

Augmented reality simulations in science education for questioning and explaining geoscience phenomena

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Abstract: One of the purposes of science education is to progress from students' initial ideas about daily phenomena to explanatory scientific models. However, explaining concepts in scientific language is not always easy for children, as many accepted scientific models involve non-visible structures. Augmented reality (AR) superimposes virtual objects onto the physical environment in real time, enabling learners to engage with representations of phenomena that would otherwise be unobservable. A significant challenge in Chile is that nearly 70% of students from low socioeconomic backgrounds fail to explain everyday phenomena using scientific concepts. Furthermore, there is a research gap in analysing the pedagogical interactions that mediate AR-supported learning in primary education for constructing explanations. We provided tablet-based AR simulations of the Earth's layers, earthquakes, and volcanoes, and used mixed methods to analyze interactions in three classrooms located in seismic zones vulnerable to these geological phenomena. The participants were 69 fourth graders and three teachers. Special attention was given to the teachers' guiding questions and their role in facilitating the construction of explanatory models. The study aimed to characterize teacher and student questions posed during AR-enhanced geoscience lessons and to identify which teacher question types promote scientific explanations in primary students. The results indicate that classroom interactions primarily included clarifications, prompted questions, and nonverbal actions such as pointing at the tablet screen. The questions that successfully mediated the explanations aimed to foster a conceptual understanding of the underlying causes and connections between the phenomena, rather than the device's operation. Metacognitive pedagogical questions played a key role in evaluating the learning gains and promoting deeper reasoning. We discuss these practices in the context of primary school science to inform further research on the use of immersive technology to learn about real-world phenomena. We conclude that the potential of AR resides not solely in its visual fidelity, but in its capacity to evoke pedagogical interactions for sense-making, and that a personal connection with the phenomena complements the technology's use.

Keywords: AR, earthquakes, volcanoes, earth layers, explanations

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1 Introduction

Contextually relevant science education encourages students to seek explanations for observed phenomena (Aydin-Ceran, 2021; Brown, 2021; Deehan et al., 2024), which requires causal scientific reasoning (Dood & Watts, 2022; Sun & Lavonen, 2022). However, explaining is a complex operation for primary school children (Gilbert, Boutler, & Rutherford, 2000; Thagard, 2012; Rappa & Tang, 2018), as many accepted scientific models rely on non-visible structures (e.g., Saure et al., 2021). Internationally, research consistently documents that primary students struggle to construct scientific explanations that go beyond surface description toward causal reasoning (Osborne, 2014; National Research Council, 2012). This challenge is especially pronounced in geoscience domains, where the phenomena are spatially and temporally inaccessible to direct observation (Gobert, 2005; Kastens & Ishikawa, 2006).

In Chile, this issue is particularly acute; nearly 70% of students from low socioeconomic backgrounds fail to explain everyday phenomena using scientific concepts (OECD, 2023). This educational inequity has direct consequences beyond academic achievement: in disaster-prone regions, the challenges of explaining phenomena such as earthquakes and tsunamis can increase vulnerability during real emergencies. Scientifically informed citizens are better positioned to interpret risk information and respond appropriately (Selby & Kagawa, 2012; Dufty, 2020). Moreover, the adequacy of resources to scaffold the construction of explanations, specifically regarding socio-environmental crises, has been critiqued (Morote et al., 2023).

In response to these challenges, there is a growing need for pedagogical approaches that not only make complex geoscientific processes visible but also support students' engagement in scientific reasoning through guided explanatory practices. Despite curricular mandates for inquiry-based learning (MINEDUC; 2012), classroom observations in science consistently reveal that instruction remains dominated by transmissive practices and lower-order questioning that do not support students in constructing explanatory models (Eliasson et al., 2017; Conejera et al., 2020). This pedagogical gap is particularly acute in geoscience instruction, where the absence of suitable visualization tools often reduces complex dynamic processes to static textbook diagrams (LaDue & Shipley, 2018). Technologies such as Augmented Reality (AR) offer unique affordances for visualizing non-observable phenomena and mediating students' interactions with scientific models when embedded within thoughtfully designed instructional contexts (Squire & Jan, 2007; Cai et al., 2022; Wen et al., 2023). In this study, AR is defined as a digital technology that superimposes virtual objects onto the physical environment in real time, enabling learners to engage with representations of phenomena that would otherwise be unobservable. AR incorporates virtual information to provide learners with new experiences that are more authentic, interactive, and engaging (Wen et al., 2023).

While extensive research has documented AR's potential to enhance conceptual understanding and engagement in science education (Basumatary & Maity, 2023; Mondro

et al., 2024), as well as its role in fostering scientific competences and argumentation skills (Cai et al., 2022; Kaya & Memiş, 2024), significant gaps remain. First, limited research has examined the pedagogical interactions—particularly teacher questioning strategies—that mediate AR-supported learning in primary education (Chang & Hwang, 2018; Wen et al., 2023). Indeed, most studies focus on learning outcomes or engagement metrics but overlook the discursive practices that scaffold students' construction of explanatory models during AR experiences. Second, primary education contexts and geoscience phenomena remain understudied in AR research, especially concerning plate tectonics and seismic events (Ahmad & Samah, 2024; Kaya & Memiş, 2024). Third, while disaster education research underscores the importance of community-situated learning for building risk awareness and preparedness (Wisner & Wisner, 2004; UNDRR, 2015), AR-enhanced science instruction has rarely been situated within disaster-prone regions or designed to leverage students' lived experiences of seismic or tsunami hazards.

To address these gaps, our research analyzes teacher-student interactions during AR simulations of the Earth's layers, earthquakes, and volcanoes in Chilean primary schools located in seismic zones. Specifically, we examined how teacher questions mediate fourth graders' understanding of non-visible geoscientific structures, exploring both the affordances of AR visualization and the critical role of questioning in transforming engagement into explanatory construction. This is essential because without understanding the pedagogical mechanisms that activate scientific reasoning, AR risks becoming merely a novelty rather than a catalyst for deep conceptual understanding.

This research offers a dual contribution. Methodologically, it brings fine-grained analysis to AR-enhanced primary science classrooms, a combination that remains rare in the literature. Contextually, it grounds this inquiry in schools located in seismically active communities, where the stakes of science understanding extend beyond academic achievement into community resilience. Although we did not compare classrooms that use AR versus those that do not—which might be considered a limitation—this study offers insights that are directly actionable for teachers, curriculum designers, and professional development practitioners working in contexts where technology-enhanced science instruction must serve both disciplinary and socioscientific goals.

1.1 Research question, aims, and purpose

How do teacher questioning strategies during AR-supported instruction mediate the interactions between students, teachers, and geoscientific content (the Earth's layers, earthquakes, and volcanoes) for explanation construction in primary school?

Accordingly, our research aims are (1) to describe the types, cognitive demand, and degree of openness of questions that emerge during AR-supported geoscience instruction; and (2) to identify which question types are associated with students' construction of scientific explanations of the Earth's layers, earthquakes, and volcanoes. The purpose is to contribute evidence-based insights for instructional design in AR-enhanced primary science.

2 Background

Contemporary research in science education has increasingly emphasized the importance of socio-scientific reasoning, explanation construction and modelling as core epistemic practices through which students come to understand natural phenomena (Herman et al., 2019; Kilag et al., 2023; Seeratan et al., 2020). These three practices are not independent: modelling provides the representational scaffold within which explanations are articulated, while socio-scientific reasoning supplies the motivational and contextual grounding that makes both modelling and explanation personally meaningful (Osborne & Patterson, 2011; Nersessian, 2008). Yet in primary school classrooms, research consistently shows that these practices are rarely integrated; lessons tend to privilege either content transmission or procedural engagement, leaving the discursive work of explanation-building largely unsupported (Scott et al., 2006; Mortimer & Scott, 2003). This disjunction between the epistemic ideals of science education and everyday classroom practice is the central tension that frames the present study, motivating the following examination of prior research on explanation construction, the role of pedagogical questioning, and the possibilities and limitations of AR instruction in supporting students' scientific explanations.

2.1 Learning and constructing explanations

Learning is understood as a joint construction of knowledge and transdisciplinary skills, incorporating social and territorial interdependence in the development of thought and communication (Holbrook et al., 2025). This sociocultural framing is particularly salient in communities with direct lived experiences of geoscientific hazards, where students bring embodied and experiential knowledge of the phenomena they are studying. From a Vygotskian perspective, such prior experiential knowledge constitutes a zone of proximal development (Vygotsky, 1978) that teachers can strategically activate to mediate the construction of scientific explanations. However, science education research has paid limited attention to how this experiential knowledge interacts with technology-enhanced instruction, particularly when the phenomena under study are personally encountered rather than merely academically relevant (Bencze et al., 2020).

From an epistemic perspective, explanations are not merely products of learning but central practices through which students organize causal relationships, test ideas, and progressively refine their understanding of phenomena (Rappa & Tang, 2018). Thus, constructing explanations provides a window into students' scientific reasoning and their engagement with disciplinary ways of knowing. Scientific reasoning involves the ability to analyze, interpret, and apply scientific concepts, which are essential for understanding phenomena grounded in plate tectonics theory (Kaya & Memiş, 2024; Squire & Jan, 2007). In geoscience learning, this type of reasoning is particularly demanding, as students must engage with complex processes that unfold across large spatial and temporal scales that are largely inaccessible to direct observation (Márquez et al., 2004). While

other student skills related to geoscience learning have been more extensively studied—such as perspective-taking or spatial skills (Goldhagen et al., 2024) and flexible thinking (Hessler, 2024)—scientific reasoning remains a central competence, as it underpins students' ability to construct explanations, interpret representations, and make sense of geoscientific phenomena.

To support this process, effective teaching strategies are required, including experimentation and the use of questions as learning mediators (García Gaitán et al., 2022). This perspective challenges the assumption that students must first fully understand a phenomenon before they can construct a model or explanation (Sanmartí, 2007). Even in the absence of a complete conceptual understanding, children can generate explanations that enable them to predict phenomena (Wellman, 2011). Consequently, school-based scientific explanations provide a valuable opportunity to examine children's reasoning processes and support their construction (Cabello & Sommer, 2020).

Within this framework, structured approaches such as the PRO strategy (premise-reasoning-outcome) have been proposed to support students in articulating scientific explanations clearly and coherently, with an emphasis on uncovering students' reasoning (Tang, 2015). This strategy consists of three key components: the premise, which identifies the accepted scientific knowledge, principles, or facts that serve as the foundation of the explanation; the scientific reasoning, which is the logical sequence that connects the premise to the phenomenon being explained, involving the application of scientific thinking to derive conclusions; and the outcome, which consists of the explanation of the specific phenomenon under study. It encourages students to move beyond rote memorization and instead engage in scientific reasoning, helping them understand what happens and why it happens. It has been implemented mainly in upper secondary physics and chemistry classrooms, assisting students in organizing their thoughts and writing more coherent scientific explanations. Moreover, teachers found it helpful in scaffolding scientific literacy and reasoning skills (Tang, 2016).

However, its results in primary education have not been reported. This absence constitutes a pedagogical gap, as primary students differ significantly from secondary students in their metacognitive awareness and their linguistic resources for verbalising causal chains (Kallery & Psillos, 2001; Loxley et al., 2017). Consequently, it is unreasonable to assume that a framework validated in upper-secondary chemistry and physics will transfer to the fourth-grade without pedagogical adaptation. While alternative frameworks for scaffolding primary scientific explanations, such as the Claim-Evidence-Reasoning (CER) model (McNeill & Krajcik, 2012), have been proposed and tested in elementary contexts, they have not been examined in conjunction with AR-based instruction. The present study addresses this gap by exploring whether PRO-aligned questioning can effectively scaffold primary students as they interact with AR simulations.

2.2 Pedagogical questions

Research on teacher questioning strategies and student questions in the context of science education has emerged as a critical area of inquiry due to its fundamental role in fostering scientific inquiry and cognitive development in primary education (Díaz, 2023). Questions play a central role in pedagogical discourse, as they can challenge perspectives, sustain dialogue, and support conceptual understanding (Márquez & Roca, 2009).

In recent decades, the field has evolved from focusing primarily on teacher-led questioning to recognizing the equal importance of student-generated questions and inquiry-based learning approaches (Wu et al., 2023), as well as the role of mediating questions between learners and technology-based instruction (López Takegami et al., 2025). Indeed, questions that promote connections between new information and students' existing knowledge structures have a substantial impact on science learning (King, 1994).

Importantly, students' own questions constitute critical indicators of their active thinking and learning processes, as they reveal attempts to make sense of phenomena, identify explanatory gaps, and establish new relationships with scientific ideas (Sanmartí, 2007; Wellman, 2011). In primary education, prior studies report that students who actively ask questions demonstrate improved science learning outcomes (e.g., Senisum & Edu, 2023).

Beyond their instructional function, teacher questions serve an epistemic role by guiding student attention toward relevant variables, eliciting causal reasoning, and supporting the articulation and revision of ideas (Joglar, 2015). The cognitive demands, openness, and underlying assumptions embedded in teachers' questions shape how students engage in scientific reasoning and explanation construction (Márquez et al., 2004; Bach & Márquez, 2017). Questions can also be analysed in terms of their purpose: motivational, evaluative, or metacognitive (Márquez & Roca, 2009). While Chin (2007) developed a distinct framework for science inquiry that distinguishes between strategies such as pumping, probing, and Socratic questioning, the framework by Márquez and Roca (2009) was designed specifically within the science education context. The latter approach integrates cognitive demand, openness, and communicative purpose into a single analytical scheme. Consequently, it is uniquely suited for the present study, which requires simultaneous analysis of both cognitive demands placed on students and the pedagogical functions the questions serve in mediating their construction of scientific explanations. Although the field lacks comparative studies examining how these two frameworks align or diverge when applied to the same dataset, this remains a gap that future research might address.

Despite the acknowledged importance of questioning in science education, a persistent problem is the predominance of closed, lower-order questions posed by teachers, which limits students' opportunities to engage in higher-order thinking (Eliasson et al., 2017; Conejera et al., 2020). This validates the present study's focus on exploring the type of questions, their cognitive demand, and their degree of openness.

Aligning with other authors (Hiltunen et al., 2021), we advocate for a balanced integration of these perspectives in research analysing students' and teachers' questions in their interactions.

2.3 Augmented reality simulations in geoscience learning

Research on augmented reality (AR) simulations within primary education has emerged as a critical area of inquiry due to its potential to enhance scientific reasoning and engagement (Morote et al., 2023). AR superimposes virtual objects onto the physical environment, offering interactive and immersive learning experiences to make abstract concepts more perceptible to students (Wen et al., 2023).

Prior studies suggest that AR can be implemented through games (Aivelo & Uitto, 2016) or applications designed to enhance long-term knowledge retention and motivation (Liu et al., 2022). Some studies have reported significant gains in learning (long-term knowledge retention) and engagement compared to traditional methods (Mondro et al., 2024; Sökmen et al., 2023). This is particularly relevant for earthquakes, which are closely linked to plate tectonics models and involve complex spatial and dynamic processes. In this respect, AR-based teaching strategies can provide three-dimensional, contextualized simulations to facilitate learning and enhance spatial perspective-taking abilities (Srivastava et al., 2024).

More broadly, simulations allow students to explore the relationships among variables within models, thereby facilitating the integration of knowledge into explanations (Geelan & Fan, 2014). Multimedia resources such as simulations or animations, when combined with concurrent narratives, have proven suitable for teaching phenomena associated with plate tectonics theory (Acuña, García, & Sánchez, 2010). Given the conceptual complexity and representational demands of this geoscience domain, interactive simulations are particularly valuable for supporting the construction of explanations (Gobert, 2005). This study focused on a marker-based AR system selected for its simplicity for novice users—specifically, children unfamiliar with such technology. These markers are usually images or QR codes that anchor a three-dimensional virtual model (Bacca et al., 2014). Within this AR environment, students can manipulate the model by rotating it to gain multiple perspectives and progressively reveal internal structures, such as the Earth's layers and core, while observing tectonic plate movements. These virtual elements are dynamically superimposed and responsive to student input, thereby distinguishing the experience from static animations, videos, or conventional screen-based simulations (Cai et al., 2022; Wen et al., 2023).

Regarding learning gains, prior meta-analyses and systematic reviews indicate that AR has a positive impact on learning outcomes across various science topics in primary education (Basumatary & Maity, 2023; Lampropoulos, 2024). AR interventions have often led to significant improvements in students' conceptual understanding and knowledge retention compared to traditional methods (Kim, 2006; Mondro et al., 2024). However, other studies reported no statistically significant differences in short-term

academic performance but noted gains in engagement that may indirectly support learning (Ortiz, 2024; Wen et al., 2023). The divergence in findings is likely attributable to methodological heterogeneity across studies- namely, variations in AR implementation fidelity, exposure duration, the presence of structured pedagogical scaffolding, assessment instruments, and student age (Merchant et al., 2014; Phipps & Merisotis, 1999). Critically, studies that report significant learning gains tend to embed AR within explicit instructional frameworks, while those reporting null or weak effects more often deploy AR as a standalone tool with limited pedagogical structuring (Makransky & Lilleholt, 2018; Wu et al., 2013). This pattern suggests that teacher mediation- such as the strategic teacher questioning investigated in the present study- may be a critical factor affecting the effectiveness of AR, despite rarely being identified or measured in the existing literature.

Concerning pedagogical factors, AR increases student engagement, motivation, and participation compared to traditional instruction (Booyoesen, 2023; Liu et al., 2022; Mondro et al., 2024), while also fostering peer interaction and attention (Martínez et al., 2019). Nonetheless, challenges related to teacher preparedness, time constraints, instructional design, and resource availability have been identified as critical factors influencing the effective integration of AR in classrooms (Abualrob, 2020; Pérez & Cortijo, 2020; Martínez et al., 2019; Wen et al., 2023).

Overall, while AR has demonstrated promise for supporting scientific inquiry skills, higher-order thinking, and epistemic beliefs (Chang & Hwang, 2018; Lin et al., 2022; Wen et al., 2023), its effects on learning outcomes and attitudes remain mixed (Kerawalla et al., 2006; Mondro et al., 2024). Although some research has highlighted AR's potential to foster argumentation, inquiry, critical thinking, and students' self-efficacy when combined with pedagogical strategies such as flipped learning or argumentation-based science learning (Chang & Hwang, 2018; Kaya & Memiş, 2024; Parma Dewi, 2026; Squire & Jan, 2007), other pedagogical interactions have received limited attention (Kaya & Memiş, 2024). Moreover, the role of pedagogical interactions supporting AR implementation in primary schools remains underexplored in specific contexts (Chang & Hwang, 2018; Wen et al., 2023).

Taken together, the three strands of literature reviewed here converge on a set of unresolved tensions. First, although explanation construction and model-based reasoning are established as central goals in primary science education, the pedagogical conditions that support these practices among primary students in geoscience contexts remain scarcely understood- particularly in communities where seismic hazards make such reasoning personally relevant. Second, while teacher questioning is widely recognised as a primary discursive mechanism through which scientific reasoning is activated or suppressed, the specific patterns of questioning that emerge when technology introduces an additional mediating layer have not yet been examined in AR-enhanced primary classrooms. Third, while AR has demonstrated the potential to engage students with non-observable phenomena, its effects on explanation construction are inconsistent and appear contingent on the quality of pedagogical mediation- a variable that has rarely been operationalised as teacher questioning in existing studies.

The present study is positioned precisely at the intersection of these three gaps. It examines how teacher questioning strategies mediate student explanations during AR-supported geoscience instruction in primary classrooms within seismically active regions of Chile - a context that simultaneously raises the scientific, pedagogical, and societal stakes of this inquiry.

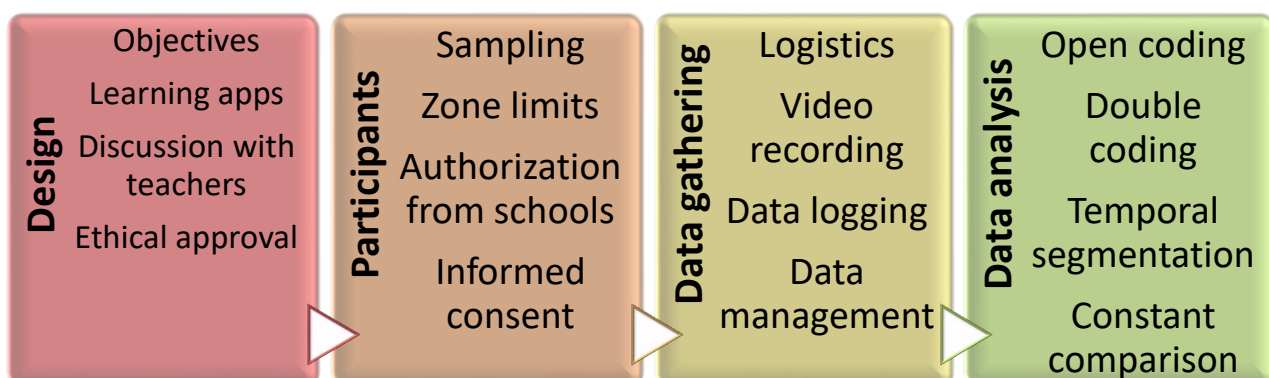
3 Methods

3.1 Study design

The study employed a cross-sectional design as part of a larger project. Data were collected at a single time point to capture the natural interactions during lessons on the Earth's layers, earthquakes, and volcanoes. There was no intervention or control group. The researchers assisted by providing the tablets on the day of the lesson and by discussing the applications' characteristics and the potential for posing questions oriented toward scientific explanations (Tang, 2016) with the teachers beforehand.

The study had a descriptive and relational scope. The descriptive component focused on describing, characterising, or mapping a phenomenon as it exists in its context, without necessarily intervening. The relational scope refers to the links that can be inferred from the data description, in this case, interpreting connections between specific variables at a particular moment (Timonen et al., 2024). The paradigm was pragmatic and integrated mixed methodologies to address the phenomenon under study (Omodan, 2024). Specifically, we used quantitative descriptions of the duration of classroom interactions and qualitative categorization of the questions that mediated the AR-based instruction. The pragmatic paradigm does not reduce social scientific knowledge to binary assumptions. Instead, it employs mixed methods to address the research inquiry, which is suitable for research aimed at exploring a solution to a specific problem in a real-world setting (King, 2023). Figure 1 shows the stages of the research process.

Figure 1. Summary of the research process stages



3.2 General study aim

To characterize the type, cognitive demand, and openness of teacher and student questions posed during AR-enhanced geoscience lessons and to identify which teacher question types promote scientific explanations in primary students.

3.3 Participants

The sampling strategy was non-probabilistic and intentional, based on criteria that maximized the richness of information about the study variables (Douglas, 2022). The criteria for selecting schools were: (a) Voluntary participation; (b) Similar socioeconomic level (middle-low); and (c) Location in a geographical area at risk of disaster due to an earthquake or tsunami. This final criterion acknowledges that Chile is a seismic country where previous studies have identified areas with a greater probability that, if an earthquake occurs, the damage will constitute a disaster (Hussain et al., 2020) or with high seismic potential (Jara-Muñoz et al., 2022). Thus, schools near the San Ramón Fault, known for its recent seismic activity, were invited to participate. The invitation was also extended to the Valparaíso region, located near the Metropolitan Region. The Valparaíso region in Chile has been identified as having high tsunami risk, with recent probabilistic hazard analyses revealing significant inundation risks in coastal areas (Aranguiz et al., 2024; León et al., 2022). This region includes schools and other critical infrastructure in the flood risk zone.

The schools were selected based on their location and the participation of fourth-grade students (primary school). However, in one of them, the video data were unusable. Table 1 presents the distribution of the 69 participating students across the three schools with valid data. All participants had completed parental consent and informed assent forms. The fact that the students lived in areas highly exposed to seismic and tsunami hazards meant that they possessed an inherent connection to the topics, which was reinforced by the schools' frequent emergency drills and evacuation simulations. This close alignment with their daily lived experiences likely mobilized their interest in earthquakes, tsunamis, and volcanoes during the lessons.

Table 1. Distribution of participants and schools

| Near San Ramón Fault (risk of earthquake) | | Near Valparaíso (risk of tsunami) | |
|---|------------------------|-----------------------------------|------------------------|
| School ID | Number of participants | School ID | Number of participants |
| School 1 | 27 | School 2 | 24 |
| | | School 3 | 18 |

Note. The table details the location of the participating schools, their IDs, and the number of participants. School 1 included 27 students near the San Ramón Fault, while Schools 2 and 3 were located near the Valparaíso region, with 24 and 18 students, respectively.

3.4 Instruments and data collection techniques

The data collection techniques involved video recording sessions in each course in which AR simulations were introduced to facilitate pedagogical work, with special emphasis on the teacher questions that arose during these sessions. We used the “Earth” and “Argeo” apps; the first focused on identifying Earth’s layers, while Argeo simulated the layers and surface changes during earthquakes and volcanic eruptions (see Figures 2 and 3).

Figure 2. Earth AR application (Magic Software, 2017)

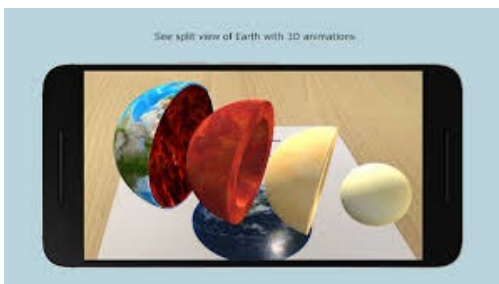
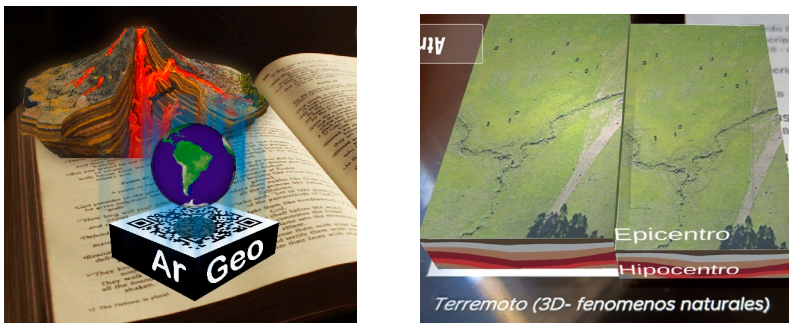


Figure 3. Argeo AR volcano and earthquake application (Golondrina Dev. 2018)



Two research assistants visited each school, distributed the tablets pre-loaded with the targeted apps, and the teacher guided the lesson. The learning objectives of the national curriculum (MINEDUC, 2012) implemented were:

- To describe, using models, that the Earth has a layered structure (crust, mantle, and core) with distinctive characteristics in terms of composition, rigidity, and temperature.
- To explain the changes in the Earth’s surface based on the interaction of its layers and the movements of plate tectonics (earthquakes, tsunamis, and volcanic eruptions).

The recording process adhered to the ethical guidelines mentioned earlier and ensured that all children participated in the activity, thereby avoiding reduced learning

opportunities. However, the recording captured only the students who volunteered and had their parents' informed consent. Consequently, the camera remained static in one corner of the classroom throughout the lesson.

3.5 Evaluation approaches

The analysis was developed from open coding of the recorded video episodes to establish emerging categories through constant comparison. Constant comparison is a process of continuously comparing sets of data, codes, and categories to identify similarities and differences, thereby allowing conceptual categories to emerge (Birks & Mills, 2023). To safeguard reliability, 20% of the material was double-coded by two researchers who worked independently to enhance research rigor. The lessons totaled 162 recorded minutes; thus, a segment approximating 32 minutes was selected for blind double-coding. This means each researcher coded the lesson without access to the other researcher's code, and then compared preliminary analyses until consensus was reached.

The analysis of interactions consisted of segmenting the video into phases and counting their durations in seconds to generate descriptive data. Moreover, the questions posed during classroom interactions were systematized and coded using discourse analysis, following the framework of Márquez and Roca (2009), which aims to identify the purpose or type of question, the cognitive demand it implies, and the degree of openness.

4 Results

The results are organized in two parts. First, the general analysis (4.1) reveals that teacher content clarifications and pointing gestures dominated lesson time across the three schools, while instances of student scientific reasoning were the least frequent category, accounting for a comparatively small proportion of total interaction time. The analysis of questions (4.2) shows that, of the 121 questions identified, teachers initiated the majority, primarily focusing on learning and classroom management. Most of these were closed-ended and low in cognitive demand, inviting recall and identification rather than causal reasoning. Nevertheless, a smaller but consistent subset of open-ended questions, present in every lesson, engaged students in higher-order thinking processes such as comparison, evaluation, and reflection. A portion of these were explanation-promoting questions.

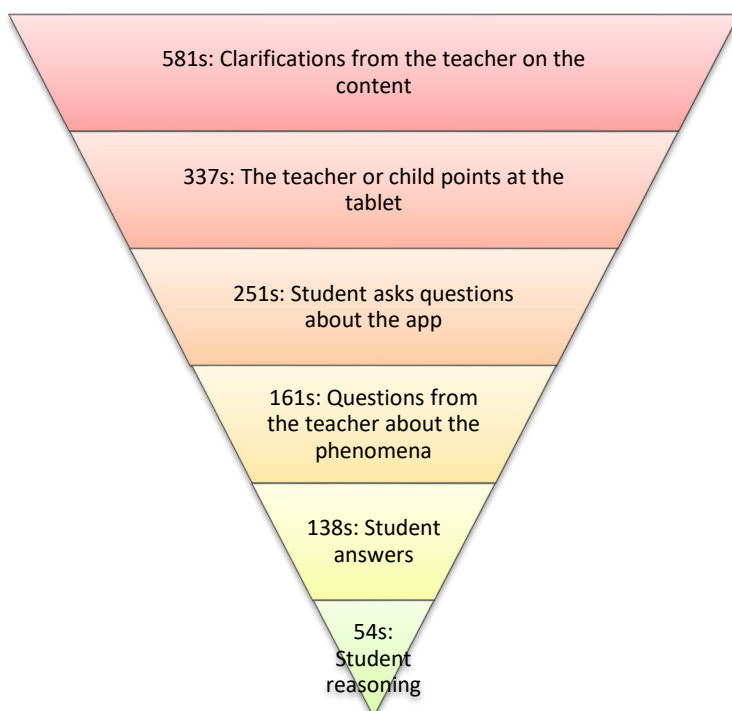
4.1 General analysis

The class videos were segmented to characterize the interactions and illustrate the general patterns. School 1 decided to dedicate two pedagogical hours to the AR instruction lesson because the students were unfamiliar with using tablets. In contrast, Schools 2 and 3 dedicated one pedagogical hour because their students were already familiar with the devices. Thus, the lesson lasted 37 minutes in School 1, 94 minutes in School 2, and 31 minutes in

School 3. In Chile, the pedagogical hour typically lasts 45 minutes, including administrative duties such as taking attendance. In this study, we did not record this administrative time.

The categories that emerged from the general analysis are presented in Figure 4, along with the duration in seconds of each specific segment. The most frequently observed category during interactions with the augmented reality simulation was teacher content clarification. Generally, these clarifications took the form of teacher explanations or descriptions that led to the differentiation of elements, for example, between an epicenter and a hypocenter. In terms of duration, the second largest category was pointing gestures by the teacher or student intended to visualize the phenomenon. Significant time was also dedicated to students' technical questions about the apps or the tablet. The next most frequent category was teacher-led questioning focused on the scientific content. Only questions initiated by the teacher and regarding the phenomena were considered here. Although other teacher-led questions were present, those were embedded within diverse interactions and counted in the fine-grain analysis (Section 4.2). Finally, instances of scientific reasoning expressed by participating children accounted for the least amount of time.

Figure 4. Distribution of general patterns of interaction during the lessons



4.2 Analysis of questions

We first focused on the types of questions identified in the three lessons and their distribution across the interactions. We counted a total of 121 questions, including student- and teacher-led interactions, which were classified into the following types (Márquez & Roca, 2009):

- Functioning questions (13.2%): Oriented toward the operational and procedural aspects of the students' work with the applications Argeo and Earth.
- Management questions (28.1%): Oriented to the regulation of classroom behavior and participation. Unlike functioning questions, which focus on tasks with the apps, managing questions address social and organizational aspects of the classroom environment.
- Learning questions (50%): Aimed at promoting students' conceptual understanding and knowledge construction through AR instruction.
- Metacognitive questions (8.3%): Invite learners to reflect on their own learning processes, or self-assess their learning, or the apps. These questions moved beyond content to focus on how learning is constructed and evaluated the usefulness of the applications.

Table 2 details the total number of questions by type and who initiated the interaction. We found that teachers initiated most of the questions (98), while students posed 23 questions across all the interactions. Most student questions concerned app functionality (e.g., *Teacher, how do I turn it on? Can I take pictures?*), followed by a few questions about classroom management (e.g., *Can I have lunch here? What is (a classmate) doing?*).

Table 2. Types of questions present in the lessons

| Who poses the question | Functioning | Management | Learning | Meta-cognitive | Total |
|------------------------|-------------|------------|----------|----------------|-------|
| Student | 12 | 6 | 5 | 0 | 23 |
| Teacher | 4 | 28 | 56 | 10 | 98 |
| Total | 16 (13,2%) | 34 (28,1%) | 61 (50%) | 10 (8,3%) | 121 |

Note. The table details the distribution of questions in the lessons by type.

The five learning-related questions raised by students were as follows:

1. Teacher, can you help me with the hypocenter?
2. Did you know that most islands in the oceans are made from marine volcanic eruptions?
3. Nobody? Has nobody arrived at the Earth's center?
4. Teacher, how do they (the scientists) discover this information?
5. What would happen if we put water into the mantle?

These students' learning-oriented questions show active help-seeking (n^o1) and curiosity (n^o 2 and n^o 3). Although in the minority, students asked questions not only to resolve doubts but also, within the context of AR instruction, to share their own knowledge with the teacher (n^o 2), contrast information (n^o 3), explore the nature of science (n^o 4), and think in hypothetical or experimental scenarios (n^o 5).

From the total of 98 questions posed by the teachers, they were primarily aimed at promoting learning (56), followed by those oriented toward managing the classroom environment (28). The least frequent questions initiated by the teachers were metacognitive (10), and those regarding the functioning of the AR applications (4). The questions categorized as metacognitive or related to learning (66 in total) were distributed across the three lessons with varying frequencies. However, of these, most were closed-ended (34) and low in cognitive demand, inviting students to remember, recall, describe, identify, and differentiate elements. Table 3 presents examples of these closed-ended, low-demand learning questions and the student responses they triggered.

Table 3. Examples of low-cognitive-demand questions and students' answers

| Questions inviting recall | | Questions inviting identification | |
|---|---------------------------------|--|----------------|
| Teacher question | Student answer | Teacher question | Student answer |
| Who remembers what a hypothesis is? | An answer before we experiment. | How many Earth's layers can you identify? Did somebody count them? | Three. |
| Have you heard these two words, hypocenter and epicenter, before? | (No answer). | Which layer has the lowest temperature? | The nucleus. |

In contrast, we also noted instances of open-ended questions focused on metacognition and higher-order thinking processes. While fewer in quantity, these were evident in every lesson observed. The cognitive demands and purposes of these questions were to invite students to compare, relate, explain, evaluate, and reflect. These types of questions, for instance, aimed to encourage students to relate the phenomena under study to their lives, compare what they had previously thought about the Earth's layers with what they learned through the AR instruction, and evaluate its utility. Table 4 presents examples of questions that demand higher-order thinking and the students' answers.

Table 4. Examples of questions that demand higher-order thinking and students' answers

| Questions inviting comparison/relation | | Questions inviting evaluation | |
|---|---|--|--|
| Teacher question | Student answer | Teacher question | Student answer |
| How had you imagined the Earth's layers? | As there was lava and nothing else under the rocks! | Can you tell me what you have learned today? | How they really move and how we see earthquakes and volcanoes... and how the volcanoes are seen. |
| Have some of you experienced something like this? | The day after I was born my mom was in the hospital, and an earthquake started. | What do you think about the app? | Very good! It has a lot of information about the planet, everything is clearer now. |

Note: This table lists four examples of high-cognitive-demand questions and their answers.

Within the group of open-ended questions, we found a small subset that invited the children to construct explanations using the premise-reasoning-outcome (PRO) strategy (Tang, 2015). However, these questions only prompted some students to express simple causes of the phenomenon, although this was still educationally relevant. Some of these questions required providing more than a single answer, for example, comparing and searching for common elements between earthquakes, tsunamis, and volcanoes. We identified these teacher questions as triggers of student reasoning because of these characteristics. In the following excerpt, a chain of these explanation-promoting questions can be observed as a dialogue between the teacher and the students.

T: What do we observe in the images, and regarding what we observe, why does this happen?

S: In the first one, I think it is an earthquake because it is spreading and moving, possibly due to the collapse. I think a tsunami passed over it.

T: Where do you see them moving, in the image?

S: Where the marked point comes out. The crack! I believe that the friction of the plate tectonics caused an earthquake, which then spread to all the houses. I remember answering the first two. In the first, I say the same thing that (a classmate) said. The second, I think there was an earthquake, and the house was destroyed a little, and possibly the earthquake was so strong that a big wave could have arrived, not a tsunami, but a little bit of a big wave, because you can see a little mud, and they are falling as if in the form of water. I think that it occurred because there was an alteration in the plate tectonics due to the Earth's rotation.

T: Why do you think that movements occur on the surface of the Earth? Why do you think that happens?

S: Because tectonic plates are in motion

S: Because the stripes collide

T: What do you think happened? What do you know about the movements of the Earth's surface?

S: How do you spell tsunami?

T: What damage can the movement cause?

S: It can cause landslides, it may also cause tectonic plates to cause the sea to move and rise, and a large wave or tsunami returns, or it may also cause the

earthquake to be as intense as the one in “1807” or something like that, the one in Valdivia. Before, an earthquake causes the houses to kind of split in two, like that, and cause big waves. In some countries where there is a sea, there are some parts where there is a plate, and under the Earth, there is another, which settles down, and at some point, they shake and tremble (noise).

T: Do you believe that there is a common cause between volcanoes, earthquakes, and tsunamis?

S: Yes, the movement of the plate.

The excerpt above illustrates how a sustained chain of open-ended teacher questions can progressively deepen students’ scientific reasoning, moving from surface-level observations based on the AR simulation to causal explanations and cross-phenomena comparisons. A closer reading of this dialogue reveals that the teacher’s questions do not simply elicit isolated answers but build iteratively on prior student responses, creating a discursive scaffold in which each turn opens a new explanatory space. Students, in turn, demonstrate an ability to mobilize partial scientific knowledge -such as tectonic plate movement, epicenter location, and wave propagation- and connect these concepts to personal memories of seismic events. This suggests that the explanatory potential of AR instruction lies not in the technology alone, but at the intersection of visualization, experiential knowledge, and pedagogical questioning. However, because these dialogic sequences remained rare, questions arise regarding the conditions under which such interactions occur and how they might be more systematically cultivated. To address these concerns, the following section contextualizes these patterns in light of prior research on teacher questioning, AR-mediated learning, and the role of socio-contextual relevance in primary science education.

5 Discussion

The present study explored the interactions among students, teachers, and content regarding the Earth’s layers, earthquakes, and volcanoes through augmented reality simulations (available on tablets) and how these interactions shape students’ opportunities to engage in scientific reasoning, with a specific focus on the teacher questions that mediated the experience. Although teacher clarifications and closed-ended questions were statistically predominant, and AR simulations facilitated the visualization of otherwise invisible processes, the instructional discourse surrounding the technology often remained focused on identifying and describing features rather than supporting explanatory reasoning. This pattern is educationally significant, as it suggests that immersive technologies do not automatically transform classroom inquiry. Rather, without intentional pedagogical mediation, AR risks reinforcing surface-level engagement and perpetuating traditional teacher-centred approaches in technologically-enhanced environments.

Consequently, this study extends existing research that has often attributed learning outcomes primarily to the representational affordances of simulations themselves (e.g.,

Rutten et al., 2012). These findings reveal that the educational value of AR depends substantially on how teachers structure participation and questioning during the activity. Conversely, a purely technologized view of learning marginalizes the role of teacher mediation, the design of lesson scenarios, and the curricular embedding of simulations over time.

While the analyses indicated meaningful patterns in interaction types and question distributions, the educational significance of these findings becomes clearer when considered in terms of classroom practice and prior research on technology-enhanced inquiry. Although students engaged with the AR applications, their reasoning about geoscientific phenomena was brief, suggesting that visualization alone is insufficient for fostering the construction of explanatory models. These results underscore the significance of pedagogical mediation if AR technologies are to transcend mere engagement and promote scientific literacy. Importantly, this indicates that relatively small pedagogical shifts in questioning strategies may have substantial effects on the quality of student thinking -a premise further illuminated by the subsequent analysis of teacher questioning. Most questions posed were closed-ended and low in cognitive demand, often guiding students to remember or describe elements while offering limited opportunities to explain or justify their thinking. However, the few questions that encouraged comparison, such as those that prompted students to search for common causes among earthquakes, tsunamis, and volcanoes, activated more complex reasoning.

Moreover, the analysis exemplified in Table 3 shows that most of these prompts were closed-ended and low in cognitive demand (e.g., “Who remembers what a hypothesis is?”). Consequently, many student responses were short and descriptive. The imbalance highlights that while students are ready to contribute, the structure of teacher questioning constrained the depth of their engagement. As shown in Table 4, open-ended or metacognitive questions (e.g., “Can you tell me what you have learned today?”) led to richer answers that included comparisons across phenomena. The relatively small proportion of open-ended questions identified in this study is therefore educationally significant, as these instances were consistently associated with richer student explanations, causal reasoning, and references to underlying mechanisms of earthquakes, tsunamis, and volcanoes. Even infrequent, well-designed prompts appeared effective in shifting classroom discourse toward explanation-construction, highlighting the leverage teachers hold in shaping the epistemic quality of AR-supported lessons.

These findings align with earlier studies suggesting that immersive technologies enhance learning primarily when coupled with inquiry-oriented pedagogy rather than direct instruction alone (e.g., Dunleavy et al., 2009; Makransky & Petersen, 2019; Mansour et al., 2025). Similar to prior classroom-based AR research, the present study confirms that the benefits of visualization are often overestimated when instructional discourse is not examined. However, this study extends the existing literature by providing fine-grained interactional evidence on how certain types of teacher questioning mediate students' use of AR representations in primary education science.

These isolated but meaningful instances show the potential of AR environments to support higher-order thinking, if teachers strategically frame their questions to invite such reasoning. This finding supports prior studies that emphasize the quality, rather than the quantity, of questions as driving conceptual development (King, 1994; Joglar, 2015). The evidence suggests that discursive strategies, such as integrating the PRO framework (Tang, 2015), could help teachers scaffold student reasoning more systematically by linking premises, reasoning, and outcomes. Unlike studies that report learning gains without examining classroom conversation, the present findings demonstrate that AR's affordances for modeling dynamic geoscientific processes are realized only when teachers prompt comparison, causal reasoning, evaluation, and connections with students' lives.

The role of AR simulations in this study was twofold. On the one hand, AR facilitated the visualization of abstract concepts such as epicenter and hypocenter, reducing representational barriers and maintaining student engagement. On the other hand, much student attention was directed toward the technology itself rather than the underlying scientific phenomena. This points to the dual potential of AR: although it can lower cognitive barriers, without explicit scaffolding, it may also reinforce surface-level interactions.

These results can be interpreted in light of previous work, as the framework of Márquez and Roca (2009) suggests that the highest cognitive-demand questions were open-ended, facilitating the expression of children's scientific reasoning. It can be argued that estimating the capacity of questions to elicit scientific reasoning is difficult at early levels of conceptual learning, such as the fourth year of primary school. However, the data from this study suggest that open-ended questions that encourage children to compare and identify common elements are pedagogically appropriate and pertinent. Therefore, the activating role of reasoning about geoscience phenomena in children, and, more importantly, their progression towards scientifically accepted models in geosciences today, can be verified by studying significant questions (Joglar, 2015). Thus, it seems crucial not to underestimate children's abilities to explain phenomena involving abstract entities while simultaneously learning complex concepts, such as the theory of plate tectonics, which aligns with prior studies on children's explanations (Legare, 2012, 2014).

Table 4 and the classroom dialogue illustrate instances where students connected AR simulations to their personal experiences of real earthquakes. For instance, the excerpt "It can cause landslides, it may also cause tectonic plates to cause the sea to move and rise, and a large wave or tsunami returns, or it may also cause the earthquake to be as intense as the one in "1807" or something like that, the one in Valdivia". These personal accounts extended beyond the app's scripted content and demonstrated that students sought to situate scientific concepts within familiar contexts. Such connections are powerful for meaning-making (Mortimer & Scott, 2003), yet they were not systematically integrated into the instructional flow. Teachers could more deliberately leverage these contributions to bridge the gap between AR representations and real-world seismic events, promoting meaningful learning. The findings thus reaffirm that digital tools must be combined with intentional pedagogical strategies to support deep learning (Cai et al., 2022; Kaya &

Memiş, 2024; Mansour et al., 2025). The findings suggest that AR has the potential to enhance geoscience learning, but only when coupled with teacher questioning that promotes higher-order reasoning and metacognitive strategies. Practically, this implies a need for teacher professional development that goes beyond technical training in AR and includes strategies for designing open, comparative, and metacognitive questions in a contextually relevant manner. Such an approach may help AR become a catalyst for the explanatory process rather than a distraction.

The findings revealed the promise and challenges of AR integration in primary geoscience education, a research gap already identified (Ahmad & Samah, 2024; Kaya & Memiş, 2024). The rare but significant instances of student scientific reasoning, linked to open-ended questioning or personal experiences, highlight the potential of AR when combined with contextually relevant pedagogy. To maximize impact, teachers may need targeted support in designing questions and scaffolds that transform AR simulations from attention-grabbing visuals that increase student motivation (Liu et al., 2022) into catalysts for more authentic scientific thinking (Kaya & Memiş, 2024). This support should also encourage teachers to purposefully invite students to connect AR experiences with their personal or community encounters with socio-natural disasters, thereby grounding abstract models in meaningful contexts that deepen understanding and meaning-making. Framing AR-enhanced inquiry in this way positions it as a powerful tool not just for engagement, but for cultivating the reasoning skills and explanatory practices essential to scientific literacy and disaster preparedness. Crucially, this distinction suggests that motivational engagement and epistemic engagement should not be conflated, particularly in primary science contexts, where novelty effects may temporarily intensify participation without deepening conceptual understanding. We conclude that AR adds more realism to the underlying causes, which are difficult to reason about when dealing with non-visible entities, and that personal connection with the phenomena complements its use.

The results have clear implications for professional development and instructional design. To maximize the impact of AR in geoscience learning, teachers can purposefully invite students to connect AR experiences with their personal or community encounters with natural disasters, thereby grounding abstract models in meaningful contexts that deepen conceptual understanding. Such practices position AR not merely as a visualization tool, but as a medium for fostering scientific reasoning, modeling, and socioscientific awareness, which is particularly relevant in disaster education contexts.

A key strength of this study lies in its focus on primary school geoscience education within seismic-risk regions, a context that has been under-explored in prior research. By situating AR-supported instruction in classrooms located in earthquake and tsunami-hazard zones, the study contributes to both the science education literature and disaster preparedness education. Another strength is the use of authentic classroom video data, which allowed for detailed analysis of teacher-student interactions and the emergence of scientific reasoning *in situ*. The combination of AR simulations with discourse analysis offers novel insights into how immersive technologies can facilitate the construction of explanatory models in young learners.

Among the limitations of this study are its sample size of 69 students and the lack of comparative measurements or control groups; consequently, the causal effects of AR utilization cannot be isolated. However, this constraint can be addressed in future studies that position other contexts as variables to be explored. This limitation also restricts the generalizability of the findings, as patterns of discourse and reasoning may change over time with repeated exposure. The findings should therefore be interpreted as context-sensitive evidence of how AR-supported discourse unfolded in these particular learning environments, rather than as definitive evidence of AR's macro-effectiveness in primary education. To address this, future experimental or design-based studies with larger samples could systematically vary teacher questioning strategies during AR-supported lessons to examine causal effects on student reasoning quality and explanatory depth. Additionally, the video data, while rich in capturing interaction, did not allow for in-depth exploration of individual learning processes or long-term conceptual development. Future research might adopt longitudinal designs to examine how the repeated use of AR, combined with structured questioning, influences the development of scientific reasoning. Such longitudinal inquiries could investigate whether sustained exposure to open-ended AR-supported discourse leads to durable changes in students' modeling competencies and disaster-related decision-making. Incorporating pre- and post-assessments or longitudinal tracking could also provide more substantial evidence of learning gains. Furthermore, future research could move beyond evaluating whether AR improves learning outcomes to examine the interactional mechanisms through which scientific reasoning is either enabled or constrained during AR-supported instruction. Particularly, our findings suggest a need for microgenetic and discourse-analytic studies investigating how teacher questioning shapes transitions from descriptive observations to explanatory reasoning. Comparative studies examining whether such discourse-oriented approaches produce stronger reasoning than visualization-focused AR instruction would be valuable. Finally, our findings are situated within a specific sociocultural and geographic context. While this context is highly relevant to disaster education, it also limits the transferability of the results to other educational settings less exposed to these phenomena. Cross-cultural comparisons would be valuable for understanding how diverse contexts mediate the integration of AR, the questioning strategies, and the development of scientific reasoning.

6 Conclusion

From a sociocultural and model-based learning perspective, understanding geoscientific phenomena requires learners to coordinate everyday experiences with abstract scientific representations that often refer to non-visible processes. This study contributes to research on AR-supported science learning by revealing that the educational value of augmented reality lies not solely in the technology but principally in how teachers create the learning environment and utilize pedagogical interactions, such as targeted questioning,

to guide students as they interpret, inquire, and explain what they observe. By combining analyses of interaction patterns with a qualitative examination of teacher questions and student answers, this investigation demonstrates that AR simulations of earthquakes and volcanic eruptions primarily supported conceptual engagement when teachers moved beyond clarification and recall toward questions that invited explanation and reflection -for instance, inquiring about the causes of the phenomena or the elements they have in common. Although AR helped students visualize difficult geoscientific concepts such as tectonic movement and volcanic activity, the findings revealed that opportunities for scientific reasoning remained limited when classroom discourse focused heavily on procedural guidance. Hence, the results suggest that the effectiveness of AR in science education depends less on technological novelty and more on the capacity of teachers to orchestrate dialogic, cognitively demanding learning environments.

A crucial insight is that students were most willing to participate when discussions drew on their own lived or community experiences of socio-natural disasters. These moments of experiential or “felt” knowledge created openings for student-generated questions and sense-making, which, when taken up by teachers, could bridge everyday experiences with scientific explanations and models. However, such connections were only sporadically developed, suggesting that this pedagogical opportunity remains largely underutilized in AR-enhanced instruction within the context of this study.

In sum, the findings suggest that AR can function as a powerful mediating tool when teachers deliberately connect students’ experiential knowledge to disciplinary questions and scientific explanations. AR activities in geoscience education can be intentionally connected to students’ local experiences and disaster-related knowledge to support meaningful model construction and socioscientific awareness. Ultimately, this study highlights the importance of treating AR not as a stand-alone instructional solution, but as a mediating resource through which educational impact emerges from the interaction of technology, classroom discourse, and learners’ real-life experiences. Doing so may not only deepen the conceptual understanding of geoscientific phenomena but also promote meaningful, relevant learning that is particularly critical in the context of disaster education and risk awareness.

Research ethics

The ethical considerations of this study were integrated into its design and implementation, with a focus on safeguarding participants’ and their families’ rights. Participation was voluntary and did not disrupt instruction, as agreed upon with the school authorities, who recognized it as part of regular curricular activities. Institutional authorizations were secured, informed consent was obtained from teachers and parents, and informed assent was obtained from children. Only data from participants with all the necessary forms signed before participation were analysed. Confidentiality and anonymity were strictly maintained during the processing and storage of participant data.

Author contributions

V.C.: conceptualization, investigation, methodology, funding acquisition, project administration, writing—original draft preparation, writing—review and editing.

M.A.: data analysis, writing—review.

A.C.D.: writing—original draft preparation, writing—review and editing.

All authors have read and agreed to the published version of the manuscript.

Artificial intelligence

We used Grammarly® to improve the legibility of our English-language text.

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Institutional review board statement

The study was evaluated by the research ethics board at Pontificia Universidad Católica de Chile under protocol number 180514006.

Informed consent statement

Informed consent was obtained from all research participants, including parents and teachers, and informed assent was obtained from children.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Conflicts of Interest

The authors declare that they have no conflicts of interest.

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