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Developing geo-sequential reasoning about tectonic processes using computational simulations

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ABSTRACT
Explaining phenomena associated with a system involves describing a system's structure and articulating the process through which the system's structure changes over time. This paper defines geo-sequential reasoning in the context of plate tectonics and uses it to analyse how students explain the geological processes that occur along convergent boundaries as part of the plate tectonics system. This study was part of design-based research on an online Plate tectonics module that included simulation-based modelling developed for secondary school students. We analysed students' explanations ($n = 950$) about phenomena found along a convergent boundary (1) as an oceanic plate and a continental plate move towards each other and (2) between two oceanic plates located on the opposite side of a tectonic plate from a divergent boundary. We also analysed images created by students of the simulation as evidence to support their explanations. We found that a majority of students used simulation-based evidence when describing the sequence of events along the convergent boundary and that the synced planet surface and cross-section views in the simulation supported students' inclusion of processes responsible for the events. These findings have implications for how teaching and research with dynamic simulations can support reasoning built with temporal evidence.

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Simulations; plate tectonics; geo-sequential reasoning

Introduction

Most Earth and space sciences, including geoscience, cannot be fully defined through the experimental inquiry often equated with research in other science disciplines. Geoscientists use observational inquiry to explore and develop descriptions of natural phenomena (King, 2008). By employing systematic observations of and comparisons across cases, geoscientists navigate between theoretical insights and empirical findings to develop explanatory accounts for the complex processes underlying natural phenomena. Scientific inquiry about Earth systems thus involves a variety of methods such as physical and computational modelling, high-resolution satellite and radar mapping, sensor-based record keeping, and systematic field observations. Advanced technologies are needed because phenomena might occur in remote locations, or over long time scales or large spatial scales, or because they occurred in the past (Kastens & Manduca, 2012).

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In geoscientific inquiry, one important reasoning skill involves thinking about time by recognising 'the vastness of geologic time, the sequence and duration of events and the rates of geologic processes' (Kastens & Manduca, 2012, p. 13). Additionally, several observable events can be found to have a common cause, but the nature of causal connections may not be immediately discernible. Developing an understanding of these types of events requires putting them in a temporal sequence based on a theory that justifies the ordering (Dodick & Orion, 2003). This study explores geo-sequential reasoning in the context of plate tectonics and uses it to analyse students' explanations of geological processes in the context of convergent plate boundaries.

Plate tectonics is an overarching theory that describes large-scale phenomena related to Earth's outermost layer composed of tectonic plates moving constantly and interacting with one another over millions of years (Mayer, 1995). Tectonic plates comprise a complex system that is difficult to study (Gobert, 2000). Understanding plate tectonics requires temporal reasoning about geologic events that occur over short periods of time such as earthquakes and volcanic eruptions, as well as events lasting hundreds of millions of years such as mountain building. While research has shown that students rarely develop a system-level understanding of plate tectonics (McDonald et al., 2019), interactive visualisations such as simulations have the potential to engage students in time-dependent reasoning (Kali & Linn, 2008).

In this study, we characterise geo-sequential reasoning as spatial and temporal reasoning necessary to think about events in three dimensions, to consider the duration and sequence of events, and to draw conclusions about causal dynamic processes for these events. We use it to investigate how students explain geological phenomena that occur along convergent plate boundaries after interacting with a three-dimensional plate tectonics computational simulation called the Tectonic Explorer. We analysed and compared students' expressions of geo-sequential reasoning in two scenarios. In the first scenario, students simulate the formation of the Andes Mountains along a convergent boundary between a plate with oceanic crust and a plate with continental crust. In the second scenario, students simulate the South American Plate and connect the phenomena along a divergent boundary to the phenomena along a convergent boundary on the other side of the plate. Students' written explanations and simulation evidence artifacts were collected as part of the fourth iteration of a design-based research study of an online technology-enhanced Plate Tectonics module. The purpose of this study is to characterise an important learning outcome related to geo-sequential reasoning, develop tasks in the module to elicit geo-sequential reasoning, collect and analyse data from the tasks for geo-sequential reasoning, and make suggestions for modifications to the tasks based on theoretically interpreted data. The research from this design-based study, therefore, only includes data collected during this one implementation of the materials. The research question is: '*How do the task structure and uses of computer simulations captured in images correlate with the geo-sequential reasoning expressed in students' explanations related to tectonic processes?*' Studying this question can provide evidence of the student learning targeted by the curriculum and indicate areas for modification of the simulation and prompts. In the study of geoscientific phenomena, being able to reason about how a sequence of related events unfolds is critical for understanding the natural world. Since many geologic events cannot be observed directly, this design-based research addressed the simulation-based task approach for supporting students' development of geo-sequential reasoning.

Literature review

Reasoning about time vs. reasoning with time in geology

Temporal reasoning in geology often involves scales associated with events that occur beyond the scope of human experience. Along with spatial reasoning, temporal reasoning is an inextricable part of geoscientific thinking and considered the second most critical geoscientific thinking skill according to the report from the 2014 Summit of the Future of Undergraduate Geoscience Education (Mosher et al., 2014). The extended timescale of geological events makes it difficult to develop explanations for how slow processes or infrequent events can lead to big transformations through the accumulation of incremental changes over millions of years (Kastens et al., 2009). Two key aspects of temporal reasoning in geoscience are: (1) thinking about geologic time to recognise the vastness of the geologic timescale with all its named periods and placing *separate* events in a relative or absolute order on the timescale (Cheek, 2010) and (2) thinking with time to develop an awareness about the duration, processes, and sequence of geologic events (Kastens et al., 2009). Most research has focused on the former, exploring whether students can understand and recall aspects of scientists' model of geologic time that marks unique periods in Earth history (Kastens et al., 2009). This research revealed that elementary students (Ault, 1982), middle and high school students (Dodick & Orion, 2003, 2006), college students (Libarkin et al., 2007), and both pre-service and K-12 teachers (Trend, 2000, 2001) all have difficulties thinking about the scale of geologic time, even if they are able to consider relative age relationships between events occurring on Earth (Dahl et al., 2005; Petcovic & Ruhf, 2008; Ryker & Jaeger, 2018).

The second aspect of temporal reasoning – considerations about the duration and sequence of events – involves grappling with causal dynamic processes that heavily depend on the progression in which *related* events unfold (Kastens & Manduca, 2012). In geoscience, this type of reasoning requires the interpretation of data and evidence that are often incomplete and, therefore, do not reveal the whole process and sometimes initially look unrelated, especially when there is no theoretical framework for understanding (Bond et al., 2011). For example, one can observe a mountain range. However, in order to describe how the mountains formed, one needs to extrapolate about the processes below Earth's surface that occurred over millions of years, of which the observer has no direct experience (Kastens & Manduca, 2012). It is hypothesised that having both an appreciation of the duration of events and the ability to articulate the processes responsible for those events is critical for geoscientific reasoning because they can support the development of understanding a theory (Resnick et al., 2012).

Simulations as observable phenomena

To support students' reasoning to explain geological phenomena, we developed a computational simulation tool that visually illustrates the dynamics embodied in the phenomena. If we look at modern science, we 'often find extensive reliance on models as the source of knowledge of physical systems especially when these systems are largely inaccessible' (Morrison, 2015, p. 210). In disciplines such as geology and astrophysics, constructing and using models enables the theoretical investigation of the processes leading to phenomena created by complex systems, such as the processes underlying earthquakes, volcanic eruptions, and the formation of stars and galaxies. While physical models can be useful, computational models have become a default choice for many scientists in the Earth science discipline. A computational model and an associated interactive simulation, hereafter called a computation simulation, can be designed to illustrate the structures and functions of complex systems, allow users to experiment with and observe complex system behaviours and outputs, and permit users to investigate phenomena across large spatial and temporal scales (National Research Council, 2012).

In education, computational simulations provide students with opportunities to derive cause and effect relationships, make predictions, explain scientific phenomena (Schwartz et al., 2009), and compare computationally simulated outcomes with real-world observations. It has been shown that computational simulations help students visualise otherwise difficult and abstract concepts (Wang & Tseng, 2018), develop better explanations and predictions about complex systems (Crawford & Cullin, 2004; Louca & Zacharia, 2012; Sins et al., 2005), and make difficult concepts more accessible to a wide variety of learners (Hegarty, 2004; Moreno & Mayer, 2007; Moreno & Valdez, 2005; Pallant & Tinker, 2004; Xie & Tinker, 2006). Smetana and Bell (2012) identified and reviewed 61 empirical studies on computer simulations that support science instruction and learning. Their reviews indicate that computer simulations can be effective in developing content knowledge and facilitating conceptual changes based on pre-test/post-test gains, observations, and interviews. More recently, research has shown that simulations can promote reasoning activities on par with experiments (Develaki, 2019). While students engaged in hands-on activities, they were more likely to discuss topics related to lab setups and measurements whereas when engaged with virtual labs, their discussions focused on understanding variable relationships, exploring patterns, making predictions, and interpreting scientific phenomena (Kapici et al., 2019; Puntambekar et al., 2021). Using simulations can engage students in advanced scientific ways of reasoning and argumentation (Develaki, 2017); improve students' science process skills (Celik, 2022; Haryadi & Pujiastuti, 2019; Siahaan et al., 2017; Smetana & Bell, 2012); and significantly improve students' scientific inquiry competency (Chou et al., 2022). Simulations can promote higher-level thinking, especially if leveraged in cases related to complex Earth science concepts (Luo et al., 2016).

These learning improvements occurred when simulations were used as supplements to classroom lessons, were accompanied by scaffolds and reflections, and were used to create conceptual dissonance (Smetana & Bell, 2012). In the hands of skilled teachers (Celik, 2022), and with proper scaffolding and design considerations (Kukkonen et al., 2014) or with automated feedback on simulation use (Lee et al., 2021), computer simulations that prioritise the potential for large impacts in science learning (Lancaster et al., 2013) can be used successfully for scientific inquiry with complex systems, such as environmental systems (Pallant & Lee, 2015), ecosystems (Wilkerson-Jerde & Wilensky, 2015), the plate tectonics system (Bodzin et al., 2016), and Earth systems that are otherwise inaccessible (Pallant et al., 2022). Seeing dynamic phenomena makes it more likely that students develop ideas related to change over time and write about them in their explanations as compared to learning about dynamic phenomena from static images (Stern et al., 2008).

Plate tectonics and learning

Plate tectonics describes the movement and interactions of Earth's tectonic plates both at and below the surface around the entire globe over a long period of time. Typically, plate tectonics is taught in middle and high school (McDonald et al., 2019) and focuses on individual plate boundary interactions. While earthquakes and volcanoes are outcomes of plate-plate interactions, they are taught before plate tectonics is introduced. As such, students have difficulties in thinking about earthquakes and volcano formations resulting from plate movement. Kortz et al. (2011) noted that students struggle to identify plates or infer plate locations or motions solely from exploring landform features and seismic data. Additional research shows that although most students are aware of features on Earth's surface and can represent changes over time (e.g. the formation of mountain ranges), they are unable to explain the tectonic processes by which these changes occur; this is true even for undergraduate students taking an introductory geology class (Libarkin & Kurdziel, 2006). What is often missing in the teaching and learning about plate tectonics is examining the dynamic plate system as a whole and exploring how surface phenomena are related to phenomena happening below the surface (Pallant et al., 2020). Clark et al. (2011) found that students using static images struggled to connect surface features to the underlying processes responsible for the formation of those features. For example, students think the formation of the mid-ocean ridge along a divergent boundary is similar to that of the high mountain ranges found along a convergent boundary because the mid-ocean ridges are topographically comparable in height to the mountain ranges despite the fact that these features arise by entirely different processes. Similarly, students do not appear to consider earthquake and volcanic data evidence of plate motion (Sibley, 2005), although most Earth science curricula rely on a map of earthquake locations as evidence of the existence of plates.

Research on students' drawings of convergent boundaries reveals two persistent alternative conceptions: (1) mountains form on the surface as if two pieces at the surface push up together while nothing is happening below the surface and (2) mountains just appear on top of moving plates like an inverted ice cream cone (Sibley, 2005). Research also reveals that students may provide rich descriptions of plate tectonics, but these descriptions typically lack a clear dynamic sequential explanatory power (Smith & Bermea, 2012). Most studies to date used static visualisations such as maps, drawings, diagrams, or concept maps to teach plate tectonics. Studies are needed to explore whether and how students can express geo-sequential reasoning by connecting phenomena at and near Earth's surface when they use an interactive computer simulation tool that makes invisible tectonic phenomena visible. This study explores a dynamic three-dimensional interactive simulation that allows students to investigate a plate tectonic system and observe the processes and sequences of geologic events as plates move and interact over time. This study shows how pairing the use of the simulation with specific tasks may change how students explain what they observe and incorporate connections between the causal interactions within the system and the outcomes.

Research context

Plate tectonics module

Plate tectonics theory states that Earth's solid outer layer is separated into plates that move over time. The plates interact with one another and with the mantle below them. The plates move apart, slide past one another, and converge endlessly. Learning about the plate system typically takes place in parts, focusing on each type of boundary separately (McDonald et al., 2019). Rarely are these parts pulled together into a complex plate system, along with the mechanisms responsible for plate interactions. We developed an online learning module for secondary school students using the driving question: 'What will Earth look like in 500 million years?' We also developed the Tectonic Explorer simulation to use as part of inquiry tasks where students independently investigate plate interactions at and below the surface and the emergent phenomena that occur over time. The Plate Tectonics module consists of five activities (Table 1) that take seven to ten 45-minute class periods to complete.

In the first activity, students determine the location of plate boundaries as well as the rate and direction of plate motion using seismic and GPS data as evidence. In the second and third activities, case studies of real-world tectonic phenomena guide student explorations of convergent, divergent, and transform boundaries. Students compare three types of evidence: (1) simulation results from the Tectonic Explorer, (2) earthquake and volcanic eruption maps from the Seismic Explorer (a data visualization tool), and (3) topographical profiles of land features (e.g. mountains, deep trenches, and mid-ocean ridges). In these two activities, students are expected to express geo-sequential reasoning in their phenomenological descriptions of what happens as plates move towards, away, and slide past each other. In the fourth activity, students learn about two mechanisms that drive plate motion – mantle convection and gravity – and connect these mechanisms to the

Table 1. Description of the plate tectonics module.

Activity	Name	Description	Student Use of Tectonic Explorer
1	Earth's moving surface	Students explore GPS data to see evidence of plate motions and investigate earthquake and volcanic eruption patterns.	Students use Tectonic Explorer to find that plate motions result in the formation of mountains and oceans.
2	Interpreting Earth's clues	Students investigate the landforms and patterns of seismic events associated with convergent boundaries.	Students set up Tectonic Explorer to create a mountain range like the Andes and an island chain like the Aleutians.
3	What happens with a lot of moving plates?	Students consider plate movements as part of a system, exploring what happens on all sides of a moving plate. Students investigate divergent and transform boundaries.	Students use Tectonic Explorer to observe interactions on multiple sides of a tectonic plate. Students set up Tectonic Explorer to explore complicated plate interactions.
4	What drives plate motion?	Students are introduced to the mechanisms that drive plate motion, including convection currents, slab pull, and ridge push.	Students consider how plates are created at a divergent boundary and subducted at a convergent boundary.
5	What will Earth look like in the future?	Students work through several case studies to determine plate movement and make predictions about what areas might look like in the distant future.	Students use Tectonic Explorer to model the formation of the Appalachian Mountains and explain why the Appalachians are not on a plate boundary today. Students hypothesise about the formation of a supercontinent in the future.

sequential order they described in the second and third activities. In the last activity, students develop explanations related to the formation of the Appalachian Mountains and make predictions about future Earth based on what they have learned in the module.

Tectonic explorer

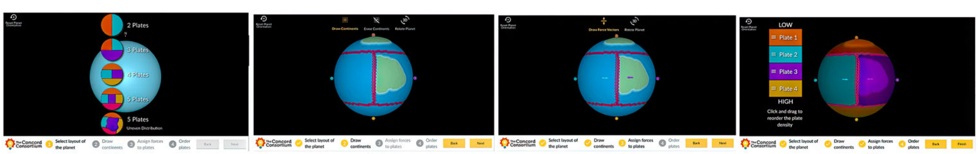
Tectonic Explorer is a computational simulation of tectonic plates on an Earth-like planet that can simultaneously visualise the tectonic plate interactions on the planet surface and subsurface in a cross-section view (roughly 600 km below the surface). In describing Tectonic Explorer, we use four strategies identified in Kali and Linn's (2008) synthesis of research on how interactive visualisations of scientific phenomena support student learning.

First, we reduced visual complexity of the plate system to help learners recognise salient information. Tectonic Explorer simplifies tectonics of an Earth-like planet with only a limited number of plates. This reduces the interactions students need to observe while also illustrating the continuous processes that are typically unobservable in the real world because they take too long, the scale is too big, or the phenomena occur out of sight below Earth's surface.

Second, we scaffolded the process of generating explanations. Tectonic Explorer is embedded in a scaffolded curriculum module. The primary goal of the module instructions and explanation prompts is to help students use the simulation to develop their conceptual development of plate interactions, synthesise their experience with the simulation, and develop spatial and temporal explanations about the tectonic system.

Third, we supported student-initiated modelling of complex science. Figure 1 shows how Tectonic Explorer enables students to set up their own plate tectonic scenarios. Students can vary the number of tectonic plates, the location of continental crust on each plate, the direction and rate of each plate's motion, and the density of each plate. When students run the simulation, they can slow the visualisation down and step backward and forward during a given run. Students can also use the computer mouse to click and drag between two locations to demarcate where a cross-section view should be created, then view a three-dimensional visualisation of the plates interacting at and below Earth's surface and in the upper mantle.

Fourth, we used multiple linked representations. The use of the cross-section view synced with the planet surface view provides a way to see changes over time at and below the surface, enabling students to generate explanations about how landforms result from plate motion (see Figure 1). With the connected views, students can investigate any location and sequence of events on the planet at any time. Importantly, the



(a) (b) (c) (d)

Figure 1. Four steps of the Tectonic Explorer setup wizard. Students can choose the number of plates (a), place continents on plates (b), assign direction of plate motion (c) and density (d) to plates.

planet surface view and the cross-section view are in sync with each other so that students can coordinate both representations.

Theoretical framework

Geoscientific reasoning characterises a geoscientist's intellectual approach and the skills intrinsic to problem solving. The main elements of geoscientific reasoning can be defined by considerations related to 'thinking about time on geological timescales, understanding the Earth as a complex system, learning in the field, and spatial thinking as applied to geosciences' (Kastens et al., 2009, p. 265). The most notable feature of geoscientific thinking is temporal reasoning. Temporal reasoning encapsulates how geoscientists construct a chain of logic from evidence about time to claims about process. Two key aspects of temporal reasoning in geoscience are: (1) recognising the vastness of the geologic timescale with all its named periods and placing *separate* events in a relative or absolute order on the timescale (Cheek, 2010) and (2) thinking with time to develop an awareness about the duration, processes, and sequence of geologic events (Kastens et al., 2009). Geo-sequential reasoning focuses on the spatial and temporal concepts related to the duration and sequence of geologic events and grapples with causal dynamic processes that heavily depend on the sequence in which *related* three-dimensional events unfold (Kastens & Manduca, 2012). Figure 2 illustrates how these reasoning frameworks overlap.

Geo-sequential reasoning encompasses aspects of both geoscientific reasoning and temporal reasoning in geosciences but does not represent the full dimensions of either of them. Table 2 highlights similarities and differences. In psychology, sequential reasoning is described as the ability to do things in order, which means understanding the procedures, engaging in one or more steps to reach a solution, and recognizing whether or not you are on track. Geo-sequential reasoning requires the ability to recognise and *describe a sequence of events over time based on causal mechanisms that connect the beginning conditions of an Earth system to the resulting phenomenon.* When the cause and its effect are observable and active, causal mechanisms and the resulting phenomena are easily describable. An observed sequence of events – first, one thing happens, which causes a second thing to happen, and then a third thing – can lead to a reasonable

Table 2. The similarities and differences between geo-sequential reasoning, geoscientific reasoning, and temporal reasoning in geosciences.

	Similarities with geo-sequential reasoning	Differences from geo-sequential reasoning
Geoscientific reasoning	Both focus on understanding Earth as a complex system, spatial thinking, and geologic time.	Geo-sequential reasoning does not focus on methods of geoscientific investigation.
	Both develop skills to approach solving problems.	Geo-sequential reasoning does not focus on the nature of geoscience or philosophical underpinnings.
Temporal reasoning in geosciences	Both focus on the sequence in which related events occur.	Geo-sequential reasoning does not focus on placing separate historical events in absolute order.
	Both require interpretation of data and evidence that are often incomplete.	Geo-sequential reasoning does not focus on the vastness of geologic time.
	Both focus on duration, processes, and sequence of geologic events.	

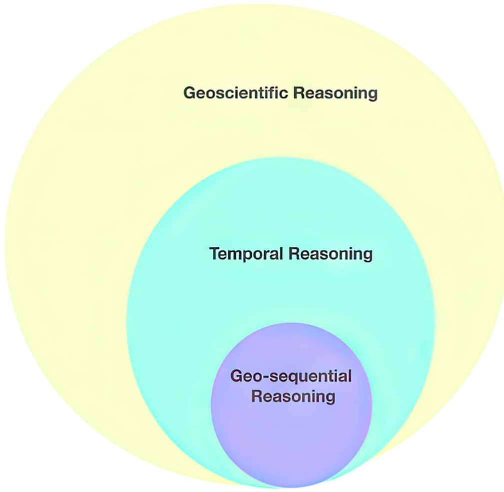


Figure 2. Geo-sequential reasoning is considered part of both geoscientific and temporal reasoning.

sequential claim. However, investigating geoscientific phenomena is often not this straightforward. In some cases, two seemingly separate events that co-occur can be causally connected. In other cases, determining the sequence of events requires the ability to extrapolate and infer about processes where the observed phenomenon is separated from the cause (Kastens & Manduca, 2012). In all cases, the sequence of events is important to puzzle out, but in the case of extrapolation, the observer sees the result of a process, but not necessarily the process that caused the phenomenon.

Reasoning about plate tectonic phenomena requires theory-guided extrapolations because the process take place over millions of years, and are too slow and inaccessible to observe directly (Kastens & Manduca, 2012). The use of interactive computer simulations, however, can reduce the spatial and temporal scales significantly in order for students to observe the entire sequence as a whole system. Currently available interactive plate tectonics simulations and animations of boundary interactions typically focus on two plates interacting near a single boundary at a fixed location in a two-dimensional space. In contrast, Tectonic Explorer is three-dimensional and students can experiment by setting up a plate system with differing number of plates (from two to five plates), each with different density properties and assigned forces. Each student's tectonic exploration is unique and different from other students' creations. As a result, students in a class do not see the same sequence of events. This provides an ideal research opportunity to investigate how students express their geo-sequential reasoning based on the evidence they created from Tectonic Explorer as no two model runs are the same. Moreover, students can observe the sequence of changes over time both on and below the planet's surface and make connections between the setup and the outcome to help them understand how the system works.

Methods

Two simulation-based geo-sequential reasoning tasks

In this study, we investigated students' geo-sequential reasoning along convergent plate boundaries in two task scenarios: Convergent and Co-occurrence. The Convergent Task appeared at the beginning of the second activity in the Plate Tectonics module. For the task, students use Tectonic Explorer to simulate the formation of the Andes Mountains, take a snapshot image of Tectonic Explorer that shows the creation of a mountain range similar to the Andes, and describe how the plate with oceanic crust and the plate with continental crust moved to form a mountain range (see Figure 3).

The Co-occurrence Task appeared in the third activity. Students use Tectonic Explorer to simulate phenomena along the divergent boundary of the South American Plate. For the task, students reset the model, rotate the planet to look at the boundary on the other side of the plate, and make a cross-section of the boundary. Students were asked to explain, 'When two plates are moving away from each other at a mid-

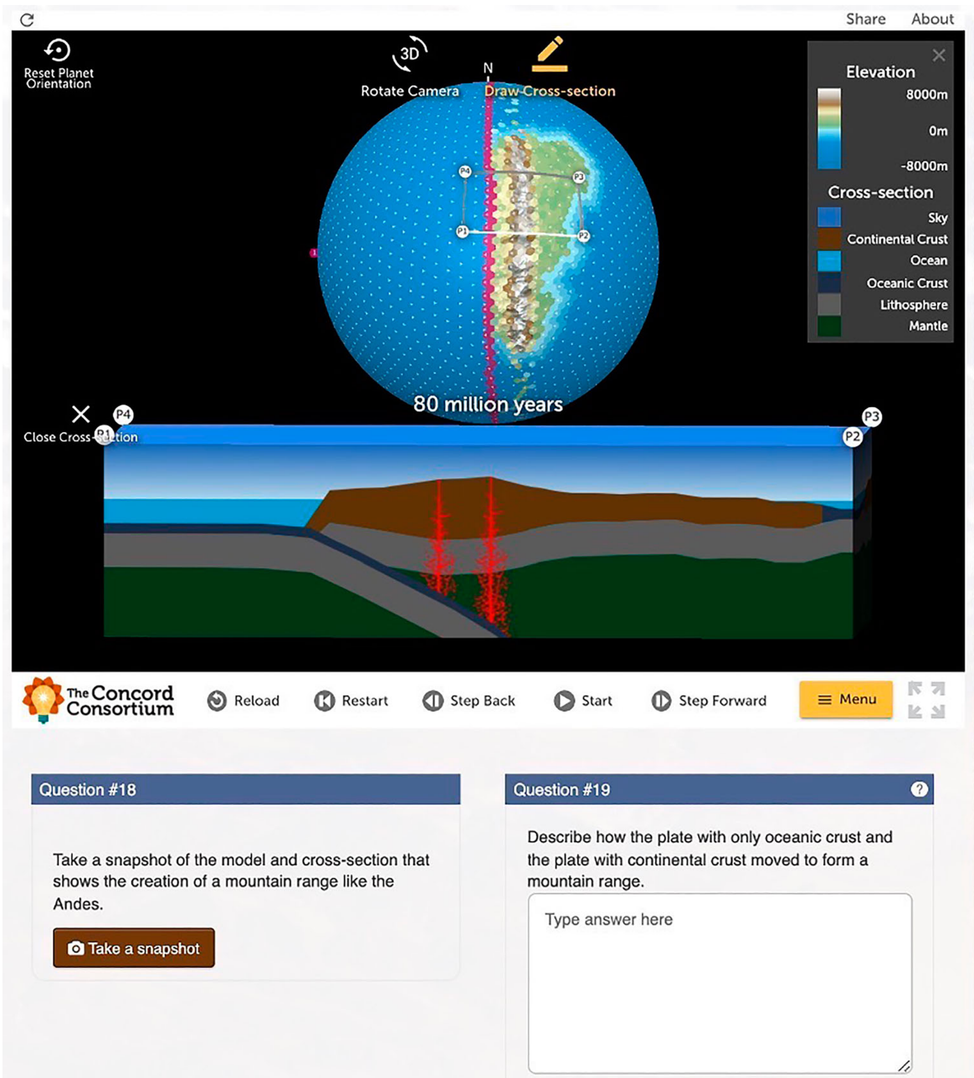
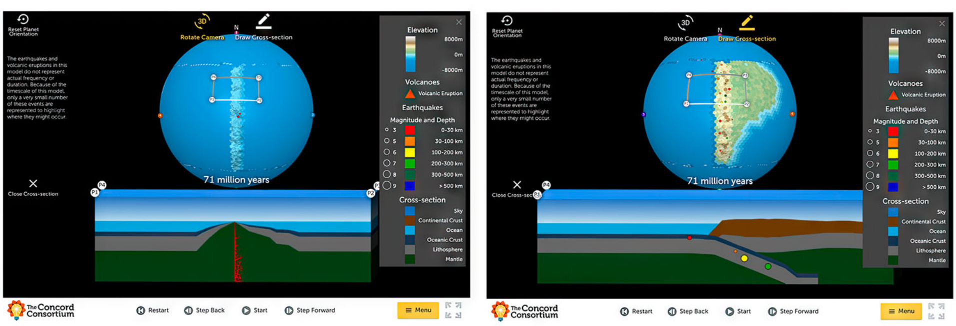


Figure 3. The Tectonic Explorer followed by the Convergent Task prompts (image and explanation). The simulation shows the cross-section view synced with the planet surface view.

ocean ridge, what happens at the plate boundary on the other side of the plate? Describe what you saw in the model' (see Figure 4). The Co-occurrence Task was more complicated than the Convergent Task because students needed to discover how the phenomena at the convergent boundary were related to the phenomena at the divergent boundary. Students needed to locate and examine the two different boundaries by rotating the planet, running and rerunning the simulation to observe what was happening at both boundaries, and creating cross-sections in both locations.

Subjects

This design-based research was carried out on the fourth iteration of our development and implementation work. The research was conducted during the implementation testing stage of the Plate Tectonics module. During the 2019–2020 school year, we recruited 25 teachers to enact the module as they saw fit. Teachers were recruited through a mailing list of teachers expressing interest in piloting Earth science curricula and on social media targeting Earth science teachers. Recruited teachers were from 15 states (California, Connecticut, Illinois, Kansas, Kentucky, Massachusetts, Michigan, Minnesota, Missouri, Nevada, New York, Ohio, Oregon, Vermont, and Washington). The module was implemented in Earth science, environmental science, physics, and general science classes. Classes contained students from remedial to advanced levels. Among the teachers, 15 taught in middle schools (grades 5–8; students aged 11–14) and 10 taught in high schools (grades 9–12; students aged 14–19). Among the teachers, 92% taught in public schools and 8% taught in private schools; 19% of the teachers' schools were in urban settings, 46% in suburban settings, and 35% in rural settings. All but two teachers were White. They had an average of 16.85 years teaching (SD = 9.10), ranging from 5 to 35 years. Nineteen teachers had teaching credentials in sciences other than Earth science. All teachers implemented on their own without the research project personnel's involvement. While there was no professional training, a teacher version of the Plate Tectonics module was available to the teachers and included subject matter knowledge, pedagogical knowledge, and pedagogical content knowledge embedded within the student version of the module (Lord et al., in press). The online server that hosted the Plate Tectonics module collected data from 1913 students of these



(a) (b)

Figure 4. The Co-occurrence Task requires students to create a divergent boundary (a), then rotate the planet to view the convergent boundary happening on the other side of the same plate (b).

teachers; 88% of the students (n = 1680) provided demographic information. Of these students, 53% were female, 43% were male, 4% selected 'other' or 'prefer not to answer' options; 13% spoke English as a second language; 66% reported having used computers for science learning prior to using these materials; 64% were middle school students and 33% were high school students. The number of students varied from 10 to 117 per teacher.

Data collection

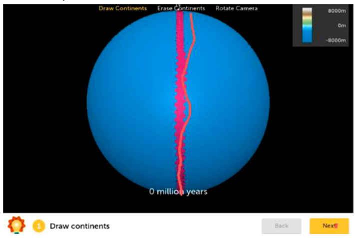
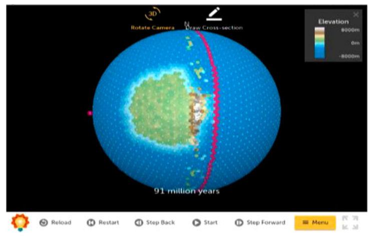
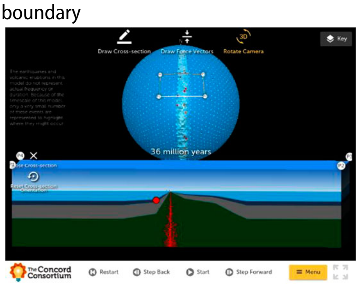
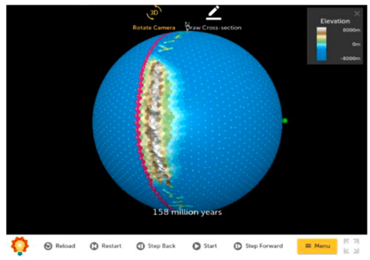
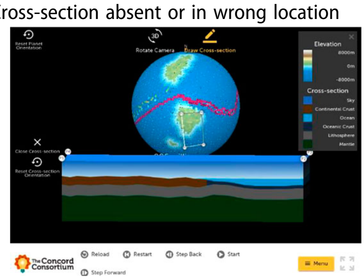
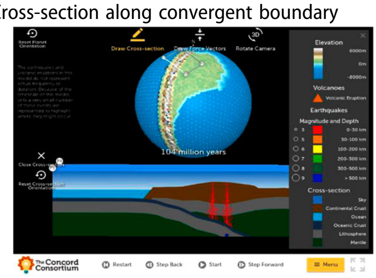
Students' responses to the image prompts and the explanation prompts in the Plate Tectonics module were automatically collected through the online portal as part of students' classwork. Of 1913 students who used the module, we selected 949 students who provided all the demographic information, had taken the pre-test, and had a complete set of images and explanations for both the Convergent and Co-occurrence Tasks. Students who did not complete both tasks – due to technical issues, lack of time, or other unknown reasons – were in the classes of all teachers, so eliminating those incomplete data did not unduly skew the results towards any particular schools. The resulting set of students included 683 middle school and 266 high school students.

Data scoring and analysis

Simulation images. We scored each image students included as evidence for their explanation in terms of simulation runtime, planet surface view, and cross-section view (Table 3). Simulation runtime was shown below the planet in millions of years. This indicated how long the simulation had run when the image was taken. We assigned a score of 1 when the simulation was run for a long enough time to see convergent boundary phenomena (from 1 million to 800 million years), and a score of 0 for images with 0 million years (simulation was not run) and more than 800 million years (the resulting visualization was too complex to interpret). However, in some cases even when an adequate amount of time was recorded, the resulting images did not include convergent boundary phenomena because students set up their own simulations and the phenomenon either did not occur or was not captured. Therefore, we scored the phenomenon that was captured on the planet surface view of the simulation. When images included phenomena related to a convergent boundary in the planet surface view, such as ocean trenches between plates, islands along the boundary, and mountains on continental crust (see Table 3, Row 2), they were given a score of 1. When they did not, they were given a score of 0. The cross-section view showed how plates interacted under the surface. When a cross-section is created perpendicular to a plate boundary, several phenomena can be observed, including subduction of one plate, magma rising, islands forming, and continental crust thickening as mountains form. Images with a cross-section depicting subduction and associated phenomena were given a score of 1. If the students' image did not include a cross-section, or it was uninterpretable, it was given a score of 0.

Geo-sequential reasoning in explanations. Geo-sequential reasoning explanations mean students describe a logical chain of events that include: (1) how plates are in motion in a particular direction, (2) how plates are interacting over time along boundaries in a specific way, and (3) how the outcome of plate motion and interactions explain observable geologic phenomena. For the Convergent Task students should describe: (1) two plates moving

Table 3. Coding method for simulation images for Convergent Task.

Categories	Score 0	Score 1
Simulation run: Did students run simulation for appropriate amount of time?	Simulation not run or run more than 800 million years  Millions of years as recorded by counter shows it was not run.	Simulation run between 1 and 800 million years  Simulation was run for 91 million years.
Planet surface view: Did students create convergent boundary?	Planet surface does not include convergent boundary  Mid-ocean ridge shown in planet surface view is evidence of a divergent boundary.	Planet surface includes convergent boundary  Mountain formation shown on continent in the planet surface view is evidence of a convergent boundary.
Cross-section view: Did students see subduction and land formation?	Cross-section absent or in wrong location  Cross-section not drawn across active plate boundary as seen by pink line in planet surface view.	Cross-section along convergent boundary  Cross-section shows subducting plate and rising magma.

towards each other, (2) one plate with oceanic crust subducting below the plate with continental crust, and (3) the formation of landforms, such as ocean trenches, mountains, and volcanoes, and geologic phenomena, including rising magma, volcanic eruptions, and earthquakes found along the subducting plate. The Co-occurrence Task should reference the same information as the Convergent Task and relate divergent motion on one side of the plate to convergent motion on the other side of the plate.

In order to characterise students' geo-sequential reasoning explanations, we created a rubric that ranged from 0 to 4 with the higher scores equating to better reasoning (see Table 4). Our focus was on how students reason about the sequence of events where

Table 4. Task scoring rubrics and examples from the Convergent Task.

Score	Criteria	Student examples from the Convergent task
0: No information	Blank or off task.	• I do not know • Off-task responses
1: Non-normative	An absence of any scientifically recognised reasoning.	• Plate boundary breaks and causes other surfaces such as continents.
2: Phenomena only	Includes description of emergent phenomena but does not include information about plate motion or interactions.	• They converged together. • Trenches form • They formed mountains
3: Partial geo-sequential reasoning	Includes an incomplete description. Explanations may include (a) plates move in a particular direction; + (b) plates interact along the boundary; OR (c) plates interact along a boundary + (d) identify phenomena that result but exclude mention about plate direction.	• They are colliding together and it's forming mountains • The one with just the oceanic crust went under the one with the continent and pushed the continent up forming the mountains on it. • The oceanic plate moved beneath the continental plate, which pushed part of the continental plate up, which caused the formation of mountains.
4: Full geo-sequential reasoning	Shows temporally contiguous processes happening along the boundary, including (a) + (b) + (c) (from partial geo-sequential reasoning above) in explanations.	• The oceanic crust and the continental crust formed a mountain range because the two plates collided together which made the oceanic crust subduct under the continental crust. After that happened the continent got pushed up in elevation and that made mountains

observation of the simulation was relevant and necessary for developing explanations. These five levels are the same for both tasks and characterise students' geo-sequential reasoning score levels: no information, non-normative information, phenomena only, partial geo-sequential reasoning, and full geo-sequential reasoning. Phenomena only reasoning describes students' explanations that did not include processes or geo-sequential reasoning, partial geo-sequential reasoning describes explanations that included spatial and temporal changes without causal processes for how these transformations are occurring, and full geo-sequential reasoning includes spatial and temporal changes with causal processes for the transformations. The interrater reliability between two coders was calculated using Kappa values: 0.87 for the Convergent Task and 0.96 for the Co-occurrence Task. Score discrepancies were discussed and a final score was assigned.

Data analysis. We examined the distribution of sequential reasoning scores for each task using Mann–Whitney U tests and then compared the Convergence and Co-occurrence Tasks using repeated measures Wilcoxon signed rank test to see which task was more difficult for students to elaborate geo-sequential reasoning related to phenomena found along convergent boundaries. We also examined the image score distributions in each task. We compared the image scores with explanation scores using chi-square to identify patterns between image features and geo-sequential reasoning scores with the alpha value at 0.05. We explained each identified significant pattern using student explanations and images.

Results

Geo-sequential reasoning expressed in explanations by task

In the Convergent Task, 16% of the students did not include explanations, 39% included phenomena only, and 38% included partial geo-sequential reasoning. Only 7% were able to write full geo-sequential reasoning explanations. In the Co-occurrence Task, 30% of the students did not have explanations or included nominal explanations, 52% included phenomena only, and 15% included partial geo-sequential reasoning. This task also had a low percentage of students (3%) achieving full geo-sequential reasoning (see Table 5). According to repeated measures Wilcoxon signed rank test, students received significantly lower geo-sequential reasoning scores in the Co-occurrence Task than the Convergent Task, $Z = -15.54$, $p < 0.001$. Among 950 students, 55% decreased their scores from the Convergent Task to the Co-occurrence Task; 14% increased scores; 31% received the same scores. This indicates that students were more explicit about the sequence of events in the first task than in the second task; it was significantly more difficult for students to set up and observe both the divergent and convergent phenomena occurring at the same time in Tectonic Explorer for the Co-occurrence Task, which asks students to consider the connection between convergence on the other side of the plate from where divergence is occurring. See Table 4 for examples of varied ways students expressed geo-sequential reasoning.

Students' uses of computer simulations by task

The inclusion of features in the image represents how students used Tectonic Explorer and what they may have observed in order to develop their explanation. To answer how the use of the simulation supports students' answers, we describe the use for each task. Table 5 shows the distribution of students in terms of whether students' run of the simulation was adequate, whether the convergent boundary was present in the planet surface view, and whether the convergent process was observed using the cross-section view. Eighty-four percent of the images in the Convergent Task and 83% of the images in the Co-occurrence Task show that the simulation was run for an appropriate amount of time, such that enough time had lapsed for plate interactions and resulting phenomena. Wilcoxon signed ranks test indicates no significant difference from the Convergent Task to the Co-occurrence Task in the simulation runtime, $Z = -0.59$, $p = 0.56$. For the planet surface view of the simulation image, 67% of the students in the

Table 5. Summary of geo-sequential reasoning scores students received for the Convergence and Co-occurrence Tasks.

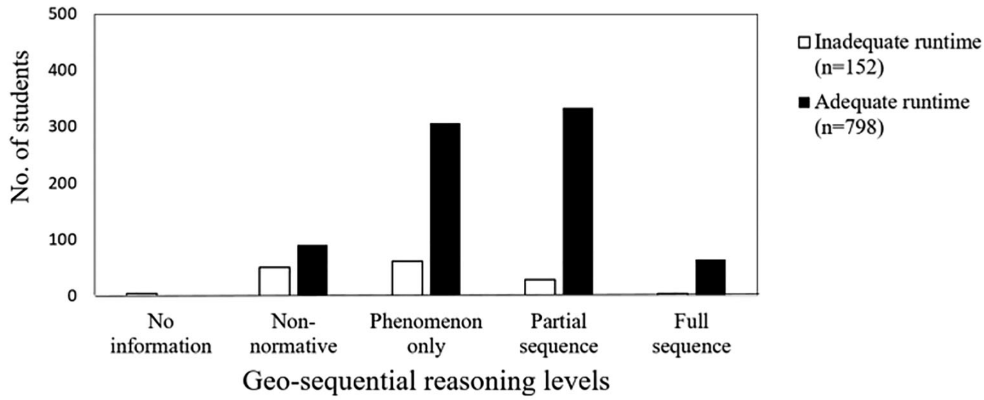
	Convergent Task ($n = 950$)	Co-occurrence Task ($n = 950$)
Explanation categories		
Score 0: No information	1%	18%
Score 1: Non-normative	15%	12%
Score 2: Phenomenon only	39%	52%
Score 3: Partial geo-sequential reasoning	38%	15%
Score 4: Full geo-sequential reasoning	7%	3%
Image scores		
(1) Simulation run		
Score 1: Appropriate run (1–800 million years)	84%	83%
Score 0: Inappropriate run (not run or overrun)	16%	17%
(2) Planet surface view		
Score 1: Includes convergent boundary	67%	74%
Score 0: No convergent boundary	33%	26%
(3) Cross-section view		
Score 1: Cross-section along convergent boundary	48%	58%
Score 0: Cross-section absent or in wrong location	52%	42%

Convergent Task had a convergent boundary while 74% had one in the Co-occurrence Task. This increase was significant, $Z = 3.82$, $p < 0.001$. Such images include a view of the planet with obvious features characteristic of convergent boundaries, such as a continent with mountains forming along the edge of the continent nearest to the boundary, deep ocean trenches (indicated by a dark blue colour) along the boundary, and islands forming on the overriding plate. For the Convergent Task, 48% of the images included a cross-section of a convergent boundary. For the Co-occurrence Task, 58% of the images did. This increase was also significant, $Z = 5.48$, $p < 0.001$. That is, significantly greater percentages of students had images with the planet surface view and the cross-section view in the Co-occurrence Task than in the Convergent Task, despite the fact that the geo-sequential reasoning scores were significantly lower in the Co-occurrence Task than in the Convergent Task.

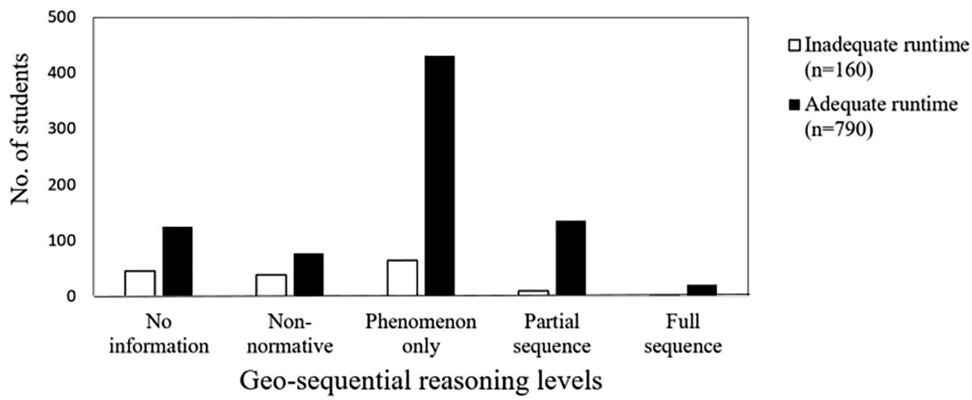
Comparing geo-sequential reasoning with simulation uses between tasks

Figure 5 compares the levels of geo-sequential reasoning found in students' explanations for students who ran the simulation for an adequate amount of time and for students who did not. Mann–Whitney U tests indicate that students' geo-sequential reasoning was significantly higher when the simulation was run for an adequate amount of time compared to when it was not within the Convergent Task, $Z = 7.83$, $p < 0.001$. The same pattern was found for the Co-occurrence Task, $Z = 9.88$, $p < 0.001$. Figure 6 compares students' inclusion of convergent boundaries in their simulation images and their geo-sequential reasoning scores. The scores were significantly higher when the images included the convergent boundary in the planet surface views for both the Convergent Task, $Z = 10.77$, $p < 0.001$, and the Co-occurrence Task, $Z = 6.55$, $p < 0.001$. Similarly, regarding the inclusion in the simulation images of a cross-section depicting a convergent boundary (Figure 7), the same pattern was found for both the Convergent Task, $Z = 11.09$, $p < 0.001$, and the Co-occurrence Task, $Z = 11.34$, $p < 0.001$. Altogether, when students' set up and ran Tectonic Explorer and then captured images that included the required features depicted in the simulation necessary for developing explanations in response to prompts, their geo-sequential reasoning as expressed in their explanations was significantly higher than for those students whose images were missing the necessary features.

Figure 8 shows the geo-sequential reasoning score distribution of students for both the Convergent Task and Co-occurrence Task with adequate simulation runtime (Figure 8(a)), convergent boundary included in the planet surface view (Figure 8(b)), and convergent boundary in the cross-section view (Figure 8(c)). The patterns were similar across the three image features. For the Convergent Task, the most frequent level of student explanations was partial geo-sequential reasoning (Score 3), followed by phenomenon only (Score 2) for each of the three image features. For the Co-occurrence Task, the most frequent level of student explanations was phenomenon only (Score 2) for all three image features. These patterns indicate that students were more likely to include phenomenon, a partial sequence, or full sequence in their explanations if their images included one of the image features. When students' image included required features (e.g. having a convergent boundary cross-section view in Figure 8(c)), their geo-sequential reasoning distribution is skewed towards higher scores in the Convergent Task than in the Co-occurrence Task. When comparing between the tasks, observing the target



(a) Convergent Task



(b) Co-occurrence Task

Figure 5. Mann–Whitney U results comparing student geo-sequential reasoning levels with simulation runtime for both the Convergent (a) and Co-occurrence (b) Tasks.

phenomena emerge was critical, but the Co-occurrence Task was more complicated. In this study, students with adequate runtime showed varied geo-sequential reasoning levels, indicating running the simulation for an adequate amount of time is necessary, but not sufficient for developing full geo-sequential reasoning. This might be explained because students may not have seen convergence, for example, they may have been observing divergence while the simulation was running or they may have created a cross-section after they paused the simulation. Even if the simulation was run for an appropriate amount of time, the image only captures a moment in time, not necessarily revealing all of what was observed as the simulation was run.

The following shows examples of two students' explanations and a description of the images they captured. Both students scored *higher* on the Convergent Task than on the Co-occurrence Task. For the Convergent Task, Student 1 created an image that showed mountain formation on the planet surface view as well as a cross-section view depicting oceanic crust subducting. Student 1 wrote a full geo-sequential reasoning explanation: 'The plates move towards each other, the oceanic crust begins to go under the continental

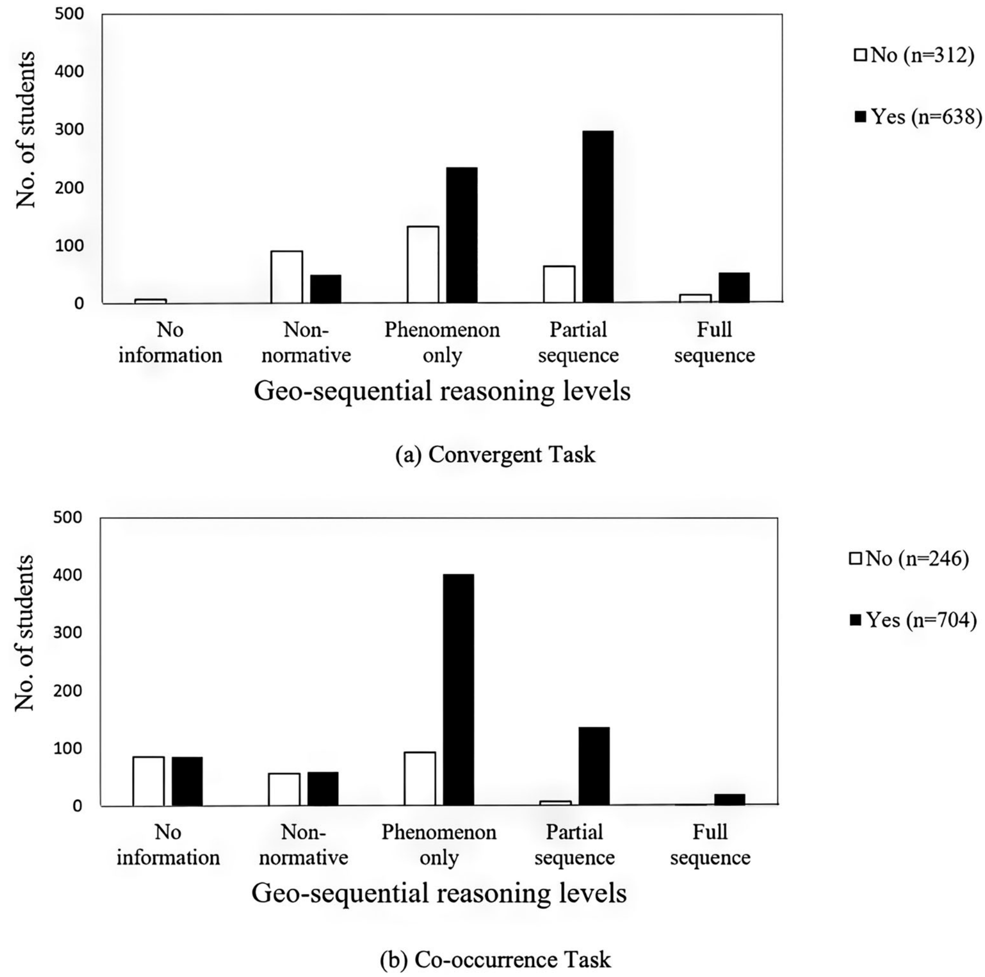
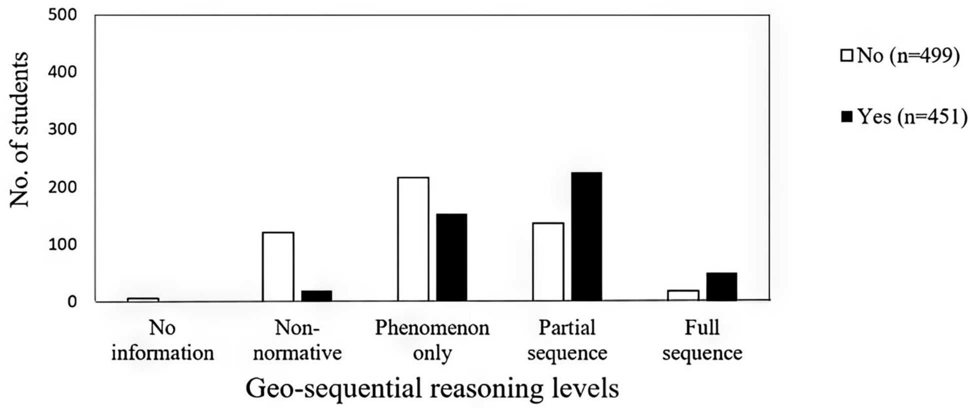
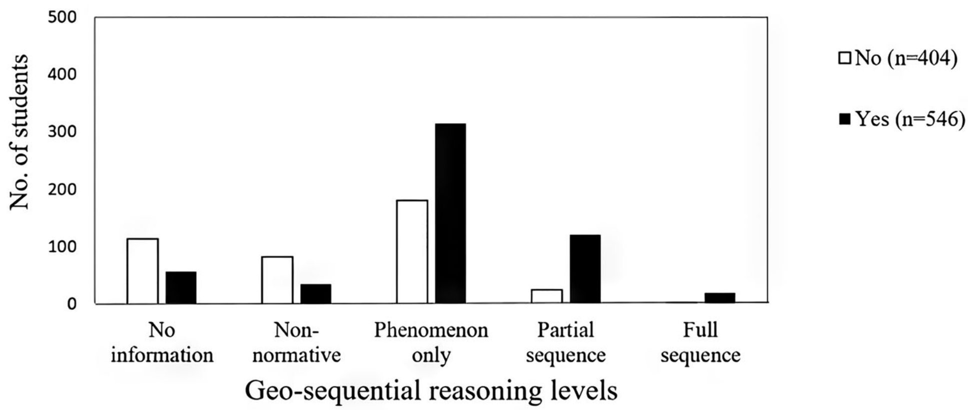


Figure 6. Mann–Whitney U results comparing student geo-sequential reasoning levels with the inclusion of a convergent boundary in planet surface views of the simulation image for both the Convergent (a) and Co-occurrence (b) Tasks.

crust, pushing it up to create mountains.' Included in the explanation is information about plate motion and the sequence of crust subducting and creating mountains. For the Co-occurrence Task, her image was of the divergent boundary complete with a cross-section of the divergent boundary. Her explanation focused on the divergent boundary and did not include any information about the convergent boundary on the other side of the plate: 'When two plates are moving away from each other a mid-ocean ridge mountain range is formed.' This was non-normative reasoning for the phenomena that happen at the plate boundary *opposite* the divergent boundary. It appears that Student 1 described what she observed in Tectonic Explorer and what she captured in her images, but she did not complete the task of rotating the planet and creating a cross-section view of the convergent boundary on the other side of the plate. This example shows how the task structure and the use of Tectonic Explorer are connected to the students' explanations. For the Convergent Task, she observed the plate motion and



(a) Convergent Task



(b) Co-occurrence Task

Figure 7. Mann–Whitney U results comparing student geo-sequential reasoning levels with the inclusion of a cross-section view in the image of the simulation for both the Convergent (a) and Co-occurrence (b) Tasks.

interactions along the boundary. For the Co-occurrence Task, this student observed the plate motion and phenomena at the divergent boundary, but she did not notice the dynamic interaction of plates along the convergent boundary. Student 2 wrote a partial geo-sequential reasoning explanation for the convergent boundary: 'The ocean plate moved under the continental plate, raising it up, to create volcanoes and mountains.' His image included a convergent boundary in both the planet surface view and the cross-section view. For the Co-occurrence Task, the student did not create a cross-section view along the convergent boundary. The image shows the convergent boundary on the planet surface view but a divergent boundary in the cross-section view, presumably drawn before rotating the planet and taking the picture. This student focused only on the phenomena and not the sequence of plate interactions that led to the outcomes: 'The mountains got higher and higher and at the edge of the continent a trench formed, getting deeper and deeper.' Student 2 described plate interactions and phenomena in the

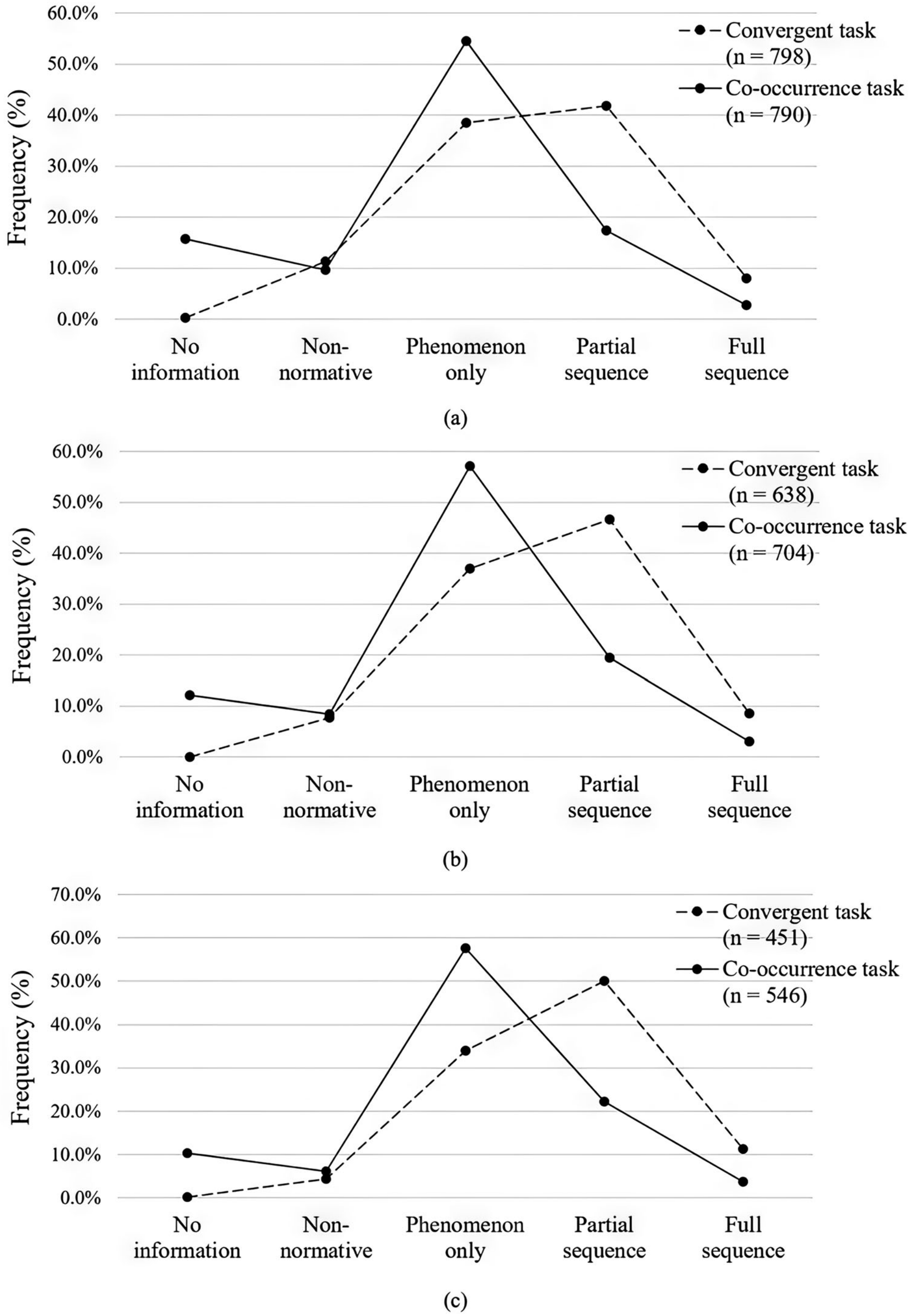


Figure 8. Distribution of geo-sequential reasoning scores (a) when simulation runtime was adequate, (b) when a convergent boundary was present in the planet surface view, and (c) when the subduction and mountain formation processes were shown in the cross-section view.

Convergent Task, but he did not include the plate interactions and only focused on the resulting phenomena as seen from the planet surface view.

Discussion

This design-based research examined how students incorporated evidence generated from a dynamic plate tectonics simulation that was specifically designed to enhance students' ability to express geo-sequential reasoning in their explanations about convergent plate boundary interactions. We analysed students' answers for evidence of geo-sequential reasoning, in particular their ability to draw relationships between plate motions and the resulting landforms and seismic events. Overall, results of this study indicate that students who set up the Tectonic Explorer simulation appropriately (e.g. adequate runtime, planet surface view, and cross-section view) and had an opportunity to observe the phenomena at a convergent boundary were more likely to incorporate observations from the simulation as a basis for their geo-sequential reasoning explanations. A majority of students used simulation-based evidence that depicted at least some part of the sequence of events that occur along convergent boundaries. In the following section, we discuss students' expression of geo-sequential reasoning with dynamic simulations and implications for designing simulation-based tasks to support geo-sequential reasoning.

Students' expression of geo-sequential reasoning with a dynamic simulation

In geoscience, it is often impossible to perform experiments on many of the geologic systems because they take place on too large a spatial scale or too long a temporal scale (Kastens et al., 2009). Computer simulations, therefore, become one method to hypothesize and investigate the processes involved with the geologic systems (Develaki, 2019; Morrison, 2015; Schwartz et al., 2009). Based on results of this study, we discuss various ways dynamic simulations can be used to support or constrain students' abilities to identify salient events and put them in a temporal sequence to develop geo-sequential reasoning.

First, we found that students' expression of geo-sequential reasoning was correlated with the presence of the planet surface and cross-section views in their images. That is, when students observed mountain formation in both planet surface and cross-section views, they were more likely to articulate the motion of the descending plate and the thickening crust in the overriding plate – features only seen in cross-section – and connect it to the mountains forming, seen most clearly in the planet surface view. This result indicates that students' integration of ideas can be facilitated when they connect multiple representations of the same phenomenon (Kali & Linn, 2008). When the planet surface and cross-section views did not match or were missing in student images, students were less likely to include the process of subduction necessary for mountain formation, trench formation, or earthquake and volcanic eruption in their explanations.

Second, while entire sequences of events were observable in the simulation, explanations of many students focused mainly on parts of the sequence related to the phenomenological outcome. While research has shown the benefits of powerful visualisations on science learning outcomes (Crawford & Cullin, 2004; Hegarty, 2004; Louca & Zacharia, 2012; Moreno & Mayer, 2007; Moreno & Valdez, 2005; Pallant & Tinker, 2004; Sins et al., 2005; Wang et al., 2016; Wang & Tseng, 2018; Xie & Tinker, 2006), students' limited experiences and knowledge make it difficult to notice the essential aspects from the visualisation necessary for developing expert-like explanations (Wang & Tseng, 2018). It is necessary to design tasks, simulations, and prompts to scaffold students' interactions with simulations so that they can attend to relevant aspects of the simulation (Jarodzka et al., 2010). In addition, we found it was important to facilitate student interpretation and understanding of the evidence and ideas that should be derived from the simulation and are relevant for the geo-sequential reasoning required by the task.

Third, with Tectonic Explorer, students had the opportunity to create, manipulate, and visualise their own plate system. In so doing, they 'make decisions about how different elements of the phenomena relate to each other' (Kali & Linn, 2008, p. 189). Even though Tectonic Explorer was a simplified version of Earth's plate system, students needed to make sense of dynamic spatial information that was evolving and changing (Gazit et al., 2005; Gazit & Chen, 2003). The images from the Co-occurrence Task revealed that some students may have lost a sense of orientation (e.g. which boundary they were looking at to answer the question) necessary for starting with the divergent boundary and connecting that phenomenon to the convergent boundary.

Fourth, we noticed that expressing geo-sequential reasoning for the Co-occurrence Task was more difficult for students than for the Convergent Task, even though their image scores significantly improved as more students included convergent boundaries on the planet surface and cross-section views. In the Co-occurrence Task, students needed to consider if 'A could cause B, or B could cause A, or C could cause both' (Kastens & Manduca, 2012, p. 16). Apparently, plate convergence as connected to plate divergence was harder than thinking about convergence alone. In the Co-occurrence Task, students were expected to observe a divergent boundary in the simulation and then rotate the planet to notice what was occurring along the convergent boundary on the other side of the plate. That is, students needed to recognize that both divergent and convergent plate boundary sequences could occur in parallel. Students could either make observations of the convergent boundary sequence after viewing the divergent boundary sequence or conceptually extend what might happen at the convergent boundary without making direct observations. Our data indicated that not all students observed the convergent process, as it occurred out of sight and at the same time as they were observing divergence. This may be why some students *only* included reasoning about the divergent boundary when asked to explain convergence. A second interpretation is that students might not have observed the process of convergence on the other side of the diverging plate because they were watching the process of divergence before their attention moved to the convergent boundary. In this case, they may have focused only on the emergent phenomena and not on the sequence itself. A third possibility is that students wrote a fuller explanation the first time they encountered the task about convergence and then chose to forgo the details about convergence in the second task, which occurred later in the module, once again focusing only on the outcome phenomena. Finally, students who did not show convergent boundaries in their images were more likely to have low geo-sequential reasoning explanation scores, indicating that their observations and their potential sensemaking of the simulation were unproductive. In other words, students need to see what is happening to be able to describe the process as a logical sequence of events in order to overcome the added complexity associated with parallel geo-sequential reasoning for both sides of a single plate.

Implications for designing simulation-based tasks to support geo-sequential reasoning

In this study, we identified what geo-sequential reasoning looks like related to plate tectonics and how geoscientists engage in temporal reasoning about sequences of geologic events (Kastens, 2010). Our initial designs for the tasks focused on getting students to characterise the phenomena and the processes students were observing when using the simulation. Our analysis allowed us to discern different levels of geo-sequential reasoning in student explanations. Our findings revealed that a majority of students who provided evidence in their images had observed what was occurring along convergent boundaries in the Tectonic Explorer. Those students were able to write about the outcome phenomena and were more likely to include a sequence of events than those who did not provide evidence that they observed the phenomena in the images. When students did not include evidence in their images, they appear to be less likely to include geo-sequential reasoning in their explanations.

From our analysis of students' expressions of geo-sequential reasoning, we realized the need for attentional guidance in how to use the simulation and changes in the prompts to better orient students to sequential and temporal processes. In this study's version of the tasks, students were limited to a single captured image as evidence for what happened in the simulation. If students were able to capture several images or short videos and write captions as they interact with the simulation, that might help focus their observations on describing a sequence of events. Further, we could change the instructions and add more information to the explanation prompts to describe the system more fully, including asking students to explicate how the plates are moving at and below the surface, how their movement *over time* results in the formation of landforms, and how their movement explains the location of earthquakes and volcanic eruptions. This could help students reference different parts of the simulation for a more detailed and descriptive explanation that includes geo-sequential reasoning. These new design ideas also reflect findings from other research that notes that while novices need to acquire an understanding of the processes in order to express their observations correctly, they need to know what to observe in order to gain this knowledge (Jarodzka et al., 2010). This means cueing students on what to pay attention to is critical (Clark et al., 2003; Rooney & Boud, 2019), especially when observing a complex dynamic simulation (Hegarty, 2004). Encouraging students to engage with a simulation for an adequate amount of time is an important part of studying complex system behaviours. Focusing students' attention on salient features as components of complex systems interact with each other is important. Moreover, task structure and prompting questions can heighten students' focus around connecting changes in one part of the system to another part (Rutten et al., 2012). Organizing students' observations across various time points in the process can support the development of multi-step sequencing of geologic events (Kastens & Manduca, 2012).

Limitations

Since this design-based research study is descriptive in nature, it did not establish a causal connection between simulation image as evidence and students' development of geo-sequential reasoning in their explanations. However, an experimental design with control groups could establish causality between the simulation and the explanations situated in the plate tectonics context. This study involved students from a wide range of school settings, although participating teachers were volunteers who wanted to use the Plate Tectonics module. The students of such early curriculum adopters may not represent the full diversity of students in the general population. We did not collect or analyse log data or videos to examine how students interacted with the simulation before the image was created. Another limitation of this study concerns the extent of the teacher effect related to how teachers used the simulation with students in their classes. However, using written explanations and images from the plate tectonics simulation, we were able to explore to some degree what students were able to observe about plate motions from Tectonic Explorer.

Geo-sequential reasoning concerns the phenomenological descriptions of observable events, which is a precursor to understanding causal underlying mechanisms that make the sequence of events occur in a certain way. As a result, the Plate Tectonics module studied in this paper was designed to establish geo-sequential reasoning associated with plate boundaries before learning about thermodynamic and gravitational forces working under the surface of the Earth. Thus, causality in the Convergent and the Co-occurrence Tasks is limited to observable interactions between plates as a starting point. The Tectonic Explorer only visualises near surface plate interactions and the upper mantle. A visualisation of convection in the mantle is not included. The limitation of this aspect of the simulation means that the role of gravity in ridge push, slab pull, and convection cannot be understood from observations during the tasks. Although these concepts were introduced through other visualisations later in the module, full geo-sequential reasoning responses would by default be limited in the tasks under study.

Conclusion

The development of students' abilities to reason about how phenomena are attributable to a sequence of predictable events means teaching a new way of supporting the development of scientific claims based on temporal reasoning. This study focused on developing students' geo-sequential reasoning as a core part of exploring dynamic geologic systems. This type of reasoning is applicable beyond the study of plate tectonics to other topics in geoscience. When studying Earth's complex systems, simulations stand in for real-world phenomena as they represent a system in a way that is accessible, manipulable, visible, and interpretable. The processes and circumstances that give rise to the observed outcomes on Earth require extrapolation of events over time. The incorporation of a simulation such as the one described in this paper can support lines of reasoning built with temporal evidence. By developing geo-sequential reasoning, students can think more like geoscientists do – being able to reconstruct events that happened in the past, forecast future changes, and reason about the sequence of events necessary to account for geologic outcomes. While only a relatively small percentage of students in this study were able to achieve full geo-sequential reasoning levels during simulation-based tasks, most students included some aspects, whether it was phenomena only or partial geo-sequential reasoning. Future research on simulations combined with explanation tasks can continue to explore how students' geo-sequential reasoning can be supported.

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