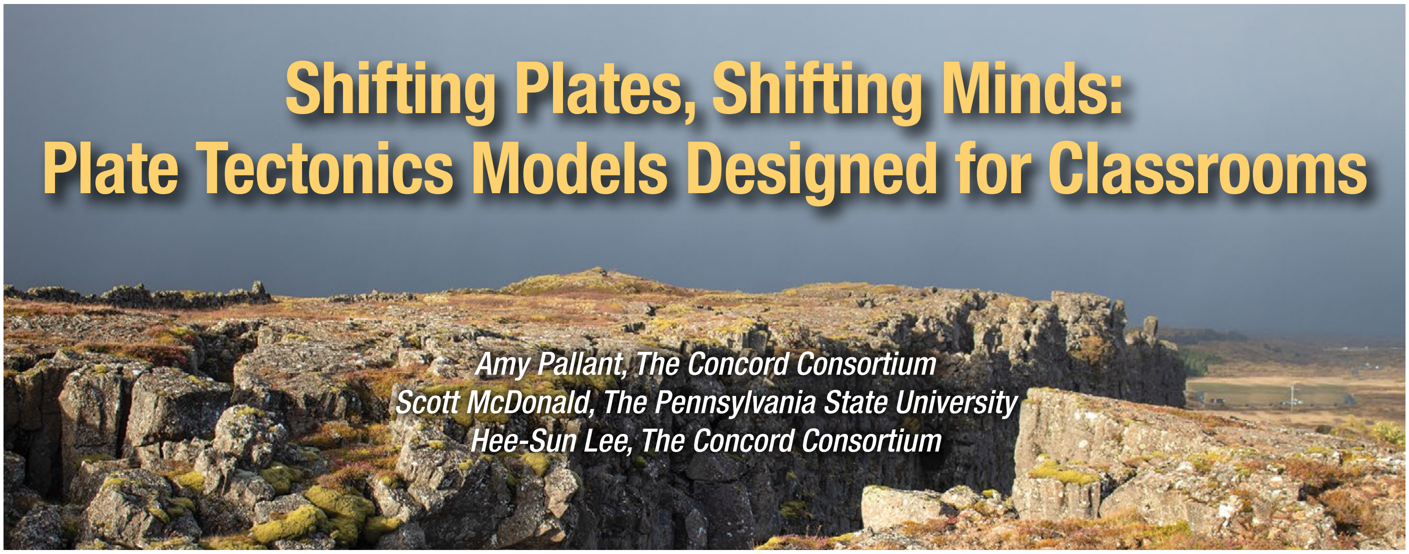

Shifting Plates, Shifting Minds: Plate Tectonics Models Designed for Classrooms

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Abstract

Understanding Earth's tectonic plate system dynamics is complicated though it is the central paradigm to explain transformations of Earth's surface. The landforms and geodynamic events resulting from plates interacting are too massive to observe at scales of human experience. It is difficult for students to connect plate movements to geologic features like the Andes Mountains and geodynamic events like earthquakes. As such, the conventional teaching of plate tectonics rarely involves student-led systematic explorations. This article introduces a new online curriculum module called "What will Earth look like in 500 million years?" Using two web-based tools, middle and high school students develop understandings of (1) how collective movements associated with a system of plates create the current distribution of landforms found on Earth's surface, and (2) how earthquakes and volcanoes provide important clues for interactions at plate boundaries. With *Seismic Explorer*, students identify patterns from earthquakes locations USGS recorded and volcanic eruptions recorded by the Smithsonian Institution Global Volcanism Program. With *Tectonic Explorer*, students vary conditions such as plate number, location, density, and force dynamics, to simulate the formation of various landforms over hundreds of millions of years on an Earth-like planet.

Introduction

What will Earth look like in 500 million years? The supercontinent of Pangea existed until about 200 million years ago, when plate movement ripped it apart, continuously moving continents into the arrangement we see today. The plates are still moving, all the while causing earthquakes and volcanic eruptions, making this conundrum a surprising way to engage students in learning about plate tectonics. Traditionally, teaching about plate tectonics relies on static illustrations, non-manipulative animations, or hands-on activities using modeling clay to represent Earth's physical layers (crust, mantle, and core). While these methods create visual artifacts, they do not help students develop an understanding of the Earth as a dynamic system, driven by energy from its' interior. Computer-based modeling technologies have the potential to allow students to manipulate aspects of plate tectonic phenomena and to visualize emergent phenomena.

This article describes a free online curriculum module developed by the Concord Consortium and Pennsylvania State University as part of the National Science Foundation-funded project called Geological models for Explorations Of the Dynamic Earth (GEODE).

> The GEODE module can be found online at learn.concord.org/geo-platetectonics. Register for a free account and access to pre and posttests and class management plus a student reporting system.

This module, called "What will Earth look like in 500 million years?" (**Figure 1**) uses two web-based tools to help students visualize what takes place both at and below the surface as plates move and interact with each other. First, *Seismic Explorer* is a real-world, data visualization tool students can use to investigate patterns of earthquakes and volcanic eruptions. Second, *Tectonic Explorer* is a 3-dimensional, interactive plate tectonics model with which students can test hypotheses about how motions of plates in different arrangements result in various landforms found on Earth.

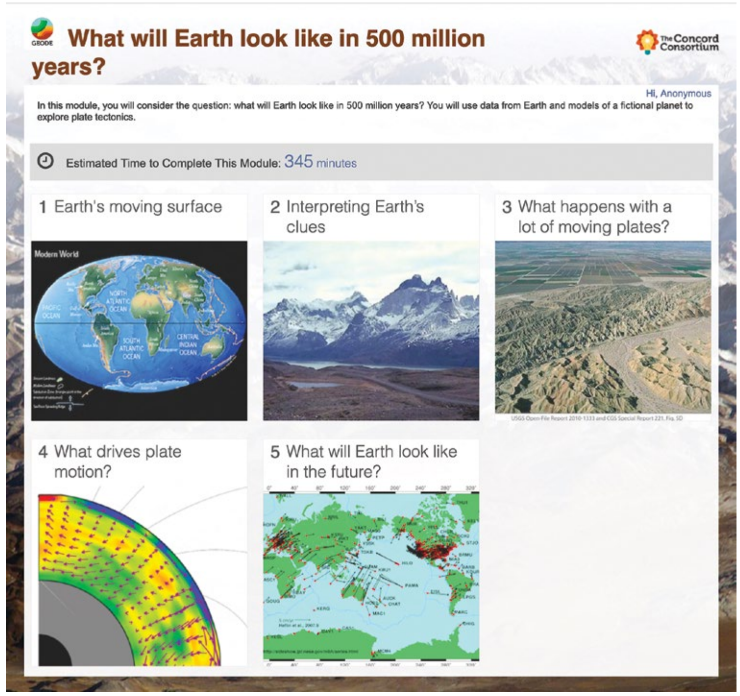


Figure 1. The GEODE module, "What will Earth look like in 500 million years?"

In secondary schools, Earth and Space Science (ESS) is not typically treated as a laboratory science, in part because the phenomena are not amenable to students' direct observation and investigation. Earth and space science phenomena happen on scales well beyond students' perception and experience and are hard for them to directly observe and control (Lee, Liu, Price, & Kendall, 2011; Tretter, Jones, & Minogue, 2006). Students typically learn about volcanoes, earthquakes, and the materials that make up the layers of the Earth independently of each other. Connecting geologic features and events to plate motion is often taught by asking students to interpret traditional data that scientists used to develop plate tectonic theory (e.g. fossil record across continents and magnetic seafloor striping); however, this is typically done without mentioning plate interactions as a main causal model (Chin & Brown, 2000). Research on learning progressions related to plate tectonics (McDonald et al., 2019) reveals that (1) students are rarely asked to develop a system-level, mechanistic understanding of plate tectonics; and (2) teaching about plate tectonics based on major historical evidence appears to create conceptual difficulties that hinder students' development of a system level understanding.

Current modeling technologies can make complex and dynamic systems visible and interactive (Honey & Hilton, 2011). Research shows that computational models provide opportunities for students to interactively explore the behavior of complex systems (Yoon, Goh, & Park, 2018) and that visualizations can improve students learning (Kali & Linn, 2008) in Earth science (Edelson Gordin & Pea, 1999) especially when the modeling instruction is interactive (Pallant & Tinker, 2004). Dynamic models of Earth systems can help students understand the underlying mechanisms and physical processes that shape Earth's surface. The explicit inclusion of modeling instruction has the potential to support science learning for students by making complex systems manipulative and by making student thinking visible (Brewe et al., 2010).

Thinking Like a Scientist

A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (National Research Council, 2012) advocates the importance of engaging students in science and engineering practices when learning science in the classroom. This focus is grounded in the idea that science teaching should be about students participating in authentic activities (Chinn & Malhotra, 2002) that are "like" what scientists do. However, typical Earth and Space Sciences teaching mostly addresses the historical nature of Earth and its properties, without treating Earth as a dynamic system with many interconnected phenomena. This makes it difficult to create authentic, inquiry-based science activities for students in K-12 classrooms. The GEODE module supports students' sense-making as they work through a series of investigations of plate tectonics-related phenomena with technology-enhanced data visualization and simulation tools. By bridging modeling and data technologies, the “scientific inquiry” promoted in the GEODE module integrates the Next Generation Science Standards core disciplinary ideas with the scientific practices of modeling and constructing explanations, and also helps students grapple with the cross cutting concept of systems and system models (NGSS Lead States, 2013).

Geoscientists increasingly use technological tools, including computer-intensive models and big data analytics, to understand the complex phenomena they study. If students are to engage in authentic scientific practices, they must carry out investigative science activities in-line with experts’ recommendations (National Academies of Sciences Engineering and Medicine, 2019). Technological tools are vital in having students explore data, identify data patterns, and explain data patterns based on their understanding developed from system models. Well-designed technological tools can overcome some of the difficulties inherent in geologic scales of time and space.

The Curriculum Context

The GEODE module consists of five activities implemented over seven 45-minute class periods. The module focuses on the big idea that the Earth’s surface is made up of simultaneously and continuously interacting tectonic plates at all sides of their borders. Students make observations about Earth, using models to test hypotheses, and explain how Earth’s system of tectonic plates created and continues to shape geological features and events on Earth.

The module deviates from the common practice of compartmentalized teaching of earthquakes, volcanoes, landforms, and plate tectonics. Instead, it helps students to cross-examine geologic processes, e.g. mountain formation, and events, e.g. volcanic eruptions, through the lens of plate tectonics theory. The intention of this design decision is to support students’ formulation of mechanistic explanations about how prominent landforms such as the Himalayas, the Andes, and the Red Sea, have formed near the boundaries of plates. In our curriculum, students make observations about Earth in the present and formulate and test their hypotheses about what caused Earth’s surface to be the way it is. The GEODE module is specifically structured to scaffold experiences for students so that they can develop their own explanations from the evidence, investigate phenomena through data representations, and test hypotheses with a simulation that models plate tectonics in action on an Earth-like planet.

In the first activity, students examine real-world data (**Figure 2**) (GPS, earthquake, and volcanic eruption data) to recognize that Earth’s surface is broken into many moving pieces (tectonic plates) and that earthquake and volcanic eruption locations can be used to identify boundaries between these pieces.

Figure 2. Volcanic eruption data to help students see distribution patterns evident on Earth’s surface.

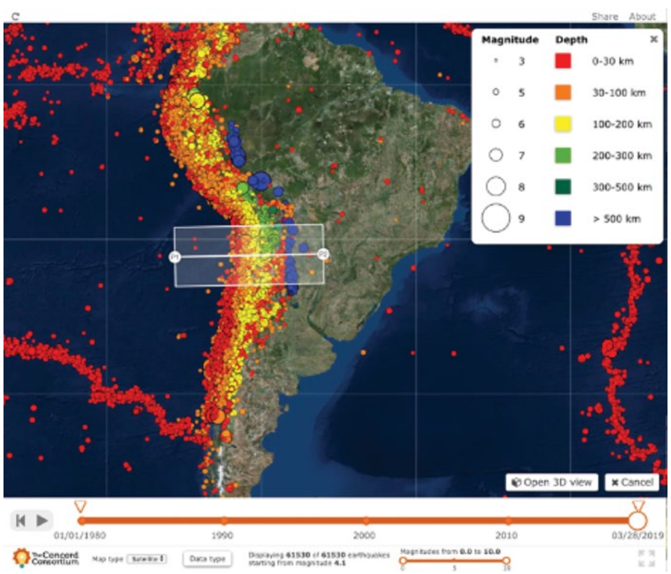
In the second activity, students investigate the distribution of landforms, earthquakes, and volcanic eruptions as consequences of plates moving towards each other at convergent boundaries. Three convergent boundary cases are used: the Andes, the Aleutian Islands, and the Himalayas. In each case study, students examine the elevation profile associated with the landform as well as earthquake and volcanic eruption patterns to develop a hypothesis about what is happening to cause these patterns (**Figure 3**).

Students then test their initial hypotheses with Tectonic Explorer (see below) to simulate the creation of landforms. In the third activity, students examine the other ways that each of Earth's tectonic plates is interacting with all its surrounding plates. Students explore case studies of divergent boundaries such as the mid-ocean ridge in the Atlantic Ocean and examine how transform boundaries often form the link between the other types of plate boundaries. They also consider how each plate must move as part of a system, interacting with all of the adjacent plates. In the fourth activity, students explore the causal mechanisms and forces that drive plate motion focusing on mantle convection currents, and some consideration of ridge push and slab pull. In the final activity, students synthesize their understandings of all the kinds of plate interactions into a system level explanation about how major geologic landforms and events are the result of the system of moving plates and that these movements can be used as important clues to predict Earth's future.

Figure 3. Students analyzing earthquake data in Seismic Explorer.

The GEODE Technology Tools

Seismic Explorer is designed to support the visualization of real-world earthquake, volcanic eruption, and plate motion data. Students use Seismic Explorer to (1) look for patterns in earthquake and volcanic eruption distribution across Earth's surface (**Figure 4a**), (2) examine the relationship among earthquake, volcanic eruption, and landform distributions, and (3) explore cross-sections to investigate earthquake depth patterns (**Figure 4b**).



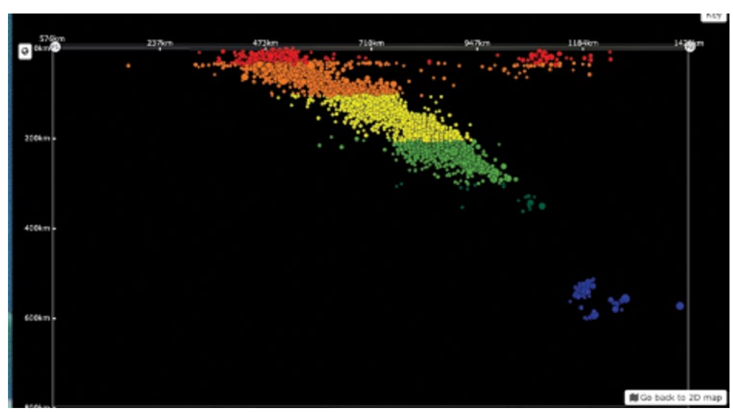


Figure 4a (left). Earthquakes as visualized in Seismic Explorer. The color of circles represents depth while size of circles represents magnitude.

Figure 4b (right). Cross-section along a convergent boundary shows earthquakes following a descending plate.

Tectonic Explorer is a dynamic model of plate interactions on an Earth-like planet. In this web-based three-dimensional simulation of multiple plates, students can change the properties of plates such as density, direction of movement, and locations of plates and continents. By experimenting with this model, students are able to witness plate interactions on a global system level, observe changes over time, and see how interactions of plates result in new landforms. With this model students can set up different initial scenarios and observe the emergent phenomena. An easy-to-use Planet Wizard allows students to choose the number of plates on the planet, draw continents on some or all of the plates, and set motion vectors and relative densities for each plate. Students can then run the model and observe the formation of mountains, ocean trenches, mid-ocean ridges,

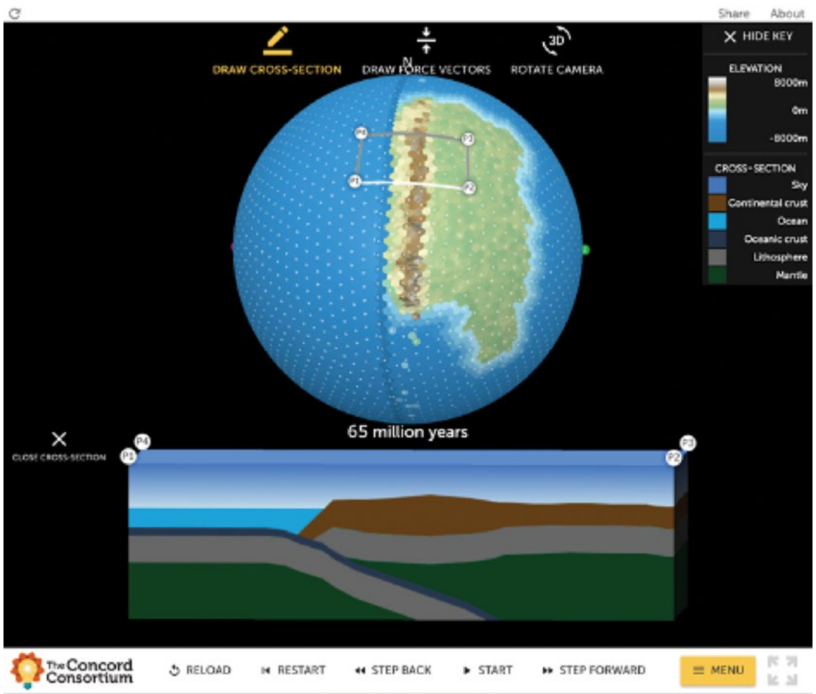


Figure 5. View of a dynamic model along a convergent boundary in an Earth-like planet using Tectonic Explorer. The cross-section shows ocean trench formation and mountains building.

volcanic eruptions, and island arcs (**Figure 5**). They can see supercontinents forming and breaking up and oceans forming and disappearing. To support students thinking across the two tools, Tectonic Explorer also has a feature that allows students to make cross-sections and simultaneously observe sequences of events dynamically changing at and below the surface. Tectonic Explorer's whole plate visualization encourages students to think not only about what is happening in one location on Earth, but also how it might affect what is happening in different locations on the planet. This system view is deeply important in developing students thinking about Earth's entire surface as constantly in motion, even if we can't see it.

In the GEODE module students use these two tools in complementary ways to carry out their investigation. In each case study, students use data gathered from Seismic Explorer, as well as geographic profiles, to develop hypotheses about the nature of the dynamics of the plate system. Students then test their hypotheses with Tectonic Explorer to model the necessary conditions needed to account for the observed phenomena.

The GEODE module is undergoing a series of design studies. In an early study, five teachers implemented the module along with pre- and post-tests in their classes with 159 middle and high school students. Overall the students made significant gains (ES=.62 SD for content understanding) from pre- to post-tests. We are currently field testing our materials with 28 teachers and 1570 students in a wide variety of settings from middle and high schools, suburban, urban, and rural schools, and with a diversity of students. Teacher post-module implementation survey responses indicates the type of thinking and reasoning teachers are witnessing in their students. One teacher told us in a feedback survey that her students discovered "that islands grow out of the ocean floor, that there is land underneath the oceans, and that if two plates are moving towards one another, at some point on earth, they would have to be spreading apart somewhere else." The teacher noted "this is really hard to show in most plate tectonics demos and simulations!" Another student mentioned "well if the plates are moving together on this side, then they have to be moving apart on the other side." This sort of system thinking is rarely seen in secondary school students. These quotes suggest the instructional values associated with data and modeling tools for Earth systems science. Similarly, another student stated "I think the most interesting thing I learned was using the 3D earthquakes model to see how deep earthquakes can go. Before this, I always thought they were near the surface." Another teacher told us she was happy to see her students make connections between earthquakes in the Seismic Explorer and plate subduction in the Tectonic Explorer.

Teaching with GEODE

It may seem like a challenging goal for middle school students to understand the interconnected and dynamic nature of plate tectonics, but evidence from learning progression research (McDonald et al., 2019) suggests that middle school students are capable of developing these sophisticated explanations about Earth's plate systems with proper support. What is often missing in plate tectonics curricula are opportunities for students to engage in investigations designed to link the dynamic nature of surface phenomena and the mechanisms that drive plate motion to real-world data and observations. With technological tools teachers can appropriately elevate their performance expectations for their students when studying plate tectonics. With technologically-enhanced, inquiry-based investigations, the teacher's role changes from directing and lecturing to supporting students in their development of explanations as students analyze, interpret and discuss the data. The tools can provide students with powerful ideas that can build on their existing knowledge and in turn help them reason about scientific phenomena (Kali & Linn, 2008). For teachers these tools can create unique learning environments where all students reason with otherwise inaccessible content. For students to develop sophisticated reasoning from the data and modeling tools, teachers and curricula must support students in identifying and interpreting the patterns in the data and considering possible causes of these patterns. Then students must make connections between each case in the module and the larger guiding question of what Earth will look like in 500 million years. We found that students using our tools were able to articulate how plate motions along convergent, divergent, and transform boundaries explain the patterns of earthquakes, volcanic eruptions, and landform distributions.

Conclusion

The idea that Earth's surface is in constant motion is very engaging. Students will wonder: In 500 million years will Australia collide with Asia? Will the Atlantic Ocean have closed again? Of course, projections into the future are speculative but can nonetheless be scientific conjectures based on GPS data that track how plates are moving in recent years combined with the existing evidence that plates have moved in the past. The GEODE module featured in this paper direct students' attention to using data about these complex interactions in order to develop conceptual models about how Earth's plates may move in the future. In this effort, modeling and data representation technologies can play an important role in engaging students in inquiry-based investigations through which they can develop deep understanding of how complex Earth systems work.

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