GEOLOGICAL CONSTRUCTION OF ROCK ARRANGEMENTS FROM TECTONICS: SYSTEMS MODELING ACROSS SCALES (GEOCRAFT)

IMPORTANCE

The motion of Earth's plates is responsible for transforming an otherwise featureless planet into the remarkably diverse and beautiful landscape we have today [1]. All landforms on Earth's surface can be traced back to the motion and interactions of these plates. There are two distinct types of crust—continental and oceanic—the existence of which is unique in our solar system and is likely the basis for the evolution of life and ultimately for modern society [2]. The cycling, transformation, and differentiation of Earth's materials have led to landforms above sea level, which are critical for supporting land-based life, and have provided natural resources on which humans depend [3]. The ability to provide improved standards of living across the globe, for example, relies on the creation and location of sand used in cement, an extremely important construction material used in the production of buildings, bridges, and roads [4]. Industry and trade are dependent on the formation of rock layers that provide valuable minerals, including copper, gold, and iron. Investigating plate tectonics and the genesis of different rock types is of particular importance because understanding the availability, production, and depletion of these resources can impact the world's economy and the sustainability of our way of life [5]. However, "Earth science curricula in the United States … is 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" [6, p. 51] and they fail to show why these interdependent processes are important to modern society [7]. Plate tectonics is the foundational theory to integrate all these topics and processes together and is essential for developing a scientifically literate citizenry [8].

Current geoscience instruction has been organized around discrete, disconnected facts. The *Next Generation Science Standards* (NGSS) [9] advocates for engaging students in science practices that reflect the epistemic origins of disciplinary core ideas [10]. Organizing science teaching around science practices authentic to scientists' inquiry [11] includes giving students access to the tools they use [12]. However, typical Earth and Space Science (ESS) classes teach geosciences as an interpretive and historical science [13] focusing on memorization of Earth structures, naming and classifying eras and periods, and identifying rock types. This does not represent how geoscientists investigate dynamic and complex Earth systems to develop causal mechanisms that explain phenomena occurring on Earth's surface. Geoscientific phenomena take place on spatial and temporal scales far beyond students' perceptions and everyday experiences [14], [15], preventing them from making direct observations. This poses a significant challenge to engaging students in constructing explanations and formulating arguments from their own investigations. Furthermore, geoscience is a system science. Controlling aspects of the phenomenon under study is impossible as part of students' scientific experimentation in the classroom. As a result, it is profoundly difficult for students to learn how Earth works as a whole system with many subsystems, how humans interact with it, and why it is relevant to their lives. Students need these understandings to make decisions about the future of humankind, our planet, and its resources [5].

Technology has the potential to transform how students investigate geodynamic phenomena. Geoscientists create computer models as representations of natural phenomena [16]. Simulations are "dynamic computer models that allow users to explore the implications of manipulating or modifying parameters within them" [17, p. 2]. When used as part of science instruction, simulations allow students to investigate complex phenomena by changing important variables in the system, adjusting external factors affecting the system, observing the processes unfolding over time, and examining emergent behaviors of the system. In particular, *interactive visual* simulations (simulations hereafter in this proposal) can support the development of students' understanding of a complex system [18], which in turn can be elicited to explain causal mechanisms underlying the phenomenon under investigation [19]. In addition, simulations can provide theoretical insights about the phenomenon [20] with which students can apply to real-world phenomena to formulate scientific arguments. Through simulations, students have opportunities to interact, observe, and investigate systems as a whole [21] that are impossible to access through other avenues of inquiry. Problem-based, computer-aided instructional programs used for learning geoscience concepts are known to produce significant improvements in both students' achievements and attitude compared to direct teaching [22]. Simulations of Earth systems can also help students access the hidden, underlying mechanisms and physical processes that shape Earth's surface and link phenomena across scales in the system.

Simulations are critical to developing authentic geoscientific investigations. Access to computational models and simulations grounded in foundational educational research provides an ideal venue for new ways of teaching geosciences in middle and high schools. The *Geological Construction of Rock Arrangements from Tectonics: Systems Modeling Across Scales (GeoCRAFT)* project will leverage current technology's capacity to develop a simulation and curriculum modules to transform how land formation, rock genesis, and the rock cycle are traditionally taught. Students will use a simulation to investigate how changes in tectonic environments over time can result in a variety of land formations and distinct rock genesis scenarios. By bridging the tectonic system with the rock genesis system through land formation processes, students will engage in scientific practices that are similar to geoscientists' work. This will enable students to both predict what types of rocks will be generated under specific tectonic situations, and just as importantly be able to use rocks and rock arrangements to determine what causal mechanisms can explain real-world phenomena found in landforms.

GOALS AND OBJECTIVES

The Concord Consortium (CC), in partnership with Pennsylvania State University (PSU), proposes a Design and Development project addressing Strand 2, Learning. The goal of the GeoCRAFT project is to build a simulation of dynamic Earth systems spanning multiple scales. The tool will be embedded in two curriculum modules targeting grades 6-9 when the bulk of Earth and Space Science (ESS) is taught. We will conduct design-based research to study the development of these materials. We will also develop teacher support materials grounded in research-based methods of science teaching drawn from model-based curriculum. This project builds on CC's significant experience in developing online curriculum materials with simulations and PSU's experience in design-based research around science teaching and teacher professional learning related to ESS in middle and high schools.

Objective 1: Create a dynamic simulation embedding rock genesis within the plate tectonics system. We will develop a simulation where students can 1) visually and interactively explore rock-forming environments and 2) investigate the evolution of rock sequences created under specific tectonic conditions. The simulation will allow students to set up specific tectonic conditions and observe the development of landforms along with the corresponding rock types and layers that emerge over time. The simulation will provide dynamic visualizations connecting three spatial scales: plate tectonic, land formation, and rock formation. The simulation will highlight salient features and processes so that students can develop mechanistic explanations of how the tectonic system drives rock genesis systems.

Objective 2: Develop two simulation-based curriculum modules. The project will create two curriculum modules built around the simulation. These modules will help transform the traditional teaching sequence of rock genesis, land formation, and plate tectonics as separate topics, to one that is tectonics-driven, focusing on causal explanations of geologic processes across spatial scales. In the first module, students investigate the relationship between tectonic movements and rock formation processes for a selected set of tectonic environments. In the second module, students investigate principles of geochronology as well as relative dating of geologic formations and geologic events using the rock record. In both modules, students will develop mechanistic explanations for real-world phenomena based on the foundational theory of plate tectonics. Working closely with teachers who will field test the curriculum modules, we will identify teaching practices necessary for enacting them in equitable ways.

Objective 3: Research on the design, development, and enactment of the curriculum and the simulation. In the first three years, design-based research will investigate how the simulation, modules, online professional learning materials, and assessment materials can support both teacher enactment and student learning. Informed by science education literature, the research will address the NGSS disciplinary core ideas and science practices related to constructing explanations and evidence-based arguments from using models and the crosscutting concept of systems and system models. We will study how the combination of the simulation, curriculum, and teaching can productively support the participation and learning of all students, including those in need of special education support, an underserved population in science. In the final year, the project will conduct a large-scale implementation study to examine the feasibility of teacher enactment across various school settings and demographics.

Objective 4: Disseminate through publications, presentations, and teacher partnerships and networks. We will produce revised and polished curriculum and assessment materials ready for wide dissemination to Earth science teachers through the Pennsylvania Earth and Space Science Teachers Association, as well as to a national audience through a project website at CC. We will present at conferences and disseminate curriculum and assessment materials through teacher networks. We will publish research results in journals for researchers, curriculum and technology developers, and teachers.

RESULTS FROM PRIOR NSF SUPPORT

Geological Models for Explorations of Dynamic Earth (GEODE) *(PI: Pallant; Co-PIs: Lee and McDonald; DRL-1621176; $2,698,654; 8/15/16 – 7/31/20)*. ***Summary of project results:*** GEODE is beginning the fourth year of a design and development project. We developed two software tools: (1) Seismic Explorer, an interactive data retrieval and visualization tool, and (2) Tectonic Explorer, a three-dimensional dynamic simulation of plate interactions on an Earth-like planet where students can change the properties of plates, such as density, direction of movement, and locations of plates and continents. Using these two tools, we developed an online plate tectonics module focused on the big idea that the Earth's surface is a system of simultaneously and continuously interacting tectonic plates at all sides of their borders. During the first three years, 34 teachers implemented the module to over 1,500 middle and high school students across 15 states. We also developed an online teacher edition, as well as a 24-item assessment instrument to measure student understanding of plate tectonics from the systems perspective (total score allowed = 61; Cronbach alpha = 0.88). Analysis of students who completed both the pre-test and post-test ($n = 619$) showed that students made significant gains by 0.92 Standard Deviation (SD), $p < .001$; pre-test mean = 20.66 to post-test mean = 28.49. ***Intellectual merit***: This project will contribute to the field's understanding of how engaging students with plate tectonic simulations supports their learning of Earth's surface features and sub-surface processes from the system perspective. ***Broader impacts:*** At its conclusion, the GEODE project will have involved over 6,000 students and 50 teachers from diverse school settings serving students with varied socioeconomic, linguistic, and minority backgrounds. ***Publications:*** Two journal articles [23], [24]; one in-house newsletter article [25]; six conference presentations; and one doctoral dissertation [26].

High-Adventure Science (HAS) and **High-Adventure Science: Earth's Systems and Sustainability (HAS: ESS)** *(PI: Pallant; Co-PIs: Lee and Larson; DRL-0929774; $695,075; 9/15/09 – 8/31/12; DRL- 1220756; $2,328,593; 10/1/12 – 12/31/16).* ***Summary of project results.*** We developed six modules on Earth and environmental science topics targeted to middle and high school students. Students use simulations of complex Earth systems, analyze real-world data, and engage in scientific reasoning and argumentation. Analysis of pre- and post-tests administered with six HAS modules showed significant improvements in student argumentation across diverse school settings by effect sizes (Cohen's d) ranging from 0.35 SD to 0.54 SD. ***Intellectual merit:*** Four design principles were extracted to address how scientists' current research and modeling practices can be incorporated into short-duration, inquiry-based curriculum modules. We developed and validated two assessment frameworks: uncertainty-infused scientific argumentation and system dynamics thinking related to complex environmental systems. ***Broader impacts:*** HAS modules have been distributed widely for free through the National Geographic Society and Concord Consortium websites. As part of the project, 132 teachers and roughly 6,300 students have enacted the modules. Google Analytics shows 350,000 people have used the HAS modules between 2017 and 2019, producing a large and growing independent community of registered users across all 50 states. ***Publications:*** Six articles in research journals [27]–[32]; eight articles in practitioner journals [33]–[40]; three in-house newsletter articles [41]–[43]; and nine conference presentations.

Investigating How to Enhance Scientific Argumentation through Automated Feedback in the Context of Two High School Earth Science Curriculum Units (ESAAF). (*PI: Liu at Educational Testing Service; Co-PIs: Pallant and Lee at CC; DRL-1418019; $2,495,604; 9/1/14 – 8/31/2019*). ***Summary of project results:*** Guided by literature on argumentation and automated text scoring, we developed automated scoring models to analyze students' performances in real time on uncertainty-infused scientific argumentation for two HAS modules. From 2014 to 2018, 18 teachers from 11 states implemented the modules. Findings indicate that automated scoring and feedback facilitated students' revision of scientific arguments featured in the HAS modules. As a result, students wrote significantly better uncertainty-infused scientific arguments after the modules by effect sizes (Cohen's d) of 0.85 SD for the climate change module and 1.52 SD for the water sustainability module. ***Intellectual merit:*** Research and design of real-time feedback based on automated scoring can facilitate the widespread use of constructed response tasks such as explanation and argumentation in the classroom. ***Broader impacts:*** Automated scoring and feedback can transform teaching and learning of Earth science content and scientific argumentation by providing students with individualized feedback in real time based on their current performance. ***Publications:*** Seven articles in research journals [32], [44]–[49]; three conference proceedings [50]–[52]; one book chapter [46]; two in-house newsletter articles [53], [54]; and 25 conference presentations.

Pennsylvania Earth and Space Science Partnership (ESSP). (*PI: Furman; Co-PI: McDonald; DUE-0962792; $9,181,723; 10/01/10 – 06/30/16*). ***Summary of project results:*** The ESSP partnership was focused on improving and promoting Earth and Space Science (ESS) in the middle grades (4-9). The project completed five years of summer workshops and academic year professional development focusing on plate tectonics, solar system astronomy, energy, water, and climate. The project has also been involved in initiatives to transform key ESS-related introductory courses in higher education. ***Intellectual merit:*** The primary project research focused on developing learning progressions in plate tectonics and solar system formation. Both learning progressions focused on students' understanding of the causal mechanism underlying the phenomena. ***Broader impacts:*** 115 teachers from the Pennsylvania Research Practice Partnership districts participated in summer workshops. The project also established the Pennsylvania Earth and Space Science Teachers Association, which has since become one of the most successful state-level NESTA associations, with over 600 members. ***Publications:*** Three articles in research journals, [55]–[57]; two articles in practitioner journals [58], [59]; and 16 conference presentations.

CURRICULUM DEVELOPMENT GROUNDED IN RESEARCH

Theoretical Foundations

1. Situating the teaching of rock formation in the context of plate tectonics. Our recent research indicates that middle school students can develop causal and system-level understanding of plate tectonics [55]. While plate tectonics is the foundational paradigm for geosciences [60], we need to better understand how student learning can be supported to connect these large-scale processes to the more observable evidence from geosciences, namely rock formations [61]. Teaching the rock cycle as a simple cycling of materials not only misrepresents the processes, but also does not provide clear connections between the causal mechanisms for rock genesis and plate tectonics [62]. Rock types and rock arrangements on Earth are critical evidence geoscientists use to develop models of dynamic Earth. In GeoCRAFT students will be able to develop their own deep understanding of geodynamic processes and phenomena [63] by connecting evidence and ideas across scales: 1) rock genesis environments where material is laid down, 2) formations of land that indicate historical relationships between these depositional environments, and 3) the dynamic plate system that drives all this activity. GeoCRAFT will help students see rock as both the evidence that leaves patterns for geoscientist to understand the dynamic Earth and the result of that dynamic plate motion [62].

2. Organizing Earth science learning as an authentic practice of investigatory science. Both *The Next Generation Science Standards* [9] and the foundational *A Framework for K-12 Science Education* [64] emphasize practices, in particular, constructing evidence-based explanations of complex science phenomena as the way students should participate in science classrooms. The science and engineering practices are meant to describe how students should engage with science ideas in ways that are epistemically authentic to the discipline of science; however, not all sub-areas of science investigate phenomena in the same way. Earth sciences are increasingly focused on the use of big data and models to create computational ways of investigating phenomena [65]. These epistemic practices are in stark contrast to Earth and space science in K-12 settings where they are almost always approached as historical sciences focused on memorization of rocks and minerals, along with formations and epochs of Earth's history, rather than being treated as laboratory-based science classes [66]. This approach teaches processes like the rock cycle as a relatively linear flow through a simplified circular representation of materials, rather than a dynamic system where events like earthquakes and volcanic eruptions are part of larger patterns of material movement and transformation through erosion and plate motions [66]. As a result, students are rarely given the opportunity to do their own sensemaking in Earth science, and thus do not develop deep understanding of the content. In GeoCRAFT, we will develop ways of supporting students' epistemically authentic investigations of geoscience processes, specifically to develop students' understanding of large-scale systems and how they produce smaller scale phenomena.

3. Using simulations to develop explanations that link systems across scales. The Earth system consists of subsystems, such as the geosphere, atmosphere, hydrosphere, and biosphere [3], [7]. Studies of Earth science focus on identifying system parts, describing their dynamic interactions, explaining emergent phenomena, tracking matter and energy flows within and across systems, and understanding feedback mechanisms that maintain the system as a whole [67], [68]. While plate tectonics is a unifying theory that governs geological systems [8], learning plate tectonics is challenging because 1) tectonic phenomena are largely hidden and cannot be observed directly by students [69], [70], 2) the processes that create the phenomena take too long or are too large for students to experience [69], and 3) students have difficulties with integrating spatial, temporal, causal, and dynamic information [70]. As a result, students and teachers alike hold plenty of misconceptions in Earth science [71], including plate tectonics [8], [72] and the rock cycle [73]. Limited research has been conducted for applying the systems approach to teach plate tectonics [55], the rock cycle [73], and stratigraphy of rock layers [61], [74]. In GeoCRAFT, students will use a simulation of Earth's systems across spatial scales to gain necessary knowledge to formulate explanations about how rock layers are formed in tectonic environments. A substantial body of research shows that students' exploration of systems through the use of simulations helps them understand the behavior of systems that are otherwise difficult to understand by other means [17], [75]–[77]. Much as geoscientists do, students can experiment with simulations by controlling the parameters, starting conditions, and conditions during a run. Informed by the scientific modeling literature, the GeoCRAFT simulation will be developed for students to interact with visual representations of Earth systems consisting of key geologic forces and processes across three scales—plate tectonics, land formation, and rock formation. The GeoCRAFT project will examine how students reconcile spatial scales in the simulation while developing mechanistic explanations.

4. Formulating scientific arguments based on real-world data while addressing uncertainty. Scientific argumentation focuses on critical interpretation of data based on established theories when making claims about a phenomenon under investigation [78], [79]. In science class, scientific argumentation can take place in written and/or spoken forms [80] and can cumulatively occur towards the end of students' investigations [81]. Research on scientific argumentation has grown substantially in the last 20 years as indicated by a growing number of reviews on the topic [82]–[86]. Research has focused on 1) identifying or supporting students' written argument artifacts, 2) examining benefits of scientific argumentation on learning of concepts and epistemic practices, and 3) interventions and teacher practices to support student argumentation. However, how students recognize and address uncertainty in formulating arguments has largely been overlooked [27]. Uncertainty can play two roles when students construct an argument [28]. One type represents students' confidence in their own knowledge and ability, which often occurs as part of knowledge construction through argumentation [87]. The other type is contextualized in the scientific domain and arises from theoretical, methodological, sampling, measurement, and analytical limitations associated with investigations [88]. The importance of simulations to this project means that issues related to the validity and reliability of conclusions, as well as the kinds of conclusions, that can be justified from these simulations make student understanding of uncertainty a central focus of the project [29]. By engaging students in the practice of scientific argumentation, along with generating and critically evaluating the evidence derived from the simulation, GeoCRAFT will highlight how scientists construct knowledge in geoscience and help students interpret real-world data and develop scientific theories about the phenomena. Considering the fact that "all models are wrong" [89, p. 501], students working with simulations need to learn to consider sources of uncertainty arising from the limitations inherent in them [20], [90], [91].

5. Creating professional learning materials to help teachers support all students. While developing tools to support students' investigations about complex dynamic systems is critical, we also recognize that teaching with such tools is challenging [92]. It is important to develop both ambitious and equitable classroom learning environments [93] where all students can productively engage with complex science ideas [94] and build their own explanations of the Earth's processes. GeoCRAFT will pay attention to supporting students who need scaffolds and structures so that they can productively participate [95], particularly in contexts where the simulation may have a high cognitive load [96], [97] and classroom talk can be complex and dynamic [31]. There also has been little research on the learning of students in need of special education support in classrooms [98] and even less on that population of students in science classrooms when learning about complex systems and building evidence-based explanations with simulations. Some of the design-based research in GeoCRAFT will focus on this particularly marginalized and under-studied group of students to develop some preliminary understandings of how to support their learning, and by extension the learning of all students.

Alignment with Next Generation Science Standards

Disciplinary Core Ideas. The proposed modules address two sets of core ideas in the *Next Generation Science Standards* [9] related to Earth and Space Science:

- ESS1: Earth's Place in the Universe (ESS1.C: The History of Planet Earth)
- ESS2: Earth's Systems (ESS2.A: Earth Materials and Systems; ESS2.B: Plate Tectonics and Large-Scale System Interactions).

Science Practices. We will develop coherent student learning experiences that engage students in Science Practice 2: developing and using models, Practice 6: constructing explanations, and Practice 7: engaging in argument from evidence. Students will "use provided computer simulations … as a tool for understanding and investigating aspects of a system, particularly those not readily visible to the naked eye" [99, p. 58]. Students will use outcomes from their exploration of the simulation to construct explanations. Students will then apply their understanding to formulate their arguments about how different geological processes and forces at the tectonic scale have created landforms and resulting rock types and distributions found in real-world phenomena. Students will also identify limitations related to using simulations to explain real-world examples.

Crosscutting Concepts. We will focus on systems and system models, paying particular attention to students' "developing models, component parts, exploring their interactions, in terms of inputs, outputs, and processes and to generating questions about aspects of their model representation of the system, and, eventually refining their models" [99, p. 93]. We will address scientific phenomena across spatial scales over a long period of time to facilitate students' development of explanations and arguments.

Proposed Modules

Below we describe concepts that will be covered in the two proposed modules built around the simulation. The modules will run approximately nine and seven days respectively and will be designed to interweave into classroom instruction. To begin the modules, students should understand that Earth's surface is broken into plates and that these plates interact in specific ways along convergent, divergent, and transform boundaries. Our intention is to replace some parts of the curriculum where the rock cycle and land formations are taught. Online teacher support materials will be developed based on design principles grounded in Ambitious Science Teaching [100] and educative curriculum [101].

Module 1: Tectonics and rock genesis. In this nine-day module, students will learn the fundamental relationship between tectonics and rock genesis. Students will use the simulation to investigate a set of rock genesis environments found in Earth's tectonic system. On the first day of the module, students will review important factors about motion and forces along convergent, divergent, and transform boundaries. On the second day, students will be introduced to real-world rocks and geologic maps to guide them into developing their own questions about where and under what conditions rocks form, and to identify patterns that might connect rocks to tectonic environments on Earth. On days three through six, students will set up initial tectonic conditions in the simulation to explore deposition along passive tectonic environments, igneous rock formation, rock layer deformation, and metamorphism along active tectonic boundaries. The module will focus on the predictive power of rock associations for each environment through tracing pathways by which one rock type can transform into another and under what conditions these transformations take place. During the final three days of the module, students will engage in geoscientific explanation-building by connecting real-world rock transformations to ancient tectonic environments and processes.

Module 2: Ancient landscapes: Interpreting geologic history. This seven-day module will focus on exploring principles of geochronology and relative dating of geologic formations and geologic events as captured in the rock record. Similar to how geoscientists observe features and sequences in rock outcrops, students will develop explanations for geologic formations in the real world based on plate tectonics. They will use the simulation to retrodict what kinds of specific time-dependent tectonic situations can account for sections of real-world rock sequences. On the first day, students will explore a set of real-world examples and hypothesize about a series of tectonic environments and events that they think could have created the formation (e.g., Figure 1). In days two through four, students will use the simulation to work through a set of cases to establish specific stratigraphic principles, such as the principle of horizontality, the principle of superposition, and crosscutting relationships. In days five and six, students will use the simulation to develop an explanation for the real-world examples from the first day that can account for spatial and temporal changes recorded in the rock record. On day seven, students will work in teams to develop explanations for the real-world explanations. Throughout this module, students will also consider the simulation's limitation for representing real-world complexity.

Technology Development

The Tectonic Explorer (TE) software developed at CC was designed to simulate plate interactions at the tectonic scale. In the GeoCRAFT project, we will need to develop the next generation of TE. This new simulation, to be called Tectonic-Rock Explorer (TRE), will be made possible by the development of a sophisticated modeling engine that uses the physics involved in geodynamic phenomena. TRE will calculate pressure and temperature in rock-forming environments, compressional and tensional forces, and isostatic forces. It will represent processes such as erosion, deposition, faulting, folding, metamorphism, and igneous intrusions, as well as rock types. Additionally, the evolution of rock arrangements connected to specific tectonic environments will be added at each scale. The core engine will be tuned for speed and flexibility for classroom use. The Tectonic Rock Cycle [102] will provide the conceptual framework to connect plate tectonic, land formation, and rock genesis scales. TRE will help students 1) explore the interconnected geologic processes in the plate tectonic and rock genesis systems through land formation processes; and 2) investigate the evolution of rock sequences and associations, which depend upon changes in tectonic environments.

Figure 2 shows how TRE can present dynamic views at each of the three spatial scales under the same timeframe. TRE will depict a three-dimensional Earth-like planet that models plate interactions and topographic changes to the planet surface. Students will make cross-sections to observe plate interactions; land formation processes such as the creation of island arcs and ocean trenches; and rock genesis occurring along passive and active tectonic boundaries. With TRE, students will be able to set up tectonic scenarios and observe and analyze phenomena emerging over time across the three scales. Students will be able to set up tectonic plates on a hypothetical planet, draw continental crust on the plates, set the direction and rate of various plate motions, and the relative density of each plate. They will be able to make cross-sections and zoom into any rock-forming environment featured anywhere on the planet. Finally, UI/UX work will be key in developing and connecting the planet view and all three cross-sectional scale views. Logging of student interactions and the simulation will be added to the software to support the research.

An Example of a GeoCRAFT class

Nia and Jasmine have been working for the last two days on the activities in the Ancient landscapes: Interpreting geologic history *module in their 7th grade Earth science class. Today they use the simulation to explore how plate motions might cause sea level changes, and how these changes might be recorded in the rock layers (Figure 1).*

Their teacher, Ms. Lord, projects the photo (Figure 1) and asks the class, "What would geologists be able to figure out from this photo? What was going on to form the rock layers highlighted in the black box on the photo? What clues do you see and what additional information do you need to explain these rock layers?"

Figure 1. Sedimentary outcrop illustrating sea levels rising and falling. Image from Geology In.

The class describes the thick uniform layer at the top and the layers below, noticing that they are all horizontal, with some that are thicker, and the different colors of the layers. Ms. Lord tells them the top layer is limestone and the layers below it are shale and sandstone. She reminds them that there are samples of these rocks on the lab tables in the back of the class. From their exploration of different tectonic environments, Nia and Jasmine know that limestone only forms in deep oceans near the equator. The teacher asks them to use Tectonic-Rock Explorer to build an explanation for how the layers formed.

Nia and Jasmine get right to work, since they are now familiar with the different tectonic configurations in the TRE. Jasmine sets up the Earth-like planet to have a continent on the center plate. They create a convergent boundary on one side of the plate and a divergent boundary on the other side of the plate. Then they make a cross-section on the passive margin where no tectonic boundary exists. They begin to take a look at the cross-section at the land formation level. After noticing the rock types in this level, Nia exclaims as she points to the screen, "There it is. There are the types of sediments Ms. Lord mentioned at the beginning of class. See the limestone, sandstone, and shale?" (Figure 2). Jasmine suggests, "Let's look at the rock layer formation level." They rotate the land formation view to explore different sites. "Whoa, it really makes a difference where in the land formation view you make the vertical cut. If you put it where there is no ocean you only get sandstone and granite, but if you put it deeper, you get granite at the bottom, then sandstone, shale, and then a limestone layer."

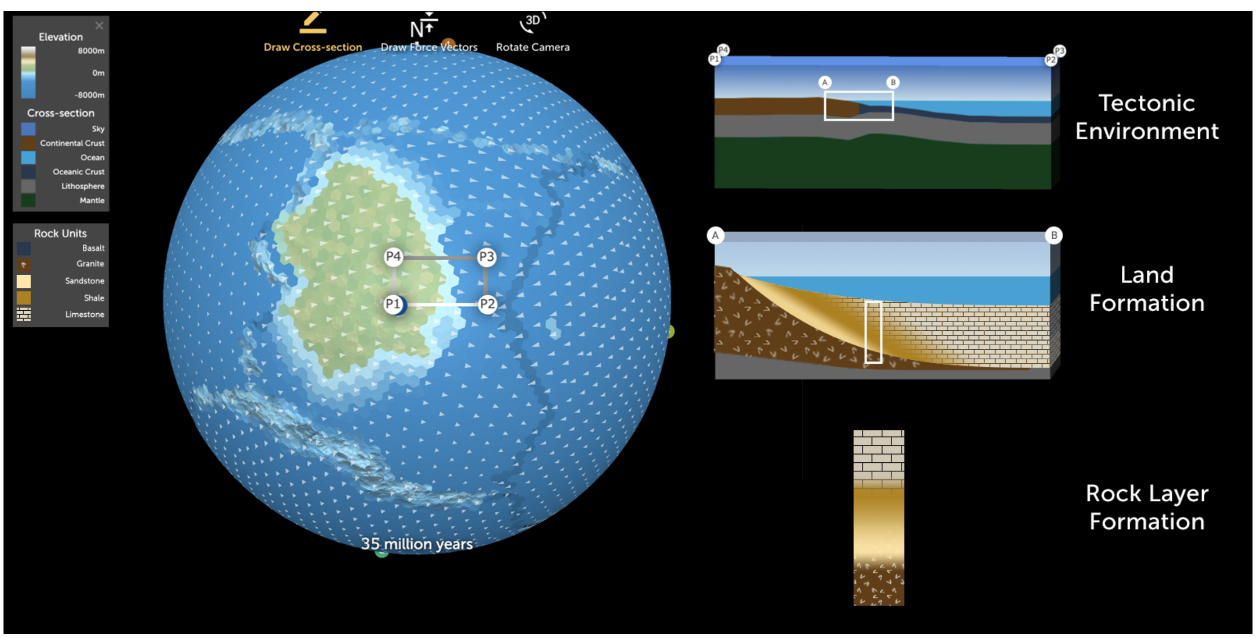

Figure 2. A mock-up of the Tectonic-Rock Explorer view of the interacting tectonic plates on an Earth-like planet (on the left) and presentations of processes at the tectonic, land formation, and rock layer formation scales.

"Let's let the simulation run a little longer and look again," Nia says, "We have the rock types, but I don't think we are sure about the layers from the picture." As Ms. Lord circulates through the classroom, she asks them, "What do you think will change for these layers if you let it run longer?" Nia and Jasmine think and respond with ideas about the layers getting thicker and then maybe something else happening. Nia points to the place where the plate is subducting. Ms. Lord asks them why the subduction might make a difference. Nia responds, "We might see magma come up through the layers," and Jasmine adds, "Maybe the ocean will go away." Nia and Jasmine run the simulation longer and then create new cross-sections and sample rock layer formations. They rerun the simulation to observe what changes at each level. Using evidence from the simulation, they write in the online curriculum module, "The ocean levels rise because the simulation showed an ocean basin getting deeper. When the ocean gets deeper, you get the same pattern of layers as in the picture." The simulation is not an exact match to the photo, so they are a bit uncertain about why the ocean is getting deeper. They are excited to try different scenarios tomorrow to clarify what causes these layers and what it means for the way that plates were moving that the limestone is on top of the sandstone and shale.

Professional Development

To support the initial development of the Tectonic-Rock Explorer and the modules, we have recruited two middle school teachers and one high school teacher who currently teach in rural, suburban, and urban schools. For the first two years of the project, these teachers will form a Teacher Advisory Group that will help co-design and give feedback on the development of the simulation and the curriculum modules. One of the teachers will also serve on the Advisory Board. All three teachers have existing relationships with CC or PSU through other NSF-funded Earth science projects. These teachers have Earth science content backgrounds, have been teaching Earth and space science, and have a demographically diverse student population with mixed-ability students, including special education students. They also have experience with technological tools for supporting student learning. In the winter and spring of Year 1, the Teacher Advisory Group will provide feedback on prototype versions of the simulation and the curriculum modules via regularly scheduled Zoom teleconference meetings. In the summer of Year 1, we will hold a two-day design and development meeting at CC with the group.

During Year 2, we will continue to work with the original three teachers via Zoom meetings, and ask each teacher to recruit a local colleague to join them in enacting the refined simulation and curriculum modules. We will maintain Zoom meetings throughout the academic year, with particular emphasis on meeting during teachers' enactment. Starting in January of Year 2 we will work with these six teachers to plan a summer professional development (PD) workshop.

In the summer of Year 2, we will host a five-day PD workshop at PSU for 15 teachers. Teacher recruitment will occur via the CC website as well as direct emails through CC's and NESTA's listservs. A faculty member from PSU with expertise in special education students in science will participate in the planning and enactment of the workshop in order to develop materials for teachers to support techniques to scaffold *all* students learning with the modules. Teachers will engage with the GeoCRAFT modules framed around principles demonstrated in *Ambitious Science Teaching (*AST) including planning for engagement with important science ideas, eliciting students ideas, supporting ongoing changes in thinking, and pressing for evidence-based explanations. [93]. The PD workshop will focus on understanding geoscience content, using the simulation, supporting student explanation building and argument writing, and enacting the curriculum in Year 3. Teachers will encounter GeoCRAFT modules as learners, followed by an in-depth debriefing session so that teachers can understand key aspects of the lessons. They will also engage in readings and video analysis, then develop practical strategies for supporting the students they teach.

In Year 3 we will focus on developing and field testing the online teacher learning materials that support teacher enactment. The online teacher materials will include interactive teacher editions that consist of teaching theory, content-related background information, and pedagogical strategies to support utilizing the curriculum within specific contexts and particular support for students identified as requiring special education. The 15 teachers from the summer workshop will provide feedback via interview and Zoom meetings to improve and refine these materials. For Year 4, we will recruit 30 teachers, some of whom will be returning from Year 3 and some new teachers. These Year 4 teachers will have access to the online professional learning materials as their primary source of support.

PROJECT RESEARCH

Research will focus on the development and implementation of curriculum modules, assessment materials, and teacher support materials. Curriculum modules will undergo three design cycles from Year 1 to 3; assessment materials will be developed and continuously revised from Year 1 to 3; teacher support materials will be outlined in Year 1, developed in Year 2, and used and revised in Year 3. In Year 4, a larger-scale implementation study will take place using the final version of the curriculum modules along with assessment and teacher learning materials.

RESEARCH QUESTIONS (RQ)

RQ1: (*Constructing explanations and argumentation across spatial scales from a simulation)* What explanations do students construct across tectonic environment, land formation, and rock layer formation scales? How do students use TRE to develop such explanations? How do students approach data from simulations and how is it different from their treatment of real-world data when formulating arguments? How do students use their knowledge to formulate arguments about real-world examples and consider sources of uncertainty?

RQ2: *(Student learning and teacher implementation outcome)* Do students make pre-test to post-test gains in their understanding of rock genesis and land formations in the context of plate tectonics? To what extent, for whom, and under what teaching contexts are the GeoCRAFT modules useful in developing such understanding?

RQ3: *(Teaching practices and curriculum enactment)* How can AST principles related to planning for engagement, eliciting students ideas, supporting changes in thinking, and pressing for evidence-based explanations be incorporated into the GeoCRAFT modules? How can teacher PD and learning materials be designed to support all students, including those identified as special education? How do the modules, in combination with teacher practices, support students' development of mechanistic explanations and formulation of arguments about real-world exemplars while working with TRE?

Year 1 to Year 3: Design-Based Research on Simulation-based Curriculum Modules

The design-based research paradigm [103] affords the application of established learning theories, available research results, and prior developers' experiences in making initial design choices. Iterative redesign and modification of materials along with design conjectures will take place based on student and teacher data from implementations [104].

Simulation-in-Activity Testing in Small Student Groups (Year 1). We will develop a prototype TRE and test it in several "clinical" trials at CC using think-aloud methods with 20 students (a few at each trial) from local schools. The goal is to focus on the user experience and interaction with the TRE so that we can improve the user interface and examine whether TRE provides adequate learning opportunities.

Curriculum Prototyping with Teacher Advisory Group (Year 1, Curriculum Design Cycle 1). Informed by science education literature and NGSS [9], we will develop student performance expectations for the GeoCRAFT modules for understanding of the domain from the system perspective and mechanistic explanation and uncertainty-infused scientific argumentation through simulation. Scientists on the Advisory Board and the Teacher Advisory Group will review and critically comment on the performance expectations. We will then prototype GeoCRAFT modules and implement them in our three teacher advisors' classrooms (roughly 240 students) to test how the modules function in real classroom settings.

Curriculum Testing by 6 Partner Teachers in Year 2 (Curriculum Design Cycle 2) and by 15 Teachers in Year 3 (Curriculum Design Cycle 3). In Year 2, the three teacher advisors and their three colleagues in the same schools will implement the GeoCRAFT modules with their students (approximately 480 students). For the PD workshop between Years 2 and 3, we will recruit a total of 15 teachers (with approximately 1,200 students) to implement the GeoCRAFT modules, along with pre-tests and post-tests.

Pre/Post-Test Data Collection and Analysis on Understanding of Linked Systems Across Scales. Before and after the modules are implemented, teachers will administer an instrument designed to elicit how well students understand geodynamic phenomena across tectonic environment, land formation, and rock formation scales from the system perspective. Additionally, we will collect students' demographic information, such as gender, ethnicity, language, and computer familiarity, English Language Learner (ELL) status, and special education needs. A learning outcome variable will be created based on student responses to the instrument. We will apply repeated measures ANCOVA with the teacher as a fixed effect and other student demographic variables as covariates. We will examine how variations in implementations impact student learning gains on the instrument as well as for whom the modules are beneficial. See the Assessment Research and Development section for details on the instrument.

Module Data Collection and Analysis. In each module, we will strategically place several embedded assessment tasks where students use TRE and formulate explanations or uncertainty-infused scientific arguments. Students' use of TRE as well as written explanations and arguments will be automatically collected on the curriculum server. Since this type of automatic log data tracks all student interactions with the curriculum modules, they provide very fine-grained information on students' simulation behaviors in relation to other parts of the activities in the modules. We will use log data to understand how much time students spend constructing, running, and revising simulation settings, and the number of iterations students go through when simulating tectonic rock genesis scenarios. We will use this set of information to examine the type and sophistication of students' explanations and arguments.

Student Video Data Collection and Analysis. In Year 2, we will collect screencast video data for two student groups, including special education students, in each class from the six teacher partners. The special education students will be those that are in regular attendance in teachers' classes. Since these teachers will have multiple classes, we plan to collect data from 30 student groups. These screencast videos include computer screens showing student interactions as well as their voices. In selecting student groups for the screencast data collection, we will consider grouping based on science achievement determined by pre-test scores as well as in consultation with the teachers, while specifically including a sample of special education students. This data will create a comprehensive picture of student activity, including dialogue between partners, support provided by the teacher, and modeling decisions made in real time. We will use screencast data to validate the log data analysis mentioned above.

Year 1 to Year 3: Assessment Research and Development

Instrument to measure student understanding. To construct the instrument, we will assemble assessment items from research papers and released item resources. We will select and modify existing items or design new items to address student understanding of geologic phenomena across spatial scales where tectonic movements, land formation, and rock genesis occur. On this instrument, student understanding will be measured using the knowledge integration (KI) scale. Some researchers consider that knowledge integration is necessary for students to understand behaviors and mechanisms associated with Earth systems [67], [73]. On the KI scale, students are measured according to their depth of understanding within and across systems. The KI rubrics target students' abilities to elicit and make links between ideas relevant to a scientific context [105], [106]. The KI assessment framework has been validated in classroom-based trials for psychometric rigor [107], sensitivity to instruction that fosters integrated understanding of science across physical, biological, and Earth sciences [108], and learning progression in energy [109]. KI-based assessments showed a Cronbach alpha value of .81 for Earth science items [107].

In Year 2, the first version of the instrument will be administered as a post-test to students (n = 480) in the six teacher advisors' classrooms; the second version will be administered as pre-test and post-test to students (n = 1,200) in 15 teachers' classrooms. In these two cycles, we will follow the construct modeling approach suggested by Wilson [110]: (1) a construct map is theorized from the relevant literature on the target construct; (2) items that elicit various levels on the construct map are selected for an instrument; (3) student responses are collected on the instrument; and (4) appropriate item response models are applied to student response data. We will use Rasch Modeling of student responses [111], [112] to establish the validity of each instrument [113]. To ensure that Rasch Modeling is appropriate, we will test for unidimensionality with exploratory factor analysis (EFA) and for local dependence [114]. We will then use psychometric properties to validate the construct underlying the instrument and the items to establish a measurement scale associated with the construct. We will also test for instructional sensitivity of the instrument to examine whether and to what extent the instrument is able to capture student learning related to the GeoCRAFT modules. Each year, the instrument will be improved. The final version of the instrument will be ready for the implementation study in Year 4.

Embedded assessment to track students' scientific argumentation. Scientific argumentation tasks will be contextualized around the use of TRE. Each argumentation task will start with a scientific question. Students will be scaffolded to make reliable claims about how tectonic movements are responsible for the rock layers found on Earth's surface. Students will develop mechanistic explanations based on observations and interactions with the simulation. Students will be scaffolded to consider uncertainty, including: 1) their own confidence with the content; 2) the simulation's limitation in representing the entire history of a region across vast time and spatial scales; and 3) theoretical limitations in interpreting the complex real-world examples where only small segments of rock formation can be reasonably explained given the current understanding. The argumentation task format consists of four parts: a multiple-choice structured claim, an open-ended explanation, an uncertainty rating, and an open-ended uncertainty attribution [115]. The uncertainty-infused scientific argumentation construct was validated using Rasch Analysis based on Partial Credit Model [112]. This unidimensional construct had a reliability of 0.91 Cronbach alpha. A set of scientific argumentation tasks will be embedded throughout the modules. We will track students' performances on these scientific argumentation tasks. Using a combination of screencast video data and log data, students' use of the simulation will be examined to identify students' interactions critical for their development of uncertainty-infused scientific arguments. We will revise the argumentation tasks during the curriculum design cycles 2 and 3.

Year 4: Implementation Study

By the end of Year 3, we will have final and refined versions of curriculum modules, assessment materials, and teacher support materials. In Year 4, these materials will be used by 30 teachers (approximately 2,400 students). We will solicit participation and select 30 teachers that represent diverse school settings in terms of students' language and ethnic minority status, school locale (suburban, urban, rural), and student population, socioeconomic, and special education status to implement the materials. Participating teachers will implement the GeoCRAFT modules in their classrooms. Before and after the modules, they will administer the pre-test and post-test. We will pool students from the teachers and conduct analyses using repeated measures ANCOVAs to investigate how student demographics, teacher enactment, and school settings impact student learning. We will also employ Hierarchical Linear Modeling, if appropriate.

EXPERTISE

Amy Pallant (PI) will direct the development of the simulation and curriculum modules and be responsible for the overall coordination and budgeting of the project.

Scott McDonald, Ph.D., (Co-PI) will oversee the PSU portion of the budget, lead professional learning activities, data collection, and analysis focused on teacher enactment of the materials.

Hee-Sun Lee, Ph.D., (Co-PI) will lead research on assessment development and validation, as well as student development of explanations from simulations of Earth systems and uncertainty-infused scientific argumentation captured before, during, and after the modules.

Jonte Taylor, Ph.D. (Senior Personnel) will consult on the design of teacher professional learning materials and the professional learning workshops for supporting special education students.

MECHANISMS TO ASSESS SUCCESS OF THE PROJECT

Dr. Xiufeng Liu, Ph.D., will serve as external evaluator. Dr. Liu has extensive experience in science assessment, science instruction, and measurement. During the design research phase, Dr. Liu will evaluate and provide feedback on research design, including sampling, data collection, and data analysis. During the implementation phases, he will report on teacher and student perceptions on the quality of the curricula and gains on student learning. He will independently evaluate the quality of curriculum, simulation, and assessment materials from both psychometric and learning outcomes perspectives. He will evaluate project reports, presentations, and materials. Dr. Liu will have access to project data and will meet with the Co-PIs in teleconference meetings to learn about project updates and provide feedback. He will also participate in the annual face-to-face Advisory Board meetings and work with the Advisory Board members to create a report that will be included in the NSF annual report each year.

Advisory Board

In Years 1 and 2 the Advisory Board will meet face-to-face. In Years 3 and 4 virtual meetings will be held.

Dr. Tanya Furman is a professor of geosciences and an associate vice president and associate dean for undergraduate education at Pennsylvania State University. She was the lead investigator on the NSF-funded Earth and Space Science Partnership.

Dr. Glen Dolphin is a professor at the University of Calgary. He has taught classes in the nature of science, qualitative research methods, and physical science, and is involved in projects focused on student identity, the relationship between teacher beliefs and practice, and the role of teacher education.

Dr. Eve Manz is an assistant professor of education at Boston University. Her research focuses on the development of epistemic practices in mathematics and science. Her research explores how to design learning environments so that practices such as modeling, experimentation, and argumentation are meaningful and useful for students.

Dr. Douglas Clark is a professor at the University of Calgary. His research investigates how people learn STEM concepts, skills, and practices, and explores the designs of physical and digital learning environments with a focus on explanation, argumentation, and digital inquiry environments.

Heath Stout is a middle school teacher at Park Forest Middle School in a suburban school in Pennsylvania. He has participated in the learning progressions research around plate tectonics, along with advising on the development of curricula and tools in GEODE.

Teacher Advisory Group

Along with Heath Stout (also on the Advisory Board), the following teachers will make up this group.

Stephanie Harmon is a high school Earth science teacher at Rockcastle County High School, a rural school in Kentucky. Since 2010, she has been a field test teacher for four previously funded NSF projects led by PI Pallant and wrote two papers in teacher practitioner journals. She was named Kentucky Science Teacher Association's Outstanding High School Teacher in 2014.

Rebecca Colo is a middle school Earth science teacher at Longsjo Middle School, a diverse urban school in Fitchburg, Massachusetts. She has been a field test teacher for several NSF projects led by PI Pallant.

DISSEMINATION

The project will create a rich legacy of materials, including simulation software, online curricular modules, online teacher guides, and research. CC will produce a GeoCRAFT project website, which will distribute the software and modules, and will include results from our research and evaluation. The CC websites have been visited by over 2.7 million unique users from 50 states and 120 countries. CC will also promote the materials through the Pennsylvania partner districts, and various digital channels, including blogs and social media. All partners will promote the project through presentations and workshops at conferences for teachers, researchers, and scientists (NSTA, NARST, AERA, AGI) and through articles published in peer-reviewed journals in science education (*Journal of Research in Science Teaching, International Journal of Science Education,* and *Science Education*), learning sciences (*Journal of the Learning Sciences*), and for teachers (*The Earth Scientist*, *The Science Teacher*). In addition, the *@Concord* biannual newsletter, distributed for free to over 35,000 digital and print subscribers, will be another communication venue. Finally, through a longstanding relationship with the National Earth Science Teacher Association (NESTA), GeoCRAFT will promote its materials to the NESTA membership, through its regional network and social media channels, reaching over 16,000 teachers, and will develop materials to distribute as part of the Earth Science Week kit distributed by American Geosciences Institute.

INTELLECTUAL MERIT

GeoCRAFT will contribute to the field's understanding of how students engage in using simulations of Earth systems to support their learning of complex Earth science concepts. It will extend the field's understanding of how students engage in scientific practices while investigating ESS phenomena to develop explanations using simulations as evidence. This research will shed light on the role uncertainty plays in reconciling simulation-based evidence with real-world phenomena when students build arguments related to real-world examples. GeoCRAFT will also allow for a characterization of teaching practices around the use of multi-scale system models and their associated uncertainty. Additionally, it will inform the teaching practices that support all students, including those identified as needing special education, to engage with NGSS-aligned ESS practices that approximate the work of scientists.

BROADER IMPACTS

GeoCRAFT will leverage technology to transform how rock formation, the rock cycle, land formation and plate tectonics are traditionally taught. The simulation can help students reason about the underlying mechanisms responsible for the processes that shape Earth and distribute resources necessary for human life. The GeoCRAFT project will provide new ways to teach rock genesis and land formation from the plate tectonics perspective. This project builds on extensive prior and current work by the proposers and development in STEM education, in particular on plate tectonics. The proposers have seen an immediate interest in the prior plate tectonic technology and curriculum of more than 8,500 users (teachers and students) while being openly available for only one semester (fall 2019). The majority of Earth science curriculum addresses the rock cycle, land formations, and plate tectonics, so we anticipate even more uptake of GeoCRAFT materials. Project materials will be developed with close attention to the needs of diverse students and will be implemented in a wide range of schools, including those that serve underrepresented students. Finally, GeoCRAFT simulation and curriculum design principles can serve as a template for other researchers, curriculum and technology developers, and teachers to design student learning experiences in ESS or other areas where simulations are used.