International Society of the Learning Sciences

Epistemic Excursions as Agentive Meaning Making within a Digital Plate Tectonics Curriculum

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Abstract: Models and modeling are essential for mediating knowledge-building processes about geologic phenomena (Stillings, 2012). We draw on constructs of expansive learning (Engeström, 1987) and personal excursions (Azevedo, 2006) to analyze a case in which two secondary students develop geologic explanations using Seismic Explorer, a tool for visualizing information about earthquakes and volcanic eruptions. We present four episodes in which the focal students conjecture and test ideas through modeling plate tectonics phenomena. Using methods of interaction analysis (Jordan & Henderson, 1995) we describe how the students actively build and revise their moment-by-moment explanations. Our analysis contributes to a deeper understanding of how the design of geologic models and data visualizations for classroom contexts can support sensemaking as a kind of journeyed relationship-building with the phenomena, associated data, and with peers, through relational events that we term *epistemic excursions*.

Introduction

Making sense of geologic phenomena—including plate tectonics, global oceanic and atmospheric patterns, and other cycling of matter requires reasoning about systems that are distributed across vast spatial and temporal scales (Anderson, 2006; Herbert, 2006; Stillings, 2012). Developing understandings of earth science requires learners' competence in thinking about complex interrelated behaviors of Earth's systems. Earth science educators can use models and simulations to make phenomena accessible at more human scales, bringing the challenges of large spatial data sets and massive time scales into manageable forms, especially for learners in classrooms (e.g., LaDue & Clark, 2012; Stillings, 2012).

Expansive learning (Engeström, 1987; Engeström & Sannino, 2017) accounts for processes of human learning in which participants create new targets of learning as the interaction unfolds. As explained by Engeström and Sannino (2017), learners "construct a new object and concept for their collective activity, and implement this new object and concept in practice" (pp. 48 - 49). This is in contrast to vertical movement toward prescribed learning goals that characterizes many school learning environments. With the metaphor of expansion in mind, we investigate two high school earth science students' work in an online learning module about plate tectonics. We are interested in deeply describing how they came to engage in a spontaneous process of epistemically-rich activity using an interactive computer-based data visualization of geologic phenomena. We are especially interested in the ways that students use and relate to models, specifically data visualizations, to approximate legitimate professional geological practices. We draw on episodes in which students display epistemic agency (e.g., Miller et al., 2018) in conjecturing and testing ideas through modeling plate tectonics and actively revise their explanations based on information generated from their interactions with models of data. We describe the ways that they attempt to develop model-based explanations of geologic phenomena through four epistemically meaningful personal excursions (Azevedo, 2006). Our analysis seeks to answer the following research questions: *How do excursions with geologic modeling and visualization tools begin and unfold? In what ways are the excursions fruitful for students' agentive work to build, test, and refine geoscientific explanations through interaction with models and with one another?*

Theoretical background

Modeling is central to professional geoscientists' understanding of geologic phenomena (Stillings, 2012). For more than 30 years, learning environments have leveraged computing tools for students to engage in modeling (e.g., Wilensky & Resnick, 1999) and use of data visualization software (e.g., Lee & Wilkerson, 2018) as activities for learning in many scientific domains. Model-based reasoning, at its fullest, requires learners to engage with content through production of scientific knowledge, so that the ideas and explanations that the models represent are "testable, revisable, explanatory, conjectural, and generative" (Windschitl, et al, 2008). Explanation-building across multiple sources of evidence is at the core of the work of geoscience. However, orchestrating learning environments in which students enact epistemic agency in proposing, testing, and revising evidence-based explanations using modeling practices remains a central challenge in science education (Russ & Berland, 2019; Windschitl et al., 2008). As argued by Hall (1996), discursive theory-building exchanges can be especially generative for understanding how learners develop competencies for the production of knowledge, especially in discipline-specific contexts.

In geoscience especially, phenomena of study often occur at very large scales of time and space (Herbert, 2006). For instance, scientists have difficulty directly engaging with mountain building in real time as it occurs beyond the scope of a human's lifetime. As a result, plate movement and mountain building have traditionally been taught using historical second-hand data (data collected by others) over long periods of time. While many may argue that first-hand data collection is more meaningful for learners and representative of geoscience practice, Lee and colleagues (2021) have demonstrated that "students do engage data collected by others in deeply personal ways" (p. 664). Learners' work with second-hand data requires complex engagements on several layers: personal, cultural, and sociopolitical (Lee et al., 2021). On a personal level, learners relate to their direct experiences with data and measurement. On a cultural level, learners recognize routines of practice and technologies associated with a data set's collection and use. Finally, on a sociopolitical level, learners recognize political narratives that may influence how data is interpreted and used.

Learning scientists have demonstrated that data science education becomes more meaningful and equitable when students experience data science as relational work (Wilkerson & Polman, 2020; Rubin, 2020). Students build relationships with the data they are working with in order to locate themselves in relation to the data and to "see" the data from the perspective of others (e.g., other students). They make personal connections, ask questions, and generate their own ideas based on data. These relationships are embedded in the specific context of the data, knowledge about the larger domain (e.g., geology), and the concepts that exist in the interaction—which are often tentative and not fully worked out. A relational view of learning in activity gives way to contexts of expansive learning (Engeström, 1987). Relationships with and to the object of study forge pursuit of individual interests, what Azevedo (2006) has termed personal excursions. Personal excursions are diversions from the initially framed activity that generate a second activity—that is, an excursion. This second activity may bring forth meaningful connections to the original goals. It is through these personal excursions that many students develop and extend connections between the content of learning activities and their own identities and interests, often positively impacting learning along stated learning goals (Azevedo, 2006; Farris & Sengupta, 2016). Personal excursions allow students to build "pragmatic, conceptual, and question-generating resources so that more extended, coherent personal pursuits are possible and more likely to take place" (Azevedo, 2006, p. 93).

Methods

The context of this study concerns learning within an interactive Plate Tectonics curriculum (https://learn.concord.org/geo-platetectonics), part of the Geological Models for Explorations of the Dynamic Earth (GEODE) project. Approximately twenty 10th and 11th grade students, along with their teacher, engaged with the curriculum within their earth science class in a public school in the Southeastern U.S. The duration of this instructional unit was approximately ten class periods of forty minutes each. We analyze video and audio recordings from one focal teacher's classroom. Students worked in pairs on one laptop. The teacher selected three pairs for recording. The teacher's selection was based on consistency in attendance and the likelihood that the students would share their ideas with one another through talk. Recordings were generated using the embedded laptop camera and microphone. Students' screens were recorded using QuickTime Player.

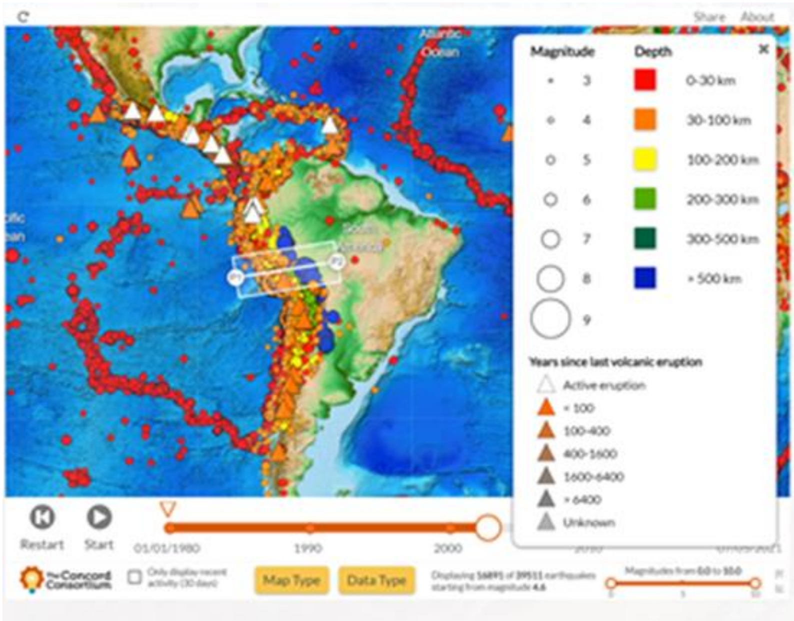
In this interaction analysis (Jordan & Henderson, 1995), we seek to understand how one pair of students––Noah and Zach—work beyond the curricular prompts to ask questions that are personally meaningful to them. We selected these students as focal students based on their talkativeness and consistent attendance. We first synchronized the screen capture and student video data to create multimodal transcripts of key moments of interaction. We describe the practices through which they share tentative sensemaking knowledge and engage in a spontaneous pattern of proposing, testing, and revising evidence-based explanations using the digital representations in the curriculum. We highlight four episodes of interaction, selected because they illuminate the ways in which Noah and Zach generate geoscience explanations as relational and sensemaking work. The episodes concern the students' conjecture relating mountain formation to volcanic activity (Episode 1), their emergent theory that seismic activity follows the leading edge of continent movement (Episode 2), their proposed mechanism of earthquake depth (Episode 3), and their explanation for the formation of the Andes Mountain range (Episode 4). These occurred on Days 2 and 3 of the 10-day curriculum.

The model: Seismic Explorer

The Plate Tectonics curriculum includes Seismic Explorer, an interactive data visualization tool. Seismic Explorer (Figure 1) is a time-oriented data visualization of earthquake epicenters, volcanic eruptions, and plate movements.

Students can view location, depth, magnitude, and frequency of earthquakes on a two-dimensional map of the world as well as in a three-dimensional cross-section. Other data included within Seismic Explorer is direction of tectonic plate movement and volcanic eruption data. We characterize Seismic Explorer as both a data visualization and a computer-based model of geologic information. The Plate Tectonics curriculum was intentionally designed to use the Seismic Explorer iteratively in support of student problem solving related to key driving questions.

Figure 1
Seismic Explorer representing volcanic eruptions and earthquake epicenters in the Andes Mountains. Students can create a cross-section as shown by the rectangular selection marked in white.



Analysis and findings

In this section, we follow four episodes that illustrate how Noah and Zach relate to models and data representations in order to sensemake within plate tectonics. In these episodes, they are at the point of the curriculum in which they are working to develop an understanding of plate interactions through historical data about plate tectonics. Each of these episodes constitutes an excursion from the prescribed activities in the curriculum, characterized by building relationship with the phenomena, associated data, and with peers. Drawing on existing work on students' epistemic agency (e.g., Miller et al., 2018) and personal excursion (Azevedo, 2006), we have termed these events *epistemic excursions*.

Epistemic excursion 1: Testing ideas of phenomena against local connections

In this episode, Noah and Zach are working with Seismic Explorer to describe the location of volcanic eruptions in the Andes Mountains, as prompted by a question in the online curriculum. Noah immediately notices that "they [the volcanoes] go along the Andes Mountain range," (see Figure 1) and Zach suggests manipulating the map to "go back up and see if any volcanoes are near the Appalachian Mountains and the Rocky Mountains." The students live within the Appalachian Mountain range. Zach recognizes that volcanoes and mountains are both located in the Andes, prompting the idea that volcanoes are associated with mountains.

Noah and Zach proceed to test the idea that volcanoes occur along mountain ranges. They use Seismic Explorer to examine volcanic history in the Appalachians and Rocky Mountains. They claim that the Appalachian Mountains are "clear [of volcanoes]" and the Rocky Mountains have "a little bit [of volcanoes]." We see this as a form of seeking coherence between curricular questions about the Andes and personal knowledge about other mountain ranges. Through this exploration of the data visualization, they conclude that there is no record of "active" volcanic activity in the Appalachian Mountains and minimal volcanic activity near the Rocky Mountains, contradicting Zach's initial theory that volcanoes are closely associated with mountain formation. This episode represents an excursion in which Noah and Zach seek to relate the correlation between mountain formation and volcanoes in the Andes Mountains to the Appalachian Mountains (where they live) as well as the Rocky

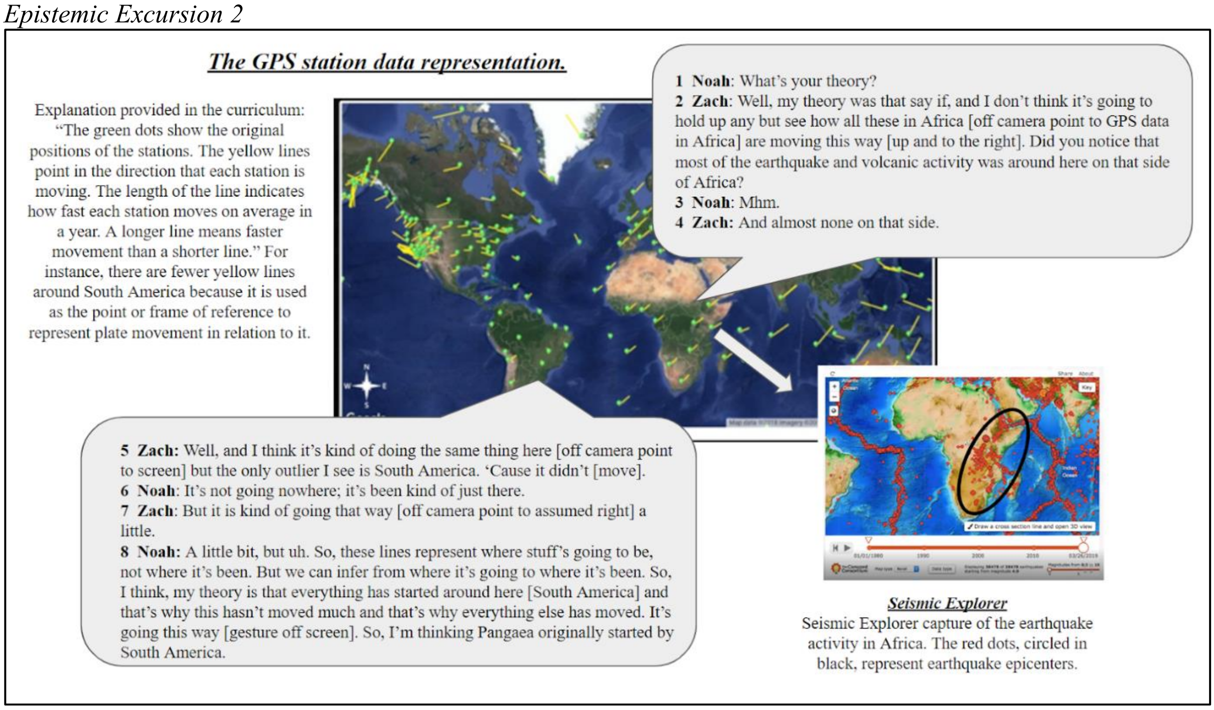
Mountains (which they have heard about). Noah and Zach begin to build a relationship to the data in which they test their emerging ideas in connection to geographies that are personally and contextually relevant to them.

Epistemic excursion 2: Presenting and refining personal theories across models

In this episode, we follow Noah and Zach's theory building talk across two days. Noah and Zach worked with Seismic Explorer to describe the patterns of earthquakes and volcanic eruptions in the Andes Mountains, as prompted by a question in the online module. Zach deviates from the exploration of the Andes Mountains and has Noah zoom in to only view the earthquake activity in Africa. After viewing this, Zach exclaims, "Ooh, I think my theory might be holding up." Noah prompts him to explain what he means. Zach says "okay, now my theory is…see Africa's going that way, right?" (see Figure 2). Zach points to the Southeast coast of Africa as he continues: "Look where all the volcanoes and earthquakes are. They're on this side." Zach has Noah then revisit South America and they compare the pattern in Southeastern Africa to South America. Noah asks "…so the way they are going determines where the earthquakes are?" to which Zach confirms "that's the theory so far." The class period ends, interrupting further discussion.

As soon as Noah and Zach begin working the next class day, they pick up the discussion of their "theories" (their word for initial claims). Zach decides he wants to test his theory developed from Seismic Explorer during the previous day against a model they saw earlier in the curriculum, the GPS station map (see Figure 2). Figure 2 shows how Noah and Zach built a "theory"—that is, a scientific claim—through talk and action as they revisit their initial ideas and this earlier representation of GPS motion data. Zach clarifies and justifies to Noah his claim that the direction and relative movement of the GPS station data suggests where volcanoes occur and adds earthquakes to his explanation. He points to the yellow traces of northeasterly station movement in Africa to convey his thinking. In Turns 2 – 7, Zach indicates that there is almost no movement in South America, highlighting the important information related to his unfinished ideas about mountain formation.

Figure 2
Epistemic Excursion 2



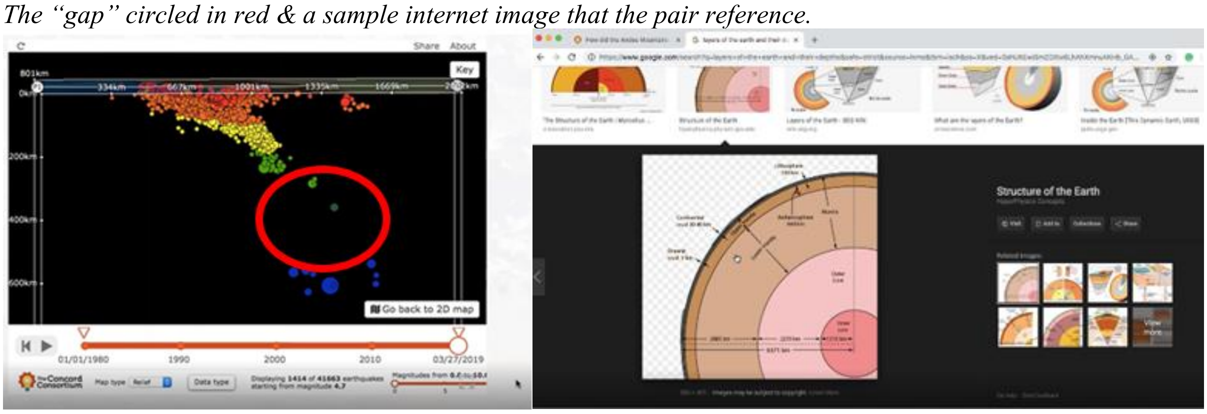
This explanation fuels Noah's own developing theory, arising from their return to the GPS station data. Referring to the relative movement and direction of continents, Noah proposes that the initial location of Pangaea (Turn 8) was around the current location of South America. However, we note that Noah and Zach's initial conceptions were based on their misinterpretation of the GPS station map as they did not consider that in order to identify movement, something needs to serve as a point of reference. The data points in South America indicate no movement because South America is the frame of reference. However, the students interpret the representation to mean that South America is stationary. However, this misinterpretation still promotes interesting theory-building conversation, even though it leads the students to an explanation that does not reflect the widely accepted perspectives of geoscientists. Our focus here is not that students develop normative explanations instantaneously while working with models, but that they iteratively test and refine their emergent theories as they move towards more sophisticated explanations and starting points for further development.

This episode highlights how Zach and Noah worked through two related instances of theory work: (1) the direction and relative movement of plates and (2), the spatial origin of Pangaea. In the first theory work, they relate their current thinking about the location of earthquakes and volcanic eruptions, which are represented in Seismic Explorer, to the relative direction and movement of tectonic plates using the GPS station representation. While the curricular questions are focused on the Andes Mountains, Noah and Zach explore other areas of the world through Seismic Explorer to gain insight on additional geologic data, such as earthquakes in Africa. This suggests that they understand that it may be useful to use information beyond the specific place-based phenomenon in the question. They choose the southeastern coast of Africa as a similar case and generate a comparison. This investigation allows the students to relate to their own personal ideas and examine a theory that Zach has regarding patterns of earthquakes and volcanic activity using Seismic Explorer. They then proceed to work on a related theory about the origin of Pangaea, against another visualization of geologic data that they had engaged with earlier in the curriculum. Noah and Zach refine their theories after discussing the GPS station map, in which the discussion leads to the development of a new theory, one initiated by Noah. Noah uses the GPS station map to "theory build" about the initial location of Pangaea, suggesting that it originated around South America due to its lack of movement. This connection to Pangaea is not part of the curriculum, suggesting that their interactions with these visualizations also prompt connections to prior knowledge. The pair iteratively relate to the personal questions that they have and to other sources of data in order to support their claims.

Epistemic excursion 3: Meaningful inquiry and connections, non-canonical ideas

In this episode, the pair return to the curriculum prompts. They use Seismic Explorer to create 3D cross sections, shown in Figure 3, in order to see the depths and magnitudes of earthquakes along the Andes Mountains as directed by the curriculum. However, Noah and Zach recognize a "gap" in the number of earthquakes at certain depths below the Andes (typically between 350-500 km below the surface). Unprompted by the curriculum materials, they question why there is a lack of earthquakes in this "gap" and wonder if this phenomenon can be explained by the layers of the Earth. Noah then seeks out a reference from outside the curriculum, using a new browser tab to search for images of the layers of the Earth. Noah asks, "what layer of the earth is that far below ground?" to which Zach responds, "you have the crust, the mantle, outer core, inner core or at least that's what I know." They continue as they investigate by clicking on several images of the layers of the Earth. Noah exclaims, "this [the gap of earthquakes] is all happening around the upper mantle." Zach then adds "that's magma, it's molten rock. What's the core supposed to be like? Nickel? Was it nickel?" The two students then debate whether the core is solid material or not, since "the core's really high pressure and heat," before returning again to the task directed by the curriculum.

Figure 3
The "gap" circled in red & a sample internet image that the pair reference.



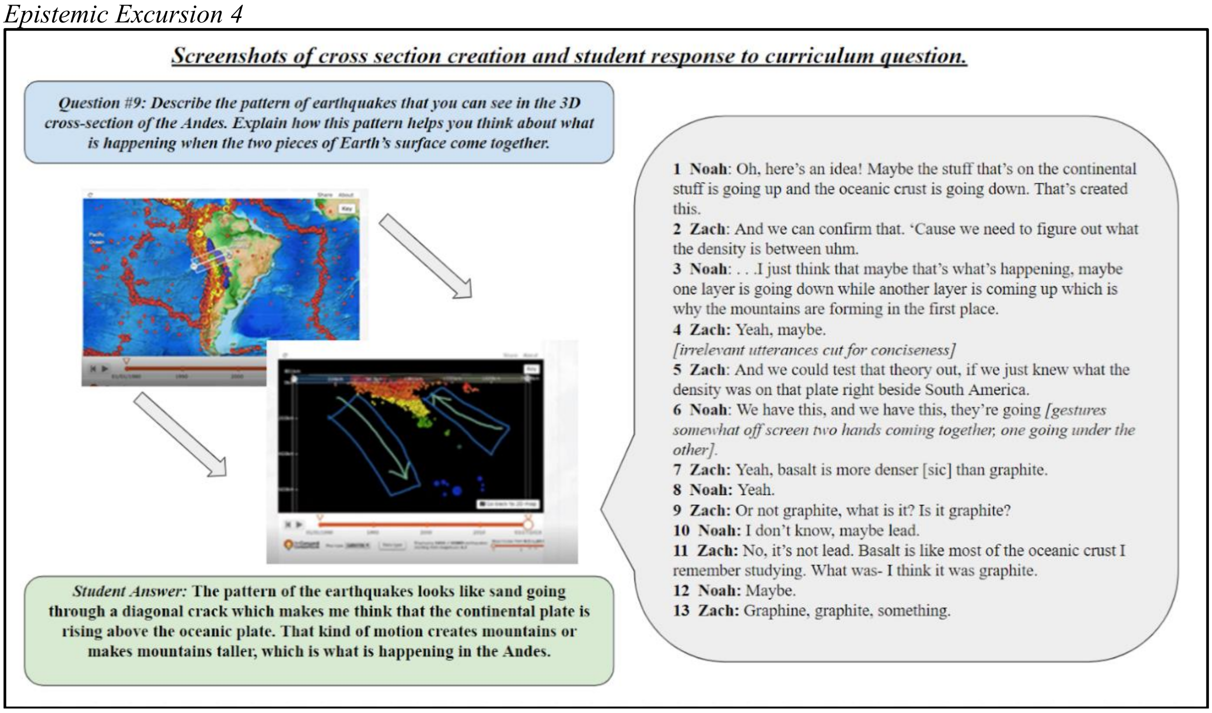
We see in this episode that Noah and Zach seek to investigate a question that is elicited by the earthquake data in Seismic Explorer. The two recognize a pattern within the cross section that there are relatively no earthquakes. They specifically relate this data-prompted investigation to their prior knowledge of the layers of the Earth. They iteratively seek to make sense of what they are seeing within the model by reaching out and referencing outside information found in their spontaneous internet search. They engage in talk about their knowledge of the layers and attempt to reach a shared understanding of the makeup of the upper mantle. This episode highlights Zach and Noah's attempts to connect existing knowledge resources about the layers of the Earth and their relative depth to earthquake activity as they work towards generating and refining shared explanations.

Epistemic excursion 4: Expansive learning full circle

The next task in the Plate Tectonics curriculum is to use Seismic Explorer to create a cross-section of earthquakes occurring underneath the Andes Mountains, prompting Noah and Zach to "describe the pattern of earthquakes that you can see in the three-dimensional cross-section of the Andes. Explain how this pattern helps you think about what is happening when the two pieces of Earth's surface come together." Figure 4 shows the selected area of the Andes Mountains using Seismic Explorer, a snapshot of Noah and Zach's cross-section, and their associated talk. The students call the two relevant tectonic plates "pieces," and specifically refer to them as the "continental stuff" and the "oceanic crust" [Turn 1] as the term "plate" is formally introduced after this task.

While looking at their cross-section, the students recognize that the trend line of the earthquake events likely corresponds with the boundary between the two plates. In cross-section view, the plates and their boundaries are invisible (see Figure 4). Noah verbalizes his idea that as the two tectonic plates converge, the continental layer (on the right side of the trend of earthquakes) is going "up" while the oceanic layer (on the left side of the trend of earthquakes) is going "down" (Turn 3). Zach then offers that they could test their theory about this relative movement if they knew the densities of the two plates to determine which plate is denser (Turn 5) and would subduct under the other. In Turn 6, Noah gestures with two hands to mimic how they expect these plates to interact, with one going under the other. In Turns 7-13, Zach and Noah discuss the geologic makeup of the oceanic plate in terms of density. As they continue to work out this idea, Noah inscribed two yellow arrows on their screen (See image of arrows on graph snapshot of cross-section in Figure 4) on each side of their earthquake depth model to represent this movement trend.

Figure 4
Epistemic Excursion 4



This episode illustrates how Zach and Noah draw on their experiences with Seismic Explorer to build a normative explanation of tectonic plate subduction in the Andes Mountains. But what makes this expansive? Similar to Episode 2, Noah and Zach draw upon shared terminology that is not introduced at this point within the curriculum, including scientific language related to plate composition and density. They garner one another's' support for the development of a theory of subduction, which, while normatively correct for this plate boundary, is beyond the intended curricular goal of this question, which was asking students to focus on the patterns evident in the depth of earthquakes that occur along the mountain range. They draw on knowledge from some experience that was not part of the Plate Tectonics curriculum concerning the ocean crust being made of basalt, which is going down (subducting) under the less dense continental plate. This episode illustrates students' use of the visualization tools within the modeling environment to examine patterns in the depth of earthquake events, and secondly, to begin to explain the phenomenon at the convergence. The match between the representational affordances of the environment and the prompt to guide what students were supposed to do with the environment supported the students to realize normative key concepts in a process of refining theories of geologic phenomena. We argue that each of these resources contribute to their decision to highlight the relative density of the plates as a key causal mechanism of plate subduction.

Discussion and conclusion

In order to craft geoscientific explanations, learners build relationships with the data they see and their sensemaking talk across representations. For Noah and Zach, using the interactive computer-based data visualization tools of Seismic Explorer and the GPS station map to think about complex geologic phenomena is a process of iteratively making, testing, critiquing, and refining explanations of what they notice. In each of the episodes, we have highlighted how Noah and Zach relate to the data directly or are prompted to relate based on their own personal excursions adjacent to or outside of the designed module. They often deviate from the curriculum to sensemake with their own emergent inquiries and curriculum-driven questions. Across these episodes, we have illustrated that Noah and Zach seek to relate to varied intertextual resources—including other models within and outside of the Plate Tectonics curriculum, their own personal geographical connections, and other existing knowledge resources—in order to sensemake around geologic data visualizations. They search to investigate their own questions as they relate to the data. In doing so, they establish their developing theories by drawing out naïve understandings and scientific language, exploring their emerging ideas within Seismic Explorer, and testing these ideas against additional interactions with the tools within the curriculum. The varied visualizations in which the students interact serve to drive forward their proposal of new explanations. Their shared theory building about geologic data transcended the given dataset and tools, yet approximates (Grossman, et al., 2009) ways that professional geoscientists leverage modeling environments (Bokulich & Oreskes, 2017; Stillings, 2012). In sum, Noah and Zach sensemake across data models, personal experiences, and their own ideas to form a disciplinarily acceptable explanation of a process of subduction near the Andes Mountains.

We argue that the fruitfulness of Noah and Zach's interaction in these episodes is largely driven by the freedom and sense of agency with which they tested tentative ideas against external sources. They demonstrate a high level of epistemic agency to draw upon additional sources and investigate their own questions. This process of relating to each other and relating the curriculum to other sources and experiences drives their sensemaking, which we argue, is instrumental in supporting their progress along disciplinary learning aims. Furthermore, we also note that many of the sources and experiences that Noah and Zach spontaneously relate to the curriculum were "conceptually risky," meaning that they were loosely connected to the phenomenon by analogy and or inference creating an indirect path toward canonical ideas.

Our focus here is not that students develop normative explanations instantaneously while working with models, but that they can iteratively test and refine their emergent theories as they move towards more sophisticated explanations. Epistemic excursions, as we have illustrated, were highly unpredictable. A real-time observer would have been unlikely to predict how these episodes were going to unfold. The "ends" of excursions were inconsistent in the degree that they led to disciplinarily key ideas about geologic phenomena. Excursions 1 and 3 contain sensemaking resources that are quickly and wisely abandoned. If analyzed in isolation, they could be deemed rabbit holes or even off-task work.

Our analysis contributes to a deeper understanding of how the design of geologic models and data visualizations for learning can support sensemaking as a kind of journeyed relationship building with the phenomena, associated data, and with peers. In these episodes, the supports of the curriculum and collaboration fostered generative epistemic practices in questioning and modeling geologic phenomena. The cases, furthermore, illustrate how excursions can be a key support for disciplinarily-relevant epistemic practices, especially within a digital learning environment. Epistemic excursions, including those that might be viewed as misaligned with canonical science, are important in a broader and more relational view of learners' sensemaking processes. Gaining insight into how students negotiate the excursion process is a step towards supporting all students with greater epistemic agency and ownership of their own processes of figuring things out in environments with extensive modeling and visualization tools.

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