Development of an Immersive Visualisation System for the 3D Learning of Complex Rock Structures

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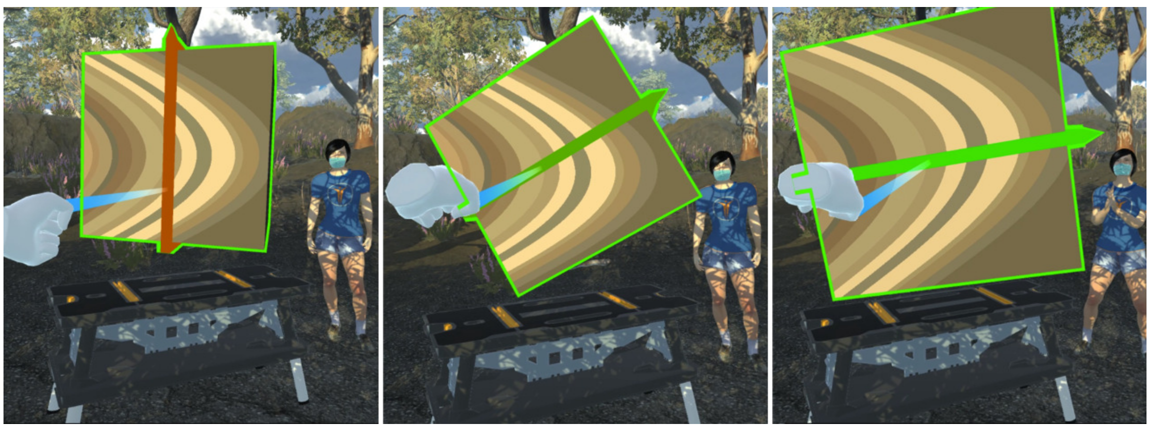

Fig. 1. A geological fold visualisation is being manipulated in the VR environment as part of a lesson. As the hand twists the cube, it alters the plane of observation until it matches the fold profile plane, indicated by the alignment bar turning green.

Geological folds are complex wave-like 3D deformation structures. The identification and measurement of characteristic geometric elements of folds (e.g., wavelength, amplitude, orientation of fold axis and fold axial plane) in rocks constitute core skills of field-based Earth scientists and prove to be challenging teaching topics for novice undergraduate geologists. This paper presents an immersive, interactive VR tool for visualising geological folds for educational purposes. We describe a novel geological folding visualisation system, designed to scaffold students in learning this complex spatial concept. Through a user-centered design with geologists, a new tool for digitally visualising geological folds for low financial and computational cost was developed. We describe its major components and visualisation approach, along with its interaction approach for providing fold visualisations. We further report findings from a usability testing (N=11) and report future design considerations.

CCS Concepts: • **Human-centered computing** → **Interactive systems and tools**; Virtual reality; • **Computing methodologies** → *Computer graphics.*

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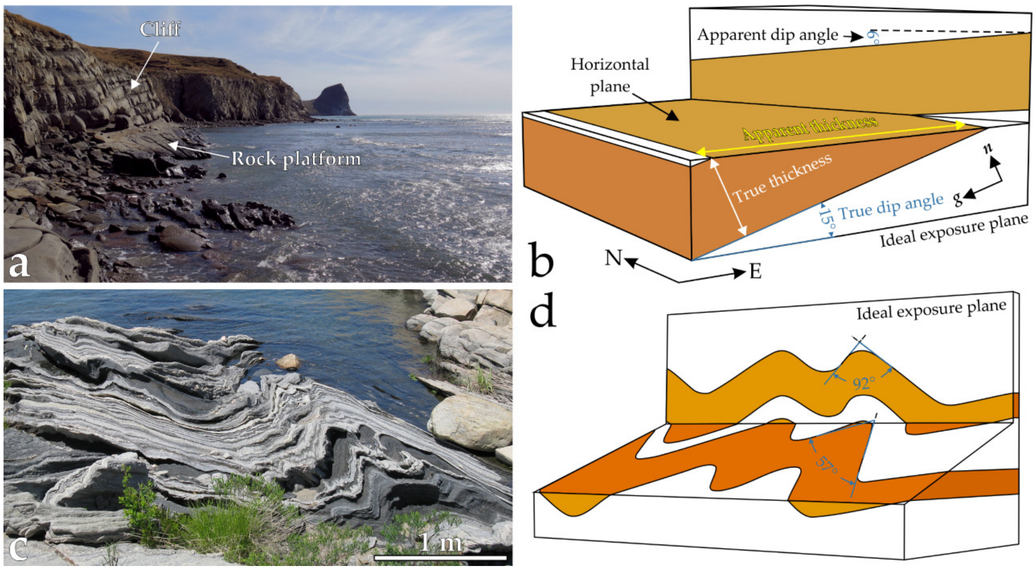

Fig. 2. (a) Coastal exposures of layered sedimentary rocks, ca. 3 km SW of Castlepoint, New Zealand. Layers appear very different on subvertical cliff and rock platforms. (b) Sectioning effects leading to the apparent-thickness and apparent-dip problem. The sketch shows an orange layer of "rock" embedded in unlayered "white rock", dipping with 15 degrees to the W. The ideal exposure plane is spanned by the unit normal vector to the plane n and a vector g, which is parallel to the dip direction of the plane. Exposure in the ideal exposure plane reveal true dip angle and layer thickness. In all other sectioning planes, layer thickness appears exaggerated, and layer dip angle is underestimated. (c) Complex folds in gneisses of the Parry Sound Domain, Ontario, Canada. Folds with wavelength between 0.5 and 2 m are most obvious. Some layers display folds with cm-scale wavelength. (d) 3D model of a two-layer fold train. Both folded (orange) layers have the same geometry. The vertical ideal exposure plane reveals the correct fold geometry of the upper layer. The lower fold layer is exposed on a gently inclined surface where the fold opening angles appear smaller, the amplitudes larger, and the layer thicknesses exaggerated. No folds are visible in the vertical plane on the right-hand side, which is perpendicular to the ideal exposure plane.

1 INTRODUCTION

One of the most difficult concepts for undergraduate students in Earth science is the challenge to visualise, analyse, and geometrically classify complex 3D geological bodies that, in nature, are usually exposed in 2D sections (road cut, rock platform, cliff, rock face) only (Fig. 2) [3]. Any true 3D volumetric model of real rock bodies must generally be reconstructed from several 2D exposures. The only exception are volumetric imaging methods such as 3D seismic imaging (at the scale of 10's to 1000's of metres [2]) or computerised tomography with X-rays (at the scale of centimetres to micrometres [6]). However, these methods are expensive, difficult to use, and usually not accessible to field geologists, let alone undergraduate students.

2D sections through 3D geological bodies are rarely truly 2D. Most naturally exposed rock faces exhibit local 3D surface topography (Fig. 2a, c). Exploiting this fact, geologists developed several geometric methods that allow practitioners to derive 3D information. In addition, they must have awareness of geometric sectioning effects (Fig. 2c, d) which arise when an outcrop surface cuts a 3D rock body such that geometric elements of interest do not appear in their true form. The simplest example of sectioning effects, usually taught in first year of the undergraduate curriculum, relate to the apparent thickness and apparent dip angle of planar-layered rocks (Fig. 2b). Sectioning effects become even more problematic when layered rocks are no longer planar but are deformed (Fig. 2d).

The development of this tool aims at improving the teaching and understanding of 3D geometric sectioning effects in undeformed and deformed layered rocks in a virtual reality (VR) module. Prior studies showed that VR can provide effective visualisations when teaching geology concepts and can improve accessibility by providing *in-situ* experiences to students who might not be able to attend geology field trips [4, 7, 10].

Layered rocks are common in the Earth and form due to sedimentary (Fig. 2a) and tectono-metamorphic processes (Fig. 2c). The orientation and thickness of planar layers constitute the most fundamental geometric properties of layer stacks Earth scientists need to measure. Fig. 2 illustrates how geometric sectioning effects can render this process challenging. If layered rocks are deformed, this challenge is exacerbated. Folds belong to the most common principal deformation structures encountered in layered rocks (Fig. 2c, d). When they are exposed in non-ideal sections, geometric properties such as wavelength, opening angle, amplitude, etc., change dramatically (Fig. 2d). In certain sections, folded rocks might even appear undeformed (Fig. 2d).

1.1 Existing Methodologies

When teaching these complex geometric concepts to undergraduate students, the best available and most commonly used teaching methods include abstract visualisations using 3D graphing software (Fig. 3), viable hand samples, 2D images of rock outcrops, or analogue deformation experiments [5]. Digital visualisations are often too simple, only showing abstract elementary trigonometric functions, possibly on oblique angles, while real rock examples may be too complicated to keep students on a stable learning trajectory. Moreover, hand samples are static (one cannot change the exposed sections or look inside the sample) and usually not available in large quantities for interaction with and assessment of large classes. Both factors limit student learning and assessment opportunities. If the same 5 practice samples are used for years, students learn to identify individual samples rather than the generic characteristics associated with folds in general.

Furthermore, hand samples do not exceed tens of centimetres in size while folds occur on scales of up to 100's of kilometres. These large structures are examined *in-situ* (in the field) and cannot be moved or removed to examine the underlying fold patterns. In many cases, due to laws or restrictions established by time, finance, or ethics, geologists are unable to split samples into smaller pieces, or remove samples from a larger outcrop. Consequently, viewers of the visible outcrop cannot necessarily visualise the layers from different perspectives, which increases the difficulty of explaining the concept.

Despite these limitations, there are some benefits of the aforementioned methodologies. These include inter-student interaction and use of multiple senses (tactile contact with rocks, for example). Any solution to the problems outlined should either supplement the current methods or aim to replicate the advantages of each. These considerations will not be included as a part of the study outlined in this paper, but may be the subject of a future investigation.

Thus, the problem is threefold; first, the visualisations are generally limited between simple and complicated, without any intermediate options. Secondly, hand specimens available to a teaching department are few in number. Lastly, the

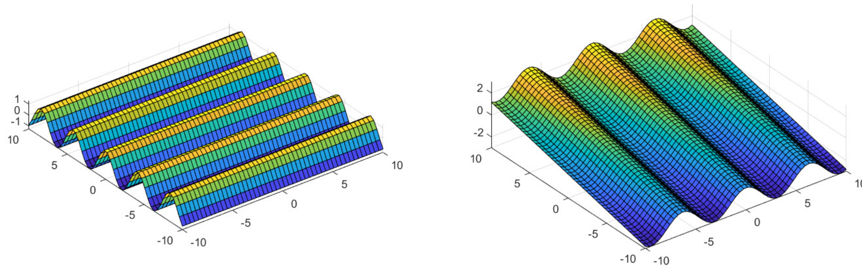

Fig. 3. Fold examples using current 3D modelling software.

available samples may not have useful perspectives from which to view the folds. A solution to these issues must offer at least intermediate complexity for visualising different deformations of rock layers, while also allowing simple and financially and computationally inexpensive creation of a large quantity of visualisations. These visualisations should allow adjustable predetermined or randomised differences for the creation of many samples, and be customisable in the visible angles of the folds. In this paper, we present the development, implementation, and a usability test of such a novel tool that will aid geology students' understanding of complex rock structures.

2 FUNCTIONALITY

In essence, the implementation is a complex form of rendering, utilising real time shader systems within the Unity 3D Game Engine [1]. These shaders enable arbitrary coloration in real time of the surface of geometry utilising programs compile to the GPU (Graphics Processing Unit) [1]. These shader programs implement rendering algorithms to affect the appearance of the world's geometry under the control of passed parameters utilising so-called surface materials.

A tool was designed to solve the problems outlined above in the introduction. An iterative development approach resulted in a shader, written in HLSL for Unity's ShaderLab, and a manager written in C#. The solution accepts a collection of colours and an ordered list of height limits between which to draw a layer. Since the rock layers should be accurate across multiple meshes in different positions throughout the environment, the shader uses the mesh's world coordinates (viz. their positions after being transformed into the virtual world). This ensures consistency between any number of samples that use the same data in a single environment, no matter the distance between them. That is, the same visualisation will be displayed regardless of an object's position, rotation, or scale, as if existing in the space itself.

Dynamic layer visualisations (i.e. updating the appearance based on world position) are also important for user experience and interaction. One of the major intended uses of the tool is for the user to find the correct angle from which to view the fold structure. Using dynamic visualisations allows the user to spatially manipulate an object until its correct viewing plane is visible. However, the tool can also be used to create static rock visualisations, such as would be found in in-situ environments. Static visualisations introduce a higher degree of challenge for users, as the sample cannot be rotated to view the folds from a better angle.

[1]Unity 3D Game Engine - www.unity.com

2.1 Parameters and Effects

Folds: The texture input governs the widths and colours of each layer, but cannot formulate geological folds. For teaching purposes, folds are commonly represented by trigonometric waves; as such, the method for depicting folds involves deforming the layers collectively with trigonometric functions. This is accomplished by adding a displacement to the layer height threshold, governed by the sum of sine and cosine waves. Applying these trigonometric functions creates a wave pattern (reminiscent of geological folds) on an object, most clearly visible on the border between layers.

For transparency, the deformation equation is listed below, where each of a, A, b, B, c, C, d, and D are parameters set by the user to shape the folds, and x, y, and z are the object's world position in Cartesian coordinates:

$$\text{Height Threshold} = y + a\sin(Ax) + b\cos(Bx) + c\sin(Cz) + d\cos(Dz)$$

Static Visualisations: For the visualisation to retain a permanent appearance and match the visual behaviour of natural rock samples, the coordinate reference is adjusted. Since the visualisation is determined by the object's position in space, it can theoretically be simulated from a different location, provided that the source position coordinates are known. I.e., the visualisation references a fixed position, rather than the object's world location. This creates the effect of a static visualisation of the rock strata, unchanged by the object's position, rotation, or scale.

Layer Transformations: More complex rock visualisations can be created by applying transformations—most significantly, rotations—to the layers. Applying transformations to the visualisation is a simple technique to achieve more complicated samples. The transformations are applied in matrix form to the object's position reference. This transformation affects only the depiction of the visualisation, and not the object itself. By including an offset position, rotation, and scale, the possible results grow in number and diversity.

2.2 Final Outcome

The final tool enables digital representations of geological folds in layered rocks. The folds are adjustable in all of: the height and colour of each layer; the shape and size in the x and z directions; the position, rotation, and, scale; and the static or dynamic nature of the visualisation. This final tool is embedded in a VR environment for usability testing.

3 TOOL IMPLEMENTATION

The fold visualisation tool is embedded in a VR module that aims to teach users about folds in a generic nature setting. The module has a virtual instructor who narrates what folds are, and some key related terminology including the profile plane which is the ideal plane in which to observe the fold shape, perpendicular to the fold axial plane.

In Unity, the shader is utilized in both its dynamic and static form depending on user requirements. This process involves having specific fold parameters in mind and adjusting the shader values to match as closely as possible. For example, a relatively vertical but also plunging fold found mostly along the Z-axis in Unity world space requires a deliberate setup and adjustment of a separate Unity material's properties, utilizing the shader. After this, the shader can then be placed upon an object in Unity, such as a cube in dynamic format, containing the manually generated fold. The cube can be rotated, allowing the user to view the sample's folds from any angle via the cube's planar surfaces. This reveals how folds can look from different vantage points and cross sections, which is not information typically permitted to geologists in the real world.

The fold visualisation tool is used to illustrate non-ideal planes of observation, and utilizes a dynamic version of the layering shader created specifically for this purpose as described above. Users are required to manipulate the sample,

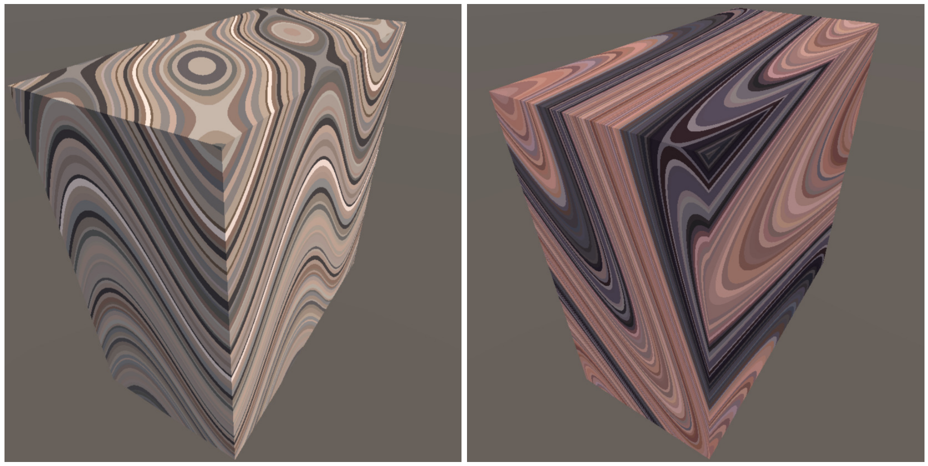

Fig. 4. Examples of possible fold visualisations using the technology outlined above. Note the counter-intuitive 2D outcrop pattern on the horizontal surface in the left example. It is not obvious to the novice that these patterns derive from a simple sinusoidal wave.

altering the plane of observation until it matches the fold profile plane (Figure 1). This is performed by 'grabbing' the sample with a controller and rotating it as if the user were holding it in their hand. In the background, this is achieved by the matching of the tool forward vector to that of the sample, which is pre-defined during initialization. A large visual indicator of the axial plane is utilized here to denote the front and top of the sample, and diffuses from red to green depending on how close the user is to the solution. Haptic feedback via controller vibration provides an additional indication of solution proximity.

Upon correctly finding the sample profile plane, the sample becomes locked and 'static' to be moved freely about the scene. The virtual instructor then instructs the user to drop the sample upon an existing empty rock outcrop where the folds are then displayed (Figure 5). The user is tasked with repeating this process two more times, finding the profile plane of samples with increasing complexity and fold diversity. Upon fully completing the module, the user is then allowed to freely roam and observe multiple interesting fold samples spawned into the environment, which are inspired by real-world examples.

4 USABILITY TESTING

The aim of the usability testing outlined below is to find preliminary results about ease of use for the tool, controls, interactions, and sequencing. These results will be used via a user-centred approach towards its development as a teaching tool. Future studies will investigate the efficacy of the tool compared to traditional pedagogy. As such, the sample group, results, and conclusions described in this section are somewhat limited compared to a full evaluation of the tool feasibility in educational geology spaces.

The tool was tested with 11 users following the procedure described above. The entire experience is about 15 minutes in length. Three participants were geology students, one was a graduate student working with geologists. The remaining were novice participants. Seven participants identified as male and four as female. The age range was between 19 and 39. They were asked their experiences with virtual reality and video games (1 - Not at all; 5 - Extremely familiar).

During the manipulation task, the researcher made observations on how the users interacted with the tool. If they had any issues, the researcher asked them to talk aloud about what they were doing to understand their experiences.

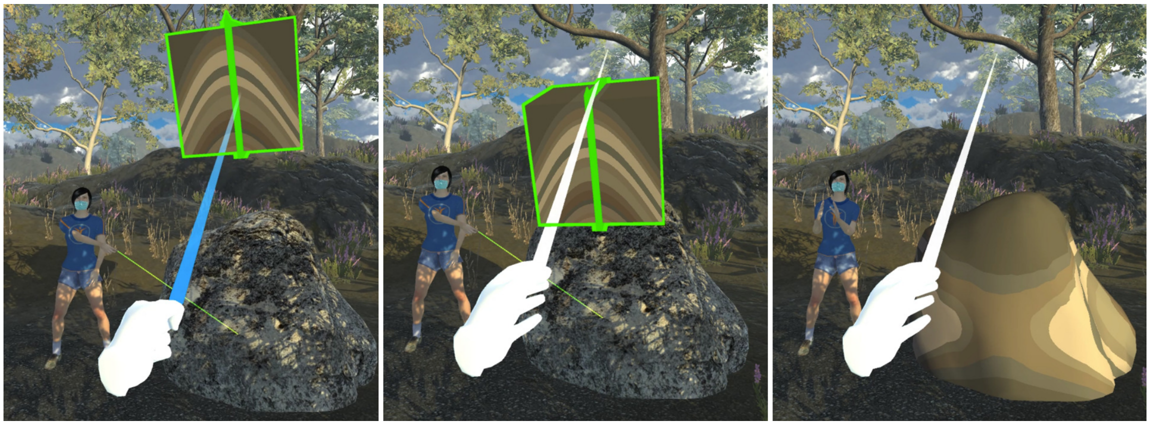

Fig. 5. User drops the tool on a blank rock to obverse its effect as folds

After they complete the module, the researcher asks the participants to talk about their interactions with the tool, which is followed by a short usability survey (see the instruments below). One participant, a geology student, did not complete the survey due to time constraints.

Usability questionnaire: Using a 5-point Likert scale (1 - Not at all; 5 - Completely), participants rated aspects of the VR training in five items: “I could see the images clearly”; “I could read the text clearly”; “I could hear and understand the voice narrator”; “I could interact with the display in a straightforward way”; “I could move around easily.”

User Satisfaction Evaluation Questionnaire (USEQ): We used a modified version of the 5-point Likert scale questionnaire with five items to evaluate users' satisfaction of the VR training [8]. The questionnaire included items such as "Were you successful using the system?"

Simulator sickness: In a 5-point Likert scale question (1 - Not at all; 5 - Extremely), participants were asked “During your VR experience, did you have any symptoms of simulator sickness (e.g., nausea, dizziness, headache, blurred vision, vertigo, dizziness)?” If they selected any option other than 'Not at all', they were asked to specify their symptoms.

Enjoyment: Participants' enjoyment was measured using the Intrinsic Motivation Inventory (IMI; [11]). This scale has seven, 7-point Likert scale items (1 - Not at all; 7 - Extremely) that ask the users to indicate how much they agree with a statement (e.g., ”I enjoyed doing this activity very much.”, ”This activity was fun to do.”).

4.1 Findings from the usability testing

Participants rated the usability aspects moderate to high. They indicated they could see images clearly (M=4.2, SD=.92); they could move around (M=3.6; SD=1.35) and interact with the tool in moderate ease (M=3.4; SD=1.58); had minimal discomfort (M=1.5; SD=.71). Those who had discomfort stated they felt slightly dizzy. The average user satisfaction was 3.9 (SD=1.06). Among the six items of USEQ, the lowest score was with the control of the interactions (M=3.2, SD=1.2). Still, they reported high enjoyment of the interactions (M=5.54, SD=1.61).

Participants liked observing how folds would look when in a rock face, and appreciated the guidance on the orientation when identifying the fold profile plane. One of the geology students said "Being able to see usually large deformation structures at a small scale is nice, and convenient." Another stated, "The red-to-green shading was very helpful in guiding orientation of the blocks." They also talked about some of the challenges using the tool. They indicated it would have been useful to visualise axes and use those to rotate the cube to a specific orientation, and a need to make the direction of rotation more intuitive. Given some participants were novice VR users, and getting used to the control could take time, they had difficulty with the sensitivity of the correctness of the fold profile plane which could be made more generous. Another issue was that when the cube turns from dynamic to static, it could appear inside users' personal space thus causing dizziness. Some also had further difficulties with controllers - e.g., using a joystick to rotate their avatar, but that would cause the user to drop the cube, which would reset their progress with the rotations. Participants remarked that position of the cube was quite high where they could not see all the sides making the task difficult.

5 FUTURE DESIGN CONSIDERATIONS

Noise: The layer visualisation works well to demonstrate a fundamental concept in geology; however, it does not allow for complex (and hence, more realistic) examples of layer arrangements. Noise is often used in computer graphics to simulate semi-realistic randomness, and special functions—like Perlin Noise [9]—are described as 'pseudo-random'. Applying this technology could offer additional complexity and realism to the tool, which could be helpful for more advanced students, or for professional use in replicating realistic samples.

Layer Manipulation: The current model does not allow manipulation of the layers on a micro-level besides non-uniform thicknesses and colour variations. A typical fold on a realistic geological sample may not have uniformly deformed layers (Fig. 2c) because of heterogeneity of layer thickness and mechanical properties. To achieve a higher degree of realism or complexity for the visualisation, properties like reflectivity, texturing, lighting, shape, and more could be applied on an individual layer basis. This would provide some uniqueness between layers on the same sample, and offer more flexibility for the needs of a wider base of users.

5.1 User Interface

GUI and User Friendliness: In future iterations, instructors will be able to manipulate the parameters of the tool (for example, modifying fold height, randomising features, etc.) in real-time to demonstrate how advanced geological processes may alter the shape of the rock layers over time, or to generate more samples without needing to exit the application. The graphical user interface would be either diegetic or spatial in the environment (though the same concepts would apply for a desktop version) to be easily used in a VR setting.

Improving Interactions in VR: We found that while participants enjoyed interacting with the tool, they had some difficulties with it. There are multiple simple ways to improve their user experiences. These include making the direction of the rotation more intuitive (e.g. holographic cube above controller, arrow indicators); reducing the sensitivity of the correctness, at least for the initial sample manipulation to scaffold their interactions; and providing an option to "solve" the cube if they had too many problems with the rotations and interactions.

6 CONCLUSION

This paper presented the development and implementation of a novel tool to visualise complex rock structures that aimed at university level geology students. The research team worked with a geology instructor throughout the iterative development and implementation of the tool. User testing with 11 participants showed that while the tool was enjoyable to both geology students and novices, we found multiple ways to improve the interactions with it, including more intuitive controls, spatial indicators, and object positioning. Future iterations will focus on improving the usability to get it ready to be used as a teaching tool for geoscience.

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