The Geological Society of America
Special Paper 474
2011

Student interpretation of a global elevation map: What it is, how it was made, and what it is useful for

Sandra Swenson*
Columbia University Teachers College, 525 West 120th St., New York, New York 10027, USA

Kim Kastens†
Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, New York 10964, USA

Looking at a contour map, the student sees lines on a paper,
the cartographer a picture of a terrain.

—Thomas S. Kuhn, *The Structure of Scientific Revolutions* (1962)

ABSTRACT

Visual representations of scientific data make these data accessible and enable students to examine the evidence used to build scientific arguments and test theories, even when the underlying data set is large or complicated. It is becoming more common in science education to use data visualizations based on data that students did not collect themselves. Teachers and instructional designers need to understand how students perceive and interpret such visualizations. This research examined the nature of students' interpretations about a colored, shaded-relief global digital elevation map useful for reasoning about a wide range of Earth processes. One hundred and ninety-six middle and high school students wrote answers to three open-ended questions while viewing the map projected on an overhead screen: "What do you think this is?" "How do you think this was made?" and "What do you think this is useful for?" Nearly half the students surveyed made no mention of topography/bathymetry or an equivalent concept. Twenty percent of the students misinterpreted the map to contain information other than elevation, including inappropriate interpretations such as water, temperature, and weather. Over half of the students did not describe any aspect of data acquisition as a component of the data map creation. In describing the utility of the map, students focused on information-retrieval tasks rather than on making inferences about Earth processes. Based on our findings about geoscience data visualization, we suggest strategies that may be beneficial in designing curriculum for teaching and learning with data maps.

*Current address: Department of Sciences, John Jay College, City University of New York (CUNY), 445 West 59th Street, New York, New York 10019, USA; sswenson@jjay.cuny.edu.
†kastens@ldeo.columbia.edu.

Swenson, S., and Kastens, K., 2011, Student interpretation of a global elevation map: What it is, how it was made, and what it is useful for, *in* Feig, A.D., and Stokes, A., eds., Qualitative Inquiry in Geoscience Education Research: Geological Society of America Special Paper 474, p. 189–211, doi:10.1130/2011.2474(13).

INTRODUCTION

Role of Data in Science Education

Using data is an important process of science that involves understanding how data are collected, manipulated, and represented in order to make informed interpretations. The National Academy of Sciences has defined science as "The use of evidence to construct testable explanations and predictions of natural phenomena, as well as the knowledge generated through this process" (NAS, 2008, p. 10). "Evidence" in science is grounded in data. If the science educators accept the National Academy of Sciences definition of "science," then they must accept responsibility for helping students understand data/evidence and not merely the knowledge that scientists have generated from data.

Most science education research on students' understanding of data has dealt with data that students collected themselves. Both qualitative and quantitative methods of education research have proven fruitful. Students' actions and thought processes while recording, analyzing, and interpreting data have been researched as students engaged in traditional data-collecting experiments such as determining the variation in a pendulum's periodicity (e.g., Germann and Aram, 1996; Kanari and Millar, 2004; Hug and McNeill, 2008) or computer-mediated activities such as using a microcomputer-based laboratory to measure distance, velocity, or thermodynamics (Brasell, 1987; Linn and Songer, 1991; Mokros and Tinker, 1987).

However, for many topics in geosciences curricula, it is not feasible to have students collect their own data. Earth phenomena are often too large (e.g., global atmospheric circulation), too far away (e.g., diminishing summer ice in the Arctic), too slow (e.g., rise in atmospheric carbon dioxide concentration), too dangerous (e.g., tornadoes), or require instrumentation that is too expensive (e.g., seafloor hydrothermal vents) for students to examine directly. Fortunately, government agencies and academic institutions have collected vast amounts of data about Earth processes that have been calibrated, quality controlled, archived, and are freely available via the Internet to the public, including schools.

Teaching and learning with data sets that students did not collect differs from working with student-collected data. Researchers are just beginning to explore the differences in teaching and learning when students do and do not collect the data they analyze. Hug and McNeill (2008) found considerable overlap in the classroom discourse stimulated by the two data types, but less discussion of error sources, more reliance on personal experiences, and different approaches to drawing conclusions from data when students had not personally collected the data used in their inquiry.

Hug and McNeill's (2008) study dealt with data that students would have been capable of collecting themselves, insofar as the methods, materials, and equipment were suitable for students of their age and experience. Other combinations of data-acquirer and data-interpreter are possible, as detailed in Table 1. All of these combinations have a potential role in science education and are ripe for educational research. The data set used to create the representation used in our study was acquired and provided by professionals (scientists, technologists, information specialists) and interpreted by students. We will refer to this configuration as "professionally collected data."

Role of Data-Based Visualizations in Science Education

The practical realities of student laboratory work means that student-collected data sets tend to be small, and thus amenable to relatively simple forms of representation, such as data tables or graphs with a few to a few hundred data points. However, when the flood gates of professionally collected data are thrown open, the volume and intricacy of the incoming data require an expanded repertoire of data-handling techniques. Scientists themselves extract insights from large data sets by rendering the data into "data visualizations," using computers to craft images that convey aspects of the data through position, color, texture, shading, and other perceptual devices that tap into human's powerful perceptual, spatial, and pattern recognition abilities (Edelson et al., 1999; Ware, 2004). Data visualizations also provide perspectives of phenomena that cannot be seen with the unaided human eye, for example, the morphology of the seafloor.

In science education, data visualizations have the potential to allow students to examine the evidence used to build scientific arguments, and to develop and test theories, even when the underlying data set is large or complicated. Use of sophisticated data visualization is growing rapidly in the applied sciences, business, and government (e.g., International Research for Climate

TABLE 1. TAXONOMY OF RELATIONSHIPS BETWEEN DATA COLLECTOR AND DATA INTERPRETER

Who collects the data?	Who interprets the data?	Literature	Terminology
Student	Same student	e.g., Germann and Aram (1996), Kanari and Millar (2004)	"First-hand data"*
Student	Another student, similar experience and ability	Hug and McNeill (2008)	"Second-hand data"*
Scientists, technologists, information specialists	Student	This study	"Professionally collected data"
Students	Professionals	Trumbull et al. (2000)	"Citizen science"

*Usage of Hug and McNeill (2008).

& Society/LDEO Climate Data Library, Tableau Software, and National Oceanic and Atmospheric Administration [NOAA] Data Explorer). Learning to extract insights from complex data is a skill that students will find useful far beyond geosciences; yet in our public school systems, this content knowledge area and skill development are sorely lacking (MacKay, 2006).

It is tempting to presume that because modern visualizations are so appealing to the eye, that their message is self-evident to all students. Evidence is beginning to accumulate that this is not true, that there are substantial differences in how people perceive and interpret data visualizations, both among students and between students and experts (Gilbert, 2005; Ishikawa and Kastens, 2005; Roth et al., 2007). Teachers and curriculum developers need to understand how students perceive and interpret data visualizations in order to craft effective instruction.

The scientific visualization of interest for the present paper is a specific type of data visualization in which the two spatial dimensions of the paper or computer screen are used to depict the two spatial dimensions of Earth's surface—in other words, a data map (Tufte, 2001). Maps, including data maps, are pervasive in geosciences, and fairly common in other sciences. Recent science education curricula that incorporate data maps have been developed by a variety of institutes and universities to help educators integrate global data sets into their instruction (e.g., Edelson et al., 1999; Hays et al., 2000; Prothero, 2006; Roushias and Anderson, 2001; Sawyer, 2005). An early pioneer in such curriculum development asked: "Do students know that data maps represent 'real, quantitative measurements about the Earth'?" (Sambrotto and Anderson, 2001, p. 57). Almost a decade later, this question remains unanswered.

Theoretical Framework

This research follows a grounded theory approach to understanding students' interpretations of a global elevation map, whereby qualitative data were collected by open-ended survey questions, but the analysis of the data was quantified. In quantifying the qualitative data, the researcher is examining the data for patterns and trends that emerge from the data and then categorizes these according to codes or concept indicators (Chi, 1997; Feig, this volume). The data are then quantified to determine frequency of responses. This approach provides a "middle ground" between traditional quantitative analysis and newer models of qualitative analysis.

Our work follows in the research tradition of probing students' conceptions (also referred to as preconceptions, prior conceptions, and misconceptions) as a necessary starting point for designing effective instruction (Driver et al., 1985, 1996; Libarkin and Kurdziel, 2002). However, we extend this line of research by examining students' understanding of data and data visualization rather than their understanding of a science concept. In a sense, we are probing their understanding of earth science—the physical and intellectual tools and techniques by which scientists learn about Earth—as opposed to probing their understanding of Earth.

Rationale and Context for Present Study

The specific intellectual and physical tools of interest in this study are bathymetric and topographic data, and the means by which such data are gathered and used. Of all data sets used in geosciences, bathymetry/topography is one of the richest in interpretive power. Solid Earth geoscientists invoke such data in identifying tectonic plate boundaries, and hydrologists use such data in defining watersheds. Oceanographers and paleoceanographers use bathymetry for identifying the gateways and boundaries that steer ocean currents. Atmospheric scientists view topography as a critical boundary constraint in explaining phenomena as varied as the location of tornadoes and the onset of monsoons. In addition, land-use planners, military officers, and civil engineers use topography, and fishermen and ships' officers use bathymetry, for making practical decisions every day.

The data visualization used in this study is a global map of the world's topography and bathymetry, created by the late William F. Haxby (Fig. 1). Haxby combined ship multibeam bathymetry data and satellite altimetry data for the oceans, plus radar interferometric data for the continents, to create a digital elevation model (DEM) that can be used to generate seamless topographic/bathymetric representations of the entire globe or portions thereof. For one commentator on the history of cartography, the Haxby map "has thematically reversed centuries of terrestrial bias" (Hall, 1992, p. 83) by displaying a detailed view of the seafloor. To an experienced geoscientist, this map can tell stories about Earth and Earth's processes, stories about plate tectonics, erosion, and deposition, and even about the placement of cities and the boundaries of nations, but what do students see when they look at the same map?

This study explored the nature of students' perception and understanding by asking them to write answers to three open-ended questions, as they viewed the Haxby map:

1. What do you think this is?
2. How do you think this was made?
3. What do you think this is useful for?

Context for Survey Question 1: "What Do You Think This Is?"

Several decades of research on children's understanding of maps have shown that mastery of what a map is and what it represents develops only gradually across childhood and even into adulthood. Liben and Downs (1989, p. 193) framed the question well: "Underpinning our discussion of maps is a fundamental question: How do children know what they are looking at? When and how do children understand that a pattern of lines and colors or gray tones on a sheet of paper stands for a particular place in the real world?"

Liben and Downs (1989) studied children's understanding of maps by asking them to identify whether or not various images were maps. Children correctly categorized as "maps" those representations that show places on a small to medium scale, have

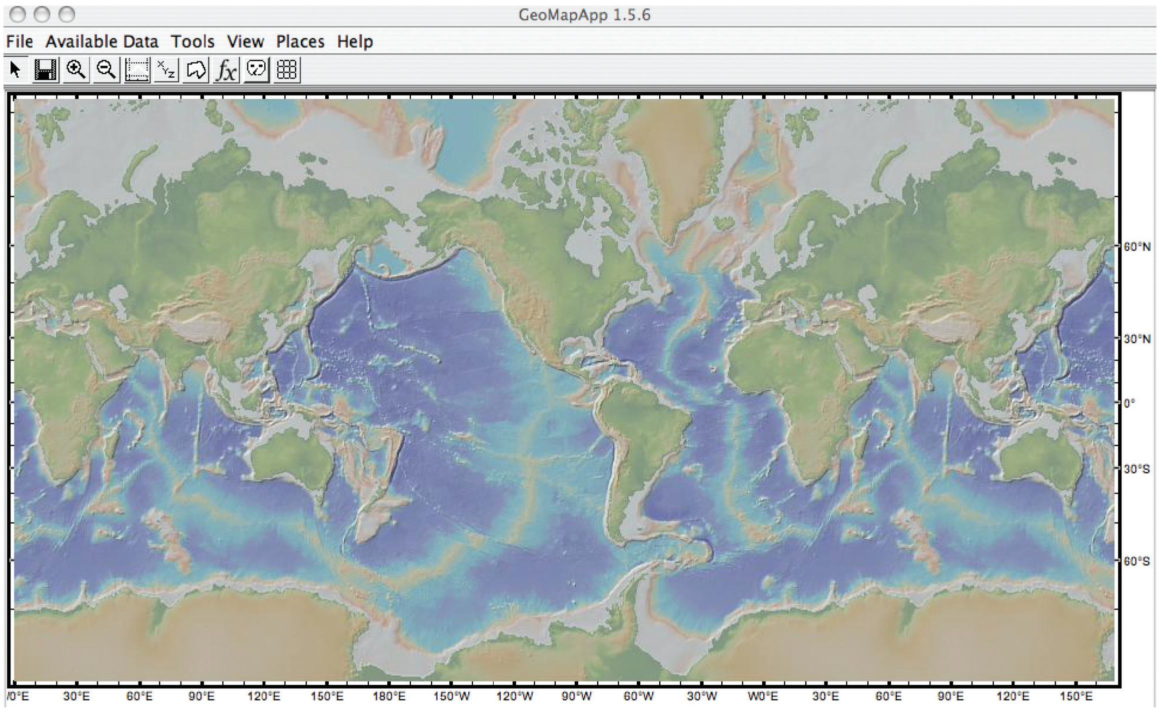

Figure 1. Digital elevation map produced by GeoMapApp as viewed by student participants. Students viewed map in color on a classroom screen, projected by a computer projector. The color version can be accessed from http://www.geomapapp.org/.

color, are seen directly from overhead, and have conventional cartographic symbols, for example, a standard road map. Any deviation from this kind of map increased the likelihood that children would not categorize the representations as a map.

All external representations, including maps, have a dual existence, in that they *are* something and at the same time they *stand for* something (DeLoache, 2000; Liben, 2003). A map exists as an entity on paper or screen, characterized by observable attributes such as color and size. At the same time, the map *stands for* something—Earth or a portion of Earth. To distinguish between these concepts, we will refer to the map as the "representation," and Earth, or more specifically the depicted aspects of Earth, as the "referent" of the map (MacEachren, 1995). Understanding the nature of a map representation does not imply that a person necessarily understands the referent or the connection between referent and representation. For example, in Liben and Down's (1989) study, students who could successfully identify a representation as "a map" did not "reasonably understand" (p. 181) the particular places the maps were intending to represent.

Context for Survey Question 2: "How Do You Think This Was Made?"

The second question examined students' epistemological model for the information displayed in the data map. Prior research (e.g., Brasell, 1987; Mokros and Tinker, 1987; Nachmias and Linn, 1987) has shown that collecting and displaying data in a microcomputer-based laboratory improves students' interpretations of graphs. When students experience the connections among the actions of the person collecting the data, the instruments collecting the data, the referent (i.e., the phenomena being measured), and the resulting representation (the graph), their ability to make insightful and accurate interpretations of the representation improves.

For many geoscience data representations, including global bathymetry/topography maps, such direct experience is lacking. Bathymetry and topography have been collected over long periods of time, using sophisticated tools that students do not have access to, and include submarine areas of Earth that people cannot view directly. Although a few exemplary geography curriculum materials involve students in making maps by direct observation of authentic environments (e.g., Sobel, 1998), most students do not have experience with making even the simplest of maps by making observations of the referent.

Based on the research on student-collected data (Germann and Aram, 1996; Kanari and Millar, 2004; Hug and McNeill, 2008), we consider it plausible, but unproven, that students' understanding of data that they did not collect would be stronger if they understood the basics of how the data were acquired and processed. There is no perfect substitute for being there oneself, making decisions as the experiment unfolds and gaining an embodied sense of the scale and scope of the phenomena of study. However, an intellectual, nonexperiential understanding of the origin of the data could enable students to detect flaws in the data (Nachmias and Linn, 1987) and may help to protect them against other forms of ignorance-based misinterpretation. An understanding of where data come from is also part of the larger science education agenda of helping students develop an epistemological model for science, i.e., an understanding of how scientists know what they know (Bransford et al., 2000).

We could find no prior research on K–12 students' understandings or misunderstandings about the ways in which bathymetric and topographic data are collected or processed into data visualizations. As a starting point for comparison, we developed an epistemological model of how an expert envisions the sequence of knowledge-generation processes that underlie the global elevation map used in our study (Fig. 2).[1] In our experts' epistemological model, data are first acquired from Earth, using a variety of sensors mounted on ships or satellites, using different technologies for the subsea and terrestrial parts of the globe. Second, the individual data streams are processed, using various assumptions and calibrations, to turn the raw sensor data plus navigation into depths and heights as a function of latitude and longitude. Next, the data from different sources are merged, coping with gaps and overlaps in data such that every point on the globe is associated with a single elevation value, to form a global digital elevation model. Finally, a representation is generated from the DEM according to choices made by the user as to color palette, vertical exaggeration, etc. Every step along this information chain is mediated by human decision makers and by software.

Context for Survey Question 3: "What Do You Think This Is Useful For?"

Maps have a purpose (Liben, 2003). Maps are useful for recording, conveying, organizing, and finding out information about the location, shape, and configuration of features on Earth's surface. Because Earth processes cause location, shape, and configuration of natural features, maps are also useful for making causal inferences about events in Earth history that shaped Earth's surface. Location, shape, and configuration of surficial features also impact human society in terms of land use, watercourses, transportation pathways, and so forth; thus, maps can be useful for explaining and planning human/environment interactions.

Another way of probing students' preconceptions is to ask them about the purpose of the map. In order to comment on purpose, students already need to have some kind of interpretation of what the symbols and colors mean as explored in question 1. However, their interpretation need not be detailed or correct in order to formulate ideas about purpose. For example, when people see the classic "Rand McNally" cartographic conventions, they know this is a road map and that road maps are for finding one's way (Downs and Liben, 1987), even though they cannot yet interpret all the symbols.

Some maps advertise their purpose, as for example, road maps and navigational charts. The map used in this study does not state its purpose, and so the students must make inferences from their prior knowledge and life experience, plus evidence within the map itself to answer these questions.

One way to formulate ideas about utility would be to consider the map itself. MacEachren (1995) suggested that individuals use feature identification and feature comparison to make sense of scientific visualizations. For example, the inclusion of latitude and longitude may be interpreted as an indication that the map was intended for navigation.

Another possible approach would be to think in terms of potential users (e.g., for students, scientists, fishermen, or the creator of the map). Thinking about the map-creator's intention may be important in light of Myers and Liben's (2008) recent finding that children's interpretations of maps depend on whether or not they were aware of the map-creator's symbolic (semiotic) intent. Since the students in our study did not collect the data or create the map itself, they do not have the insight about the creator's mindset that they would have had if they had collected the data and created the map themselves.

Contributions of This Study

The purpose of this study was to investigate conceptions that students have about a data map of a type that is widely used by the geoscience community in order to design curriculum and pedagogical methods suitable for using such a map in the K–12 science classroom.

After analyzing 196 student responses, we were able to make observations and inferences about student awareness of:

1. the nature of the representation;
2. the scope of the referent;
3. the aspect of the referent that is depicted;
4. the fact that some kind of information/data/observation had to be acquired from Earth to make the map;

[1]Development of the experts' epistemological model: Prior work that informed the epistemological model included Robinson and Petchenik's (1975) classic depiction of cartographic information flow from the represented space, through the mapmaker, to the map, and thence to the map reader, and Chayes' (1999) diagram of information flow from sensors to geoscience data products. Kastens extended Robinson and Petchenik's concept to environmental policy and Earth system education in Ishikawa et al. (2005) and Kastens and Turrin (2006). The initial draft of the current model was developed by Kastens, drawing from her training and experience in marine geology. Kastens' initial model was then refined through iteration with two additional experts: Dale Chayes and Andrew Goodwille. An oceanographic engineer, Chayes is the codeveloper of a widely used software system for processing and analyzing swath bathymetric data (Caress and Chayes, 2009), has installed and supported seafloor mapping hardware and software on numerous oceanographic ships, and has collected geoscience data on over 100 research expeditions on land, sea, and ice. Trained as a geophysicist, Goodwille is the data manager and education coordinator for the Marine Geoscience Data Center, the facility that developed, maintains, and serves the database and visualization tool used to make the visualization used in this study. Kastens, Swenson, Chayes, and Goodwille cycled through multiple versions of the epistemological model seeking a balance among the following criteria: accuracy, simplicity for communication with a nonspecialist audience, and extensibility to other Earth data types. The prototype version of the epistemological model motivated our decision to ask question 2. The final version of the epistemological model was informed by the student responses to question 2.

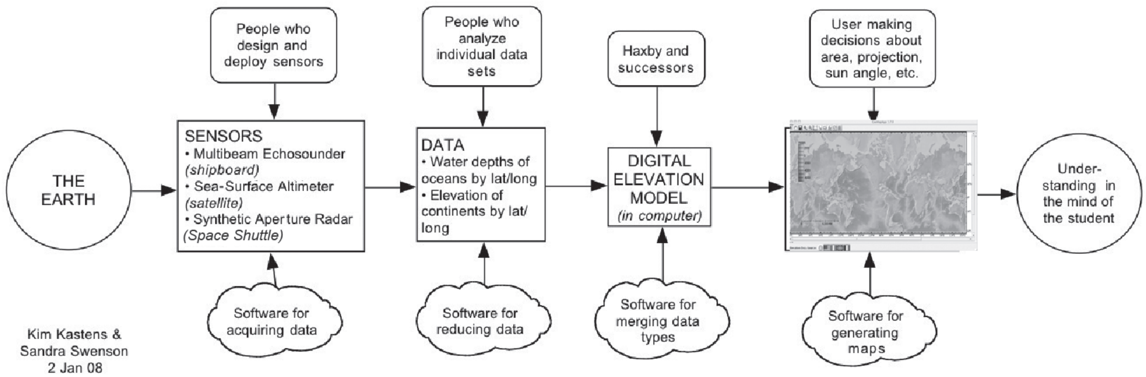

Figure 2. Diagram summarizes an expert's epistemological model for the knowledge encapsulated in the GeoMapApp representation. How much of this do teachers and students need to know to teach and learn effectively from the representation?

5. the roles, if any, of people, instrumentation and equipment, and computers and computer software in making the map; and
6. the usefulness of the map and for whom the map would be useful.

METHODOLOGY

Our methodology builds on prior research on learner's conceptions and alternative conceptions (e.g., Driver et al., 1985, 1996); however, we extend this line of research by examining students' understanding of data and data visualization rather than their understanding of a science concept. This research is grounded in the views of the participants of this study (Creswell, 2003, p. 14) who were surveyed in the natural setting of their classroom with their teacher and a researcher (Swenson) present.

Participants

In total, 196 science students participated in the study. The students were studying various science courses in grades 8 through 12 in suburban New Jersey and New York. A breakdown of the participants is as follows: 105 eighth-grade earth science students, 26 ninth-grade biology students, 43 twelfth-grade marine science students, and 22 twelfth-grade Advanced Placement (AP) biology students. Except for a few students who moved in from out of state, all participants had studied earth science for at least a half-year in the current year or an earlier grade. All had studied landforms and topographic maps in their class.

The objective of this sample was to cast a broad net to gather a wide range of conceptions on a previously under-researched topic from a relatively large and varied population of students. Grades 8–12 were targeted because it is in those years where students' "knowledge and use of representations should expand in scope and complexity" (National Council of Teachers of Mathematics, 2000, p. 361) and they should be developing the skill of "mak[ing] inferences and drawing conclusions from maps and other geographic representations" (Geography Education Standards Project, 1994, p. 55). It was not our goal to make comparisons between schools or across grades.

Materials

The digital topographic and bathymetric map that students viewed (Fig. 1) was the default global map created by GeoMapApp (Carbotte et al., 2004, 2005). GeoMapApp is a scientists' tool, and at the time of our study, the map was not incorporated in any educational or outreach materials. This representation is a Mercator projection with latitude and longitude tick marks along the margin. Latitude spans from 60°S to 80°N, while longitude includes 360° plus a repeat of another 170°. This projection allows an uninterrupted view of all the world's oceans and seas except for the central Arctic and far southern oceans. The topography and bathymetry are shown as color-coded shaded relief, with a vertical exaggeration of 2×. Topography is represented by shades of green and brown, while deepening shades of blue represent bathymetry. The color choices and shaded relief combine to create a representation that resembles Earth as seen with the human eye. The extent to which a representation is similar to its referent (rather than relying on arbitrary or culturally specific symbols) is called "iconicity" (MacEachren, 1995); the map used in this study has a high degree of iconicity. No map key is included on the GeoMapApp default map.

Instrument

A survey design was chosen in order to sample the greatest number of students. The survey was conducted using three open-ended questions: (1) What do you think this is? (2) How do you think this was made? (3) What do you think this is useful for? Respondents wrote their ideas on one sheet of paper.

Open-ended questions were used because there was little applicable prior research, and we did not want to prejudge or constrain the nature of the understandings and misunderstandings that could emerge from the study. This instrument was not pilot-tested because the researchers did not want to be bound to pre-established constructs but rather to utilize an inductive approach to analyze the collected data. Miles and Huberman (1994) explained that predesigned and structured instruments may preclude the researcher from context-rich phenomena that emerge from the data. The questions asked of students in this study were intended to be general enough so as not to be leading, allowing key themes to emerge naturalistically from the data rather than fitting the data into a predetermined framework.

Researchers' Location Relative to this Study

The first author's background is in science education, and she came to this area of research through an interest in understanding the conceptions (and alternative conceptions) students have about scientific data and data visualizations. The first author has been a science teacher of middle school, high school, and college. She completed a doctorate in earth science education based on dissertation research (Swenson, 2010) that examined another type of topography/bathymetry representation as well as the one used in this study. Her role in this study was to recruit the volunteer teachers, acquire the data in the classroom, develop the initial coding scheme, and draft the manuscript.

The second author is a marine geologist by training who has extensive experience collecting and analyzing data of the type found in the Haxby map, including ~22 mo at sea and publication of original bathymetric maps (e.g., Kastens et al., 2000). She came to this study through an interest in students' understanding of maps (Kastens et al., 2001; Kastens and Liben, 2007) and as the education and outreach coordinator for the Ridge 2000 Open Data Exchange System (RODES). She identified the data set as important and deserving of educational research, brought expertise on spatial thinking to the project, developed the epistemological model, served as second coder on all the data, and assisted in writing the manuscript.

As an earth science educator and an earth scientist, we are deeply familiar with the data visualization used in this study, and we realize that this may have interfered with our ability to "see though the eyes of" a student viewing this data set for the first time.

Procedures

The location of this research was the students' normal classroom environment. The researcher was invited into the classroom by the instructor to administer the survey and to provide follow-up discussion about the three questions the next day. At the beginning of a regular class session, students were able to observe the teacher and experimenter using the classroom computer to retrieve from the Internet the topography/bathymetry representation and then project it on a screen.

Students were then handed the questionnaire and were requested to respond as best they could while viewing the overhead display. They were told that there were no right or wrong responses because the researcher was seeking intuitive responses from the students, that is, what came naturally to them rather than a response the participants thought the researcher or instructor would want to hear. What students "choose to talk about is an indication of what they think is important, even if they don't talk about everything they know" (Chi, 1997, p. 305). Students were given the class period to complete the questionnaire, but all finished within 35 min of class time. In a class meeting the following day, the experimenter debriefed the students by having a discussion about the three survey questions. She also led a hands-on activity in the computer laboratory, making use of some of the more advanced capabilities of the GeoMapApp tool. After participating in these activities, the students could download the data set onto their home computer if they chose to do so, because the data set is freely accessible via the Internet.

We also had an opportunity to survey 33 geoscientists with these three questions as they viewed this same data map. The experts were given the survey prior to a research seminar on students' understanding of maps and were therefore self-selected for an interest in this topic. These expert responses informed our suggestions about how to move students toward greater expertise in the use of data maps.

Coding

In thematic content analysis, the themes are extracted from the text of the participants' responses rather than established a priori, so that themes emerge naturally from the data and can be linked or reorganized to develop a dominant structure (Miles and Huberman, 1994; Chi, 1997; Libarkin and Kurdziel, 2002). In the analysis, the experimenters examined the keywords and phrases that students used to describe what they were seeing, how they thought the representation was made, and what they thought the representation was useful for.

After a discussion of a sample of student responses, the lead author created an initial coding scheme, criteria, and examples for each question. Coding categories were iterated until both authors felt the categories captured the range of responses. Each researcher then read each student response separately and tallied the responses under the code that they thought best matched the student response. Inter-rater reliability was determined to be 91% for question 1, 96% for question 2, and 93% for question 3. Disagreements in analysis were resolved through discussion until a consensus analysis could be agreed upon.

Examination of the initial broad-scale coding generated follow-up questions, which we pursued by further dividing or combining some initial categories. This second-order coding was treated the same as the first-order coding with respect to iterating coding categories, independent tallying by both researchers, and resolution of discrepancies through discussion.

Coding for question 1 was completed before beginning coding for question 2, and coding for question 2 was completed before beginning question 3; however, the researchers were free to use the other two responses by the same student in order to clarify ambiguities in a response.

In interpreting the results, readers should keep constantly in mind that whereas presence of an element in a student's response surely means that they had awareness of that element, absence does not necessarily mean that they were *un*aware of this element.

Establishment of Validity and Reliability

As discussed already, we intentionally designed the instrument with broad, open-ended, simply worded questions to allow whatever was in the forefront of the students' minds to emerge in their own words. The use of open-ended questions is in the tradition of research on students' prior and alternative conceptions (Driver et al., 1985). Although such questions bring forth the students' ideas cast in the students' own words, a limitation of this technique is that respondents may not say everything that they know.

The reliability of this instrument was corroborated in two subsequent contexts. Swenson (2010) used questions 1 and 2 along with follow-up interviews with a population of college, non–science majors. Swenson (personal observ.) used all three questions with a population of geoscience experts. In both cases, the same broad themes emerged from the responses.

Within the current study, inter-rater consistency of the coding categories and the assignment of student responses to coding categories were evaluated through dual coding by both authors of every response to every question. Inter-rater reliability was calculated for each question, as described previously, and all were above 90%.

RESULTS

Question 1: "What Do You Think This Is?"

Primary Coding

In 88% of the responses, students indicated (1) that the displayed image was a map and (2) that it was about Earth. In other words, a high percentage appeared to grasp both the nature of the representation, and the basic representation-referent relationship.

Within the near-universal understanding that students were viewing a map of Earth, the most common theme (Table 2) that emerged included responses that provided only very basic geographic information, such as the existence of continents and oceans and a latitude/longitude grid. Illustrative are "1 and a half map[s] of the world," and "map of the world with all of the coordinates." A geoscientist would view such a map as a basemap onto which additional data types could be layered, so we coded such responses as "Basemap." A visualization of the "Basemap" construct might look something like the diagram in Figure 3, a map showing just basic geographical information. Forty-four percent of the total student responses (87/196) fell into the "Basemap" category (Table 3; Fig. 4). For all classes except eighth-grade earth science, "Basemap" was the modal response.

The second theme was student descriptions about topography and/or bathymetry ("Topo"). This is the accepted interpretation of the representation that was intended by the data map creator and would be offered by most geoscientists. Responses in this category may include "Basemap" information, but they stated or implied something about height (elevation) or depth below sea level or the shape of Earth's surface or the existence of specific landforms. Most students are not familiar with the word "bathymetry," so we relied upon descriptions about physical features of the seafloor, such as "showing all land and water mass on Earth, including undersea mountain ranges" (Table 2). Thirty percent of the total student population (59/196) described the map as representing topography/bathymetry (Table 3; Fig. 4).

The third theme was student descriptions of aspects of the Earth *other than* topography/bathymetry. "NonTopo" responses were usually alternative observations or interpretations of the representation referring to attributes of the Earth that were not shown on the provided map. Examples include: weather patterns, clouds, ocean currents, tides, or even the level of sodium (Table 2). Some alternative interpretations seem to have been triggered by the map's colors, for example, "… It looks like the different colors in the water especially are showing different currents," and "… the type of terrain found on certain regions of the Earth. While green represents a lush and treeful environment, dark browns symbolize a barren and desert-like terrain." Between 11% and 14% of each class stated that the map showed aspects of Earth that were not in fact on the map (Table 3; Fig. 4).

Some responses referred to topography/bathymetry but also included NonTopo (Table 2). Such responses were coded as "Topo&NonTopo," for example, "I think this is an elevational topics chart. Showing elevation by ridges and tan color. Shows temperature by different blues also white for cold water." Between 5% (twelfth grade AP) and 11% (eighth grade) responded in the "Topo&NonTopo" category (Table 3).

Finally, we included an "Ambiguous" and a "No response" category for responses that were not clear or when a student did not respond.

Secondary Coding

To better understand students' conceptions about what the map represented, we further subdivided the nontopographic responses in the "NonTopo" and "Topo&NonTopo" categories (Table 4). There were 24 "NonTopo" responses plus 17 "Topo&NonTopo" responses, giving a total of 41 responses analyzed; however, some descriptions included multiple elements and so were tallied in multiple categories. Seventeen out of 41 students (41%) described the digital elevation map as displaying something about the fluid Earth, where most of these responses were about tides and currents. Twenty-two out of 41 (54%) responded with a description about the solid Earth, including plate tectonics. A small percentage (7%) discussed the global elevation map within the context of biology. Information about the fluid Earth, biomes, and plate tectonics might be inferred from the data map, but the map itself does not represent any of these phenomena directly.

TABLE 2. CODING OF MAJOR THEMES THAT EMERGED FROM QUESTION 1: "WHAT DO YOU THINK THIS IS?"

Category/criteria	Keywords	Examples
Basemap: • States or implies an area of Earth's surface, may be a region or the entire planet. • Focus on basic geography, including continents, lat/long grid • No mention of any earth science data types	Map, globe, Earth, World, latitude and longitude, continent, coastlines	• I think this is a map showing the latitudes and longitudes of a part of the world. 8th gr. • A map creator that allows you to focus on certain coordinates. 8th gr. • A world map. 8th gr. • Map of the world with two Africas, Europes, and Australias. 9th gr. • 1 and a half map[s] of the world. 9th gr. • A map of the world. 12th gr. OS • A map of the globe, but flattened. 12th gr. AP
Topo: • Must mention either height/depth or shape of Earth's surface • May also include "basemap" information • Need not include terms "bathymetry" or "topography"	Height, depth, ocean depth, elevation, topography, physical features Also names for specific landforms such as mountain	• I think this is a topographic map, and it shows different level[s] of continent and ocean. 8th gr. • This is a map of the world showing elevations of different areas of the Earth (altitudes). 9th gr. • A map showing a physical landscape of the Earth. I think it shows elevation/depression indicated by color. 9th gr. • World map (Mercator map) showing all land and water mass on Earth, including undersea mountain ranges. 12th gr. AP
NonTopo: • May include "Basemap" information • Must not include "Topo" information • Must also include one or more other aspect of Earth, neither "Topo" nor "Basemap"	Terms for natural phenomena, such as weather, climate, biomes, or geological structures Terms for Earth processes such as tides, plate movement, or continental drift	• A map of the world's boundaries along with the climates of the Earth (ex. white near the pole is snow/glaciers, tundra). 8th gr. • High tide and low tide. 8th gr. • A map showing the different kinds of lands around the world, example: swamp, dessert *[sic]*. 8th gr. • Fault lines on the map of the world. 9th gr. • I think this is a map of the world that shows weather conditions and things like that. It looks like there are clouds. 12 gr. OS
Topo&NonTopo: • Must include "Topo" information • Must include "Other" information • May include "Basemap" information	See above	• I think this is an elevational topics chart. Showing elevation by ridges and tan color. Shows temperature by different blues also white for cold water. 8th gr. • I think this is a topographic map of the world which also depicts fault lines of major tectonic plates. 9th gr. • It is a map of the Earth, showing not only topography but sediment deposits as well. 12th gr. OS • This is a map of the world after much of the ocean was evaporated away or underwater volcanoes. 12th gr. AP
Ambiguous • Response was not clear		• I think this is a map of everything and telling you where you can find it. 8th gr. • I think this is what the world used to look like. 9th gr. • Earth's shifting over time. 9th gr.
No Response • Student did not answer question 1		

Because GeoMapApp was developed for marine geology and geophysics, the map design was optimized for examinations of the ocean basins. To examine to what extent students attended to the ocean basins, we further divided question 1 responses in the "Topo," "Basemap," and "NonTopo" categories into "Continent," "Ocean," "Both oceans and continents," or "Neither" (Table 5). As a group, the Basemap responders attended to neither the oceans nor continents—77% of "Basemap" responses fell in the Neither category. Instead, most "Basemap" descriptions were about "a map of the world," with some references to "latitude and longitude" or "coordinates." The "Topo" group paid more attention to continents than oceans (44% vs. 5%), whereas the "NonTopo" group paid more attention to oceans than continents (38% vs. 25%).

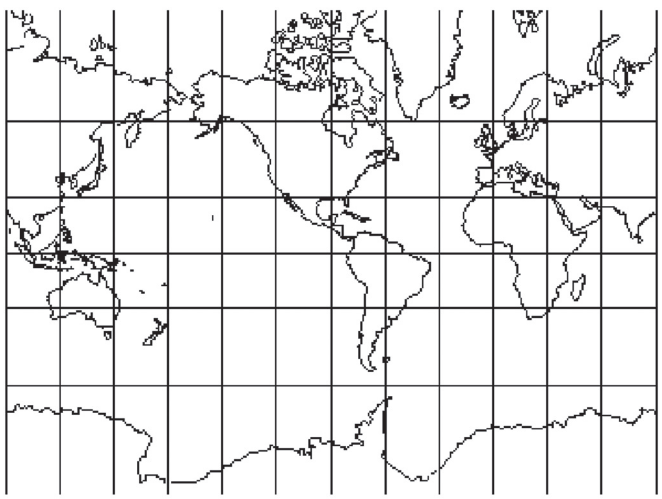

Figure 3. A visual representation of the "Basemap" coding category of question 1. This type of response mentioning only area, latitude, longitude, and perhaps continents or coastlines was the most common response across the population studied (from G. Evenden, U.S. Geological Survey, 1995, public domain; accessed June 2008).

Question 2: "How Do You Think This Was Made?

Primary Coding

Five themes emerged for question 2 (Table 6). Many of the responses included multiple themes; therefore, the researchers allowed more than one coding category for each response.

The first theme was that students stated or implied that the representation was made by a person or people. Such answers might mention a specialist such as a "scientist" or a "cartographer," or a more generic "person," or "someone." Diverse roles were described for these people, related to both collecting the data and generating the representation. Illustrative responses are: "I think this map was made by people who discover and research the features of the land," and "A cartographer most likely started out by mapping the land masses and water regions of the Earth as he would normally do for a spherical globe, but then spread his reproduction into the shape of a rectangle." Eleven percent (21/196) of the total student population responses was coded as mentioning that a person or people were involved in making the map (Table 7; Fig. 5).

The second theme encompassed various aspects of data acquisition, subdivided according to whether the focus was on the type of data acquired or on the tool used for data acquisition. The essential element of this theme is that the response stated or implied engagement with the referent, Earth. Data types mentioned by students included data height and depth (coded as category 2A-1), or a physical property other than topography/bathymetry (2A-2), for example, salinity. Data acquisition tools ranged from "satellite," spaceship, or "space station" (2B-1) to "pictures" (2B-2) to "ship" or "submarine" (2B-3). We also included categories for other tools (2B-4) and data acquisition without a specified tool or other data type (2C).

Data acquired from a satellite or spaceship (2B-1) was the highest percentage in all of the categories for data acquisition,

TABLE 3. DISTRIBUTION OF STUDENT RESPONSES TO QUESTION 1: "WHAT DO YOU THINK THIS IS?"

	Eighth-grade earth science (%)	Ninth-grade honors (%)	Twelfth-grade ocean science (%)	Twelfth-grade Advanced Placement (%)	Total (%)
	n = 105	*n* = 26	*n* = 43	*n* = 22	*n* = 196
Basemap	32	50	65	55	44
Topo	39	23	14	27	30
NonTopo	11	12	14	14	12
Topo&NonTopo	11	8	7	5	9
Ambiguous	3	8	0	0	3
No response	4	0	0	0	2

Note: Table shows percentage of student responses in each class that were coded in each category. For question 1, primary coding, each response was coded in only one category. Columns may not sum exactly to 100% because of rounding errors.

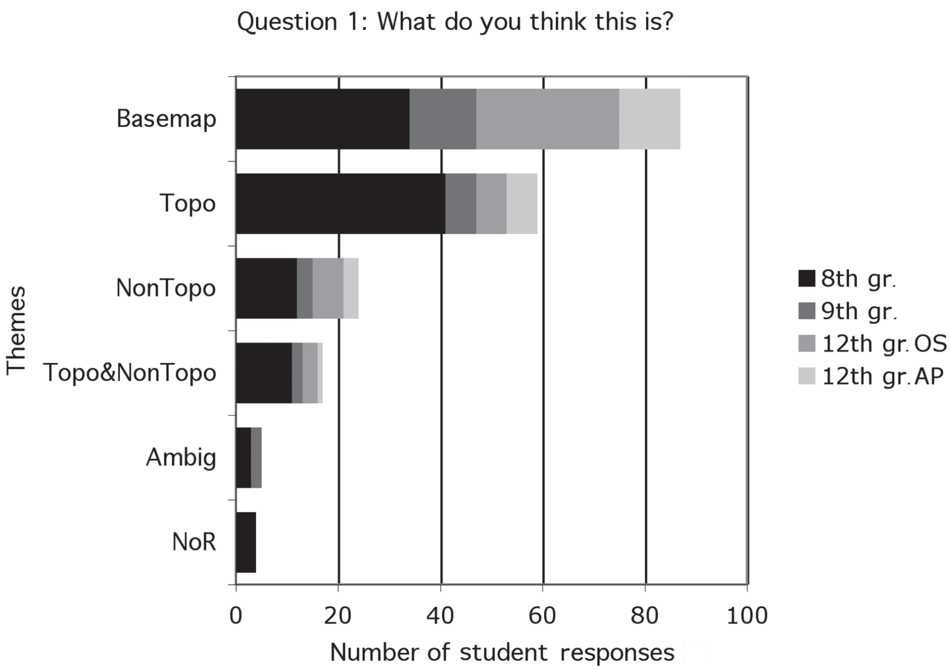

Figure 4. Student response to question 1: "What do you think this is?" The graph shows the number of student responses per coding category, as defined in Table 2. Close to half of the students (87/196 or 44%) described a map with only basic geographic information ("Basemap" category). Less than a third (59/196, or 30%) of total students interpreted the data elevation map to represent elevations/depths or landforms ("Topo" category), which is the professionally accepted interpretation. Eleven percent of the students described other aspects of Earth ("NonTopo" category) that were not in fact represented on the map.

TABLE 4. SECONDARY ANALYSIS OF NONTOPOGRAPHIC RESPONSES TO QUESTION 1

Key concepts	Keywords	Examples	Number of occurrences	Total
Fluid Earth: Student states or implies attributes about the ocean or atmosphere.	Tides, currents, ice	• A map of the world showing tides • I think this is a picture of a map with longitude and latitude degrees on it. It looks like the different colors in the water especially are showing different currents.	9	
	Weather, winds, clouds	• In addition to demonstrating measurements of longitude and latitude, the map seems to exhibit weather patterns.	3	
	Sodium, salinity, saltiness	• I think this is a map of where there are high levels of sodium.	1	
	Air temp., water temperature	• A temperature/thermo map • This is an image of the water temperature for all of Earth's oceans.	4	**17**
Solid Earth: Student states or implies attributes about the solid Earth.	Kinds of land/types of terrain	• A map of the world['']s boundaries along with the climates of the earth (ex. white near the pole is snow/glaciers, tundra). • A map showing the different kinds of lands around the world, example swamp, dessert [*sic*].	6	
	Plate tectonics/plate boundaries, crust, fault lines, volcanoes	• A map of the world's plate boundaries and countries. • It's a map of the world, however, Australia is noticed twice instead of once. Also plates are noticed in the background while countries are in the foreground.	11	
	Rock types; sediment	• It is a map of the Earth, showing not only topography but sediment deposits as well. • Some sort of geological map w/coordinates so you can pinpoint certain locations.	5	**22**
Biology: Student states or implies attributes about living things.	Animal/ migration patterns; plants/vegetation; biomes	• A map of the world that shows vegetation with green and either desert or tundra with off white. • This is a map of the world showing tidal water flow or migration patterns.	3	

Note: This table encompasses 24 responses coded "NonTopo" plus the erroneous portion of 17 responses coded "Topo&NonTopo." A response could be counted in more than one category of this tally.

TABLE 5. TALLIES OF RESPONSES ABOUT THE CONTINENTS, OCEANS, BOTH, OR NEITHER

Response type	"Topography"	"Basemap"	"Other"
	$n = 59$	$n = 87$	$n = 24$
Continent	<u>44%</u>	14%	25%
Ocean	5%	0	<u>38%</u>
Both ocean and continents	36%	9%	8%
Neither	15%	<u>77%</u>	29%

Note: Underlined values are the most abundant in both their row and column.

TABLE 6. CODING OF MAJOR THEMES THAT EMERGED FROM QUESTION 2: "HOW DO YOU THINK THIS WAS MADE?"

Category/criteria	Subcategories and keywords	Examples
1. *People/scientist or man-made:* The student response refers to a person involved. Focus on description about a person.	"Scientists, "human," "someone."	• I think it was made by scientists who explored the ocean, and somehow predicted what the layout of the ocean would be if the world continues its process. 8th gr. • A combination of satellite and human examination and surveying. 9th gr.
2A. *Data acquisition type:* Student states or implies that some kind of data of a specific type were acquired.	**2A-1.** Student response refers to acquisition of height or depth data: "depth," "height."	• By measuring the land depth and sea depth. 8th gr. • This was probably made by collecting measurement of each region's height in relation to sea level, and then shown in this image comparatively. 9th gr.
	2A-2. Student response refers to acquisition of specified data type, neither topo/bathy.	• I think it was made by scanning a map into the computer & highlighting the places of high *sodium*. 8th gr. • I think this was made by scientists who study *precipitation*. 12th gr. AP
2B. *Data acquisition tools:* Student states or implies that a data acquisition tool was used to make the representation.	**2B-1.** Student response refers to a tool in space: "satellite," "space ship."	• Satellite pictures. 8th gr. • This was made from satellite images. 8th gr.
	2B-2. Student response refers to "photos" or "pictures" to acquire data.	• I think it was made by taking a picture of the Earth, and then making a flat, square kind of Earth. 8th gr. • Picture from space. 8th gr.
	2B-3. Student response refers to tool in the ocean: "ship," "submarine," "sonar."	• I think that this was made from information taken by a satellite and possibly deep water submarines or submersibles such as "Alvin." 12th gr. OS
	2B-4. Student response refers to other tools: "heat sensors," "infrared heat imaging."	• Most likely using a compilation of satellite imaging and geological surveying as well as infrared heat imaging. 12th gr. AP • Heat sensors. 12th gr. OS
2C. *Data acquisition:* Unspecified; student does not specify data type or tool.	"Measurement," "observations," "accurate data collection," "studying physical features."	• This map was probably made from accurate data collection and carefully planned pointing out of some of the Earth's physical features. 8th gr.
3. *Representational technique and technology*	**3A.** High-tech: Computer or computer software	• This was probably made with spiffy editing equipment that allows the image to be copied and pasted. 9th gr. • A computer and other technologically advanced equipment. 12th gr. AP • This was made by computer graphics. 12th gr. OS
	3B. Low-tech: sketch, clay	• Plastics/ paper/gluing. 8th gr. • By taking two pictures of Earth and sticking them together. 9th gr.
4. *Prior map:* Student states or implies a map was the starting point used to create the representation.		• This was made with a map then adding different color[s] where they wanted areas to stand out. 8th gr. • I think this was made by a computer flattening out a globe and connecting the two resulting pictures.12th gr. AP
5. *Referent:* Response describes how the referent or an aspect of the referent was made rather than the representation.		• From the moon pulling from the Earth. 8th gr. • Continental drift. 9th gr. • By God. 12th gr. OS

TABLE 7. TALLIES OF RESPONSES FOR QUESTION 2: "HOW DO YOU THINK THIS WAS MADE?"

Coded category	Primary coding (%)	Secondary coding (%)
1. People	**11**	
2A-1. Data acquisition: Data types: height, depth	**9**	**44**
2A-2. Data acquisition: Data types: other	**2**	
2B-1. Data acquisition: Tools: satellite, or from space in general	**27**	
2B-2. Data acquisition: Tools: photography/taking pictures	**12**	
2B-3. Data acquisition: Ship, submarine, sonar	**2**	
2B-4. Data acquisition: Other	**5**	
2C. Data acquisition: Unspecified tool and technique	**8**	
3A. High-tech: Computer: computer software or program	**39**	
3B. Low-tech: representation methods (sketch, etc.)	**14**	
4. Prior map	**13**	
5. Referent	**8**	
6. No idea, not sure	**4**	

Note: Primary coding equals number of students providing this response divided by 196 students; column does not sum to 100 because some responses contained multiple elements. Secondary coding equals number of students providing *any* data acquisition (2A-1 through 2C) divided by 196 students.

with 27% (53/196) of the student responses coded in this category. The second most frequent response was in the category for data acquisition tools such as photography, or taking pictures 12% (24/196). Only 2% of the students responded that data from a ship, submarine, or sonar were used to create this representation (Table 7; Fig. 5).

The third theme focused on making the representation rather than acquiring the data. The means of making the representation might be high-tech (coding category 3A, distinguished by keywords such as "computer," "computer software," "computer applications," "scanner," or "printer"), or low-tech (category 3B, such as "made by clay," or "sketching"). Out of the total student responses, 39% (76/196) tallied in the "computer" category. This was by far the most frequent response type for question 2, making up more than a third of the students surveyed. Fourteen percent (27/196) of the students described a "low-tech" method of map-making (Table 7; Fig. 5).

The fourth theme was found when a student stated or implied that the starting point for making the representation was an existing map, picture, or globe, rather than Earth (Table 6). For example, "This was made with a map then adding different color[s] where they wanted areas to stand out," or "I think this was made by adding texture to a map of the world to show the physical features." We coded such responses as "Prior map." Thirteen percent (26/196) responded that the starting point for making the map was a map itself (Table 7; Fig. 5).

Finally, for the fifth category (Table 6), students answered the question by describing how they thought the referent was made rather than how the representation was made. For example, some students suggested "the moon pulling from the Earth," "continental drift," and "by God." We coded such examples as "Referent." Eight percent (16/196) of the students responded in terms of making the referent rather than the representation (Table 7; Fig. 5).

Secondary Coding

A key distinction among the responses to question 2 was whether or not the student indicated any kind of data acquisition (Table 7, secondary coding category). Some students provided a rich description of the data acquisition process, including multiple category 2 subcodes, but 56% (110/196) gave no indication at all that some kind of observation or measurement or data collection or engagement with Earth itself was required to make the representation.

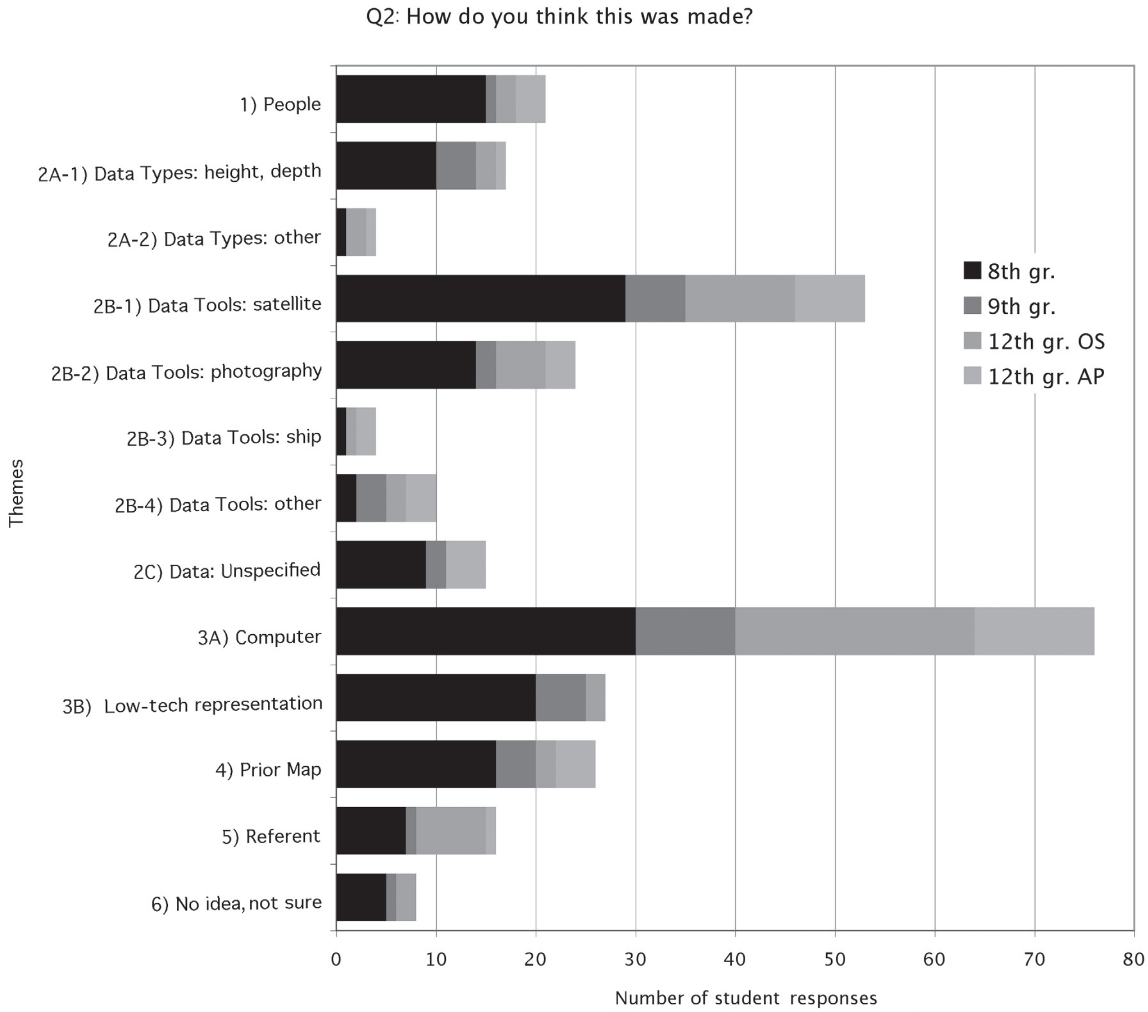

Figure 5. Student response to question 2: "How do you think this was made?" Bars represent the number of student responses exhibiting each coded theme or subtheme; some responses contained multiple themes. Among the responses involving data acquisition (theme 2), data acquired from a satellite or spaceship (2B-1) was the most common, with 27% (53/196) of the students providing responses that were coded in this category. Almost nobody mentioned use of a ship or other seagoing survey platform. Across all of the question 2 subthemes, use of a computer (hardware and/or software) was the most frequently mentioned, with 39% (76/196) of the student responses coded into this category.

Question 3: "What Do You Think This Is Useful For?"

Three major themes emerged from the third research question (Table 8). As in question 2, many of the responses included multiple elements; therefore, the researchers tallied the data, allowing more than one coding category per student response (Table 9; Fig. 6).

The first coding category was "Navigation," where the student described finding one's way or directing the course of a vehicle or vessel. A key element of this category was a sense of movement through space within or across the referent. Illustrative are: "I think this is useful for navigating the ocean floor," or "To show sailors' boats where land masses are on our planet" (Table 8). As a result, 7% (14/196) of the student responses were about navigation (Table 9).

The second theme, "Observations," concerned structures or features of Earth that could be observed directly from the provided map. One subcategory was "Observation about location of Earth's structures or features" (Table 8, 2A), for example, "I think this is useful for finding underwater mountain ranges, deep parts in the ocean and high mountains." The second subcategory was observations about "the shape or configuration [geomorphology] of Earth's structures or features" (Table 8, 2B). For example, "This is useful for discriminating elevations and depths, and finding landmasses and bodies of water." The total number of student responses for observations about location was 39%

TABLE 8. CODING OF MAJOR THEMES THAT EMERGED FROM QUESTION 3: "WHAT DO YOU THINK THIS IS USEFUL FOR?"

Category	Criteria	Examples
1. *Navigation*	Student response includes directing the course of something. May be oneself or an external object. Includes answers that are about travel, but without a specific mention of figuring out where you are while traveling.	• I think this is useful for **navigating the ocean floor**. 8th gr. • To show sailors['] boats where land masses are on our planet **for navigation purposes.** 8th gr. • To **predict the next islands and/or to avoid those places when in a ship.** 9th gr. • Visualizing the continents; **navigating the wide open waters** of our beautiful oceans. 12th gr. AP
2A. *Observation* about location of Earth's structures or features.	The response includes learning about the Earth by observing the map. For example, finding another location, physical feature, or structure.	• I think that this is useful for **finding underwater mountain ranges,** deep parts in the ocean and high mountains. 8th gr. • This is useful for trying to **figure out where everything is.** 8th gr.
2B. *Observation* about the shape or configuration of Earth's structures.	The response includes information about height and/or depth, shape, or physical attributes. Student is making an observation about geomorphology.	• This is useful because it shows us the fault lines and the **different elevations of physical features**. 8th gr. • This is useful for **discriminating elevations and depths,** and finding landmasses and bodies of water. 9th gr. • See different elevations such as mountains. Underwater volcanoes, plates. 9th gr.
3A. *Inferences* about solid Earth, including solid Earth processes.	Student response is about identifying, understanding, or predicting Earth processes. May include identifying patterns or making predictions.	• I think this is useful for **predicting possibilities of volcanic activity or earthquakes/other seismic activity** on the Earth. 9th gr. • Understanding the dynamics of the Earth's crust and the **movements of the tectonic plates.** 12th gr. AP • **Predicting earthquake threats** (as impossible as it might seem); studying marine geography/topography; oil drilling rigs. 12th gr. AP
3B. *Inferences other than* solid Earth.	Student response is an inference about anything other than solid Earth, including atmosphere, ocean (water), plants or animals, people and human activities.	• I think this lets people know **where a lot of sodium is so that they can fish in certain places.** 8th gr. • I think this is useful for **the directions of the currents & how the water moves around the earth.** 8th gr. • If people wish to **predict natural disasters or observe climate patterns,** this map would be a simple way to do it. 9th gr. • Predicting weather patterns and effects. 12th gr. AP
4. *Too general*	Response is too general to convey how this map is useful.	• Learning about the world. 8th gr. • Estimating how Earth will change in the future, and how it has in the past. 8th gr.
5. *No response*	Students did not respond, stated they did not know, or apparently misunderstood the question.	• I have no clue. 8th gr. • It is useful for people to live on and survive. 12th gr. OS *[Here, the student appears to be describing the referent.]*

Note: Only the portion of each response shown in boldface fits the coding category for the row. Response could be coded in more than one category.

(77/196) and for observations about geomorphology was 37% (72/196) (Table 9). These two were by far the most frequently coded response types for question 3.

The third theme, "Inferences," built on the idea that the global elevation map can be useful for making inferences about Earth, even of phenomena that are not directly shown on the map. Making inferences from data is an important skill at the heart of what scientists do. The two subcategories were inferences about the solid Earth (3A) and inferences about anything other than solid Earth (3B). The first subcategory included student responses such as, "I think this is useful for predicting possibilities of volcanic activity or earthquakes/other seismic activity on the Earth," and "Understanding the dynamics of the Earth's crust and the movements of the tectonic plates." The second category included inferences such as, "I think this is useful for the directions of the currents & how the water moves around the earth," or to "predict natural disasters or observe climate patterns" (Table 8). Most inferences focused on making predictions (e.g., of earthquakes) or making inferences from patterns (e.g., location of plate boundaries). No student explained how their suggested inferences could be made from the provided map. Total student responses in these two coding categories were 17% (34/196) for interpretations about the solid Earth and 21% (41/196) for inferences other than solid Earth (Table 9).

TABLE 9. DISTRIBUTION OF RESPONSES BY THEME TO QUESTION 3: "WHAT DO YOU THINK THIS IS USEFUL FOR?"

N = 196	Total (%)
1. Navigation	7
2A. Observations: locations	39
2B. Observations: geomorphology	37
3A. Inferences: solid Earth	17
3B. Inferences: other	21
4. Too general	8
5. No response	9

Note: Column does not sum to 100% because some responses included more than one information type.

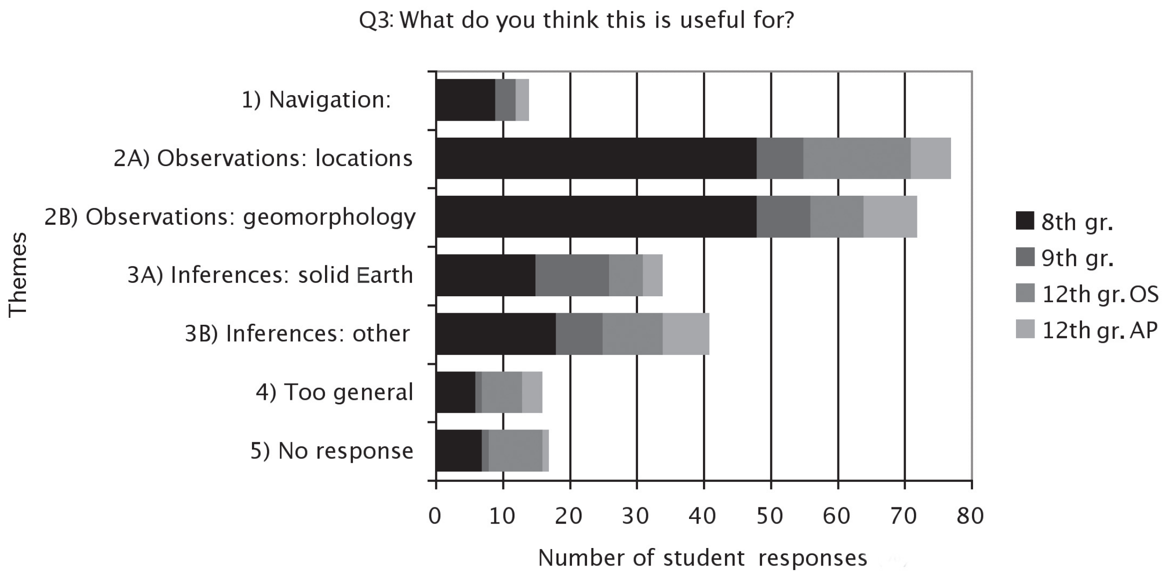

Figure 6. Student response to question 3: "What do you think this is useful for?" Bars represent the number of student responses exhibiting each coded theme or subtheme; some responses contained multiple themes. Most responses focused on using the map to obtain information that could be observed directly on the map, including location and shape of features.

The last three coding categories were about student responses that were too general to convey how the map could be useful (8%) or did not answer the question (9%).

DISCUSSION

Students' Understandings about What the Representation Is

Almost without exception, student responses to question 1 showed that they recognized that they were viewing a map, and that this map represents Earth. This was not a foregone conclusion; in a similar study (Swenson, 2010), involving a less iconic representation of global bathymetry/topography, a nontrivial minority (6%) of college non–science majors described only the colors of the representation, as though describing a work of abstract art, without mentioning the referent. The fact that our study participants were able to recognize the referent, Earth, on a representation they had probably never seen before, suggests that the distinctive visual pattern of the shapes and configurations of the continents are widespread in the visual recognition vocabulary of the population represented by these students.

Forty-four percent of the student responses (those coded as "Basemap") went only as far as identifying the scope of the referent (Earth with its continents and oceans), but they failed to mention any specific data type or aspect of the referent depicted by the representation. Our interpretation of what these students extracted from the viewed map resembles Figure 3 rather than Figure 1.

Only 30% of the responses (those coded "Topo") described a map of topography and bathymetry or allied concepts such as landforms, physical features, mountains, height of the land, or depth of the ocean. We find this result surprisingly low for several reasons. The participants were either current earth science students or had studied earth science within the past 4 yr, and the global bathymetry/topography data set is a fundamental constraint on solid Earth, ocean, and atmospheric processes. Moreover, the map portrays an aspect of Earth (relief) that students have had an opportunity to experience through direct perception and is an iconic representation that resembles the referent.

Students' Alternative Conceptions of the Representation

Responses to question 1 that were coded as "NonTopo" or "Topo/NonTopo" stated or implied that the data map contained information that simply is not there, for example, "I think that this is a world map of different ocean currents of the world. I think that the white and lighter blue lines on the map are the currents and the darker blue is the water," and "…green represents a lush and treeful environment, dark browns symbolize a barren and desert-like terrain."

Why might this be? We infer several possible sources of students' alternative conceptions from the nature of their responses.

First, some students seem to have made assumptions about iconicity that do not match the intentions of the map creator, for example, in interpreting green as vegetation (rather than low elevation) and white as ice or clouds (rather than shallow water depths). They may have assumed that the color scheme they saw on another map (for example, a biome map or weather map) carried over to this map. This would be an instance of "negative transfer," a situation in which a student's "experience with one set of events could hurt performance on related tasks" (Bransford et al., 2000, p. 53). Students may not have sufficient knowledge of visual representational strategies in general or cartographic conventions in particular to realize that the same colors can have different meanings on different maps.

Some students may not have had the life experiences that would have allowed them to take advantage of the iconicity put there by the map-maker. If they have never examined a terrain from an airplane or scenic overlook, the shaded relief aspect of the provided map may not be communicative. If they have not seen how water shades darker as it deepens going offshore across a beach or harbor, the significance of the varied shades of blue on the provided map may have escaped them.

Alternative conceptions were more common for the oceanic parts of the map than for the continents. Among responses coded as "Topo," a plurality (44%) mentioned only the continents; they constructed their answers by ignoring the oceans (Table 5). Conversely, among responses coded as "NonTopo," a plurality (38%) mentioned *only* the oceans. Among the hybrid "Topo&NonTopo" responses, a common pattern is that the alternative conception (NonTopo) refers to the oceans, for example: "I think this is an elevational topics chart. Showing elevation by ridges and tan color. Shows temperature by different blues also white for cold water." Although we do not have data to this effect, we strongly suspect that study participants had greater prior knowledge of the land surface than of the seafloor, because earth science and geography curricula focus on continents and because students' life experience is on land. If this is true, then the pattern of responses to question 1 suggests that students are more likely to misinterpret aspects of the representation where they come to the map with weak prior knowledge of corresponding aspects of the referent.

Finally, some students seem not to have adequately distinguished between "what this is a map of" and "what might be interpreted from the map." Strictly speaking, this is not "a map of fault lines," or "volcanoes," or "plate boundaries." Although the shape of landforms can be suggestive of causal processes such as faulting or volcanism, those are interpretative assertions rather than attributes of the map, and thus are not a correct response to the question "what is this?" Such answers to question 1 actually require a high level of knowledge of earth sciences, and can be considered as *overinterpretations* of the map, the opposite problem from the underinterpretations seen in the "Basemap" responses.

Students' Individual and Collective Knowledge of How the Map Was Made

Data maps are made by acquiring data in the field, processing the data into a manageable form with the intention of communicating something about the referent, and then generating a representation, with human decision making and software mediating each step along the way. Figure 2 illustrates experts' understanding of how the provided representation was created. We had no expectation that students would know how this data map was created, and, not surprisingly, no individual student articulated the entirety of Figure 2. However, encouragingly, most ideas expressed by students fell within the experts' model, and, collectively, the group of students is aware of all the major elements of the model. Students' existing knowledge provides a starting point to inform more purposeful curriculum design going forward.

With respect to the 11% of students who mentioned that a person or people were involved in making the data map, awareness that people are involved in making the representation humanizes the process of science, including the many different contributions made by technicians, engineers, cartographers, and scientists. Moreover, scholars who study symbol systems, of which maps are an example, emphasize that it is a developmental accomplishment for a young symbol-interpreter to understand the "intentionality" of the symbol-creator (Callaghan and Rochat, 2003), in other words, that "symbols mean what they are intended to mean by a creator (not what they happen to resemble)" (Myers and Liben, 2008, p. 682). This is particularly true for arbitrary symbols that have little or no physical resemblance to their referents, such as the colors on our study map. "Intentionality" is a human trait, and thus understanding that a person designed the map is prerequisite to understanding intentionality.

Among the 39% of students who mentioned that computer hardware and/or software was involved in creating the representation, some responses reflect only the awareness that the experimenter used a computer projector to show the image, but others indicate more varied roles for hardware and software in collecting and processing the data, for example, "computer design, drawing software'" "with a satellite through a computer," and "This was made using different programming languages using images probably Flash."

Within the secondary coding category, 44% of all students surveyed said something about data being acquired to make this representation (Table 7). Data acquired from a satellite or spaceship (2B-1) was the highest percentage among the subcategories of data acquisition, followed by photography (2B-2). These two elements were often combined (i.e., taking pictures from space), perhaps because students reason that the field of view of a photograph gets larger as the photographer moves farther away from the subject (Liben, 2008), and so to see the whole globe requires a vantage point in outer space. The actual data type (height and depth) and one of the actual tool types (ship, submarine, or sonar) were rarely mentioned.

On the other hand, 56% of the students did not mention that data were acquired from Earth. Of this group, nearly half indicated that the representation was made by a computer or some computer method with no mention of data acquisition (i.e., their response included 3A but none of the data acquisition codes). In terms of the epistemological model of Figure 2, these students expressed an understanding that reaches only slightly upstream from the representation itself, to the process of making the representation, and not all the way upstream to the processes of collecting and analyzing the underlying data.

Only a handful of responses indicated some process or element that is completely outside of the experts' epistemological model. The 14% (27/196) of students who answered in category 3B low-tech (e.g., "clay," "sketching") described a concept-driven visualization made with artistic techniques rather than a data-driven visualization (Clark and Wiebe, 2000; Kastens, 2009a).

In summary, individual students in our study possessed a partial understanding of where the data map came from and how it was made. Although no student articulated the entire big picture, *collectively*, the group was aware of all of the major elements in the experts' model: people, data acquisition of various types with various instruments, computer hardware and software, the image itself, and cartographic strategies (Fig. 2).

Students' Understanding of Utility of the Map

Students' responses to question 3 ("What do you think this is useful for?") spanned both observations and inferences. Most responses described using the map as a source of information that is actually shown on the map and can be directly observed on the map. Such responses encompassed the concepts of location (response category 2A) and shape (geomorphology, category 2B). As described previously ("Context for Survey Question 3"), maps can be used to depict location, shape, and configuration. Configuration is easy to depict on a map but difficult to express in words, so we could not tell whether students understood that maps are useful as a source of information about the configuration of Earth features.

A substantial fraction of students' responses to question 3 conveyed that maps can be used as the basis for inferences about features or phenomena that are not actually shown on the maps (Table 9; Fig. 6, categories 3A and 3B, "Inferences"), such as location of tectonic plates or volcanoes. In order to use a map to make inferences, the user needs to bring to the table additional information that is not in the map. In the case of the provided data map, the user needs to have and make use of the insight that Earth is dynamic and undergoes processes that cause it to differ from place to place and time to time. The bumps and wiggles of Earth's surface carry meaning or significance, in terms of (1) causative processes (e.g., plate tectonics) and (2) societal and human consequences (e.g., constraints on land use) (Kastens, 2009b).

As is apparent from this discussion, most responses concerned the purpose or purposes for which a map could be used. Some respondents also mentioned the types of people who might find the map useful. A map can be useful to the map creator, as a means of recording and organizing information. A map can also be useful to a recipient of the completed map for finding out or thinking about information. Among such responses to question 3, the apparent beneficiary was always a map recipient; no response suggested the insight that a data map is also useful to the creator of the map.

Liben and Downs (1989) noted that young children can recognize a road map as something useful for finding places before they can interpret the details of the map, let alone use it themselves for personal navigation. Similarly, students in our study were able to recognize and describe uses for the topography/bathymetry map even without full mastery of either the representational strategies or how to use the map themselves. This is a promising finding from an instructional perspective, because it suggests that it should be possible to sequence instruction by beginning with a motivational discussion of what the data map is useful for, without having to first slog through the details of the map's representational strategies and symbol system.

Implications for Instructional Design

The overwhelming finding from our study is that many students who are currently studying or have recently studied earth science do not demonstrate a robust understanding of one of the most fundamental data sets in geosciences, the shape of the solid Earth's surface. Substantial fractions of the study population misinterpreted an iconic representation of global bathymetry/topography and displayed at best fragmentary knowledge of how such a representation could have been made. Curriculum designers and instructors need to guard against the assumption that students will find data visualizations easy or obvious just because they appear more intuitively accessible than, for example, graphs or tables of numbers.

Participants in our study were more likely to misread those parts of the provided map where they had less prior knowledge of the referent, i.e., the seafloor. Student descriptions of the oceanic parts of the map deviated far from the normative answer, encompassing currents, tides, water temperature, and level of sodium, suggesting that although they knew conceptually that the oceans had currents, tides, sodium, etc., they knew very little about the spatial distribution of those phenomena, which bear no resemblance to the provided map. Learning about Earth through maps and other representations would seem to be an iterative or spiral process, in which one needs to know something about the referent to understand the representation (Dutrow, 2007), at which point one can use the representation to deepen one's knowledge of the referent, after which one may be able to appreciate more subtle nuances of the representation, and so on. Uttal (2000, p. 247–248) documented a reciprocal relationship: "As children acquire new and more sophisticated ways of mentally representing and using spatial information, their understanding of maps improves. Likewise, children's developing conception of maps affects how they understand and conceive of spatial information." This reciprocal relationship suggests that students will benefit from repeated exposure to rich data sets such as bathymetry/topography, which continue to yield new insights as students' knowledge of both Earth processes and representational strategies grows from elementary school through graduate school.

At present, the burden of providing frequent exposure to data maps and other data visualizations lies with the teacher. The illustrations for middle school and high school earth science textbooks are overwhelmingly concept-driven visualizations and photographs, with data-driven visualizations comprising only a few percent of the figures (Kastens, personal observ.). We would encourage teachers to hang data maps on their classroom walls and use the rich assortment of data maps available from the Internet as visual aids in explanations and as the focal point for class discussions, modeling how the data can be used as evidence to support inferences about natural processes and human-Earth interactions. Textbook authors should move toward incorporating more data-driven visualizations alongside photographs and concept-driven visualizations; the college textbook by Reynolds et al. (2007) is a good model.

Students need to do more than look at data visualizations passively; they need to engage with them actively (Dutrow, 2007). Wiggins and McTighe (2006) suggested that instructional design should be guided by a vision of what learning performance students should be able to do after instruction. For this design tradition, a useful roadmap is provided by Liben's (1997) research-based taxonomy of four ways in which children can demonstrate map understanding. Liben's first two methods take place in a field setting, where the representation and the referent can be directly compared and contrasted. The realization that children need to have firsthand experience with a terrain rather than just learning from a map goes back at least to John Dewey (1902, p. 26), who wrote, "The map is not a substitute for a personal experience. The map does not take the place of an actual journey." In Liben's "production methods" (1997), the learner produces a map based on observations of the referent or adds information to an existing map based on direct observation of the referent, as in geological mapping. In "comprehension methods," the child interprets a map in the field and demonstrates understanding by performing an action within the real world guided by information on the map, for example, by moving to a series of sampling stations. Liben's third and fourth demonstrations of map mastery are suitable for classroom use, where a map or maps are present but the referent is not. In "representational correspondence methods," the child transfers information from one form of representation to another, as from a relief map to a profile. A variant of this method would be to compare and contrast information from two or more representations, for example, a geological map and a relief map, or a population distribution map and a relief map, and draw inferences about the referent based on this comparison. Liben's final category of map mastery is "metarepresentional methods," in which the child reflects on the relationship between the representation and the referent, for example, by explaining the meaning of the colors in Figure 1 or by describing how the data were collected to make a specific data map. In our opinion, all four methods have a place in a thorough earth science education.

Although individual students had only fragmentary understanding of how the data map was made, the group of students collectively had knowledge of all of the elements contained in the experts' epistemological model of Figure 2: data acquisition by sensors in the field, involvement of people who collect data and make representations, use of computer hardware and software, and decisions about how to represent the data. This suggests that students might benefit from a group activity in which students combine their fragmentary knowledge to assemble a more nearly complete group understanding of how the provided representation was created, for example, by collaborating to fill in a partially incomplete version of Figure 2. To guide such an activity, the teachers themselves will need a good understanding of the epistemological model.

One final suggestion emerges from our finding that some of the students who had the strongest apparent knowledge base about the provided map responded to question 1 by making interpretive assertions (e.g., this is a map of faults, volcanoes, or plate boundaries). In fact, the map shows physiography; faults, volcanoes, and plate boundaries can be inferred but are not part of this map. As in all other aspects of science education, teaching with data maps requires constant attention to the distinction between what is observation (e.g., this is a bathymetric trench) and what is interpretation (e.g., this is a subduction zone). Students need multiple opportunities to examine experts' interpretations from data maps, teasing out the data-based evidence from the line of reasoning that leads from the data to the interpretation. Next, they need opportunities to make their own interpretations and defend those interpretations with evidence derived from the data map.

Directions for Future Research

In order to keep the research design tractable, the map used in this study was static (Libarkin and Brick, 2002). However, GeoMapApp, like other modern data visualization tools, provides a rich suite of interactivity, including the capability to zoom into areas of interest, to create profiles at any desired azimuth and position, to create "3-D" terrain-like representations, and to adjust color, sun angle, and vertical exaggeration at will. In what ways would access to any or all of these functions improve or change students' understanding of what this data map is or is useful for? A fruitful line of research would be observational and think-aloud studies of how individuals navigate through the rich set of functions provided by modern data visualization tools in pursuit of answers to authentic geoscience inquiries; such observations would help researchers understand how students are conceptualizing and prioritizing the information in the database.

The data map used in this study depicts a data type that quantifies an aspect of the referent Earth that students have experienced directly, by walking across nonhorizontal terrain and by viewing landscapes with their own stereoscopic visual system. For this data type, students are relatively rich in direct knowledge of the referent (in terms of Liben, 1999, 2006). Similar research should be conducted on students' understanding of representations of geoscience data types where students come equipped with less direct knowledge of the referent. Such a research agenda should encompass aspects of the referent that students can sense but not see as a spatial array in nature (e.g., sea-surface temperature) as well as aspects that are not sensible at all through human senses (e.g., magnetic field).

We infer that difficulties for our study participants arose from *both* inadequate grasp of representational strategies (as when they assumed that green symbolized vegetation) and incomplete knowledge of the referent (as when the same students interpreted the continents correctly and the oceans incorrectly). As Edelson (1998) pointed out, when a scientist interprets a scientific visualization, he or she draws on a rich knowledge of scientific phenomena. Many of the specialized representations used by geoscientists present a chicken-and-egg situation, in which learners must understand something about Earth to interpret the representation and yet the representation is the means by which we teach about Earth (Kastens and Manduca, 2009). Following the lead of Dutrow (2007), we suggest a spiraling instructional progression in which gradually deepening knowledge of Earth and gradually more sophisticated mastery of representational strategies are built up in parallel. The burgeoning field of research on learning progressions (e.g., Mohan et al., 2009; Duschl et al., 2007) may be able to provide insight into the situation where the learner needs to have some understanding of A to understand B, and yet needs to understand B in order to understand A. Blades (2000) stressed how little research has been done on the ways in which learners integrate information learned from spatial representations with information gained through direct experience with the environment.

The relationship between students' ability to extract insights from data they did not collect and their knowledge of how the data were collected remains an area of active research. This question could be addressed through intervention studies: Does the experience of collecting and interpreting a small data set in one's own locality transfer into increased ability to extract insights from professionally collected large-scale data sets, perhaps by providing needed context (Winn et al., 2006)? Does learning about how scientists collect and process data (for example, through videos of field research) transfer into deeper insights about Earth when students later work with data maps and other data visualizations? Geoscientists, especially geoscientists who do field-based research, would tend to say "yes, obviously." However, there is little educational research to test this assertion or to elucidate the nature of the transfer; this topic is ripe for a combination of qualitative and quantitative research.

Liben (1999, 2006) makes the case that if learners do not grasp the representational strategies that have been used by a map-maker, they are vulnerable to "mis-mediated knowledge" of the referent when the representation is used as the means to study the referent. We consider that "representational strategies" are not limited to merely the last step of generating an external representation from data, but rather constitute the entire "chain of inscriptions" (Latour, 1986, 1987) from the referent to the representation shown in Figure 2. It is unclear how much students at different levels need to know about the processes shown in Figure 2 in order to avoid mis-mediated knowledge of Earth. Surely an eighth grader does not need a complete understanding of Figure 2 in order to avoid mis-mediated knowledge at an educationally appropriate level, but a doctoral student in marine geology certainly does. What about students in between? What is the nature of the mis-mediation caused by various forms of missing or mistaken knowledge of representational strategies?

CONCLUSIONS

Almost all study participants recognized the most basic elements of the provided visualization: the nature of the representation (a map), the scope of the referent (Earth), and a familiar pattern (the outlines of the continents). A substantial minority of the students recognized that the land (and less often the ocean) portions of the map show elevation/relief/landforms. Among the group of students taken as a whole, there was some awareness of each of the major processes that had contributed to making the data map, and some awareness of the utility of the map for both practical purposes (such as navigation) and scientific research (such as interpreting plate boundaries).

On the other hand, many students described the map in terms that depart wildly from the normative answer, as a map of vegetation, climatic zones, tides, migration patterns, sodium level, currents, weather, clouds, etc. No individual student presented a coherent explanation of how the data map was made, linking something about data acquisition, something about data processing, and something about representational techniques. Most students' ideas about what the map might be useful for were confined to low-level information-retrieval tasks, such as finding out where something is located or what its shape is.

Although the documented level of understanding provides a good foundation for further instruction, it seems to be a low level for students who are currently enrolled in or have completed an earth science course. Elevation is not esoteric: it is one of the most fundamental global geoscience data sets for explaining solid Earth, ocean, and atmospheric processes, and one best grounded in everyday experience. We recognize that different probes or follow-up questions might have revealed broader knowledge or deeper insight, but the pattern of responses taken as a whole suggests knowledge that is rather fragmentary, in which the elevation data do not connect back to Earth through a series of data acquisition and processing steps, nor forward to interpretation though lines of logical reasoning. Certainly, most of these students do not seem ready to use global elevation data in the way envisioned by the National Academy of Sciences in the opening quote in our introduction, as "evidence to construct testable explanations and predictions of natural phenomena."

The pattern of responses, interpreted in light of prior research on spatial thinking and student learning, suggests several factors that may have contributed to the observed difficulties. Students may have inappropriately interpreted the symbol system of the provided map because they expected that colors on the map would directly correspond to colors in the referent, because they negatively transferred symbol systems from other maps, or because they lacked relevant personal experience such as viewing terrain from an airplane or a mountaintop. The alternative conceptions that emerged in response to question 1 suggest that knowledge of the referent and understanding of the representation intertwine in a complicated way: To produce an answer of "currents" or "temperature" or "sodium level," it seems that the student must simultaneously *possess* the conceptual knowledge that oceans have currents, temperature variation, etc., but *lack* the spatial knowledge of how those attributes are distributed. To use the information on the data map as evidence in support of inference, students need to understand that the map records the bumps and wiggles in the referent, *and* that the bumps and wiggles in the referent record Earth processes.

To build on the documented level of student understanding through instruction, we offer the following suggestions. Data visualizations, including data maps, should feature prominently in all aspects of earth science instruction, including teachers' presentations, class discussions, inquiry activities, and textbooks (where the ratio of concept-driven visualizations to data-driven visualizations is currently overbalanced toward concept-driven). The abundance of geoscience data visualizations available through the Internet makes this suggestion viable as never before in educational history. However, teachers need support in developing the pedagogical content knowledge that will enable them to choose data wisely and use it effectively (Edelson, 1998). Students should work with local data maps in the field, in production and comprehension activities that require them to translate back and forth between the representation and the referent when both are within view. In preparation for this form of teaching, preservice and in-service teacher professional development for earth science teachers should include instruction and practice in field-based education. Finally, there is a need for additional middle- and high-school level inquiry activities in which students use evidence from data maps to construct explanations and predictions.

ACKNOWLEDGMENTS

The authors gratefully acknowledge advice and encouragement from O. Roger Anderson, Dale Chayes, Andrew Goodwille, the late William Haxby, Ann Rivet, William B.F. Ryan, and the Advisory Committee of the Marine Geoscience Data System. We appreciate the insights provided by the participating students and their teachers and by two anonymous reviewers and Special Paper 474 co-editors Stokes and Feig. Partial funding was provided by the National Science Foundation RIDGE2000 program through grant OCE-03-28117. This is a Lamont-Doherty Earth Observatory contribution.

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Manuscript Accepted by the Society 23 June 2010

Printed in the USA