Thinking Outside the Box of Rocks

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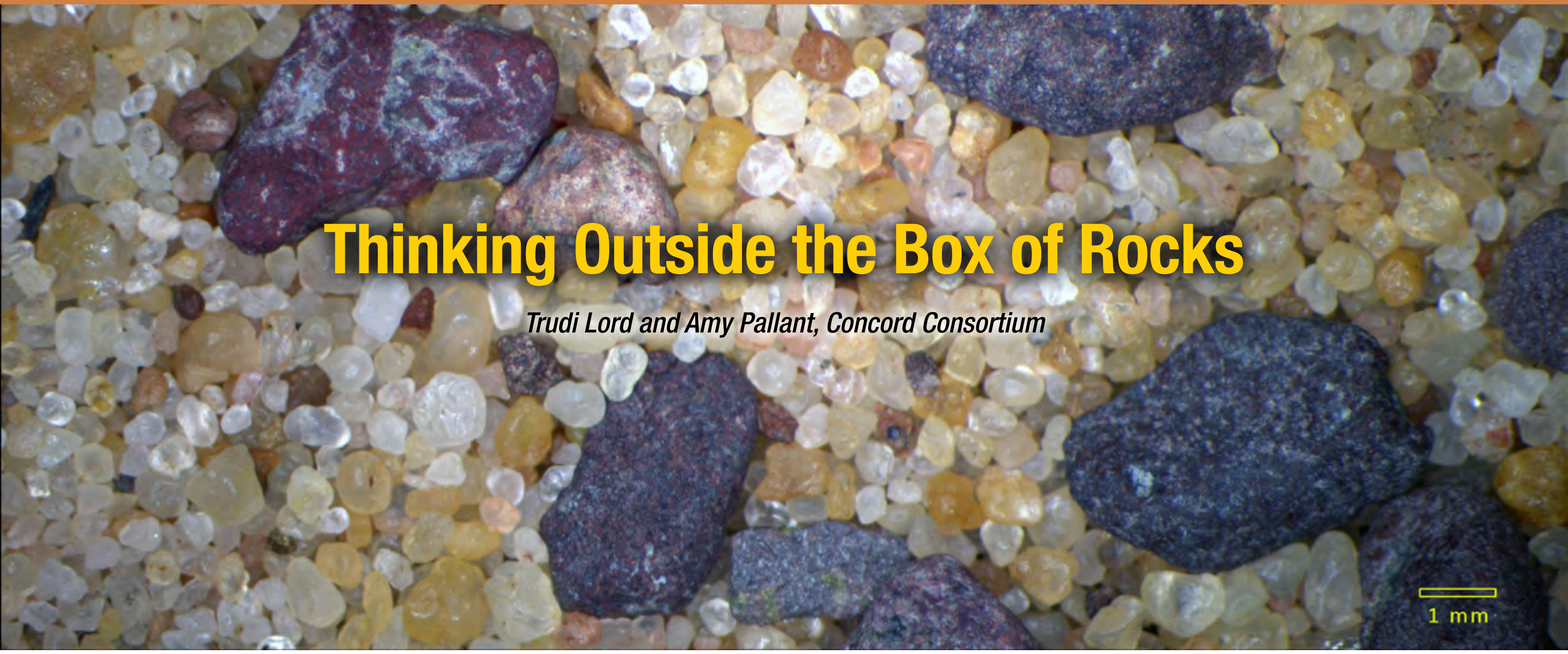

Sample of mixed sediment shown under a microscope at 7.5x magnification. Dark-colored, coarse-grained stamp sands are readily distinguishable from light-colored, finer-grained native sand. Scale bar at bottom right for reference. Photo credit: Jason Chaytor, USGS.

Abstract

In this article we introduce a National Science Foundation-funded research project called TecRocks that has developed new interactive simulations and an innovative online curriculum module that weaves rock formation and plate tectonics together such that secondary teachers and students can approach these two topics as integrated systems. In the 2022-23 school year, the curriculum was implemented in middle and high school classrooms across the United States. Results showed a significant increase in students' conceptual understanding and systems reasoning about tectonic environments, the rock-forming processes occurring in these environments, and the rocks that are formed as a result of those processes. Student materials and teacher support resources developed through the project are freely available on the Concord Consortium's STEM Resource Finder at (https://learn.concord.org/geo-tecrocks).

Introduction

The rock cycle, taught in nearly every Earth science class, is an abstract representation of a series of processes that create and transform rocks on Earth. Teachers often present students with a box of rocks and minerals and focus on classification during instruction about the rock cycle. Students categorize specimens as igneous, metamorphic, or sedimentary based on their physical traits and chemical composition, but those characteristics capture a rock's state at a single snapshot in time—the rock is unchanging. However, neither rock classification nor the rock cycle diagram help students reason about where on Earth the dynamic processes responsible for rock formation are happening (Fichter, 1996). Indeed, rocks have a history—they are formed in specific locations by processes taking place on and under the Earth's surface—and thus a story to tell about their formation. Earth science instruction should include this part of their story.

The Next Generation Science Standards (NGSS Lead States, 2013) promotes a systems approach, developing students' causal reasoning about phenomena occurring on Earth. To engage in Earth systems thinking, students need to be able to identify the components of the system as well as the processes and dynamic relationships within the system, which also call for temporal thinking (Assaraf & Orion, 2005). A systems approach to the rock cycle requires putting it in the context of plate tectonics. When a geologist analyzes a rock, she may classify it as igneous, metamorphic, or sedimentary, but she undoubtedly also considers how that rock represents a geologic history of processes that occurred over a very long time and under specific environmental conditions. Geologists inextricably connect rock formation to tectonic plate motion and interactions (Whitmeyer et al., 2007), telling a complex and dynamic story about what has happened on Earth over millions of years.

While plate tectonics is the foundational paradigm for geosciences, rarely are the processes associated with tectonic interactions connected to causal mechanisms involved in rock formation at the secondary school level (Raia, 2005). The National Science Foundation-funded TecRocks project set out to change how this content is introduced in middle and high school Earth science classes with the goal of developing students' ability to connect rock genesis to plate tectonics. This reasoning typically requires learning a subset of fundamental ideas in the Tectonic Rock Cycle (Whitmeyer et al., 2007). However, our instructional approach excludes the super-continental cycles in favor of inquiry-based activities that connect tectonic environments and rock-forming processes to the rock types that typically form in those environments.

Thinking about tectonic and rock forming events means students need to consider causal dynamic processes and specific sequencing of events (Pallant, 2023). Interactive simulations for this topic have the potential to engage students in systems reasoning (Kali & Linn, 2008) because they provide the opportunity to interact with and explore the behavior of the complex system (Pallant & Tinker, 2004; Yoon et al., 2018). We developed, tested, and refined a free online curriculum module called Rocks & Tectonics, which includes three web-based tools that help students learn about rock formation as part of Earth's plate tectonic system. By focusing on this integration, rather than learning about rock formation and plate tectonics in discrete units, students have the opportunity to make deep connections about the planet on which they live.

Interactive Tools

Below we describe a computer simulation and two data visualization tools that students use to investigate the intersection of plate tectonic phenomena and rock-forming phenomena. These tools are embedded in the Rocks & Tectonics module (http://learn.concord.org/geo-tecrocks) and were designed to work together to help students form a holistic systems view.

TecRocks Explorer (https://tectonic-explorer.concord.org/?rocks=true) is a computer web-based simulation of an Earth-like planet that allows students to investigate the relationship between Earth's plate tectonic system and the conditions under which many different types of rocks form (Figure 1). TecRocks Explorer is designed to provide middle and high school students the opportunity to observe phenomena and reason about these processes in context. The design intentionally simplifies the systems by reducing the number of plates and limiting the variety of rocks generated.

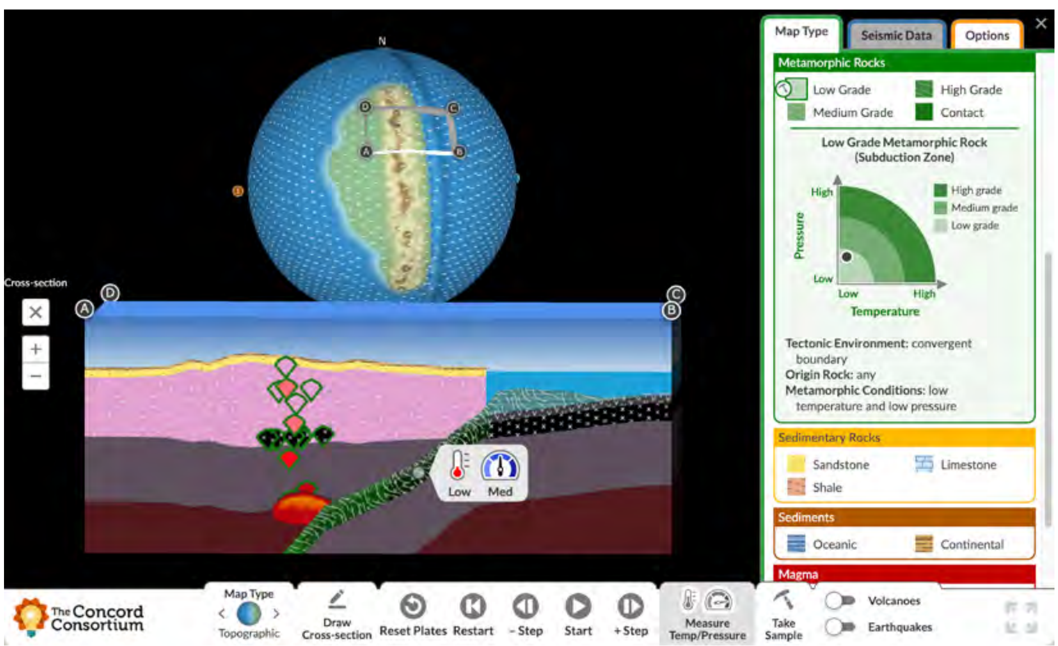

Figure 1. A convergent boundary shown in TecRocks Explorer. The temperature and pressure tool is used to show the conditions at a particular location on the subducting plate. A key includes rock types and properties.

Before starting the simulation, students can add continental crust and determine which boundaries are convergent and which are divergent. Once the simulation starts, plates pull apart and collide. Transform boundaries emerge that show plates grinding past each other. New rocks do not typically form at transform boundaries; rather, transform boundaries form to compensate for the differences in velocity and/or angles of movement along nearby divergent and convergent boundaries. By simplifying the geometry in TecRocks Explorer and limiting students to choosing between convergent and divergent boundaries, we were able to guide students away from accidentally simulating very complex plate interactions that would make the study of basic rock-forming environments difficult to visualize and overly confusing.

In TecRocks Explorer, students can create three-dimensional cross-sections to observe plate interactions below the surface. Students can sample rocks anywhere on the planet's surface or in the cross-section. When students sample a rock, a key expands and provides information about the rock type. Students can also measure the relative temperature and pressure anywhere below Earth's surface in the cross-section. Finally, students can pause the simulation and collect data from multiple rocks as well as other elements in the simulation like magma and sediments. This feature was designed to facilitate students' recognition of patterns in rock formation and properties such as the difference in iron content of igneous rocks shown in Figure 2.

Question #23

Sample rocks throughout the cross section of the TecRocks Explorer. Use the table to show the different types of rock that solidify from magma rising through the crust.

Pin	Category	Type	Iron Content
1	Magma	Iron-rich Magma	Iron-rich minerals — Iron-poor minerals
2	Magma	Intermediate Magma	Iron-rich minerals — Iron-poor minerals
3	Igneous	Gabbro	Iron-rich minerals — Iron-poor minerals
4	Igneous	Diorite	Iron-rich minerals — Iron-poor minerals
5	Igneous	Granite	Iron-rich minerals — Iron-poor minerals
6	Igneous	Rhyolite	Iron-rich minerals — Iron-poor minerals

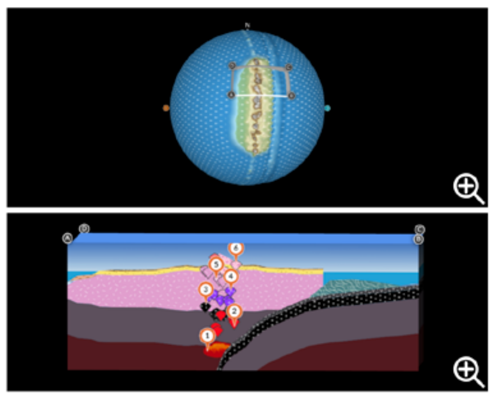

Figure 2. A data table of samples collected within the TecRocks Explorer.

Figure 3. Earth Rocks Map displaying Earth's surface geology.

Earth Rocks Map (https://earth-rocks.concord.org/) is a unique representation of Earth's geology, displaying a generalized distribution of igneous, metamorphic, and sedimentary rocks on the surface of a globe as well as a two-dimensional map projection. This simplified map (Figure 3) does not include typical geologic era information, instead foregrounding the locations on Earth where specific rock types are currently found. Further, the subset of rock types shown connect to those in TecRocks Explorer.

Using consistent representations between the two tools enables students to make connections between the simulation and real-world data. Students can rotate the Earth Rocks Map, show plate boundaries, and zoom into the globe for a closer look. They can turn different rock types on and off to reveal patterns about their distribution on Earth surface. For example, by selecting the display variable "Igneous Rocks," students can see that granitic rocks are only found on continents.

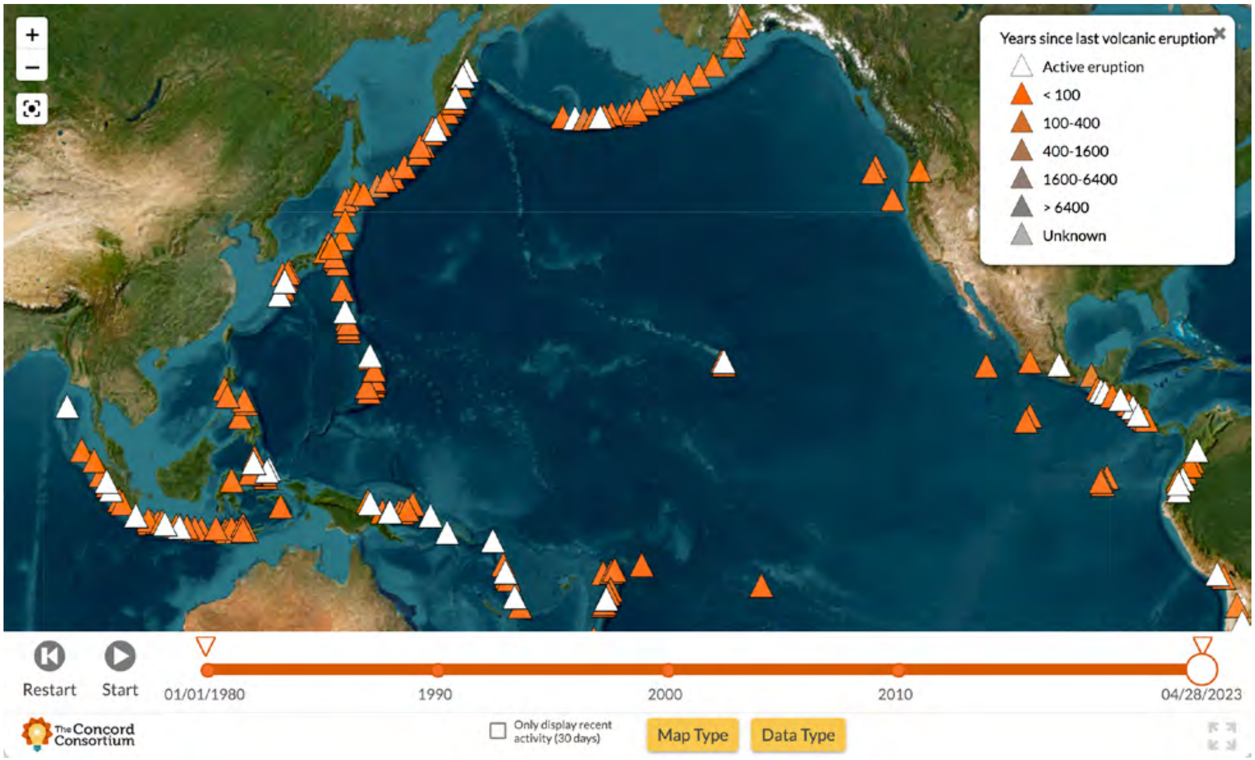

Figure 4. Seismic Explorer showing volcanic eruptions along plate boundaries.

Seismic Explorer (http://seismic-explorer.concord.org/) was designed to visualize up-to-date earthquake, volcanic eruption, and plate motion data. Students use this tool to look for patterns in earthquake and volcanic eruption distribution (Figure 4) on Earth's surface and can connect this data to evidence of plate motion and areas of new rock formation. Seismic Explorer also has a cross-section feature that allows students to delve beneath the surface and see telltale patterns of earthquakes along different types of plate boundaries.

The Rocks & Tectonics Module

The Rocks & Tectonics module has been tested and refined through design-based implementation research (Brown, 1992), including three design cycles. In the first two cycles, we designed, tested, and refined the embedded tools, curriculum module, assessments, and teacher support materials. Early testing resulted in improvements in question prompts as well as written and visual instructions. This led to the creation of "how to" videos and multi-panel cartoons to illustrate the steps needed to fully access the functionality of the embedded tools. In addition, analysis of student explanations uncovered a set of specific concepts that required more scaffolding to support students' understanding. To address these issues, we designed three animations that zoom into the processes underlying metamorphism, fractionation, and sedimentation and compaction. Finally, feedback from early implementations informed the development of a comprehensive suite of teacher support materials that provide theory and background information, detailed instructions on how to use the tools, a full answer key including exemplar student answers, tips on how to further evolve students' thinking, prompts to engage students in class discussion, and links to extension activities.

The module is aligned with NGSS middle and high school disciplinary core ideas, science practices, and crosscutting concepts. Students use the embedded tools to conduct investigations using simulations, test their ideas, and develop explanations. These tools also provide students with systems modeling experience, an important crosscutting concept that they can apply to Earth's many complex systems. In particular, the Rocks & Tectonics module addresses these core ideas:

- MS-ESS2-3: Analyze and interpret data on the distribution of fossils and rocks...to provide evidence of the past plate motions;
- MS-ESS2-1 Develop a model to describe the cycling of Earth's materials and the flow of energy that drives the process; and
- HS-ESS2-1 Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean floor features.

The Rocks & Tectonics module supports students' sense-making through five scaffolded activities that focus on different tectonic environments, rock-forming processes at those locations, and the rocks that are formed there.

Activity 1: Earth: It's Rocky Out There!

This introductory activity begins by asking students where they think rocks are found on Earth. Students may be surprised to find that rocks make up the entire surface of the planet. Students are primed to think about why there are different types of rocks in different locations on Earth.

Activity 2: Eruptions Everywhere

In the second activity, students investigate the connection between volcanic eruptions, plate boundaries, and where new igneous rock forms. The activity is framed by the 2021 volcanic eruption of La Palma, where students can observe where new land formed. Students are prompted to use Seismic Explorer to connect volcanic eruptions with plate boundaries. They then use TecRocks Explorer to investigate the rock forming at the surface (extrusive) and below the surface (intrusive) along divergent boundaries. Through the cross-section tool, the rock sampling tool, and embedded directions and question prompts, students explore rock forming along plate boundaries. They are then challenged to explain why the entire ocean floor is made of basalt (Figure 5). Students use the TecRocks Explorer to develop an explanation, and then are introduced to the idea that there are specific locations in which rock-forming processes occur.

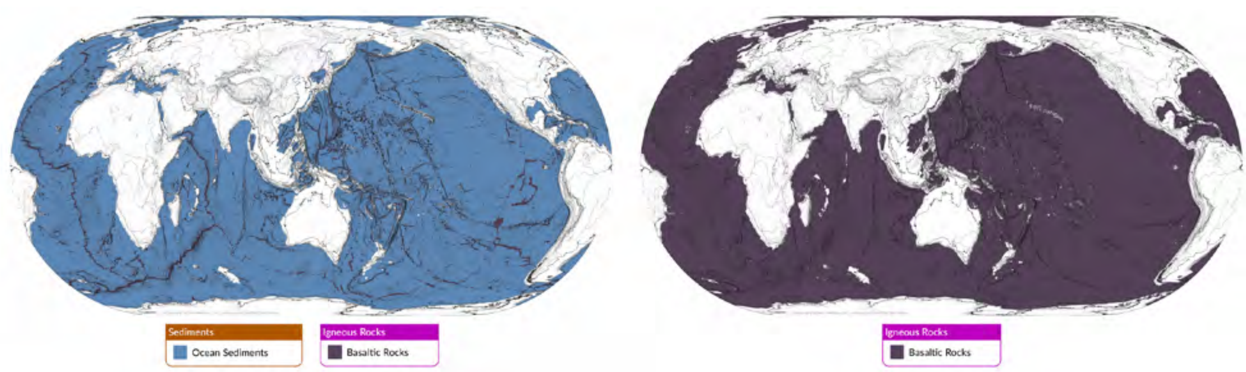

Figure 5. A map showing that the entire ocean surface is composed of basaltic rock. Photo Credit: Sean Morrison

Activity 3: Recipes for Rock

In the third activity, students investigate the formation of the Aleutian Islands. To do this, students are challenged to consider whether the rocks forming in the volcanoes at the convergent boundary of the Aleutian Islands are the same type of igneous rock found at divergent boundaries. Students begin by using Seismic Explorer to determine what type of plate boundary is associated with the formation of island arcs. Then, students use TecRocks Explorer to set up a simulation that creates an island arc similar to the Aleutian Islands. They do this by choosing a convergent boundary between two oceanic plates in the simulation. Using the cross-section and rock sample tools, students are able to investigate the otherwise invisible process of rocks forming along this convergent boundary.

Students follow a similar instructional series of steps to investigate the types of igneous rocks forming along the Andes Mountain range. As students sample the rocks that form as the magma rises through continental crust, they can investigate magma composition changing as it rises and different igneous rocks forming. Students can sample magma and rock in the cross-section view. When the sample data is displayed in the data table, as shown in Figure 2, students can begin to observe patterns of change for both the magma and the igneous rock forming in different convergent boundaries. Because this pattern recognition is complicated, we developed an animation (Figure 6) to help students understand the changing composition of both the magma and the rock (without having to get into the Bowen reaction series diagrams). Through guided steps in the module and suggested classroom discussions facilitated by their teachers, students can describe the connection between various types of igneous rocks that form, the fractionation process associated with the rise of magma from the mantle, and the tectonic environments in which they form.

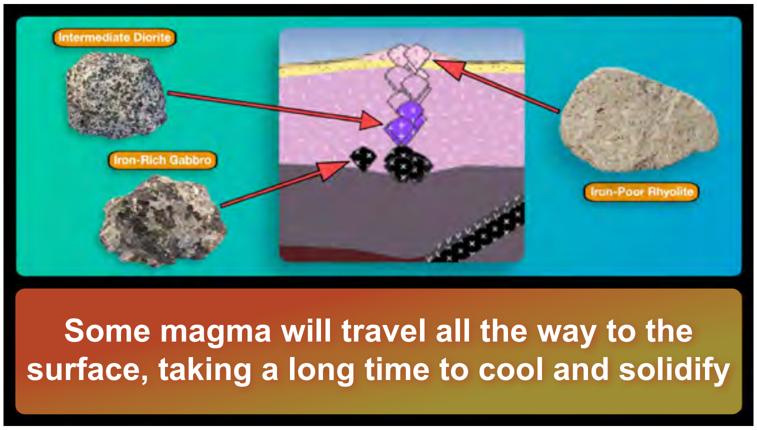

Figure 6. A snapshot of an animation that illustrates magma fractionation.
Photo Credit: Andrew Sao

Activity 4: Rock Transformation

In the fourth activity, students use the TecRocks Explorer to determine how changes in a rock's environment can create metamorphic rocks. Students investigate how a rock layer in a subducting plate is subject to changes in its environment as it travels from the surface towards the mantle. Students measure the temperature and pressure with an embedded tool to learn about the conditions. To reason about the connection between tectonic environment and the formation of metamorphic rocks, students are asked to explain how the motion and interaction between African and Eurasian plates create the metamorphic rocks found throughout the Alps mountains. To support teachers when reviewing their students' responses, we provide background information and student exemplar answers. For example, an "ideal" student explanation may state, "When plates are moving towards each other, one subducts under the other. If both those plates have continental crust, the continents will eventually collide. In the TecRocks Explorer, I saw that this collision causes the pieces of continental crust to push up against each other. This increases the pressure in the land where the mountains form. As the crust thickens and mountains form, a pattern of metamorphic rocks can be seen. I used the sample tool to find that there was higher pressure and temperature deeper in the mountain compared to closer to the surface."

Activity 5: From Sediment to Rock

In the fifth and final activity, students investigate the question, "Do all rocks form at active plate margins?" Students explore sediment thickness and distribution as well as the processes necessary for sediments to form into sedimentary rocks. They compare sediments deposited on passive margins versus active tectonic boundaries and explain the connection between sedimentary rock formation and distance from active tectonic plate boundaries. Due to the scale represented in TecRocks Explorer, it does not simulate sedimentary strata forming over geologic time. Instead, the focus is on how distance from a plate boundary can help explain why sedimentary rocks form where they do. As described in the teacher resources for extension activities, principles related to the interpretation of strata are a natural complement to this activity. By the end of this activity, students have explored the formation of all the major rock types in relationship to both active plate boundaries and passive plate margins.

Teaching with Rocks & Tectonics Module

During the spring semester of the 2022-23 school year, the final version of the Rocks & Tectonics module was implemented by 10 teachers in 9 different states (Arizona, California, Florida, Kentucky, Michigan, New Jersey (2), New York, and Ohio). Five of the schools were located in suburban areas, three in urban areas, and one in a rural area. Six of the schools were middle schools and four were high schools. Among the students (N = 321), 42% were female, 51% were male, 7% identified as non-binary, and 89% spoke English as their first language. All 10 teachers were familiar with the curriculum as they had received professional development during the summer prior to teaching this module in their classrooms. The teacher workshop included lessons on both science content and pedagogical strategies for teaching with the embedded tools.

During classroom implementations, we collected pre-test, post-test, and student responses to questions within the module, as well as teacher feedback via extensive teacher post-surveys. Selected classrooms were observed in person (Figure 7).

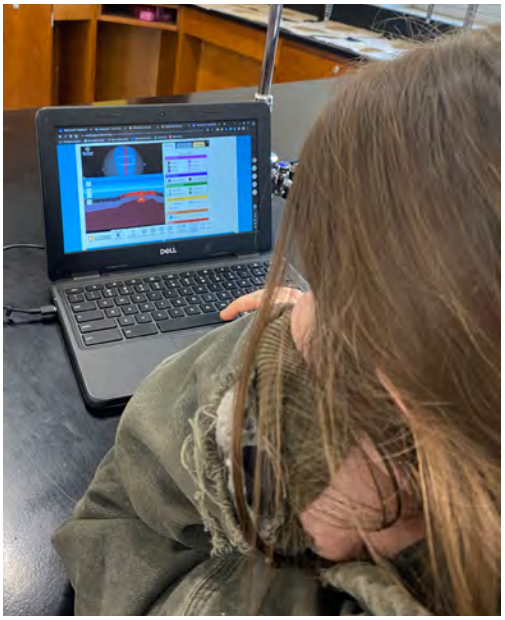

Figure 7. A student uses the TecRocks Explorer to investigate an oceanic divergent boundary.

Photo Credit: Stephanie Harmon

The mean student score from pre-test (11.25) to post-test (17.88) showed a significant increase ($p < 0.001$). Furthermore, while middle school students' pre-test scores were much lower than high school students' pre-test scores, the middle school students' post-test scores were similar to the high school students' post-test scores, which indicates that middle school students are able to reason through these complex concepts and make connections between plate tectonics and rock genesis. We also found that there was no significant difference in learning based on gender, race, middle vs. high school learners, or English language learning status.

Teacher post-surveys indicated that while the content was challenging for students, teachers saw the benefits of teaching rocks and tectonics as an integrated system. One teacher reported, "The student conversations around this work were so rich! In the past, we studied the rock cycle using a traditional rock cycle diagram as a reference point in conversations. The simulation provides a better reference point as it supports students thinking about what happened to create the rock rather than 'Oh, here's this rock, wonder why that's here?'" Another noted, "I usually don't teach about the locations of the different rock types, and now I think this is very important to connect the genesis of rock types with plate movement. I will most definitely teach plate tectonics and the rock cycle in a connected fashion as this module does."

Conclusion

When middle and high school introductory Earth science students engage in investigations purposefully designed to link plate motion to the processes and conditions in which different types of rocks form, they can reason about and understand the connections between the plate tectonic system and rock formation. With interactive technological tools, scaffolded activities, and a suite of teacher resources, the Rocks & Tectonics module is designed to bring this important understanding to secondary Earth science classrooms.

We have found that students can successfully reason about how rock-forming processes are connected to the tectonic environment in which they form. This type of geologic thinking can help students see that Earth is dynamic and evolving over time, and that rocks are recordings of the processes that occurred at a wide range of scales and timeframes. Equipped with a new framework for understanding, students can now look at everything from a single rock specimen to an outcrop, gorge, or sea cliff and marvel at the long and storied history of these rocks. With this foundational experience, students will be better prepared for further study in geosciences.

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