Journal of Geoscience Education

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ujge20

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To cite this article: Amy Pallant, Christopher Lore, Hee-Sun Lee, Stephanie Seevers & Trudi Lord (01 Oct 2024): Integrating the plate tectonic and rock genesis systems for secondary school students, Journal of Geoscience Education, DOI: 10.1080/10899995.2024.2407748

To link to this article: https://doi.org/10.1080/10899995.2024.2407748

Published online: 01 Oct 2024.

JOURNAL OF GEOSCIENCE EDUCATION
https://doi.org/10.1080/10899995.2024.2407748

Integrating the plate tectonic and rock genesis systems for secondary school students

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ABSTRACT
This paper describes how plate tectonics and rock genesis, two topics that are typically addressed separately in secondary Earth science classes, can be taught together as an integrated system. We define the TecRocks Reasoning Framework, developed to support student reasoning about rock formation situated in the context of plate tectonics. We also explain how we leveraged the framework in the designs of a new curriculum, interactive computer simulation, and assessment instrument. We show how the instrument was used to evaluate the curriculum, which included the computer simulation. We analyzed pretest and post-test data of 319 students taught by 10 teachers in diverse middle and high schools in the United States. Our analysis allowed us to discern different levels of reasoning in student explanations. On average, students made a significant pretest to post-test gain (p < .001) with a large effect size (Cohen's $d = 1.03$) after using the curriculum. All student groups made significant gains regardless of their gender, English language status, race, or school level. However, the amount of gain significantly differed by school level, p < .001. The middle school students as a group made a larger pretest to post-test gain ($d = 1.42$) than the high school students ($d = 0.66$).

ARTICLE HISTORY
Received 3 January 2024
Revised 18 September 2024
Accepted 19 September 2024

KEYWORDS
computer simulations; online curriculum; plate tectonics; rock cycle

Purpose and learning goals

Earth science education reform efforts emphasize teaching various phenomena from an integrated Earth system perspective. What then does teaching and learning look like if plate tectonics and rock genesis, which are typically taught separately, are instead taught together? In this paper, we present a new complex Earth systems framework, called the TecRocks Reasoning Framework (TR Framework hereafter) that integrates these topics under a single unified system. In combining these two topics, the TR Framework focuses on the interactions and relationships between tectonic environments and the rocks that form. We describe a new online curriculum developed to teach middle and high school students about the connection between plate tectonics and rock genesis. The curriculum consists of a computer simulation, data visualizations, online activities, and an instrument to measure student learning. The overarching goal of the curriculum is to improve students' abilities to reason about how the motion and interactions of tectonic plates produce the environments and conditions in which all varieties of rocks are formed.

We first review literature related to rock genesis and plate tectonics in science education. We then describe the TR Framework in terms of its elements and relationships that integrate plate tectonics and rock genesis. Based on the TR Framework, we detail the design of a curriculum, a computer simulation called TecRocks Explorer, an assessment, and a rubric. We describe curriculum implementation settings, curriculum evaluation procedures based on a pretest and post-test design, and evaluation results using student learning gains at the item and student levels. This work addresses the following research question: To what extent and for whom is the curriculum, which was designed based on the TR framework, useful in developing students' reasoning about the connection between the rock genesis and plate tectonics systems? Finally, we discuss these results in light of teaching complex Earth systems at the secondary school level.

Literature context

Teaching about the rock cycle

Learning about rocks and how they form is key to understanding Earth's history and Earth processes (Kortz & Murray, 2009). While there are diverse pedagogical strategies for teaching rock formation concepts (Schifman et al., 2013), a common strategy is to use the rock cycle (Eves & Davis, 1988; Kim, 2016; Remmen & Frøyland, 2020; Sprague et al., 2020). The rock cycle describes how rocks are formed and transformed over time. Teaching the rock cycle largely focuses on local and micro-scale rock formation processes, such as sedimentation and lithification in a river delta (Assaraf & Orion, 2010; Guffey & Slater, 2020). The rock cycle diagram creates a conceptual schema for the rock

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formation system consisting of rock types and processes, helping students understand that geologic phenomena are part of a continuum where the processes and materials are connected (Eves & Davis, 1988).

However, researchers have found that when rock formation is taught using the abstract representation of the rock cycle, students do not see rocks as holding clues about how they formed, the spatial and temporal scales in which rock formation processes occur, or the relationships between magma, sediments, minerals, and rocks (Bonaccorsi et al., 2019; Guffey & Slater, 2020; Remmen & Frøyland, 2020). Schifman et al. (2013) cites an effort by Rhode Island schools to add inquiry-based investigations into middle and high school classrooms in which students link rock types to the processes that formed them, but they did not go on to investigate the tectonic settings that produced different rock-forming environments. Another study looked at Grade 8 Australian students' drawings to determine the connections they were making between tectonic settings, such as divergent boundaries, and the associated conditions and processes, and recommended strategies for teachers to improve students' understanding of the processes occurring in the plate tectonic system (McLure et al., 2021). But the students did not link those processes to rock generation. Furthermore, it is difficult for students to see how rock categories and characteristics are connected with the processes that form them or the underlying mechanisms that drive rock formation (Cheek, 2010; Francek, 2013). This is because traditional rock cycle instruction relates rocks to abstracted general processes rather than concretely situating them spatially according to the tectonic environments in which they form (Whitmeyer, et al., 2007).

Connecting plate tectonics and rock genesis

The rock cycle presents a decontextualized perspective of the rock genesis system and does not connect it to the large-scale plate tectonic system in which plate movement creates conditions for rock formation processes to take place. In other words, the current rock cycle diagram limits students' ability to reason about Earth's rock formation processes and products embedded in the whole Earth system because tectonic processes and other surficial processes are not systematically included in this representation (Fichter, 1996). *A Framework for K-12 Science Education* (National Research Council, 2012) and the Next Generation Science Standards (NGSS) (NGSS Lead States, 2013) both connect plate motion with the distribution of rocks within Earth's crust and highlight plate tectonics as the unifying theory that explains the past and current formation and movement of rock at Earth's surface. This framing acknowledges that these two topics are building blocks for further knowledge construction of other geology concepts. However, Earth science curricula are "…still commonly organized into discrete bits of content. Generally speaking, learning objectives are arranged with elements such as landform development, plate tectonics, and rock genesis as separate, distinct topics, often with limited integrative connections" (Whitmeyer et al., 2007, p. 51). Such instruction fails to show how all these processes are connected. When these topics are taught separately, it is difficult for students to develop an understanding of how plate tectonics theory helps explain rock formation and vice versa (Raia, 2005). Educators and geologists alike have recognized the value of contextualizing the rock cycle into macro-scale Earth processes occurring under specific conditions and at predictable locations (Fichter & Whitmeyer, 2019). This study seeks to add to the body of pedagogical approaches to teach from an Earth system science viewpoint that encourages reasoning about phenomena within and across multiple linked systems.

Need for complex earth systems reasoning

Key to being able to reason about complex Earth systems is the ability to combine geoscientific reasoning and systems thinking in order to make sense of the processes on Earth that generate specific emergent phenomena. Earth system science considers Earth processes as part of a whole system composed of interrelated subsystems that are recycling energy and matter over both time and space across many scales (Orion, 2019). The complexity inherent in Earth system science means understanding the mechanisms that enable processes, such as self-organization, adaptation, and emergence (Raia, 2005). The ability and propensity of geoscientists to apply a systems approach to understanding the Earth is an important attribute of their expertise (Kastens et al., 2009). Based on a literature review of systems thinking, Assaraf and Orion (2005) identified eight characteristics of systems thinking needed to understand an Earth system: 1) identify the components and processes within the system, 2) identify relationships among the system's components, 3) organize the components and processes within a framework of relationships, 4) make generalizations, 5) recognize dynamic relationships within the system, 6) understand the hidden dimensions, 7) understand the cyclic nature of the system, and 8) think temporally.

There has been a push to integrate complexity into Earth science teaching (Herbert, 2005; Raia, 2012). In the context of complex Earth systems, reasoning is based on causality among components or parts of the system, between levels of the system, and between the system and the environment in which it is situated (Raia, 2005). In addition, spatial and temporal thinking are required for making sense of the behavior of complex phenomena (Bar-Yam, 2016; Orion, 2019). Through complex system reasoning, students can recognize that Earth systems are continuously changing and must be understood over time and space, as well as from micro to macro scales (Catley et al., 2005; Catley & Novick, 2009; Krell et al., 2022; Raia, 2008).

In this paper, we describe the new TR Framework developed to support student reasoning about the central phenomena of rock formation situated in the context of plate tectonics. This framework highlights only one example of reasoning within and across Earth systems. Another example would be connecting ocean current and atmospheric systems to reason about climate. In order to connect tectonic and rock-forming events, students need to consider causal processes in a temporal sequence of geologic events (Pallant et al., 2023) while interacting with a simulation to observe the behavior of the complex system (Pallant & Tinker, 2004; Yoon et al., 2018). Unique to this curriculum approach is the application of the TR Framework that guided the development of the interactive computer simulation, the student activities in the curriculum, the assessment instrument, and the rubric. By integrating the plate tectonic and rock genesis systems, rather than treating them as separate topics, we provide evidence for how such a curriculum approach is associated with changes in the extent to which middle and high school students make connections between these two Earth systems.

Study population and setting

The curriculum module and the assessment instrument were implemented by 10 teachers in 9 different schools located in 8 U.S. states (Arizona, California, Florida, Kentucky, Michigan, New Jersey, New York, and Ohio). Two of the states, Arizona and Florida, have not adopted NGSS while New York has created its own standards based on NGSS. Two of the schools were in rural areas, five were in suburban areas, and two were in urban areas. Among the students ($N = 319$), gender identity distribution was as follows: 51.1% identified as male, 42.3% as female, 2.8% as non-binary, and 3.8% opted not to disclose their gender identity. Regarding race, 45.1% reported being White, 11.9% Hispanic or Latino, 5.6% Black or African American, 5.6% Asian, 22.9% of mixed races, and 4.4% chose not to specify their racial identity. English was the first language for 88.7% of the students, while 11.3% reported it as their second language. The participants spanned several grade levels: 6th grade accounted for 29.5% of the students, 7th grade for 30.7%, 8th grade for 1.9%, 9th grade for 31.0%, 10th grade for 0.9%, 11th grade for 4.4%, and 12th grade for 1.6%. Overall, 62.1% of the students were in middle school (grades 6-8), and 37.9% were in high school (grades 9-12).

Materials and teacher training

The following section describes the TR Framework which was developed to illustrate different ways students can express their understanding, followed by descriptions of the interactive computer simulation, curriculum design, and teacher support materials.

The TecRocks reasoning framework

TecRocks reasoning is an example of complex Earth systems thinking and domain-specific reasoning woven together. The TR Framework articulates three essential elements and how these elements, when connected, capture the relationship between tectonic processes and rock formation (Figure 1).

The first element in the TR Framework is the tectonic environment, which describes a broad array of observable phenomena and geological features that result from plate movement, e.g., plates moving away from each other, toward each other, or sliding past each other. The TR Framework emphasizes the idea that Earth's surface is covered with a dynamic set of tectonic plates moving and interacting at and below the surface. The tectonic environment includes areas near active plate boundaries as well as areas far from plate boundaries, such as the passive margins where Earth's erosional and depositional processes are dominant.

The second element is the rock-forming processes, which describe the conditions and processes through which Earth's materials form rocks. Conditions and processes include material transformations highlighted in the rock cycle, such as how an increase of temperature and pressure can change an igneous rock into a metamorphic rock. Other processes include magma fractionation, deposition and compaction, and deformation.

The third element addresses the three major rock categories: igneous, metamorphic, and sedimentary. Each rock type has unique characteristics—composition, crystal size, crystal orientation, grain size, etc.—that can be used to help categorize rocks and provide clues about their formation. Rock types "record" the microscopic and macroscopic processes and pathways by which the rock formed and the conditions in which the rock formed.

By defining the integrated systems with these three elements, our goal was not to diminish the complexity involved but to identify the basic conceptual knowledge necessary to connect the rock genesis and plate tectonic systems. We used the TR Framework to develop performance expectations around student explanations of rock genesis through the lens of plate tectonic processes. In particular, we sought to identify students' reasoning about how the tectonic environment and the conditions caused by plate motion can lead to the types of rocks that form in a particular tectonic environment, and conversely how a rock type reveals the conditions and tectonic environment in which it forms.

Expected reasoning across the elements

We articulate the reasoning necessary to connect the elements in the TR Framework by beginning with one element and asking what links the element to another. See arrows in Figure 1.

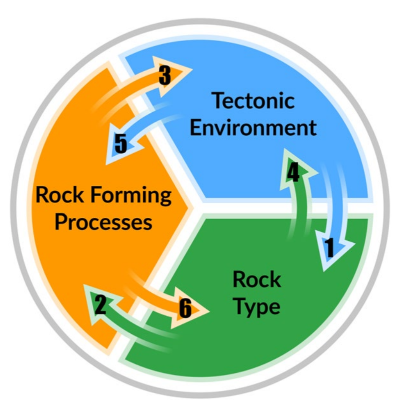


Figure 1. The TecRocks Framework illustrates the links among the tectonic environment, the rock-forming processes, and the rock types.

Arrow 1: *Beginning with a tectonic environment, what can one reason about the type of rocks that might be forming in that environment?* Each tectonic environment has unique characteristics related to plate motion, crust type, and landform features. Knowledge about tectonic plate motion and boundary interactions reveals patterns in rock types forming around Earth. For example, a divergent boundary where two oceanic plates move away from each other produces basalt and gabbro, two mafic igneous rocks.

Arrow 2: *Beginning with knowledge about rock type, what can one reason about the rock-forming processes that were in the environment when it formed?* Rocks offer evidence about the processes and conditions in the environments in which they form. For example, a low-grade metamorphic rock indicates that a parent rock was subject to changes in temperature and/or pressure over a period of time. The change in environmental conditions leads to the change in the crystal structure of the rock, creating a metamorphic rock.

Arrow 3**:** *Beginning with knowledge about specific rock-forming processes, what can one reason about the tectonic environment in which these processes are found?* Processes such as magma fractionation, in which magma differentiates from an original magma source through crystallization and removal of minerals, reveals insight into the conditions through which magma changes. The evolution of rising magma—in which early formed crystals are removed from the magma by crystal settling, leaving behind a liquid of slightly different composition—reveals insight into the tectonic environment through which the magma is moving. Notably, conditions in divergent boundaries do not allow as many types of crystals to settle as in convergent boundaries.

Arrow 4: *Beginning with knowledge about rock type, what can one reason about the tectonic environment the rock formed in?* Rocks form in limited locations around Earth. The rock type, therefore, holds evidence about the tectonic environment in which it formed. Sedimentary rocks reflect how tectonic environments created topographic highs (for erosion) and lows (for deposition). Sedimentary rocks thus indicate that they are formed where a large quantity of sediments can be deposited, such as where rivers deposit sediments on continental shelves.

Arrow 5: *Beginning with knowledge about a tectonic environment, what can one reason about the rock-forming processes in that environment?* Information on the tectonic environment reveals the characteristic conditions and processes occurring in these locations. For example, a convergent boundary where plates move toward each other can be used to reason about how surrounding temperature and pressure are increasing as an oceanic plate made of basalt and gabbro subducts below another plate and moves deeper into the mantle, causing the rocks to metamorphose.

Arrow 6: *Beginning with knowledge about rock-forming processes, what can one reason about the rock type?* Conditions such as temperature, pressure, thickness of crust, and water depth, and processes such as fractionation, deposition, and compaction all influence the type of rock that is forming. For example, when water from rivers reaches the ocean, the flow slows down. Sediments suspended in the water are deposited on continental margins. Over time, if left undisturbed, the sediments, due to the weight of layers above them, are compacted and cemented together, forming sedimentary rocks.

Ultimately, full engagement with TecRocks reasoning requires consideration of all three elements. The direction of reasoning depends on the starting element. Whether looking at the distribution of rocks around Earth or a specific outcrop, or exploring land formation related to tectonic interactions, students are expected to eventually be able to reason based on all three elements featured in the TR Framework.

The TecRocks Explorer

The TR Framework guided the design of an interactive computer simulation, called the TecRocks Explorer (Figure 2). The simulation integrates a simplified plate tectonics system with a simplified rock genesis system. With this simulation, students can investigate tectonic environments and the rocks that form in these environments. The TecRocks Explorer limits the number of plates students can test in the model. It also reduces the types of rocks by highlighting a selection that can be used to help students reason about the rock types generated under specific tectonic conditions.

In the TecRocks Explorer, students can set the initial tectonic environments on an Earthlike planet by deciding on the number of plates, drawing continents on the planet's surface, and choosing plate boundary interactions. As the simulation runs, students can observe the landforms that are created and the rocks that form as the results of plate motion. With several tools embedded in the TecRocks Explorer, students can investigate each of the three elements in the TR Framework. For example, a rock sampling tool allows students to identify the rock type and other characteristics of any rock visualized in the simulation. Another tool enables students to explore how temperature and pressure vary below the planet's surface. The linked representations of the surface and subsurface dynamics provide opportunities to investigate this complex Earth system that is typically unobservable in the real world. For example, a cross-section view linked with the planet surface view shows coordinated changes at the surface with processes occurring in the crust, thus connecting rock formation with specific tectonic environments.

Figure 2 illustrates what students can investigate near an oceanic-continental convergent boundary when using the TecRocks Explorer. Using the "Take Sample" tool, students can analyze how rocks transform from basalt, an igneous rock on the ocean floor, to different grades of metamorphic rock as the plate carrying the rock descends into the mantle during the process of subduction. Students can use the "Measure Temp/Pressure" tool to explore how the plate and the surrounding environment changes as it descends.

The TecRocks curriculum

The power of plate tectonics to explain why landforms are located where they are and why geologic phenomena such as earthquakes and volcanic eruptions are found in narrow bands around the globe should also be expanded to explain the distribution of rock types on Earth. This connection is missing from traditional curriculum. We designed an online curriculum called "Rocks & Tectonics" for middle and high school Earth

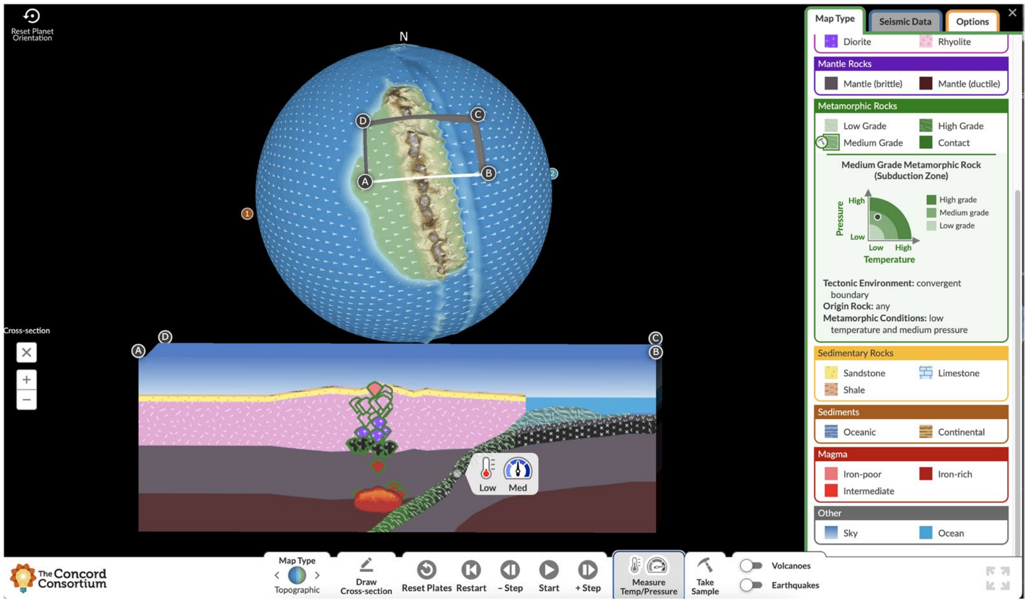


Figure 2. The TecRocks Explorer (https://tectonic-explorer.concord.org/) showing a convergent boundary on the Earthlike planet along with a cross-section where metamorphic rocks are forming as the oceanic plate subducts and igneous rocks are forming as magma rises through the continental crust. The igneous rocks that form differ as a result of magma fractionation.

science students that scaffolds such an integration of concepts and systems reasoning in order to develop students' ability to make sense of the relationship between plate tectonics and rock genesis. This curriculum, available for free at https://learn.concord.org/geo-tecrocks, consists of five activities, each of which has students interact with the TecRocks Explorer to investigate the relationship between tectonic plate movement and different types of rock-forming phenomenon. Each activity takes one class period (approximately 45 min) to complete. The learning goals for the module are: 1) make sense of rock-forming phenomena in specific tectonic environments using a computer simulation and 2) use evidence from the simulation and other visualizations to construct explanations that reflect complex Earth systems reasoning as articulated in the TR Framework. The detailed learning goals and reasoning based on the TR Framework are available in Table 1. To illustrate how the design of the Rocks & Tectonics curriculum reflects the TR Framework, we describe each activity.

In Activity 1, as an introduction to rocks in the context of the whole Earth, students examine rock type distribution around the globe and think about what rocks can reveal about the locations where they form. Students use a simplified world geologic map called "Earth Rocks Map" (Figure 3) to explore the phenomena of rock type distribution across the surface of Earth. Through initial interactions with the TecRocks Explorer, students become familiar with creating and running various tectonic scenarios, observing plate motions and resulting land formations, and using a cross-section tool to observe the processes of plate interactions and rock formation below the Earthlike planet's surface. The activity ends with students developing their own questions from their observations.

Activity 2 scaffolds students' reasoning, beginning with connecting rock type to the tectonic environment in which it was formed. The activity addresses how new land can form on Earth. Students first observe satellite imagery of lava flows from the Palma volcano located on one of the Canary Islands and think about how volcanic eruptions can be responsible for adding land onto the island. Students then use the TecRocks Explorer to examine locations where new rocks form from magma and use evidence from the simulation to identify rock types forming along divergent boundaries. Finally, students explain how the plate motion connects to the rock types forming along the East Pacific Rise by identifying the basalt and gabbro being added to each plate from magma rising from the mantle between the two plates.

In Activity 3, students investigate why different types of igneous rocks form as magma rises to the surface along convergent boundaries. Investigating island arcs and land volcanoes, students use tools in the TecRocks Explorer to sample igneous rocks forming in these locations and explore similar and dissimilar conditions and processes. Students learn about magma fractionation and are asked to explain how the interactions between convergent tectonic plates create volcanic mountains and a variety of igneous rock types.

Activity 4 focuses primarily on the rock-forming processes that transform one rock type into another. Students identify the tectonic settings that cause metamorphism around the Earthlike planet and use the TecRocks Explorer to investigate how the heat and pressure conditions in these locations are connected to rock transformations. Students then consider how the low-grade metamorphic rock exposed at the surface of the Alps as shown on the Earth Rocks Map formed and use evidence from the simulation about the tectonic environment in which this happened.

In Activity 5, students explore the progression of the types of sedimentary rocks at increasing distance from the shore and explain what different sedimentary rock types are forming in these environments. Students explain one case in which sedimentary rocks from along continents but far from an active plate boundary. In this case, students develop an understanding that sediments need a sediment source and the time and space to accumulate.

Table 1. The learning goals, alignment with NGSS performance expectations in the Rocks & Tectonic curriculum, and the TecRocks reasoning expected for each activity.

Activity	Learning goals	TecRocks reasoning
Activity 1: Earth! It's Rocky out There	• Illustrate that rocks comprise the materials that make up the surface and interior of Earth • Identify patterns of locations of rock types on Earth's surface (MS-ESS2-2; MS-ESS2-3)	Conclude there are connections between tectonic processes and rock-forming processes
Activity 2: Eruptions Everywhere	• Identify how locations of volcanic eruptions are connected to tectonic plate motion along boundaries • Identify the types of rocks that form at divergent boundaries • Use evidence from TecRocks Explorer to explain the process by which new rock is formed at divergent boundaries on the ocean floor (MS-ESS2-1; MS-ESS2-2; MS-ESS2-3; HS-ESS1-5; HS-ESS2-3)	Reason about how and why the igneous rocks basalt and gabbro are the only two rock types forming along a divergent boundary
Activity 3: Recipes for Rocks	• Explain the relationship between the distance magma rises through preexisting crust and the resulting changes in iron composition of the igneous rocks formed • Use evidence from TecRocks Explorer to explain how the motion of the tectonic plates at convergent plate boundaries creates conditions needed for the different types of igneous rocks to form (MS-ESS2-2; HS-ESS1-5; HS-ESS2-1)	Explain the rock-forming processes responsible for magma fractionation resulting in different igneous rock types along convergent boundaries
Activity 4: Rock Transformation	• Identify the types of tectonic settings that cause metamorphism • Use evidence from TecRocks Explorer to explain how increased heat and pressure cause rocks to change from one type to another (MS-ESS2-1; MS-ESS2-2; HS-ESS2-1)	Explicate how convergent tectonic environments create the increase in temperature and pressure that transforms rock from parent rock to metamorphic rock types
Activity 5: From Sediment to Rock	• Differentiate between rock-forming processes at passive margins vs. active tectonic regions • Use evidence from TecRocks Explorer to describe the progression of types of sedimentary rocks at increasing distances from shore • Explain the characteristics of tectonic margins that allow for sedimentary rocks to form in a particular location (MS-ESS2-1; MS-ESS2-2; HS-ESS2-1; HS-ESS2-5)	Interpret sedimentary rock formation and explain the rock-forming processes found in these environments that allow for sedimentary rocks to form

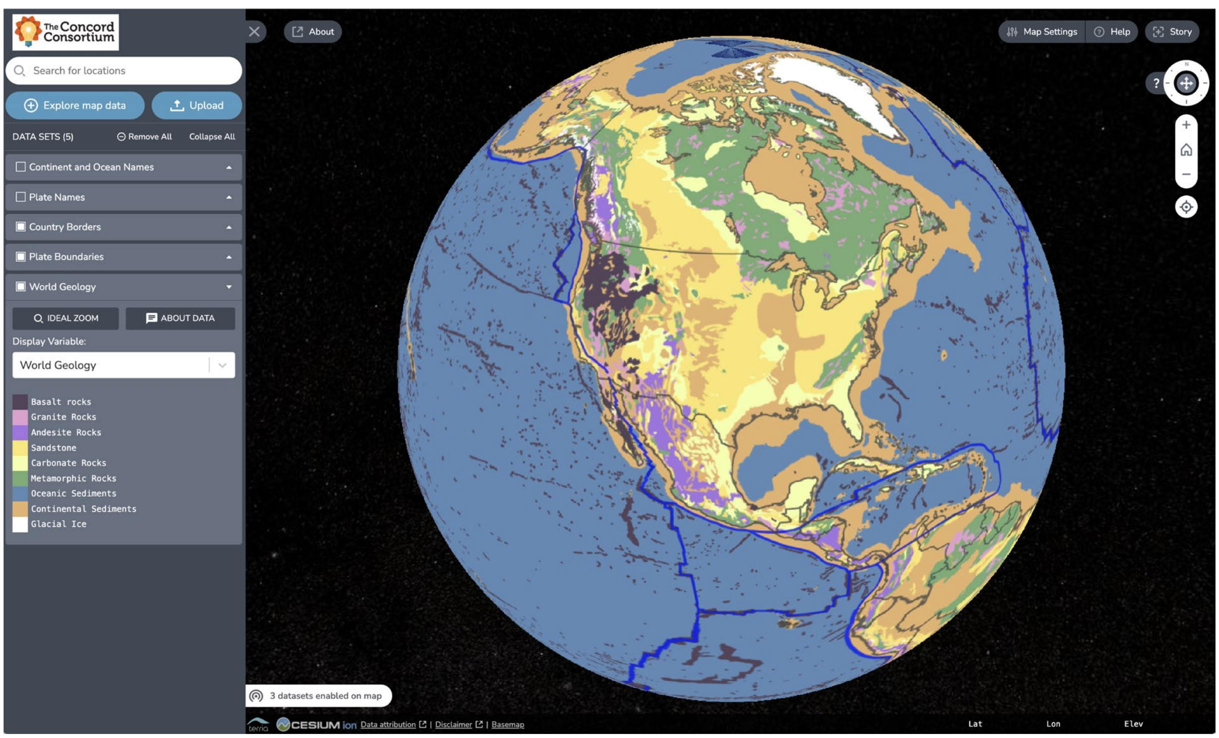


Figure 3. The Earth Rocks Map (https://earth-rocks.concord.org/) showing a distribution of the three major rock types on Earth's surface: igneous, metamorphic, and sedimentary.

Teacher training and support materials

All 10 teachers participated in an online professional development workshop during the summer prior to implementing the curriculum in their classrooms. Teachers learned about the curriculum's pedagogical approach, gained an understanding of the geoscience content, investigated the use of computer simulations for teaching and learning, and explored ways to encourage systems thinking in the context of plate tectonics and rock genesis. In addition, the online curriculum itself included an educative teacher-viewable layer of comprehensive support materials (Lord et al., 2023) that contained pedagogical theory and scientific background information, detailed instructions on how to use the simulations, a full answer key including exemplar student answers, tips on developing students' thinking, prompts to engage students in class discussions, and links to extension activities. The TR Framework is referred to throughout the teacher support materials along with guidance on how to understand the framework and the type of reasoning it aims to promote.

Evaluation

Overall design and strategies

To evaluate the effectiveness of the curriculum, we applied a pretest-post-test design and analyzed student gains at the item level and at the whole test level. The TecRocks assessment instrument was aligned with the topics addressed in the curriculum and provided opportunities for students to elaborate TecRocks reasoning about the tectonic environment, rock-forming processes, and rock types. We used the item-level analysis to show which items students made significant gains on and the test-level analysis to show which demographic subgroups made significant pretest to post-test gains. We applied a general linear model to determine which of these demographic variables are significant predictors of the gain scores.

Data source: TecRocks assessment instrument

To assess student engagement with TecRocks reasoning, we developed the TecRocks assessment instrument, comprising six multiple-choice (MC) and six open-ended explanation (EX) items, as outlined in Table 2. These items were designed around four distinct scenarios reflective of key topics covered by the curriculum: magma formation at divergent boundaries (Q1 and Q2), formation of igneous rocks at both divergent (Q3) and convergent boundaries (Q4 to Q6), metamorphic rock formation (Q7 to Q9), and sedimentary rock formation (Q10 to Q12). These scenarios align with TecRocks reasoning expected from completing Activities 2-5 of the curriculum. All items ask students to connect one element such as tectonic environment to another element such as rock-forming processes. Several items ask students to connect all three elements. Each scenario involved visualizations (e.g., relief maps and diagrams) to anchor rock formation in the broader tectonic context. Additionally, certain EX items were designed to complement their preceding MC counterparts. For instance, Q2 asked students to explain the choice they made for Q1, and Q6 was linked to both Q4 and Q5. Administered online, the TecRocks assessment presented each scenario on a separate page, with open-ended items offering a text box for responses, imposing no restriction on explanation length. There was no language support for English language learners in the TecRocks instrument, but students could type their responses in their primary language.

Data collection

The TecRocks assessment instrument was administered online before and after the curriculum was implemented. We also collected student demographic information related to gender,

Table 2. Description of the items from the TecRocks assessment instrument.

Scenario and Description of scenario visualizations.	Item No. (type)	Item content
Scenario: Magma formation at divergent boundary **Visualization:** Relief map depicting South America and the Mid-Atlantic ridge.	Q1 (MC)	Where on the map would magma be **actively forming** rocks? A is on a convergent boundary, B is in the middle of the ocean floor, and C is on a divergent boundary. **(Arrow 1)**
	Q2 (EX)	Explain why magma is forming at locations you chose. **(Arrow 1, Arrow 3)**
Scenario: Igneous rock formation at divergent and convergent boundaries **Visualization:** A cross-section of Earth's surface. Location X is on a divergent boundary. Location Y is on a convergent boundary.	Q3 (EX)	Explain how movement of tectonic plates at location X [divergent boundary] creates igneous rock. **(Arrow 5)**
	Q4 (MC)	How does the iron content of the igneous rocks formed at location X compare with those at location Y? **(Arrow 6)**
	Q5 (MC)	Why are the igneous rocks formed at location X [different from those at location Y? **(Arrow 6)**
	Q6 (EX)	Using your answers from Q4 and Q5, explain how the movement of tectonic plates at **location Y** creates the type of igneous rocks that form there. **(Arrow 5 and Arrow 6)**
Scenario: Metamorphic rock formation **Visualization:** A cross-section of Earth's surface. Point 1 on oceanic plate along the seafloor, point 2, on oceanic plate just below place of subduction, point 3 on oceanic plate subducted into the mantle.	Q7 (MC)	Which of the following processes results in high-grade metamorphic rock? **(Arrow 6)**
	Q8 (MC)	At which location(s) do **the most changes** occur to form high-grade metamorphic rock? **(Arrow 5)**
	Q9 (EX)	Plates are constantly moving. Explain how the movement of the tectonic plates changes the rock that starts at point 1and moves to point 3. **(Arrow 5 and Arrow 6)**
Scenario: Sedimentary rock formation **Visualizations:** (1) Map and photo showing sediment deposits at mouth of Amazon River (2) Map of North America. Location A is on the continental shelf on the West Coast. Location B is on the continental shelf on East Coast.	Q10 (MC)	What makes this location [continental shelf at the mouth of the Amazon River] a likely place for sedimentary rocks to form? **(Arrow 1)**
	Q11 (EX)	Explain why this location is a likely place for sedimentary rocks to form. **(Arrow 2)**
	Q12 (EX)	Explain the **likelihood** of sedimentary rocks forming in locations A and B. **(Arrow 1 and Arrow 2)**

Each item set starts with an observable phenomena on Earth. The items require students to link elements from the TR Framework. In the column on the right we added a reference to the arrow(s) from the framework representing the expected reasoning when answering the question.
Note: MC = multiple-choice; EX = explanation.

race, English as a first or second language, and grade level. Students' responses to the Rocks & Tectonics module and the TecRocks assessment instrument were automatically collected through an online portal as part of students' classwork. We focused on 319 students who provided all of the demographic information and completed at least 90% of the pretest, the module, and the post-test. Since we were evaluating the curriculum's effectiveness on developing students' TecRocks reasoning, we selected students who were fully exposed to the entire curriculum sequence. Students who completed less than 90% were present across all teachers due to technical issues, absences, or other unknown reasons.

Data analysis

We used the TR Framework to guide scoring and interpretation of student learning that occurred between pre- and post-tests. For the MC items students selected concepts related to one of the elements in the framework. We scored MC items 1 for correct and 0 for incorrect. For the open-ended explanation items, we used the TR Framework to assess students' responses in terms of including individual elements (tectonic environment, rock-forming processes, or rock type), linking one element to another, and integrating the rock genesis system and plate tectonics system. We created a rubric (see Table 3) that ranged from 0 to 4: no information (score 0), non-normative information (score 1), elements only (score 2), partial TecRocks reasoning, i.e., connecting between two elements (score 3), and full TecRocks reasoning, i.e., connecting all three elements (score 4). Elements only reasoning was assigned to students' explanations that included any one of the three elements in the framework but did not contain a link between any of them. Partial TecRocks reasoning represented students' explanations that causally linked one element to another. Full TecRocks reasoning explanations connected all three elements of the TR Framework: plate movement, how plate motion accounts for conditions and processes occurring, and the types of rocks that result. The progression within this rubric can be viewed as integrating more and more elements identified in the TR Framework, leading to higher levels of understanding by integrating both the rock genesis and plate tectonic systems (Kali et al., 2003).

To illustrate scoring, we use the metamorphic rock formation item set from the TecRocks assessment instrument shown in Figure 4. Students who chose "When the temperature and pressure on the rock increase" in Question 7 and "Location 3" for Question 8 received a score of 1 for each question. Question 9 asks students to describe how oceanic crust at the bottom of an ocean basin would change as the plate is subducted below continental crust. Students were expected to consider changes in temperature and pressure the oceanic plate rock encounters as it moves down into the mantle. Pressure and temperature increase with depth in the Earth's crust. When the plate is subjected to the changing conditions as it subducts, the rock will first transform from igneous rock to low-grade metamorphic rock, followed by higher levels of metamorphism as it continues subducting. Students could express their ideas in various ways and with different levels of sophistication. We accounted for student variability when we scored for inclusion of correct ideas. For example, we accepted ideas expressed below as representative of each element.

- Tectonic environment: plates move toward each other; subduction occurs; one plate goes under another plate; convergent boundary, etc.
- Processes: temperature increases as depth increases; pressure increases as depth increases
- Rock type: high-, medium-, and low-grade metamorphic rocks

Following the rubric structure, Table 3 shows the criteria used to score Q9 and student response examples for each level.

Based on these scores, we analyzed student gains from the pretest to the post-test. Using a within-subject nonparametric

Table 3. TecRocks reasoning rubric includes how these elements are used to score students' responses to Q9 featured in Figure 5.

TecRocks reasoning score	Criteria	Student response examples
No Information (0)	Off topic, no answer	• I don't know • I'm confused
Non-normative (1)	Non-normative or vague ideas	• It changes because of the amount of movement. • it can cause the rock to skip a point.
Elements Only (2)	Unconnected elements	• because it slides down under the other plate • Tectonic plates changes the rock point because while the plates move, the rocks tend to follow with it and they move to different points. • The plates collide causing the rocks to move down.
Partial TecRocks Reasoning (3)	Two causally connected elements	• The tectonic plates change the rock that starts at point 1 and moves to point 3 by moving it down to where there is more pressure and heat. • At a convergent boundary, rock that is on the surface can slide down to more heat and pressure because it moves with the plate as it goes down.
Full TecRocks Reasoning (4)	Three connected elements in a causal sequence	• The plate subducts down and as it goes down, it is put under heat and pressure, and changes into higher grade metamorphic rock. • The further it goes down the more heat and pressure it has, but when it get to a certain point the metamorphic rock melts, while at point 2 it is the perfect spot for the metamorphic rock to be formed. Point 1 is getting there but is still to close to Earth's surface and it is too cool and not enough pressure for a lot of metamorphic rock to form.

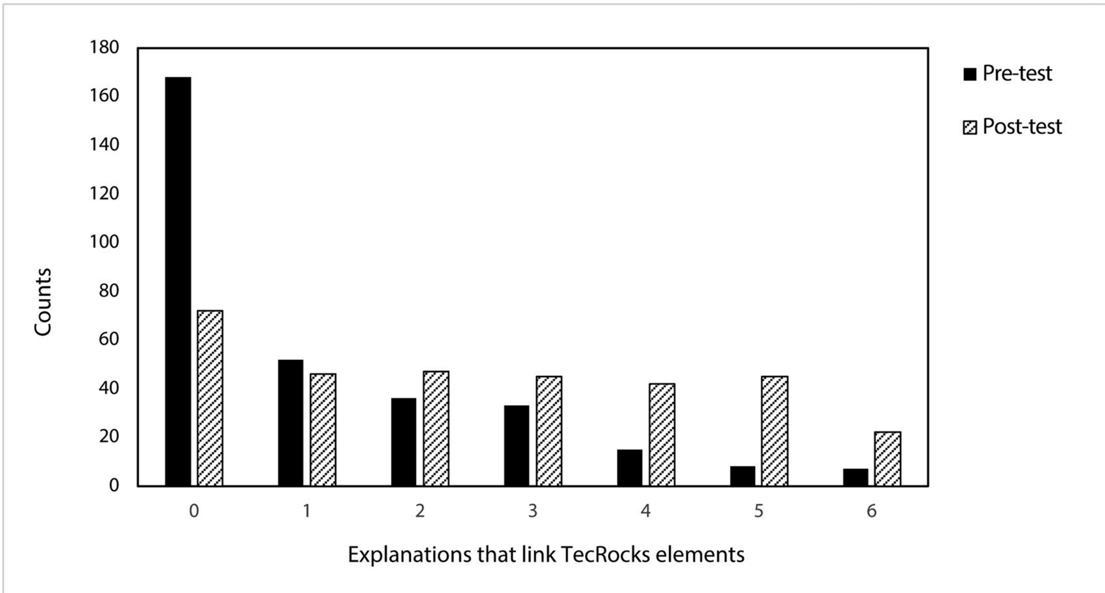


Figure 4. The number of explanations that linked two or more TecRocks reasoning elements for both the pretest and the post-test.

test called the Wilcoxon signed rank test, we examined whether individual students made gains from the pretest to the post-test at the item level. The Wilcoxon signed rank test is based on the sign and magnitude difference between two repeated measurements of each individual. Since the sign is calculated as the first measurement (pretest) minus the second measurement (post-test), a negative sign of the z value indicates a gain. We interpreted the significance of the gain based on the z score and the p value at an alpha of 0.05.

We then calculated a total pretest score and a total post-test score as a sum of scores a student received on each test. The maximum score for the test was 30. Initial descriptive statistics were calculated for student pretest and post-test scores across various demographics: gender, speaking English as first or second language, race, and school level. We conducted paired-samples t-tests to determine the significance level between pretest and post-test scores at an alpha of 0.05, with effect size (ES) calculated using Cohen's *d*, defined as the mean difference in scores divided by the pooled standard deviation. When interpreting effect sizes (Cohen's *d*), we use large ($d = 0.8$), medium ($d = 0.5$), and small ($d = 0.2$) (Cohen, 1988). To assess if these demographic factors are significant predictors for student gains, we performed general linear modeling on the gain scores (post-test score minus pretest score), incorporating gender, race, English, and school level as fixed effects. We only examined the main effects of these variables due to the sample imbalance.

Validity and reliability

We address the validity issue in three ways. First, to support students' elicitation of ideas related to connecting the tectonic and rock genesis systems, we used graphics and problem contexts suitable for different tectonic environments and three rock types. Second, we used the TR Framework to create the rubric to score students' explanations so that we were able to interpret students' gains in scores as an indication of students developing TecRocks reasoning. Third, when designing the test, two teachers who consulted on the project reviewed the items to check whether the items addressed domain-specific ideas students learned from the module. For test reliability, the Cronbach alpha value of the TecRocks assessment instrument was 0.88 based on all students' responses to both pretest and post-test. We use Cohen's Kappa to show scoring reliability between two coders who independently scored all student responses. Table 4 shows Cohen's Kappa values ranging from 0.79 (Q12) to 0.87 (Q3 and Q11).

Results

Pre-post student gains at the item level

Table 4 summarizes pretest and post-test score distributions across the 12 items. On the pretest, few students were able to make at least one link between two elements (scores 3 and 4 combined), ranging from 13% on Q2 and Q11 to 32% on Q3. This means that most students did not make connections among tectonic environments, rock-forming processes, and rock types. On the post-test, much greater percentages of students made at least one link, ranging from 33% on Q2 to 47% on Q6. According to the Wilcoxon signed rank tests, significantly greater percentages of students increased their scores than those who decreased across all items. That is, students made significant gains across all items, regardless of item type or rock formation scenario.

Figure 4 displays the number of explanations that linked two or more TecRocks reasoning elements (i.e., scores of 3 and 4) for the pretest and the post-test. With six open-ended explanation items within the TecRocks assessment instrument, each student had the opportunity to create up to six connected explanations. On the pretest, 52.7% of students failed to make any connected explanations across the six open-ended items. However, this figure notably decreased to

Table 4. Inter-rater reliability, score distributions, and Wilcoxon signed rank test results.

			Pretest score (%) ($n=319$)					Post-test score (%) ($n=319$)					Wilcoxon signed rank Test
No.	Item type	Cohen's kappa	0	1	2	3	4	0	1	2	3	4	*Z, p*
1	MC	–	46	54	–	–	–	28	72	–	–	–	−5.32***
2	EX	0.83	10	46	31	12	1	3	20	45	27	5	−9.02***
3	EX	0.87	20	26	22	25	7	3	17	36	26	18	−7.88***
4	MC	–	77	23	–	–	–	46	54	–	–	–	−7.60***
5	MC	–	80	20	–	–	–	50	50	–	–	–	−7.84***
6	EX	0.81	25	22	29	18	6	4	15	34	35	12	−8.35***
7	MC	–	51	49	–	–	–	20	80	–	–	–	−8.28***
8	MC	–	65	35	–	–	–	28	72	–	–	–	−9.38***
9	EX	0.81	20	30	32	11	7	3	11	39	27	20	−10.76***
10	MC	–	49	51	–	–	–	24	76	–	–	–	−7.02***
11	EX	0.87	22	47	18	13	0	2	23	36	31	8	−11.31***
12	EX	0.79	18	42	26	13	1	3	23	33	28	13	−10.67***

Note: *** = $p<.001$.

22.3% in the post-test. The paired samples t-test analysis reveals that students significantly increased their number of connected explanations from the pretest ($M=1.14$, $SD=1.55$) to the post-test ($M=2.51$, $SD=1.96$), $t(318) = 18.43$, $p < .001$.

To further illustrate student learning gains, we use the three questions from the metamorphic rock formation item (Figure 5). Students providing a correct answer increased from 49% to 80% on Q7 and from 35% to 72% on Q8. On Q9, 18% of students on the pretest were able to make at least one link between the elements (scores 3 and 4). On the post-test, 47% of students were able to make at least one link (scores 3) while 20% linked all three elements, exhibiting full TecRocks reasoning (score 4). An example of one student increasing their TecRocks reasoning can be illustrated from Q9. A student responded on the pretest: "The tectonic plates move and alter the rock next to it." This response was given a score of 2 because the student mentions one element of the TR Framework, tectonic environment, but does not link it to another element of the framework in a detailed way. On the post-test, this same student wrote: "The plate that is pushing underneath the other plate creates more pressure at the bottom. This means the rock at point 1 is much less high-grade than metamorphic rocks you would find at point 3. Metamorphic rocks are made by heat and pressure crushing and heating different rocks. You would find that most at point 3." This response earned a score of 4 because it displayed complete TecRocks reasoning by linking all three elements. The student described the tectonic environment where plates move toward each other and subduct, the rock-forming processes of changing heat and pressure found at point 3, and the rock type (low grade at point 1 and high grade at point 3).

Pre-post student gains by demographic subgroups

Table 5 shows paired samples t-tests results, which indicate an overall statistically significant gain with an effect size of 1.03 in TecRocks reasoning following students' engagement with the Rocks & Tectonics curriculum. Significant gains were observed across all demographic subgroups, defined by gender, English as first or second language (English), race, and school level. According to the effect size interpretation proposed by Cohen (1988), all effect sizes but one were greater than large ($d=0.8$). High school students' effect size was greater than medium ($d=0.5$). However, the magnitude of these gains varied among the groups, as delineated by each demographic variable. The effect size for the "Prefer not to answer" group was the highest ($d=1.41$) among the gender subgroups. The effect size for the English as a first language group ($d=1.05$) was greater than that of the English as a second language group ($d=0.86$). Middle school students exhibited notably higher gains with a greater effect size ($d=1.42$) compared to high school students ($d=0.66$). Additionally, effect sizes varied significantly among racial groups, ranging from 0.93 for White students to 1.85 for Asian American students.

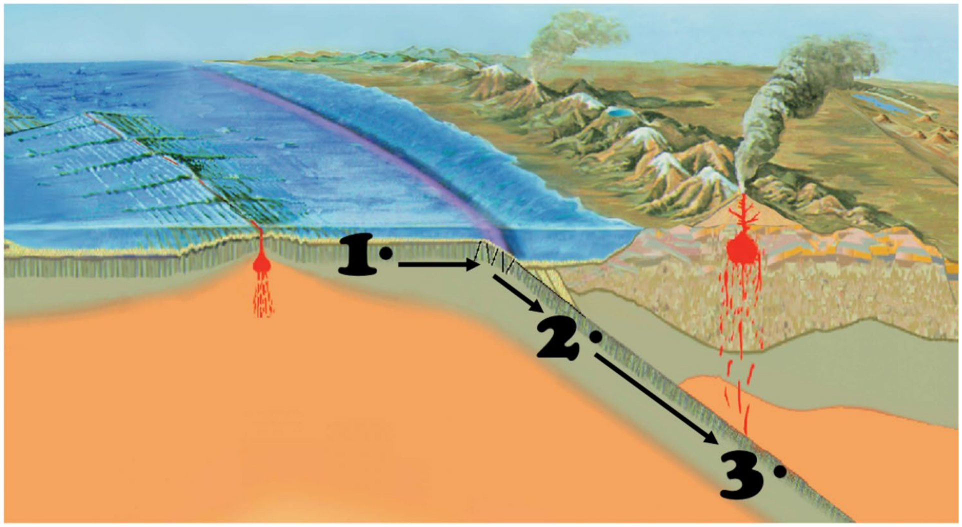
The general linear modeling results (Table 6) indicate that the school level and race factors were significant predictors for the gain scores. See Table 5 for pretest and post-test score differences as well as effect size comparison statements in terms of the school level and race subgroups. The English and gender factors were not significant, indicating the subgroups in each variable made statistically comparable gains. We note that the sample sizes for certain demographic subgroups were relatively small; therefore, these observed differences require further examination with larger samples.

Interpretation/Discussion

This paper reports on to what extent and for whom the simulation-based curriculum approach was useful in developing students' reasoning about the connection between the plate tectonics and rock genesis systems. In this study, we defined the TR Framework and applied that framework to our curriculum design in order to guide students to characterize the phenomena and the patterns associated with connecting the plate tectonics and rock genesis systems through investigations with the TecRocks Explorer simulation.

Our analysis discerned different levels of TecRocks reasoning in student explanations of igneous, metamorphic, and sedimentary rock formation based on the processes found in various tectonic environments. Our findings revealed that middle and high school students, when provided with a curriculum and simulation, were able to formulate explanations involving elements of the TR Framework and make links between plate tectonics and rock genesis. This study indicated that students, regardless of their gender, English as first or second language, race, and school

As the surrounding environment changes, a rock can become a different type of rock called metamorphic rock.
The arrows in the image below show the direction of plate motion.



Q7. Which of the following processes results in high-grade metamorphic rock?
- When magma is cooled by ocean water and forms rock
- When the temperature and pressure on the rock increase (correct)
- When the temperature and pressure on the rock decrease
- When wind and water break rock down into sediments

Q8. At which location(s) do the most changes occur to form high-grade metamorphic rock?
- Location 1
- Location 2
- Location 3 (correct)
- All of the above

Q9. Plates are constantly moving. Explain how the movement of the tectonic plates changes the rock that starts at point 1 and moves to point 3.

Figure 5. The setup and question prompts used for the metamorphic rock scenario from the TecRocks assessment instrument.

Table 5. Pretest and post-test gains analysis results based on paired samples T-test with Cohen's *d* (effect size).

Subgroups	n	Pretest	Post-test	*t*	*p*	Effect size
All	319	11.27	17.84	18.43	***	1.03
(a) Gender						
Male	163	11.35	17.34	12.48	***	0.98
Female	135	11.23	18.25	12.50	***	1.08
Non-binary	9	14.44	19.33	3.21	*	1.07
Prefer not to answer	12	8.33	18.92	4.87	***	1.41
(b) English						
First Language	283	11.52	18.17	17.74	***	1.05
Second Language	36	9.33	15.31	5.18	***	0.86
(c) Race						
White	144	12.96	18.52	11.10	***	0.93
Hispanic or Latino	38	9.53	13.95	6.13	***	0.99
Black or African American	18	8.78	13.39	4.48	***	1.06
Asian American	18	9.11	21.72	7.85	***	1.85
Mixed	73	11.03	18.04	9.42	***	1.10
Prefer not to answer	28	8.61	19.50	8.08	***	1.53
(d) School						
Middle	198	8.69	17.70	19.96	***	1.42
High	121	15.50	18.07	7.27	***	0.66

Note. * indicates $p < .05$; *** indicates $p < .001$.

level, made significant gains from the pretest to the post-test. When broken down by subgroups based on race and school level, the results show significantly larger gains in some groups than others. Specifically, middle school students had significantly greater gains than high school students. We posit that result is due to high school students starting the curriculum with greater prior knowledge (as indicated by the pretest scores) than middle school students, likely due to prior instruction about the different rock types, the rock cycle, and some rock-forming processes. Yet despite this initial knowledge gap, middle school students were able to achieve a level of TecRocks reasoning similar to high school

Table 6. General linear model results.

Source	df	F	p
Corrected model	10	16.00	***
Intercept	1	67.70	***
School level	1	96.50	***
Race	5	6.77	***
English	1	1.54	.22
Gender	3	1.18	.32
Error	308		
Total	319		
Corrected total	318		

Note: * $p < .05$, ** $p < .01$, *** $p < .001$; R Squared = 0.34.

students. The similar scores on the post-test between middle and high school students indicate that the complex systems reasoning in the Rocks & Tectonics curriculum is accessible to middle school students. Significant gains were observed among racial sub-groups, with Hispanic or Latino, Black or African American, Asian American, Mixed, and those preferring not to answer all showing greater effect sizes than the White group. White students' pretest scores were higher than other racial subgroups; however, this group did not show significant gains from pretest to post-test. The unequal sample sizes across these racial categories present challenges in generalizing these findings.

Although useful in presenting the spatial and temporal relationships within a dynamic simulation, our curriculum approach does not address many concepts that are taught in relation to both rock genesis and plate tectonics, including concepts such as magnetic and seismic evidence used for developing the theory of plate tectonics or how solar energy is responsible for erosion and weathering of rocks on Earth's surface. These ideas are important but can also distract from the core unifying systems reasoning of our focus.

Students were not explicitly exposed to the TR framework in the curriculum. This was a design choice. The organization of the instructions, questions guiding the interpretations of the simulation, the Earth Rocks Map, and other visualizations had students consider all three elements of the framework by the end of each activity. The TR Framework was shared with the teachers who were free to share it with their students if they wished to do so. We did not collect data on whether any teacher explicitly used it with their students during the implementation. The strategy of making the students explicitly aware of the TR Framework has potential for helping students as they develop the explanations. This could be the focus of another study.

For this study, we concentrated on the idea that virtually every concept about Earth's surface and interior only makes sense in terms of plate tectonics. When considering the content from this perspective, it is essential to connect rock formation to tectonic processes. Grasping the idea that Earth's plates are endlessly diverging, converging, colliding, and changing direction is challenging for novice learners because of the scale and the three-dimensional nature of the system (Kastens et al., 2009; McDonald et al., 2019; Pallant et al., 2023). These concepts are made accessible to students by visualizing respective phenomena as part of the TecRocks Explorer dynamic simulation, which provides a great deal of information about spatial and temporal relationships among rock structures, rock-forming processes, and about the likelihood of rock type formation. As part of middle and high school Earth science education, students typically learn about plate tectonics and the rock cycle, but we present a way to bring these topics together by exploring, identifying, and reasoning about what has occurred on Earth in the past, what is happening in the present, and what will continue into the future.

The analysis of student work using the TR Framework also provides a way for teachers and researchers to determine what students are able to explicate. The TR Framework reveals students' level of understanding. Our results indicate that overall, this approach is feasible to implement in secondary schools and provides students with the ability to reason that goes beyond simple descriptions or memorizations. TecRocks reasoning involves complex systems thinking that is also important in other areas of Earth science. Similar frameworks could be developed for exploring the integration of the climate system and ocean current system or natural hazard systems and climate change. Such merging of subsystems has the potential to establish more coherent learning across topics than when these topics are taught separately.

Limitations

Our curriculum evaluation showed that students who learned using the Rocks & Tectonics curriculum made improvements in TecRocks reasoning. However, it is not clear that extending this result to the general secondary school population is warranted. We also note that our analysis subdivided the students into different racial and gender groups. The subdivision meant the sample size for some groups was small enough to make the comparison less representative. We would need to increase the sample size to be more confident in the results.

While we recruited teachers to represent school settings serving different demographic groups, we did not sample them from the general teacher population. Our analysis did not account for teacher influence or teacher preparation that might affect what and how much students could learn. Future teacher training could include differentiation strategies and guidance for struggling students. The Rocks & Tectonics curriculum represents a new pedagogical approach, so teachers' background and knowledge of this complex systems approach likely played an important role in student outcomes. In our analysis, we only included students who completed 90% of the curriculum to assure full exposure to the intervention. In typical classroom settings, this may be difficult to enforce. Future research could further explore curriculum design, professional development, and implementation variations. Given the difficulty of teaching and learning about complex Earth systems, research on various curriculum design approaches would be a valuable contribution to the field.

Conclusion

The TR Framework embodies Earth system science in which plate tectonics is the organizing paradigm into which rock genesis must connect. This approach suggests a potential direction for restructuring K-12 Earth science instruction. The TR Framework that guided the development of the curriculum materials and the TecRocks Explorer simulation enabled students to develop systems reasoning about a complex Earth system. The TR Framework, which highlights links among the tectonic environment, the rock-forming processes, and the rock types, allows researchers to assess the explanatory connections students make. Future research could address how this framework might work for explanations derived from fieldwork or labs, where students begin with landforms and rock types. Additionally, research can continue to explore how to support this type of systems reasoning through curriculum design.

Acknowledgment

The authors gratefully acknowledge the students and teachers who participated in this study.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This material is based on work supported by the National Science Foundation under Grant No. DRL-2006144. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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