digital data representation (Hurst, 1998; Shipley et al., 2013). For example, the British Geological Survey's FieldMove application enables geologists to record data and generate 3D geological maps in real time, while China's Geo-Cloud platform allows nationwide sharing of geological information. The development of virtual simulation platforms in China reflects this trend. Chinese universities have created distinct systems focused on three main goals: building integrated teaching processes for foundational skills (Jiao et al., 2023), designing specialized modules for complex geological analysis (Wei et al., 2019; Bi et al., 2021), and exploring advanced technological applications, as demonstrated by platforms developed by Southwest Petroleum University and China University of Geosciences (Beijing).

Internationally, similar efforts are underway. The University of Illinois created the Yellowstone module for rock and hydrothermal studies; the University of Lausanne developed InterGEO for European geoheritage education using the Moodle platform; and RWTH Aachen University uses an AR sandbox for terrain visualization. Stanford University's virtual field

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practice system, which simulates complex geological settings, helps overcome the time and space limitations of traditional field training (Chang et al., 2009; Deng et al., 2016).

These platforms often integrate physical and virtual elements, thereby significantly enriching the educational content that can be delivered. However, most remain limited to static displays and lack the detail needed for close observation (Qiang et al., 2020). Future research should focus on enhancing multi-scale modeling through the integration of techniques like tilt photography and laser scanning, and on developing the capability to model temporal changes for visualizing geological processes (Cho & Clary, 2020).

3 Methods

3.1 Data

The platform was constructed by integrating diverse geological datasets. The core datasets supported by the platform include basic geological information (e.g., remote sensing imagery, topographic maps and tectonic maps), detailed geological data including stratigraphic features and geophysical exploration results, as well as practical teaching materials (e.g., routes, field study sites, and explanatory text). Supplementary resources such as field photographs, documents, and audiovisual materials further enrich the dataset.

Based on these datasets, we developed digital models of key geological phenomena. It systematically compiles and analyzes various geological sections, including stratigraphic profiles (regional and local standards), magmatic, metamorphic, and sedimentary rock sections, as well as tectonic structures ranging from large-scale zones (e.g., Tantanlu Fault Zone) to smaller features (e.g., Xusu Arc). The modeling result is a comprehensive 3D dataset of the internship area, forming the foundation for a realistic virtual simulation platform that supports immersive teaching, geological observation, and science communication.

3.2 System design

The platform architecture is illustrated in Figure 1. The platform employs a frontend-backend separation architecture. The frontend is a modern single-page application implemented using the Vue.js framework. HTML defines the page structure, CSS delivers refined visual effects and responsive layouts, while JavaScript and Vue's reactive capabilities provide rich, fluid dynamic interactions. PostgreSQL was employed as the relational database management system for data storage. Ultimately, the front-end Vue application, following build optimization, is deployed to static resource servers, forming a complete, stable, and easily maintainable web platform.

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The proposed platform includes four sub-systems: (1) an intelligent spatial analysis system that provides powerful spatial analysis capability and rich means of visual expression; (2) a real-scene 3D virtual reality practice system that guides the overall practice content; (3) a 3D virtual training test and examination system that is used to carry out petrological and palaeontological identification tests, etc.; (4) a practice data management system that realizes the systematic management of big data and teaching practice resources.

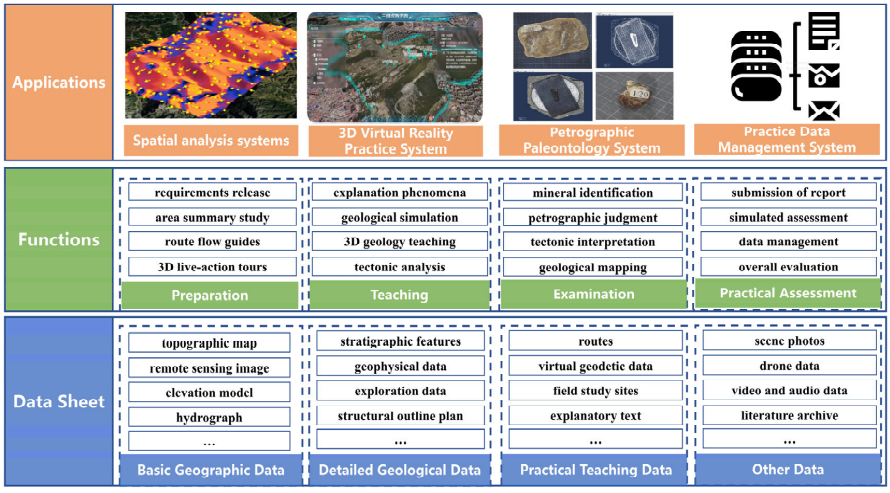


Figure 1: Realistic 3D VR field geological practice platform architecture.

3.3 Questionnaire survey

Data was collected from undergraduate students of Class 2022 and Class 2023 in the School of Resources and Geosciences. Among them, the students of Class 2022 did not use the realistic 3D VR field geology practice platform when they participated in practice teaching, so the information about their scores we have had; the students of Class 2023 used the platform for practice when they were teaching, and after they finished using the platform for learning, a questionnaire was distributed through the platform, and the information was directly updated to the backend database through the front-end collection.

The questionnaire comprises 12 questions, numbered Q1 to Q12. Questions Q1 to Q3 gather information regarding students' usage duration of the platform; Questions Q4 to Q12 concern students' feedback and satisfaction with the platform. Responses were recorded on a 5-point Likert scale for each item. The experiment design is attached as supplement materials.

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3.4 Statistical analysis

To evaluate the platform's pedagogical efficacy, three statistical analysis methods were employed. Firstly, descriptive statistics were used to summarize the central tendency and dispersion of student performance across both year groups, aiming to visually present and compare learning outcome distributions among different student cohorts. Secondly, given that this study collected subjective data on student perceptions of platform usage via a 5-point Likert scale, Cronbach's alpha was calculated to assess the internal consistency of the scale. Cronbach's alpha serves as a standard metric for assessing internal consistency in psychometric scales—particularly graded scales like the Likert scale. It effectively evaluates whether individual items measure the same construct, thereby ensuring subsequent analyses are grounded in trustworthy data. Finally, to investigate the intrinsic relationship between students' platform usage behaviour and their learning outcomes, we employed Pearson's correlation coefficient. This method was selected because both usage duration and performance are continuous variables, and our objective is to precisely measure whether a linear relationship exists between them and to what extent.

4 Platform functionality

The platform's functionality encompasses the entire teaching process including preview, teaching, exercise, and evaluation, as illustrated in Figure 2.

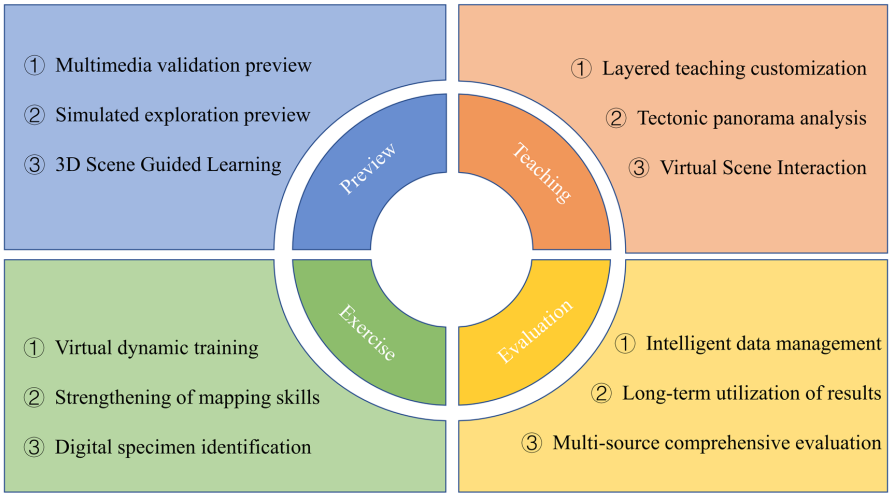


Figure 2: The platform's functions throughout the full teaching cycle.

4.1 Preview practical session for students

The platform provides a virtual tutorial environment for geological fieldwork, delivering a more intuitive learning experience. This environment features three-dimensional representations of essential geological elements—such as landforms, faults, folds,

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fieldwork sites, and multiple field routes—as illustrated in Figure 3. Each observation point is supplemented with detailed text descriptions, audio explanations, and relevant video demonstrations.

This system enables students to simulate real geological survey processes before actual fieldwork, thereby facilitating the observation of varied topography, geological structures, and rock characteristics. As a result, they can develop a deeper understanding of complex geological concepts and their practical significance. This form of course guidance addresses the limitations of conventional pre-fieldwork materials, which are typically static and limited in scope, by providing a dynamic and multi-faceted preparatory experience.



Figure 3: Example of a Realistic 3D. The view can be rotated 360 degrees by dragging with the mouse.

4.2 Practical teaching design and demonstration

Using this system, course leaders can construct tailored teaching modules by designing diverse geological scenarios online, shown as Figure 4. The top left ‘Layer Resources’ panel lists 3D models, imagery maps, contour lines, sites, routes. The bottom toolbar provides options refresh, marker placement, screenshot capture, zoom, view reset, etc. The highlighted route illustrates the practical line of practice with triangles showing observation points. Users may view the specific details of each location by clicking on it.

Course leaders can design and display different classes of geological profiles, including regional standard profiles, magmatic body profiles, metamorphic facies profiles, and sedimentary facies profiles. This helps students better comprehend lithological variations and tectonic evolution across different geological contexts.

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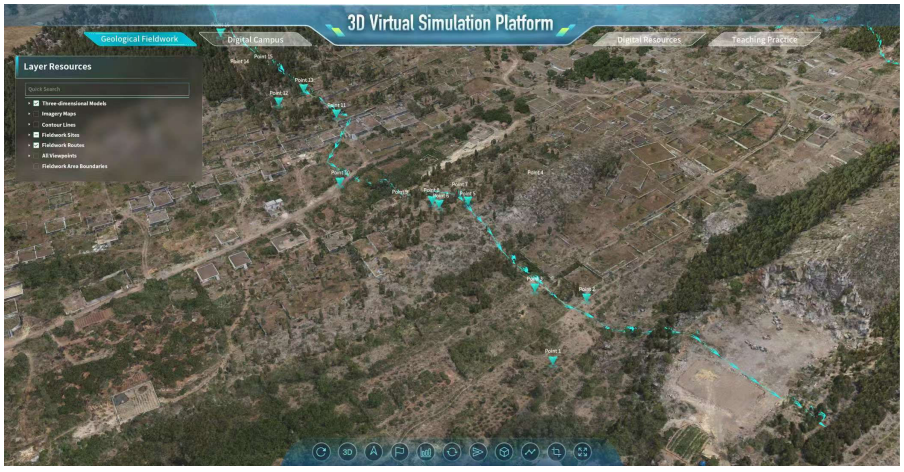


Figure 4: Display of geological profiles for course teaching practice.

Furthermore, the system models a broad spectrum of geological and tectonic features, from the large-scale Tan-Lu Fault Zone to the medium- and small-scale structures of the Xuzhou-Suzhou Arc Belt, thereby improving student understanding of structural complexity. In mineral and ore deposit instruction, teachers can also systematically display typical deposit types—such as metallic, non-metallic, and energy resources—to provide a multi-dimensional perspective on their formation and distribution.

4.3 Enhance practical skills through simulated exercises.

The system simulates various typical geological environments, containing complex units such as faults, folds, stratigraphic sequences, unconformity surfaces, and intersecting rock veins. By interacting with accurate models in the virtual scene, students can intuitively observe geological formations in 3D and conduct detailed discussions and analyses, thereby enhancing their comprehension of geological phenomena.

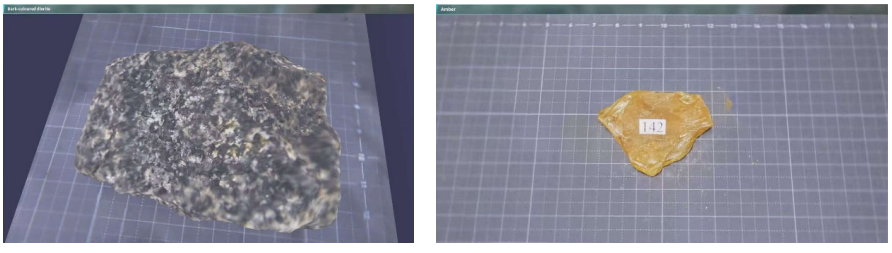


Figure 5: 3D digitalised rock and palaeontological specimens observed using the platform.

The system includes three-dimensional digital specimens of various minerals, rocks, and palaeontological specimens. Students can use these specimens for training in mineral identification, lithological recognition, and paleontological analysis, as

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illustrated in Figure 5. Furthermore, the platform enables students to draft geological sections and maps, simulating common tasks encountered in actual field exploration, thereby improving their cartographic skills and field operational competence.

4.4 Establishing a new student evaluation system through the platform

We have identified several issues by using the existing student evaluation system.

(1) The evaluation content is relatively subjective. Since different teachers instruct different classes to practice, it is easy to form overall differences between classes due to the different evaluation standards of different teachers.

(2) Low differentiation of student completion. The same class is guided by the same teacher, and the content of the course leader's dictation recorded by the students is largely the same, so the content of the final internship record book and internship report formed by the students is largely the same.

(3) Low degree of digitalization of results. For a long time, the internship records, internship reports and geological maps formed by students are all submitted in the form of paper content. However, such paper information is difficult to summarize, count and integrate, and will even be erased within a certain period of time, losing the possibility of secondary analysis and utilization.

By utilising the virtual resources and functionalities of our platform, course leaders can conduct more comprehensive student evaluations. Table 1 outlines the evaluation methods currently in place.

The new evaluation system incorporates objective quizzes, which collectively account for 40% of the total grade. Upon completion of the course, students upload all practical materials, including the internship record book, report, and geological map, to the practical data management system. The system stores these documents according to student identification numbers. This approach effectively addresses the limitations of traditional paper-based submissions, which were difficult to preserve, manage, and evaluate consistently. It also enables the long-term storage and potential reuse of internship data.

Table 1: A new evaluation system built upon the platform.

Evaluation contents		Percentage of evaluations
Internship record book		15%
Internship report writing		15%
Tests	Basic geological background test	15%
	Lithological palaeontological identification	15%
	Field measurement test	10%
Geological mapping	Field geological mapping	10%

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	Tectonic outline map	10%
	Column chart of geological ages	10%

5 Results

5.1 Platform engagement

Table 2 shows the platform engagement statistics by hours from 226 students. The first row of data represents the time spent by students throughout the entire course; the second row indicates the time spent by students on the preview module, which was entirely self-directed with no stipulated duration; the third row of data reflects the time spent using the platform during classroom sessions alongside teacher instruction.

Table 2: Student online duration statistics table. Levels 1-5 denote varying durations of use, as per the 5-point Likert. The first question's levels 1-5 correspond to 0-2 hours, 2-4 hours, 4-6 hours, 6-8 hours, and over 8 hours respectively; The second and third questions' levels 1-5 correspond to 0-1 hour, 1-2 hours, 2-3 hours, 3-4 hours, and over 4 hours respectively. The specific correspondence can be viewed via the provided questionnaire.

options / questions	Level1	Level2	Level3	Level4	Level5
Total hours of platform use	0	0	13.3%	32.3%	54.4%
Hours of preview use	6.2%	11.5%	23.0%	31.4%	27.9%
Hours of teaching use	0	0	0	33.2%	66.8%

(1) The hours of teaching use are highly concentrated in levels 4 and 5 (33.2% and 66.8% respectively), with the actual hours of use in the corresponding scales exceeding 3 hours. This concentrated distribution mainly stems from the systematic drive of course leaders' instructional design, which can reflect that the platform is widely used by course leaders in teaching, and course leaders can use the platform to achieve a better display of the teaching effect in the process of teaching, simulating the dynamic evolution that can not be simulated or observed in the field, so that the hours of instructional use in the feedback from the students show a high value.

(2) The distribution of teaching hours shows a spindle-shaped structure of high in the middle and low at both ends. It is mainly concentrated in level 3 (23%), level 4 (31.4%) and level 5 (27.9%), while the number of students in level 1 and level 2 is relatively small. On the one hand, it may be due to the fact that the introductory part is completed by students independently, and some students may not adapt to the online introductory learning method, and there may also be 3D vertigo, so students

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may complete the introductory tasks in their own accustomed way; on the other hand, it is the fact that the introductory tasks are not too many, and students can complete the introductory content through the platform relatively quickly.

(3) Regarding the total duration of platform use, the data is highly concentrated in level 4-5 (86.7%), which can reflect the overall long duration of students' guiding and course leaders' teaching. However, based on the above analysis, it can be concluded that a large part of it is still the effectiveness of course leaders' teaching, and the length of platform use for teaching is greater than that for guided learning. Reflecting that the course tasks of teaching are relatively more relative to the learning tasks of guided learning, it can be considered that some shallow teaching tasks are classified into guided learning, encouraging students to complete them more independently and flexibly.

5.2 Learning effectiveness

Fieldwork assessment results were collected for students from the 2022 and 2023 cohorts, comprising 232 students from the 2022 cohort and 226 students from the 2023 cohort. Owing to the differing cohort sizes, analysis was conducted using the percentage of students within each score bracket.

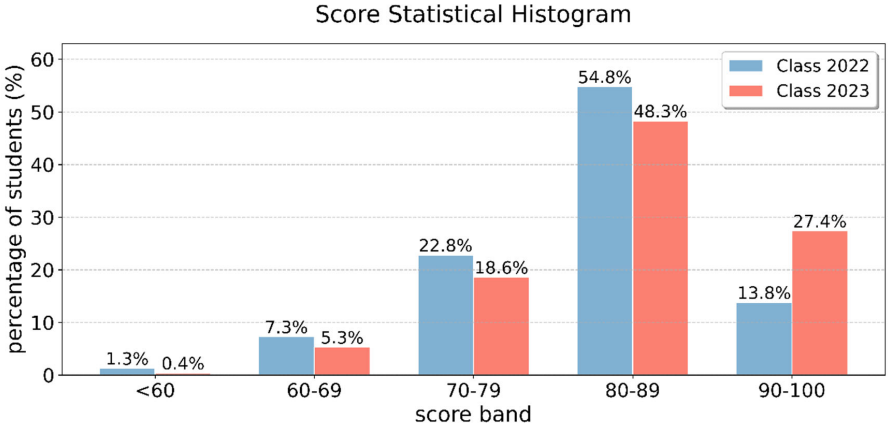


Figure 6: Histogram of field geology practice scores for students in classes 2022 and 2023.

A histogram depicting the field geology practice scores for the 2022 and 2023 cohorts is presented in Figure 6. Regarding the core score distribution, the 2022 cohort exhibited a pronounced single-peak structure, with 54.8% of students concentrated in the 80–89 band, accounting for over half of the total cohort. The 2023 cohort exhibits a more balanced distribution, with the 80-89 band decreasing to 48.3%. Conversely, the 90-100 band significantly increased to 27.4%, becoming the second largest segment. This indicates a marked expansion of the high-scoring cohort, shifting the distribution from a 'right-skewed single peak' towards a 'bimodal near-normal distribution'. In the lower score brackets, the contrast between the two cohorts is equally pronounced: the proportion scoring below 60 points decreased from 1.3% in the 2022 cohort to 0.4% in the 2023 cohort,

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rendering the failure rate virtually negligible; the proportion scoring 60-69 points fell from 7.3% to 5.3%. Notably, while the proportion scoring 70-79 points in the 2023 cohort 18.6% slightly decreased from 22.8% in the 2022 cohort, this was offset by growth in the high-scoring segment. This indicates a reduction in the lower-middle group and an expansion of the high-achieving cohort.

Pearson's correlation coefficients were calculated for the class of 2023 for the total number of hours of use of the platform, the number of hours of use during the guided learning period, and the number of hours of use during the instructional period, which were 0.393, 0.604, and 0.268, respectively. The above correlation coefficients showed that the highest correlation coefficient was found for the number of hours of use of the platform during the guided learning period (r=0.604), presenting a significant moderate positive correlation, indicating that the students' independent learning input has a strong predictive power for performance improvement. The bimodal distribution of teaching hours leads to a lack of dispersion, and this extreme concentration essentially forms a quasi-constant variable, which greatly weakens the validity of the statistical test. However, the effectiveness of instructional platform use can be reflected as an overall rise in student achievement.

5.3 Student satisfaction

The questionnaire gathered usage feedback from 226 students utilising the platform. Q 4 to Q6 concerned personal assessments of how platform usage enhanced learning; Q7 to Q9 addressed the comprehensiveness of platform features; Q10 focused on the evaluation system; Q11 measured satisfaction with the user interface; and Q12 assessed willingness to continue using the platform.

Calculated from the 226 statistical questionnaires, this study's Cronbach's α reliability coefficient was 0.801, significantly exceeding the 0.7 threshold standard. This indicates the scale possesses high internal consistency when measuring ‘platform usage feedback’. Theoretically, an α value between 0.8 and 0.9 is considered good, supporting the reliability of research conclusions. Practically, this result validates the scale's design rationale, as items focus on two core dimensions – ‘learning facilitation effectiveness’ and ‘functional completeness’ – effectively capturing users' core platform experiences.

Frequency distributions and variances across items reveal significant differences in user feedback. For instance, Q12 exhibits the lowest variance at 0.349, with all respondents selecting ‘Agree’ or ‘Strongly Agree,’ indicating robust user retention. However, this extreme positive skew may obscure underlying issues. Conversely, Q7 displays the highest variance at 0.526, with 44 neutral responses accounting for 19.5%. Combined with open-ended feedback, this suggests some users harbour

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concerns regarding the personalisation of tutorial content or operational convenience. Furthermore, neutral feedback accounted for 18.6% of responses to Q10, highlighting the need to address transparency and fairness in evaluation criteria.

Overall, student perceptions of the platform exhibit a pattern of 'broad endorsement with localised variations'. Core functional value receives strong affirmation—over 90% of students acknowledge the learning-enhancing role of teaching and exercise modules (Q5, Q6, Q8, Q9), with willingness to continue usage (Q12). This indicates the platform has preliminarily established a positive learning cycle encompassing 'preview-teaching-exercise-evaluation'. However, fragmented experiences in certain modules warrant attention: neutral feedback on the guided learning function (Q7) and evaluation system (Q10) approached 20%, indicating a disconnect between these components and students' actual needs. Further investigation and refinement are required.

6 Conclusion

This study verifies the significant promotion effect of 3D reality and virtual simulation technology on geological practice teaching through the application of the 3D VR field geology practice platform and the construction of the whole process practice teaching system of 'introduction-teaching-exercise-evaluation'. Comparing the scores of students of Class 2022 and Class 2023, it is found that students' practical scores have been significantly improved after the application of the platform, and the proportion of students with high scores (90-100) has nearly doubled, and the independent exploratory behaviors of the introductory module have a significant positive correlation with the improvement of scores, which indicates the key role of immersive teaching in the cultivation of spatial cognitive ability. The student satisfaction survey shows that 93.4% of the participants believe that the platform is helpful to their own learning and are willing to use it continuously, but some students believe that the adaptability of the guided learning content and the fairness of the evaluation system still need to be optimized. In the future, the development of technology should focus on multi-scale dynamic modelling, AI-assisted decision-making (e.g., intelligent identification of minerals) and collaborative observation by robots, as well as the promotion of cloud sharing of educational resources and the construction of an open-source ecosystem. This study provides an innovative path to break the traditional geological teaching dilemma, and lays a practical foundation for the integration of artificial intelligence, extended reality and other emerging technologies into geology education.

Code and data availability

The materials and relevant code for platform construction can be found in the GitHub repository: https://github.com/LiuYuhang321/3DSimulation-Web/tree/master.

Information regarding the platform's setup environment can be found in the Readme file. Similarly, contact details are

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provided within the Readme file.

The research survey data collected in this paper will be made available on request.

Ethical statement

This study was conducted as part of a routine teaching reform and educational evaluation activity. The questionnaire and platform-use data were collected from students who had participated in the field geology practice course. Participation in the questionnaire was voluntary, and the data used for analysis were anonymized and reported only in aggregate form. No sensitive personal information was collected, and no intervention beyond normal teaching activities was introduced. Therefore, formal institutional ethical approval was not required under the authors' institutional policy for low-risk educational evaluation research. The study followed the principles of informed participation, confidentiality, and responsible use of educational data.

Author contributions

HY conceptualized the study, curated the data, validated the results, prepared the visualizations, wrote the original draft, and reviewed and edited the manuscript. YL developed the software, conducted the investigation, and reviewed and edited the manuscript. JW curated the data, administered the project, and reviewed and edited the manuscript. GF, YZ, and LC reviewed and edited the manuscript. HT provided resources.

Competing interests

The authors declare that they have no competing interests.

Financial support

This work was supported by the following funds:

The Fundamental Research Funds for the Central Universities (2024ZDPYCH1002)

Key Project of Jiangsu Province Degree and Graduate Education Teaching Reform Research (JGKT24_B039)

Key Project of Jiangsu Higher Education Society (2024JSGJ10)

Key Sub-Project of China University of Mining and Technology Teaching Research Project (2023ZDKT03-103)

https://doi.org/10.5194/egusphere-2026-4843
Preprint. Discussion started: 30 September 2026
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