Analogue modelling to enhance spatial reasoning and understanding of tectonic processes in geoscience education

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Abstract

Analogue modelling offers a powerful means for communicating and understanding geological processes that operate across spatial and temporal scales beyond direct human observation. Despite its long-standing use in tectonic research, its application as a pedagogical tool in geoscience education remains limited. This study presents a collaborative teaching approach that incorporates physical models to strengthen spatial reasoning and support the interpretation of three-dimensional geological structures in university-level geoscience education. We outline the role of representations and spatial abilities in geology and other sciences, provide a brief overview of analogue modelling in the Earth Sciences, and present the theoretical framework, instructional design, and results of two analogue-modelling activities implemented in Structural Geology laboratory courses for engineering students at the Universidad de Santiago de Chile. The activities focus on brittle deformation and fault-related fracture systems, processes central to Andean tectonics that require strong three-dimensional and temporal reasoning skills. Insights drawn from student feedback and observed learning outcomes highlight the relevance of decision-making, model-based reasoning, and embodied interaction with evolving physical models that simulate geological systems. The findings indicate that hands-on physical modelling can serve as an effective tool for communicating complex geoscientific concepts and fostering spatial thinking skills that are essential for future geoscience and engineering professionals working in structurally complex orogenic settings such as the Andes.

Keywords: analogue modelling, spatial reasoning, geoscience education, structural geology.

Modelación analógica para fortalecer el razonamiento espacial y la comprensión de procesos tectónicos en la educación en geociencias. La modelación analógica es una herramienta poderosa para comunicar y comprender procesos geológicos que operan en escalas espaciales y temporales que van más allá de la observación humana directa. A pesar de su uso prolongado en la investigación tectónica, su aplicación como herramienta pedagógica en la educación en geociencias sigue siendo limitada. Este estudio presenta una estrategia de enseñanza colaborativa que incorpora modelos físicos para fortalecer el razonamiento espacial y apoyar la interpretación de estructuras geológicas tridimensionales en la educación universitaria en geociencias. Se describe el papel de las representaciones y habilidades espaciales en la geología y otras ciencias, se presenta una breve revisión de la modelación analógica en las Ciencias de la Tierra, y se exponen el marco teórico, el diseño instruccional y los resultados de dos actividades de modelación analógica implementadas en cursos de laboratorio de Geología Estructural para estudiantes de ingeniería en la Universidad de Santiago de Chile. Las actividades se centran en la deformación frágil y en sistemas de fracturas asociados a fallas, procesos fundamentales de la tectónica andina que requieren sólidas habilidades de razonamiento tridimensional y temporal. Los resultados obtenidos a partir de la retroalimentación de los estudiantes y de los aprendizajes observados destacan la relevancia de la toma de decisiones, el razonamiento basado en modelos y la interacción corporal con modelos físicos dinámicos que simulan sistemas geológicos. Los hallazgos indican que la modelación física puede constituir una herramienta efectiva para comunicar conceptos geocientíficos complejos y fomentar habilidades de pensamiento espacial esenciales para futuros profesionales de las geociencias y la ingeniería que trabajen en contextos orogénicos estructuralmente complejos, como los Andes.

Palabras clave: modelación analógica, razonamiento espacial, educación en geociencias, geología estructural.

1. Introduction

The need to strengthen three-dimensional and process-based understanding in STEM education has been widely recognised (e.g., Sorby *et al.*, 2014; Stieff *et al.*, 2016). In geosciences, this challenge is relevant because many fundamental processes operate in three spatial dimensions and evolve over geological timescales that are inaccessible to direct observation. In tectonically active regions such as the Andes, the complex geological history and strong influence on economic development, territorial planning, and risk management make this strengthening evident, especially for Earth Science and engineering students.

Understanding the geometry, kinematics, and temporal evolution of geological structures in active tectonic settings is not only an academic requirement but a professional necessity (Kastens and Ishikawa, 2006). The formation and deformation of a mountain range, the evolution of magmatic systems, and the generation of economically significant porphyry deposits, together with the presence of other tectonic and geodynamic processes, require a solid understanding of the relationships among three-dimensional structures at different spatial and temporal scales.

Various scientific disciplines face the challenge of modelling processes that occur in three spatial dimensions, often with a temporal component. External representations such as drawings, diagrams, physical models, and 3D simulations have proven to be valuable learning tools. However, the geoscience education literature has consistently shown that spatial thinking, understood as the ability to visualise, rotate, transform, and mentally manipulate three-dimensional objects, is a critical component for understanding complex geological phenomena, and that these skills require explicit training (Baenninger and Newcombe, 1989; Shipley *et al*., 2013; Gagnier *et al*., 2016; Jara *et al*., 2017). In structural geology, the capacity to visualise, interpret, and model complex geological structures represents a core professional competency. Promoting the robust use of spatial reasoning skills through active methodologies, such as analogue modelling, is therefore essential for the accurate interpretation of geological data and informed decision-making, particularly in countries whose identity and challenges are strongly shaped by dynamic Andean tectonics.

Although current technologies can enhance geoscience education through advanced digital visualisation tools such as Virtual Reality, which provide immersive learning experiences in interactive three-dimensional environments (Yang *et al*., 2023), physical analogue models offer complementary cognitive advantages. Physical modelling has been shown to support students' understanding of three-dimensional architecture and enhance spatial visualisation abilities more effectively than some virtual alternatives (Sun *et al*., 2014). This advantage is attributed to their embodied, manipulative, and exploratory nature, supporting hypothesis formulation and model-based reasoning.

The use of physical modelling tools in teaching has proven highly valuable for learners across a wide range of educational levels, from preschool to primary, secondary, and university students (Álvarez and García de la Torre, 1996; Pinto and Vergara, 2015; Vergara-Díaz *et al*., 2020). In university courses that incorporate structural geology topics, the use of analogue models allows direct observation of fault propagation, folding, strain partitioning, and the evolution of surface deformation, processes that are central to understanding the tectonic configuration of the Andes and other orogenic systems.

The purpose of this work is to present the analogue modelling activities developed in an upper-level undergraduate engineering program at the Universidad de Santiago de Chile, and to examine how this methodology contributes to students' understanding of key tectonic processes. By situating these activities within an Andean tectonic context, this study aims to contribute to the relatively scarce body of literature addressing the pedagogical use of physical analogue models in structurally complex orogenic settings and to highlight their value as tools that integrate three-dimensionality, temporality, and active learning in the training of future geoscience and engineering professionals.

The article also outlines the theoretical foundations supporting the use of analogue models in geoscience education, emphasising their role in strengthening spatial reasoning. As a practical example, it presents the instructional design, implementation, and observed outcomes of two modelling experiences focused on brittle deformation and fault-related fracture systems. To protect student anonymity and avoid any potential academic or professional bias, specific references to academic years, cohorts, or individual degree programs have been intentionally omitted. This ensures that the educational outcomes discussed here cannot be linked to individual students or specific generations, aligning with ethical considerations in educational research.

2. Background: use of representations and spatial ability

There is theoretical evidence supporting the advantages of using representations (e.g., drawings, diagrams, graphs, physical models) for learning in science, both for understanding the phenomenon or object under study and for improving spatial abilities. These visual skills are important not only in geology but also in other sciences, engineering, and the arts (e.g., Bolacha *et al*., 2012; Sorby *et al*., 2013). External representations function as cognitive tools that support the construction of internal mental models, making abstract relationships visible and reducing cognitive load during learning.

Previous research has highlighted that the development of spatial thinking is a critical predictor of disciplinary learning and that concrete models enhance representational competence and the understanding of spatial transformations (Stieff *et al*., 2016). Multi-institutional studies have revealed that students' spatial abilities, such as mental rotation, penetrative thinking, and complex spatial reasoning, vary widely and show only limited improvement without intentional intervention (Ormand *et al*., 2014). Shipley *et al*. (2013), for instance, emphasised the importance of recognising the range of students' spatial-thinking abilities and highlighted the potential for these skills to be developed through appropriate instruction. This view is supported by findings from cognitive science showing that spatial skills can be improved through training (Baenninger and Newcombe, 1989). In line with this, more recent studies have demonstrated that curricula explicitly designed to strengthen these skills produce sustained improvements in cross-sectional visualisation and other spatial abilities in geosciences (Ormand *et al*., 2017).

Shipley *et al*. (2013) and Shipley and Tikoff (2016) presented a framework for spatial reasoning that can support structural geologists in both teaching and research. Their framework includes recommendations grounded in cognitive science, building on the use of physical models. Likewise, literature has highlighted that external representations, physical, digital, or multimodal, can in fact facilitate the creation and revision of mental models, promote inferential reasoning, and enhance the understanding of structure-process relationships in the geosciences (e.g., Van Meter and Garner, 2005; Waldrip *et al*., 2010; Turner and Libarkin, 2012).

The temporal dimension of geological reasoning requires explicit consideration because geological processes unfold across timescales largely beyond direct human experience. Previous studies have shown that students often struggle to integrate spatial change with temporal duration, sequence, and rate, and that visual or dynamic representations may either support or hinder this reasoning depending on how they are designed and interpreted (Ainsworth and VanLabeke, 2004; Cheek *et al*., 2017; Myer *et al*., 2018; Ryker *et al*., 2018). In this sense, analogue models should not be understood as providing a literal experience of geological time; rather, their pedagogical value lies in making temporal ordering, progressive deformation, and cause-effect relationships observable within a scaled and simplified system. When accompanied by explicit discussion of scaling and geological time, dynamic physical models can help students reason about evolving geological processes without conflating laboratory duration with natural timescales.

Taken together, this body of literature provides a theoretical foundation for the use of analogue modelling as a pedagogical tool in geoscience education. By integrating three-dimensional geometry, temporal evolution, and embodied interaction, analogue models are therefore able to address key spatial and representational challenges.

3. Analogue modelling: a brief overview of its use in the Earth Sciences

The earliest analogue modelling experiments were carried out in the early nineteenth century. Hall (1815), through the construction of a modelling table, supported the hypothesis that natural folds in rock strata were the result of horizontal compressive stresses. Throughout that century, several naturalists made significant advances using analogue experimentation, highlighting the role of compressive forces in the formation of mountain belts (e.g., Cadell, 1889; Fig. 1).

Fig. 1. Cadell (1889) deforming layers of clay in a compressional system.

Various experimental set-ups were developed throughout the twentieth century to study different natural prototypes at scale. A fundamental advance in analogue modelling techniques was the introduction of scaling theory (Hubbert, 1937), which enabled analogue models to be used for quantitative rather than merely descriptive purposes, provided that geometric, kinematic, and dynamic similarity criteria were met. Before rigorous scaling, analogue experiments primarily supported qualitative geometric understanding of geological phenomena. The development of scaling methodology has enabled the study of systems in which model materials (e.g., Schellart, 2000) behave analogously to their natural prototypes, allowing deformational upper crustal processes to be reproduced properly in scaled experiments (e.g., Dahlen *et al*., 1984; Buiter, 2012). Although the classical Hubbertian approach remains foundational, analogue modelling also relies on similarity-based scaling strategies, in which material choice is guided by the capacity of analogue materials to reproduce key mechanical behaviours and deformation patterns of natural rocks rather than by strict one-to-one equivalence of all properties (Schellart, 2000; Reber *et al.*, 2020).

The use of diverse materials to simulate different rheological behaviors, together with a broad range of experimental set-ups, has enabled major advances in the analysis of complex tectonic settings, including doubly vergent thrust wedges (McClay and Whitehouse, 2004), basin inversion and fault reactivation (Del Ventisette *et al*., 2006; Bonini *et al*., 2012; Martínez et al., 2016), and brittle compressional wedge dynamics (Buiter, 2012). In Andean tectonics, analogue modelling has contributed to the study of orogenic curvature and fold-and-thrust belt development (Ghiglione and Cristallini, 2007; Jara *et al*., 2023), oblique inversion and inherited extensional structures (Yagupsky *et al*., 2008; Bechis *et al*., 2014), shortcut fault systems and depositional loading (Muñoz-Sáez *et al*., 2014), strike-slip deformation and rigid-block effects (Nalpas *et al*., 2011), along-strike structural variations and strain partitioning (Likerman *et al*., 2013), and the role of intrusive or mechanically competent bodies in fold-and-thrust belt deformation (Villarroel *et al*., 2021; López *et al*., 2025).

While analogue modelling has traditionally been associated with tectonic research, its pedagogical potential has gained increasing recognition over the last few decades. The same attributes that support scientific investigation also make analogue models effective for teaching and learning structural geology.

More recently, analogue modelling has been strengthened through the integration of data-acquisition technologies, its complementarity with numerical modelling, and the use of three-dimensional visualisation and digital reconstruction techniques. These developments have expanded the applicability of analogue models in research by improving the documentation, analysis, and comparison of experimental results (Buiter, 2012; Reber *et al*., 2020), while also broadening their potential as educational tools when combined with digital and immersive visualisation strategies (Turner and Libarkin, 2012; Yang *et al*., 2023).

4. Analogue modelling and learning in Structural Geology

4.1 Analogue modelling as a pedagogical tool in Structural Geology

Numerous analogue models have been developed within the Earth Sciences because geological processes operate across vast spatial scales, making direct observation impossible. Although some large-scale processes can be monitored, most geological phenomena occur over timescales inaccessible to direct observation. As a result, geoscientists have traditionally relied on models as essential tools for exploring, explaining, and teaching geological processes (e.g., Nersessian, 2008; Gogolin and Krüger, 2018).

In university teaching, geological processes are still often taught through theoretical explanations, samples, images, or animations. However, research in geoscience education has increasingly demonstrated that hands-on model construction and manipulation can lead to deeper conceptual understanding, particularly for phenomena requiring abstraction across spatial and temporal dimensions. Prain and Tytler (2012) emphasised that models serve as external representations that support students' development of internal mental models. Documented classroom implementations using deformational sandboxes (the same kind of analogue device employed in tectonic research) have shown how physical models can scaffold inquiry-based instruction, enabling learners to pose questions, observe deformation as it unfolds, and revise their interpretations through direct manipulation of the system (Feldman *et al*., 2010).

Analogue models enable students to visualise process evolution through scaled prototypes, thereby bridging theoretical content with observable behaviour. This relation is consistent with findings that highlight the importance of connecting structural geometry with process-based reasoning in geology education (Kastens and Manduca, 2012; Shipley *et al*., 2013). By engaging students in constructing, deforming, and interpreting models, analogue modelling mirrors key aspects of authentic geological practice.

This pedagogical use of analogue models is consistent with a longer tradition in Earth Science education that frames the sandbox as a tabletop physical model for scientific inquiry (Feldman *et al*., 2010) and aligns with discovery and model-based learning frameworks (Rivet and Kastens, 2012; Markauskaite *et al*., 2020).

4.2. Spatial and temporal scales: three-dimensional visualisation and geological time

A central challenge for students entering a Structural Geology course is reasoning across multiple spatial and temporal scales simultaneously. Many struggle to mentally project 3D objects and interpret them from 2D representations such as maps and cross-sections, a difficulty widely documented (Blanco and Crespo, 2007; Liben and Titus, 2012; Gagnier *et al*., 2016, 2017). Likewise, reasoning about geological time, with processes unfolding across a spectrum from instantaneous events to multi-million-year transformations, represents one of the most persistent conceptual challenges for students (Cheek *et al*., 2017; Myer *et al*., 2018).

Analogue modelling addresses both dimensions. Like a maquette, it offers a direct view of three-dimensional geometry while also allowing students to manipulate the system and observe deformation as it evolves. This combination supports penetrative thinking, the coordination of multiple representational formats, and the construction of mental models that integrate geometry with temporal evolution, skills that are central to geoscience expertise (Reynolds *et al*., 2005; Sell *et al*., 2006; Ormand *et al*., 2014). In this study, geological processes are understood precisely as this interaction between structure and time, a perspective essential for interpreting phenomena such as orogenesis, erosion, fault growth, and fold development.

Critically, analogue modelling requires respecting scale across all spatial and temporal dimensions, and this is where its pedagogical value deepens. Scaling in analogue models is not a simplification but a rigorous condition: for a model to be a valid representation of a natural prototype, geometric, kinematic, and dynamic similarity must be satisfied (Hubbert, 1937). This means that material properties, model dimensions, and applied forces must be scaled consistently so that the model deforms in a manner mechanically analogous to that of crustal rocks. Through this process, students are explicitly exposed to principles of proportionality, geometric similarity, and physical scaling, concepts fundamental not only to analogue modelling but to geological interpretation more broadly (Rivet and Kastens, 2012). The requirement to maintain physical scaling also introduces students to realistic magnitudes of natural stress and strain, strengthening quantitative reasoning and fostering an intuitive understanding of geological dimensions and process rates.

5. Classroom experience

This contribution presents the objectives and selected outcomes of analogue-modelling activities carried out with students enrolled in the Structural Geology laboratory course. This course is taught in several academic programs, including Geology, Geological Engineering, and Mining Engineering, at the Universidad de Santiago de Chile (Chile) and the Universidad de Buenos Aires (Argentina). The experience presented here corresponds to its implementation with students in an engineering program at the Universidad de Santiago de Chile.

The Structural Geology course combines a theoretical and a laboratory component. The theoretical classes typically include approximately 40 students, while laboratory sessions are conducted with smaller groups of around 20 students to allow hands-on work. Within each laboratory session, students work in small teams of four to five participants per analogue model, enabling active engagement, discussion, and shared decision-making during the experiments.

Although a number of analogue exercises were developed throughout the courses, this article focuses on two specific activities designed to illustrate fundamental concepts of brittle deformation and fault-related structures: (1) Analogue brittle deformation experiment using sand, and (2) Riedel shear model for secondary fractures associated with a principal fault. These two exercises were selected because they provide students with clear, observable links between experimental deformation patterns and natural structural geometries, facilitating the transition from theoretical understanding to process reasoning. Additionally, both models are well-suited for discussing geological processes particularly relevant to the Andean orogenic context, where brittle structures, fault kinematics and shear-zone architectures play a central role in crustal deformation and mineralisation pathways.

The primary objective of developing the analogue modelling was to support students' learning and enhance their three-dimensional visualisation of the geological processes studied simultaneously in the theoretical component of the course. In the first experiment, these included: compression, fracturing, faulting, strike, true and apparent dip, erosion, and topography. In the second experiment the focus was on shear, fracture development, kinematic indicators, the Riedel shear model, and rheology.

The experiments were conceived as pedagogical analogue demonstrations focused on structural visualisation rather than as rigorously scaled physical models reproducing a specific natural prototype. Consequently, the materials were selected empirically based on their ability to consistently generate the target structures within the practical constraints of a classroom setting.

5.1. When and how to carry out an analogue model?

The first questions that arise when planning this type of activity are when and how to implement it. Regarding timing, it is essential to align the activity with the learning objectives it is intended to address. As highlighted by Kastens and Manduca (2012), the sequencing of representational tasks is important for scaffolding conceptual development, and timing strongly influences what students can extract from an activity. In this case, and given the specific objectives described above, the activity was implemented when students take the course containing the concepts that will later be explored through analogue experiments.

Whether performed at the beginning, middle, or end of the semester, analogue modelling can benefit student learning. Early implementation may support the development of foundational spatial reasoning skills, crucial for geoscience learning (Ormand *et al*., 2014, 2017; Gagnier *et al*., 2016), potentially improving later performance. Conversely, implementing the activity later in the semester enables deeper conceptual engagement and supports the type of model-based reasoning described by Rivet and Kastens (2012), allowing students to connect observed structures with underlying processes and mechanics. Here, the latter implementation was chosen: the activities were performed during one of the final sessions of the semester. This decision aligns with findings from Shipley *et al*. (2013), who noted that students with more developed conceptual frameworks can extract more sophisticated information from dynamic representations such as analogue models.

The second question (how?) can be addressed from several perspectives. With respect to the organisation of the modelling environment and the instructor's role, this study describes the following setup: the activity was conducted with a group of 20 students in a classroom equipped with workbenches, allowing students to work in teams of four to five. At the beginning of the session, students receive general instructions from the instructor, delivered orally to the entire class. These initial guidelines aim to contextualise the experiment (theoretical background) and to indicate essential methodological considerations to ensure that the modelling activity is successful (technical and procedural aspects), which is consistent with the recommendations of Markauskaite *et al*. (2020), who emphasised the importance of explicit scaffolding and instructional guidance when students work with multiple representations and complex modelling tasks. Once group work begins, the laboratory assistants (two) and the instructor circulate among the workbenches, observing progress, guiding students in cases of methodological errors, answering questions, and prompting reflection when relevant issues arise. This interactive environment supports iterative meaning-making processes (de Vries, 2006; Sell *et al*., 2006).

5.2 Experiment 1: "Analogue model of brittle deformation in sand"

5.2.1 Theoretical considerations for Experiment 1

Analogue modelling allows simplification of both the rheological properties of natural rocks and the spatial and temporal scales associated with deformation. To approximate natural prototypes as closely as possible, the materials most commonly used in brittle-deformation analogue simulations are dry sand and wet clay. For the Structural Geology laboratory exercises presented here, we used layers of dry quartz sand composed of rounded, well-sorted grains smaller than 500 µm, with cohesion values below 100 Pa and an internal friction angle of ~32.7°. These properties are consistent with values reported in previous experimental studies, and they have long been used as scaled mechanical analogues for upper-crustal rocks since the classic work of Hubbert (1951).

At a broad scale, deformation in upper-crustal rocks can occur either continuously (e.g., ductile deformation and fold development) or discontinuously (e.g., brittle deformation and fracture generation). Moreover, a deformation process governed by brittle mechanisms may appear ductile at certain scales, producing structures such as folds. When a rock loses cohesion, it develops a discontinuity called a fracture that separates two blocks; when relative motion occurs between these blocks, the fracture becomes a fault.

The geometric description of fractures and faults is commonly expressed in terms of strike (the horizontal orientation of the fracture plane relative to geographic north) and dip (the angle, between 0° and 90°, measured perpendicular to strike). Faults may also be classified by relative block motion: strike-slip faults accommodate displacement parallel to strike, whereas normal and reverse faults accommodate dip-slip motion. Strike-slip motion is best visualised in map view, whereas normal and reverse slip are more evident in cross-section (Fig. 2A). More complex systems can also be represented using analogue models, which allow learners to observe not only geometric relationships but also the progressive development of structures over time.

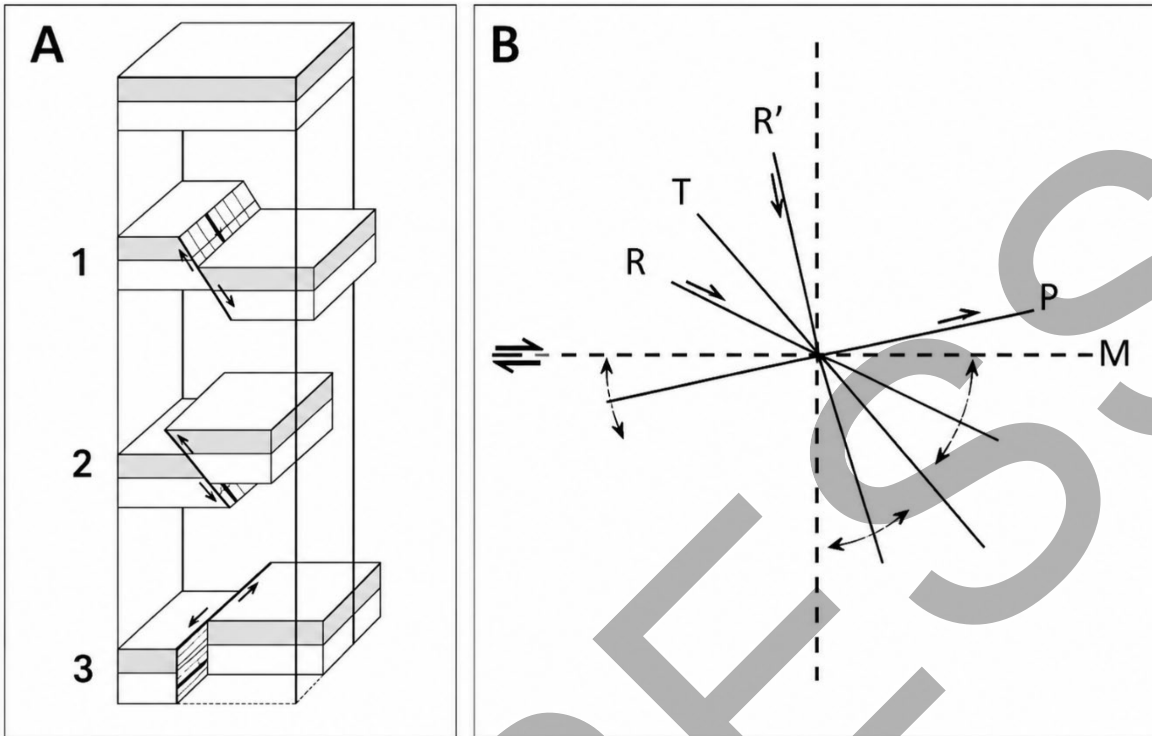

Fig. 2. A. Types of faults according to the relative motion of the blocks: (1) normal fault, (2) reverse fault, and (3) strike-slip fault. **B.** Secondary fractures R, R', T, and P associated with the displacement of the main fault M (figure modified from Liesa *et al*., 1997, and Niemeyer, 2008).

5.2.2 Methodological description of Experiment 1

The basic materials required for the experiment include sand (at least two colours), wooden boards of various sizes, water, a knife, and cleaning supplies. These materials and the main construction steps are illustrated in figure 3A. Ideally, the model is constructed inside a transparent-walled box (e.g., made of polycarbonate) with one movable wall, although a layered "cake" built with wooden guides provides a practical alternative when direct visualisation of the internal structure during deformation is not required. The movable wall may be displaced manually or connected to a motorised system to apply controlled deformation.

Because sand layers simulating sedimentary or crustal strata would not be distinguishable without a colour contrast, the first stage involves preparing coloured sand layers. Sand is mixed with a small amount of indelible ink in a container and stirred thoroughly until a homogeneous mixture is achieved; the mixture must be completely dry before use.

In the classroom, and when a polycarbonate box is available, students receive an introduction to the activity before beginning the construction of stratified layers. Their first task is to deposit the sand in layers no more than 1 cm thick. Although the transparent box is extremely useful for teaching purposes, achieving layers of uniform thickness is challenging, and variations in layer thickness may later complicate the interpretation of deformation structures.

An alternative, and often more reliable approach is to construct a “layer cake” using wooden boards 5 mm to 1 cm thick. The boards are placed to define the lateral limits of the model, the space between them is filled with sand, and excess material is levelled off with a flat board or rod (Fig. 3A). The process is repeated until at least five alternating-coloured layers are produced, after which the boards are removed. In this configuration, the deformation mode must be determined in advance so that a movable base or a fixed wall can be positioned appropriately to generate the desired displacement. The outer margins of these models should not be used for analysis, as they often exhibit edge effects associated with material collapse.

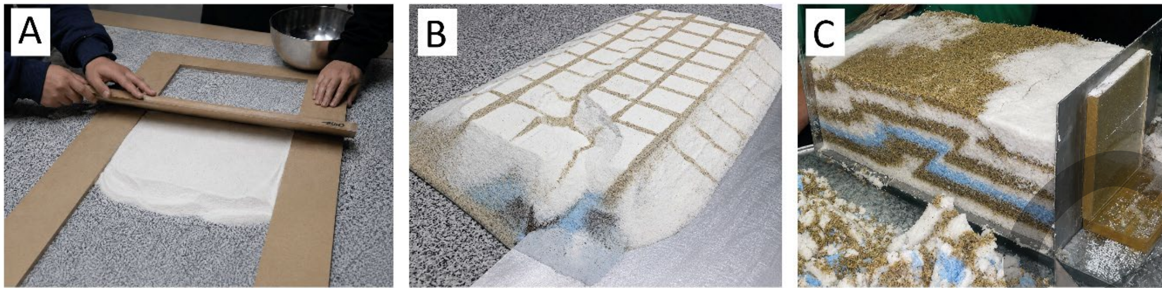

Fig. 3. A. Construction process of a stratified sand-layer cake of uniform thickness. **B.** Completed stratified sand cake with a displaced grid resulting from a deformation event. **C.** Interior of a stratified sand model deformed by compression.

A disadvantage of the “layer cake” compared with the transparent-walled box is that deformation can be observed only in plan view; the model's internal structure becomes visible only after the experiment is completed and the model is cut open. To avoid losing valuable information about the deformation process, students are instructed to construct a grid on the uppermost layer of their sand “layer cake.” As deformation progresses, this grid provides visual cues that indicate zones of uplift or subsidence, as well as the presence of faults when discontinuities or offsets in the grid become evident (Fig. 3B).

Once the polycarbonate box has been filled with sand or the layered “cake” has been constructed, the model is deformed using the selected mechanism (chosen in advance, typically a movable wall used to apply compression, a basal aluminium sheet used to induce extension, or another device devised by the students to generate displacement). The applied motion produces either longitudinal extension or shortening, which should be expressed through the development of geological structures that students are expected to identify. Under compressional conditions, the formation of reverse faults and folds is anticipated.

To promote clearer observation and understanding of the process, students are encouraged to apply deformation gradually by using a slow, steady displacement of the mobile wall or base. During deformation, students are instructed to take notes and photographs, documenting the evolution of structures.

Once observable deformation structures have developed, either in cross-section for the box experiment or in plan view for the layer-cake model, the next step is to cut sections to reveal the model's internal deformation. To avoid disturbing the structures, the sand must first be lightly moistened by gently pouring water over the model. After the material has settled, the model is cut using knives or spatulas to expose its interior (Fig. 3C).

5.3. Experiment 2: "Riedel shear model for secondary fractures"

5.3.1 Theoretical considerations for Experiment 2

The second analogue modelling activity reproduces the conditions under which natural fracturing occurs, illustrating how secondary structures develop in response to displacement along a principal fault. In the Riedel shear model (Riedel, 1929), progressive displacement is applied between two blocks bounded by the M (Main) fault. As slip accumulates, characteristic sets of secondary fractures form within one or both blocks, each with predictable orientations and kinematics (Fig. 2B).

The R fractures typically form at an angle of approximately 15° to the principal M fault and display synthetic motion relative to it. The R' fractures are conjugate to the R set and therefore accommodate antithetic slip relative to both the M and R fractures. A third set, T fractures, are tensional features that form without shear displacement and generally strike ~45° to the M fault (Fig. 2B).

These fracture systems are widely reported in naturally deformed rocks and, when formed during a single deformation event, they can serve as valuable kinematic indicators. Their recognition is particularly useful when unambiguous displacement markers, such as offset stratigraphic layers, are absent. Understanding the expected geometry and kinematics of R, R’ and T fractures thus provides students with a conceptual toolset for interpreting fault motion in both outcrop and subsurface data.

5.3.2. Methodological description of Experiment 2

The Riedel experiment is straightforward to set up and requires only a few materials per working group: one or two blocks of modelling clay, and two rigid surfaces (such as metal, cardboard, or wood) that, when placed side by side, act as the discontinuity representing the principal M fault. Additional recommended materials include water, cleaning supplies, and recording tools (camera and notebook).

The activity begins with an explanation of the experiment so that students understand the role of the basal plates and how to position them correctly for subsequent displacement. The modelling clay is placed and flattened across the two plates so that the discontinuity between them lies near the centre of the model (Fig. 4A). The resulting clay layer is then subjected to relative displacement between the plates (Fig. 4B). This step completes the initial model setup.

Before initiating displacement, students are instructed to move one of the plates gradually, millimetre by millimetre, so that the discontinuity evolves into an active fault. Slow, incremental displacement is essential because the secondary R, R′, and T fractures develop before the main discontinuity propagates upward through the clay layer, as illustrated by the deformed clay layer in plan view (Fig. 4C). At each increment, students must pause to examine whether any structures have formed, document their geometry, and observe how they deform as displacement continues. Proper recording tools must therefore be kept on hand throughout the experiment.

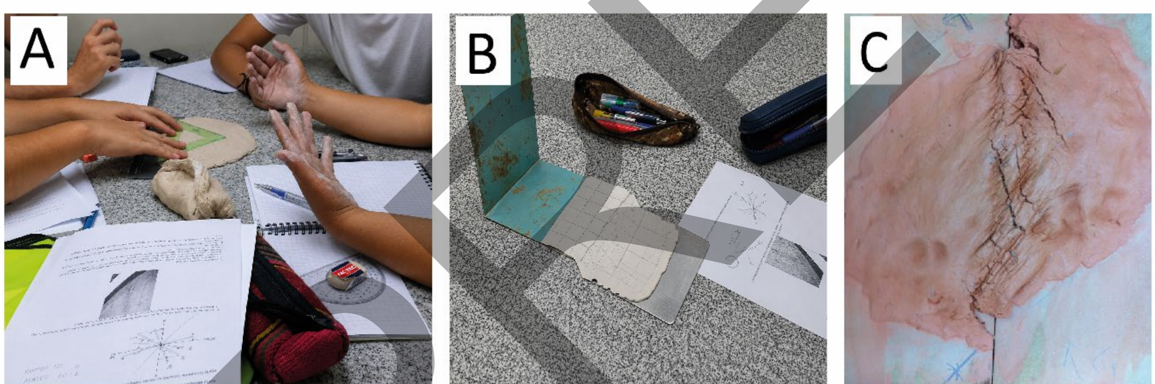

Fig. 4. Riedel model setup and deformation observed during the classroom experiment. **A.** Students placing and flattening the modelling clay across the two plates to achieve a uniform thickness, with the discontinuity positioned near the centre of the model. **B.** Clay layer of uniform thickness placed across the two plates during relative displacement. **C.** Plan view of the deformed clay after relative displacement, showing the structures that developed within the clay layer.

It is important to note that the appearance of structures in this experiment depends on several factors, including the clay's moisture content, its thickness, and the rate at which displacement is applied to the basal plates. Failure to manage these parameters may result in the absence of secondary structures, which students could perceive as an unsuccessful outcome. As highlighted in analogue modelling methodology (e.g., Riedel, 1929; Hubbert, 1937), the emergence of diagnostic structures is highly sensitive to material properties and scaling conditions.

6. Results and recommendations

The results of both analogue modelling activities are presented together, as the emphasis of this study lies on the academic and educational outcomes rather than on the technical performance of each specific model. The modelling sessions were conducted in three separate laboratory courses across different semesters, and not all of them produced the same structural results. For this reason, it is recommended that instructors carefully test the materials before use to ensure they behave as expected with respect to their mechanical properties.

To mitigate frustration and transform potential "failed experiments" into meaningful learning opportunities, it is recommended that instructors include a theoretical discussion of the method beforehand. This pedagogical strategy enables students to intentionally treat factors such as moisture, strain rate, and layer thickness as variables rather than sources of error. Students may then repeat the experiment under modified conditions and compare results, promoting inquiry-based learning, metacognitive reflection, and a deeper understanding of the mechanical controls on fault-related fracturing. Such iterative, student-driven experimentation aligns with established principles in geoscience education that emphasise active learning, hypothesis testing, and guided discovery (e.g., Kastens and Manduca, 2012; Liben and Titus, 2012; Ormand *et al.*, 2017).

At the end of each session, students participated in a guided walkthrough, during which each group presented and explained its model outcomes to classmates. These peer explanations offer the instructor valuable insights into students' understanding of the theoretical content, while allowing students to articulate geological reasoning in their own words, thereby strengthening conceptual consolidation and spatial reasoning (Liben and Titus, 2012; Ormand *et al*., 2017). This process also benefits groups that did not obtain the expected structures: by comparing their results with those of their peers, students can analyse methodological differences, evaluate possible sources of error, and discuss how experimental variables influence material behaviour.

Some student groups devised their own systems of surface and profile markers (Fig. 5A). These decisions reinforce autonomy, foster scientific decision-making, and enhance students' engagement with the modelling process, skills considered fundamental for developing spatial thinking and geological interpretation abilities (e.g., Kastens and Ishikawa, 2006; Shipley et al., 2013).

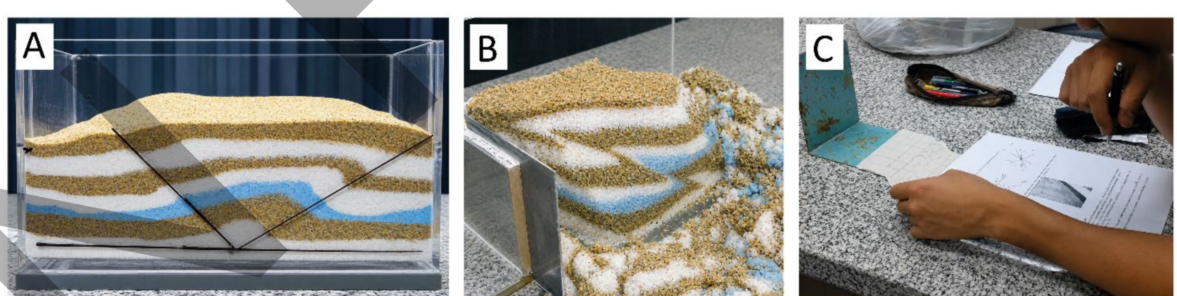

Fig. 5. A. Compressive model of sand layers; the markings and measurements made by the students for their analysis can be observed. **B.** Stratified sand model that was cut in different directions to observe the apparent dip. **C.** Students analysing the results of a Riedel model with the expected orientation based on the underlying theory.

In Experiment 1, the analogue model of brittle deformation in sand, the learning objectives were successfully achieved. Students were able to identify and apply the concepts of compression, fracturing, faulting, strike, true and apparent dip, erosion, and topography, based on their observations of different cross-sections (Fig. 5B). Students also engaged with more advanced concepts, such as the recognition of deformation partitioning, fault interference patterns, and the geometric relationships between faults and associated folds.

In Experiment 2, the Riedel shear model of secondary fracturing associated with a principal fault, the intended learning objectives were achieved. Students successfully engaged with key concepts, including shear, fracturing, kinematic indicators, the Riedel shear model, and rheology. A particularly noteworthy outcome was their ability to correlate the theoretical diagrams presented in the lecture with the structures produced in their own analogue experiments (Fig. 5C). This connection demonstrates not only conceptual understanding but also an enhanced capacity to interpret deformation patterns and relate them to expected kinematic frameworks.

The outcomes of both types of analogue modelling activities were positive, largely due to the students' engagement and the essential support provided by the teaching assistants. This support ensured that the activity remained productive within the time constraints of scheduled laboratory sessions.

6.1. Feedback on the learning experience

Students were observed actively engaging in the modelling activities, with sustained participation and minimal off-task behaviour during the sessions. The teamwork required to complete each model fostered stronger connections among students and contributed to an atmosphere of collaboration well suited to hands-on work. This activity also aligns closely with several graduate profile competencies common across Earth Science and engineering programs, particularly teamwork, since each group was given autonomy to organise itself and make decisions regarding the design and execution of their models.

Providing students with some freedom in deciding their experimental setup encouraged them to ask questions such as “What happens if we change…?” This behaviour suggests engagement with the underlying processes and a desire to explore the variables influencing the results. From an instructional standpoint, such questions suggest a deeper understanding of the theory behind each experiment.

Student feedback, collected through informal classroom discussions and follow-up email comments after the activities, also highlighted differences in perspective regarding the timing of the activity. Several commented that conducting the sessions earlier in the semester might have helped them better understand abstract theoretical concepts as they were introduced. However, carrying out the experiments later in the term enabled students to predict expected structures, discuss possible outcomes using more advanced technical vocabulary, and connect the analogue models more directly with the theoretical content they had already internalised.

Additional comments received by email emphasised the value of analogue modelling for visualising geological processes and linking theory with observation, including:

"The clay activity helped me understand how main faults work and how secondary faults form. On paper, this is not as clear, but modelling it allowed us to observe these processes graphically and in real time."

"It was extremely enriching to carry out the entire process ourselves, from building coloured sedimentary layers to applying the stresses and finally observing the resulting structures."

"We want to formally thank you for enabling a laboratory of this type. Much like fieldwork, it allows us to observe how things 'actually happen' in reality, but through a fully experimental approach."

These and other positive comments have motivated us to continue refining the activities and to incorporate them into future course offerings.

6.2. Student performance and pre-test results

An optional pre-test was administered before the implementation of the analogue-modelling activities to assess students' initial understanding of analogue modelling and its role in geological analysis. A total of 16 students responded to the pre-test. Half of the respondents (8 students) left the question on defining or explaining what they understood by analogue modelling blank. The remaining students provided brief written responses, generally associating models with the representation of geological processes.

All students had previously completed courses in general geology, petrology, and mineralogy, but had limited formal exposure to physical modelling. As a result, while some basic structural concepts (e.g., faults, strike, and dip) were familiar to them, their understanding was often described as fragmentary or vague at the beginning of the semester.

Analogue-modelling activities were implemented as part of the laboratory component of the course. For all semesters considered, two sets of results are reported: (1) the final laboratory grade, and (2) the final course grade, which integrates both laboratory and theoretical components. This structure allows a direct comparison between practical performance and overall conceptual understanding.

Quantitative performance data were compiled from four consecutive course offerings: two semesters in which analogue-modelling activities were incorporated into the laboratory sessions and two semesters in which this methodology was not applied.

Figure 6 summarises the distribution of laboratory and final course grades across the four semesters, presented in chronological order: (1) a course prior to the implementation of analogue modelling, (2) a course incorporating analogue-modelling activities, (3) the subsequent course without analogue modelling, and (4) a later course in which analogue modelling was reintroduced.

To complement the graphical comparison, the distribution of student performance across defined proficiency levels is detailed in Table 1. Under the Chilean institutional grading system, the minimum threshold for academic approval is a 4.0 on a scale reaching a maximum of 7.0. Consequently, results falling below 4.0 denote unsatisfactory outcomes, whereas scores between 4.0 and 5.0 are classified as satisfactory, and those exceeding 5.0 signify a robust mastery of the course material.

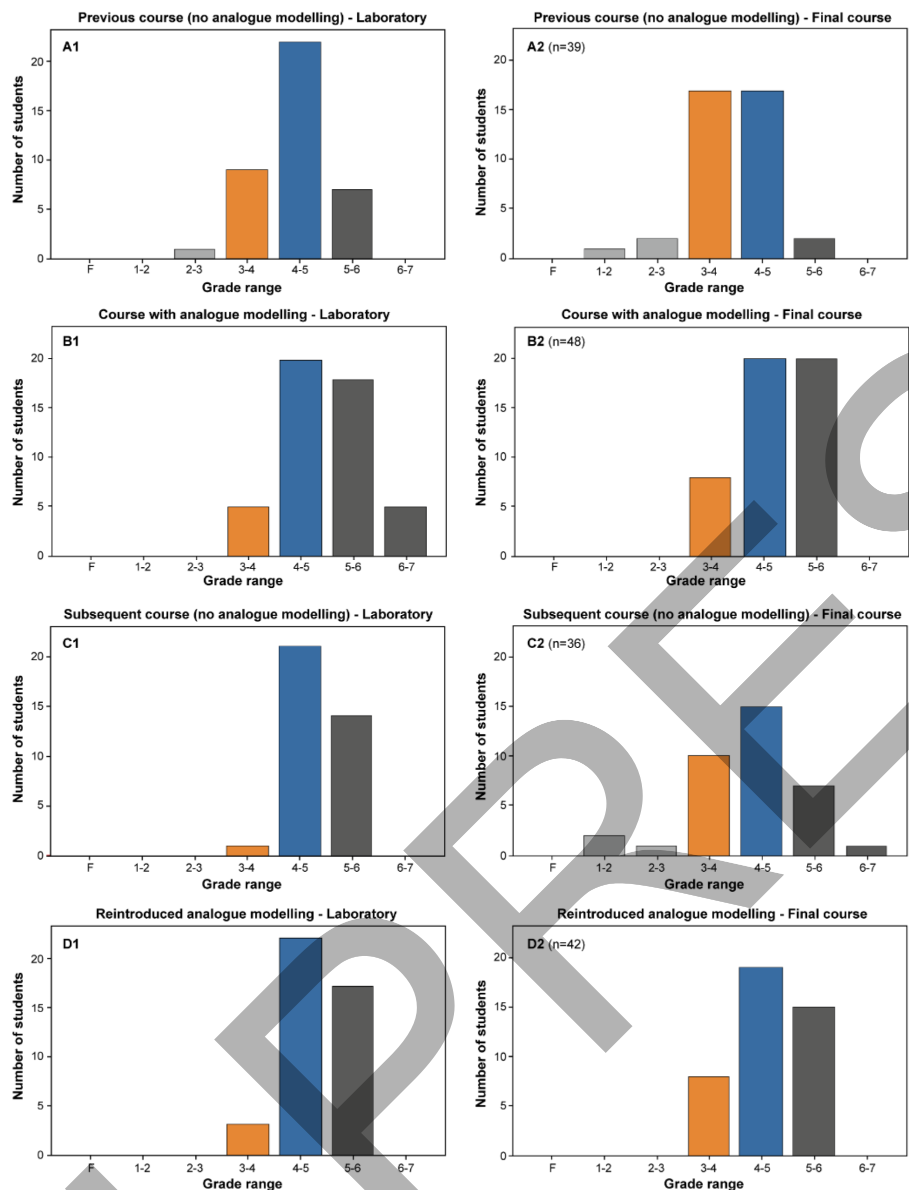

Fig. 6. Student performance across four course implementations with and without analogue modelling. Distribution of laboratory and final course grades for four consecutive courses. **A.** Previous course without analogue modelling (39 students). **B.** Course with analogue modelling (48 students). **C.** Subsequent course without analogue modelling (36 students). **D.** Course with analogue modelling reintroduced (42 students). Grades are grouped according to the institutional grading scale. Courses including analogue modelling show a higher proportion of grades ≥4.0 in both laboratory and final course evaluations.

Table 1. Distribution of grades by performance level across final course implementations

Course	Analogue modelling	1-3 (%)	3-4 (%)	4-5(%)	≥5 (%)
Previous course	No	7.7	43.6	43.6	5.1
Course with analogue modelling	Yes	0.0	16.6	41.7	41.7
Subsequent course	No	8.3	27.8	41.7	22.2
Course with analogue modelling reintroduced	Yes	0.0	19.0	45.3	35.7

Given the differences in cohort size, course dynamics, evaluation activities, and semester-specific conditions across implementations, the grade distributions presented here are intended as a descriptive and exploratory comparison rather than as a formal statistical evaluation of learning outcomes. Accordingly, the histograms are interpreted qualitatively to identify general trends associated with the implementation of analogue-modelling activities.

Despite the variability between cohorts and course conditions, the graphical comparison suggests a consistent pattern. In the two semesters in which analogue modelling was incorporated into the laboratory sessions, student performance in laboratory assessments was higher, while failure rates (grades below 4.0) in the final course evaluation were markedly lower, falling below 20%. In contrast, in semesters without analogue modelling, failure rates in the final course evaluation increased substantially, exceeding 36% and reaching 50% or more in the semester preceding the intervention, despite relatively strong laboratory performance in some cases. This trend is observed across different course coordinations and student cohorts, suggesting that it was not limited to a single cohort or course implementation. Notably, in the semester following the initial implementation of analogue modelling, when the methodology was not applied, performance patterns reverted toward those observed prior to the intervention. When analogue modelling was reintroduced in a subsequent semester, student performance improved again, both in laboratory outcomes and final course grades (Fig. 6).

Overall, the graphical comparison of these four courses suggests an internally consistent association between the implementation of analogue-modelling activities and improved student performance. Although these observations should be interpreted cautiously due to differences between cohorts and course implementations, the results support the value of analogue modelling as an instructional strategy within the Structural Geology curriculum.

Collectively, these results also show that variability in analogue-model outcomes should be treated as an integral part of the learning process rather than as a purely technical limitation. Not all experiments yielded the anticipated structures, a situation that can arise from factors such as moisture content, layer thickness, the total amount of shortening or extension applied, and other experimental conditions. This variability is well documented in analogue modelling literature, where scaling sensitivity and material rheology strongly influence outcomes (e.g., Hubbert, 1937; Galland *et al*., 2007).

7. Discussion

The analogue modelling activities presented here offer important insights into how physical models can support the development of spatial reasoning, conceptual understanding, and model-based thinking in geoscience students. Earlier experiences indicate that limitations in spatial visualisation and three-dimensional interpretation represent a significant challenge for engineering students in geoscience-related courses, particularly in structurally complex tectonic settings (Jara *et al*., 2017). Across classroom experiences and supported by multi-semester performance data, the results suggest that hands-on modelling, when combined with guided construction, observation, and analysis, creates powerful opportunities for students to link theoretical concepts with the dynamic and three-dimensional nature of geological deformation.

7.1. Analogue models as external representations that scaffold spatial reasoning

Both models functioned as external representations, a category of learning tools shown to play a key role in supporting cognitive processes in the geosciences (Kastens and Manduca, 2012). In Experiment 1, the analogue model of brittle deformation in sand enabled students to connect observable surface deformation with the underlying processes driving it. This connection aligns with the literature indicating that simplified physical systems can help students understand otherwise abstract relationships between stress, strain, and structure development (Ormand *et al*., 2014; Gagnier *et al*., 2017). Moreover, recent syntheses emphasise that geoscience learners benefit significantly from external, manipulable representations when developing both intrinsic and extrinsic spatial skills (McLaughlin and Bailey, 2023).

The construction and manipulation of physical layers supported spatial visualisation and penetrative thinking, essential skills for interpreting subsurface geometries (Ormand *et al*., 2014; Gagnier *et al*., 2017). Techniques such as the application of surface grids enhanced these representational connections: the progressive distortion of the grid provided immediate visual feedback on faulting, folding, uplift, and subsidence, strengthening students' ability to recognise geometric and kinematic patterns. This result is consistent with studies showing that multimodal and embodied representational systems enhance coordination between 2D and 3D information (Atit *et al*., 2015).

Similarly, in Experiment 2, the Riedel shear model provided students with a concrete representation of the geometric relationships among R, R', and T fractures. This type of structured, visual representation is particularly effective for helping students develop and apply kinematic interpretation skills, as noted in studies of spatial reasoning and structural geology education (Shipley *et al*., 2013; Ormand *et al*., 2014). Recent reviews further suggest that iterative comparison between observed and predicted geometries strengthens geologically relevant spatial typologies (Newcombe and Shipley, 2015; McLaughlin and Bailey, 2023).

7.2 Progressive observation, temporal sequencing, and model-based reasoning

A central educational benefit of analogue modelling lies in its capacity to represent geological processes dynamically rather than as static end products. Although digital technologies also allow observation of dynamic processes, their educational value depends on how learners interact with them: animations or simulations may support temporal reasoning when students are guided to interpret sequence, rate, and causality, but they can be less effective when learners remain passive observers or when the representation is not explicitly connected to the underlying geological process (Ainsworth and VanLabeke, 2004). In contrast, physical analogue models generate dynamic representations through direct manipulation, supporting temporal sequencing, a critical but under-practised dynamic spatial skill (McLaughlin and Bailey, 2023). This observable deformation reinforces model-based reasoning, an ability highlighted by Rivet and Kastens (2012) as fundamental for interpreting geological phenomena. Dynamic, manipulable models also support spatial updating and sequential thinking, skills often underdeveloped in undergraduate learners (Atit *et al*., 2015; McLaughlin and Bailey, 2023).

In Experiment 1, observing fault propagation, folding, and surface warping in real time allowed students to link progressive deformation with resulting structures. In the present implementation, deformation was intentionally limited to emphasise the development and visualisation of a single fault structure; however, extended experiments could also allow students to observe the progressive evolution of more complex fold-and-thrust belt systems. The procedural sequence (model setup, deformation, documentation, and slicing) provided scaffolding that supported integrating theoretical concepts with material behaviour (Kastens and Manduca, 2012). In Experiment 2, millimeter-scale displacement encouraged careful observation of fracture initiation and evolution, fostering iterative hypothesis testing and reflective reasoning consistent with authentic scientific practice.

7.3. Penetrative views and the integration of surface and subsurface interpretations

Cutting the sand model at the end of Experiment 1 provided students with a penetrative view of internal structures, allowing them to correlate surface expressions with subsurface geometries. This relation aligns with research on penetrative thinking, which highlights the importance of visualizing hidden structures based on surface observations (Ormand *et al*., 2014; Gagnier *et al*., 2017). Recent analyses emphasise that penetrative thinking remains one of the most difficult spatial skills to develop and is particularly strengthened through physical slicing (McLaughlin and Bailey, 2023).

Comparing internal structures with previously documented surface deformation reinforced representational connections essential for expert geoscientific reasoning (Kastens and Manduca, 2012), transforming the analogue model into a conceptual bridge between observation and theory.

7.4. Variability, inquiry, and learning transfer

Variability in experimental outcomes, arising from differences in material properties or deformation conditions, proved pedagogically valuable. Rather than constituting failure, such variability prompted comparison, discussion, and methodological reflection among student groups, promoting inquiry-based learning and metacognitive engagement (Kastens and Manduca, 2012; Liben and Titus, 2012). Such processes are particularly effective when learners must adapt to ambiguous or unexpected results (Atit *et al.*, 2015; McLaughlin and Bailey, 2023).

Providing students with autonomy over decisions such as marker design, layering technique, and deformation rate reinforced their role as investigators rather than passive observers. This instructor-as-facilitator model aligns with best practices in geoscience education that emphasise guided discovery, decision-making, and student ownership of the learning process (Liben and Titus, 2012; Vergara-Díaz et al., 2020).

While the comparisons are descriptive rather than statistically controlled, the performance data across four semesters (Fig. 6) indicate that the potential benefits of analogue modelling may extend beyond laboratory tasks. In semesters without analogue modelling, laboratory performance remained relatively strong, yet final course outcomes declined. Beyond laboratory performance, the distribution of final course grades suggests a shift from borderline (3-4) to consolidated and high performance levels (≥4 and ≥5, respectively), suggesting a transfer of learning from hands-on experimentation to broader conceptual reasoning assessed at the course level.

7.5 Educational value in the Andean geological context

The educational value of analogue modelling is particularly relevant in the Andean context, where complex structural geometries and multi-phase deformation histories demand strong spatial and temporal reasoning skills (Libarkin and Brick, 2002; Kastens and Ishikawa, 2006). Analogue models provide an effective bridge between classroom theory and real-world geological interpretation, where students will face real-world challenges involving structural complexity, mineral exploration, geotechnical analysis, and natural hazard assessment. “Spatializing” geoscience education, that is, the ability to analyze deformation structures and draw inferences from incomplete data (McLaughlin and Bailey, 2023), is essential for professional practice in such environments.

By enabling students to visualize processes such as brittle deformation, fault propagation, and shear-zone development, the analogue models provide a training platform that bridges classroom theory with the complexities of Andean geology.

8. Conclusions

The use of representations and physical models in Earth Science education contributes significantly to the development of spatial thinking skills and facilitates the incorporation of complex theoretical concepts. Their manipulative and exploratory nature supports meaningful learning by enabling students to discover geometric, kinematic, and temporal relationships through direct experience.

Analogue modelling strengthens decision-making, teamwork, and results discussion, skills that are central to the graduate profiles of various engineering and Earth Science programs. Since analogue models do not allow complete control over all variables, and therefore outcomes do not always match theoretical expectations, it becomes essential to provide students with an adequate degree of autonomy in experimental design, model construction, and data acquisition. This guided autonomy encourages reflection on the factors influencing model behavior and supports deeper conceptual understanding.

Conducting these activities near the end of the semester enables students to recognize, describe, and explain geological structures using more precise language grounded in previously internalized theory. Introducing such activities earlier could enhance discovery-based learning and support the initial comprehension of three-dimensional and temporal concepts that are often abstract.

The comparative results across four semesters suggest that participation in analogue modelling activities is associated with improved laboratory and final course assessments, indicating a transfer of learning to broader conceptual understanding. In this contribution, student performance was evaluated through laboratory assessments, final course grades, and qualitative feedback. For future applications, it is suggested that qualitative and/or quantitative indicators be incorporated to assess learning outcomes more precisely, as well as the development of instruments to compare the performance of students who undertake the activity versus those who do not.

Analogue modelling represents a robust, powerful and accessible instructional methodology. By directly linking theory with experience, these activities promote deep learning, strengthen essential skills for geological interpretation, and better prepare future professionals to address the challenges associated with studying and managing territory in tectonically complex settings such as the Andes.

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