JOURNAL OF GEOSCIENCE EDUCATION **64**, 125–137 (2016)

Quantifying the Level of Inquiry in a Reformed Introductory Geology Lab Course

Elizabeth Moss[1] and Cinzia Cervato[1,a]

ABSTRACT

As part of a campus-wide effort to transform introductory science courses to be more engaging and more accurately convey the excitement of discovery in science, the curriculum of an introductory physical geology lab course was redesigned. What had been a series of "cookbook" lab activities was transformed into a sequence of activities based on scientific inquiry and cooperative learning. The first two semesters were spent developing and implementing the new lab activities, and two more semesters were spent refining them. In the second semester of each of these two phases, students enrolled in the lab completed a 15-question version of the Geoscience Concept Inventory (GCI; Libarkin and Anderson, 2005); there were significant improvements from pretest to posttest scores. Student evaluations before and after the reform are not significantly different and overall positive. This paper presents an overview of the lab activities in the new curriculum, a detailed analysis of the type and level of inquiry in each lab, and the assessment of the impact on student learning. © *2016 National Association of Geoscience Teachers*. [DOI: 10.5408/15-096.1]

Key words: inquiry, introductory geology lab

INTRODUCTION

At many research universities, one-credit introductory geology labs are offered to students who need to fulfill a general education requirement for a natural science lab course. In our department, the lab course was decoupled from the lecture over two decades ago after the university eliminated a requirement for all introductory science courses to include a lab. This resulted in a larger enrollment in the lecture (about 500 students each semester) and a decrease in the number of graduate teaching assistants (TAs) available to teach them. A single classroom is currently dedicated to lab instruction. Enrollment in the lab has varied between 75 and 125 students each semester, and while geology and Earth science majors are required to take the lab, the vast majority of students enrolled come from a broad range of other majors.

The traditional approach had been to use the National Association of Geoscience Teachers/American Geosciences Institute (NAGT/AGI) lab manual (Busch, 2009) and select 12–14 chapters to cover throughout the semester. The format included a short lecture by the TA, accompanied by the assignment of several problems to solve in the lab manual. Ideally, students would complete the questions in the lab with the assistance of the TA. In reality, many students would leave right after the lecture and hand in the completed questions at the beginning of the following lab period. This approach did not encourage group work or the exploration of the material beyond what was included in the required set of questions. This model likely reinforced students' ideas that science is boring, and did not do much to increase the scientific literacy of the students involved. However, students liked this passive format: student evaluations of their TA were consistently above 4.0 on a 1–5 scale, with 5 representing "excellent" (Fall 2009–Fall 2010 average, 4.62; SD, 0.55; $n = 203$). This was a missed opportunity to truly engage the students, the vast majority of which were not science, technology, engineering, and math (STEM) majors, for the entire duration of the lab. In Spring 2011, the curriculum was changed to focus on student engagement, cooperative learning, and scientific inquiry. This paper describes the results of this process.

PEDAGOGICAL BACKGROUND

Constructivist teaching focuses on moving away from passive instruction to active learning and learner-centered teaching using students' existing knowledge as a basis on which to build new knowledge (Bransford et al., 2000). Active learning strategies engage students in learning the content instead of passively receiving it from the instructor (Handelsman et al., 2001; Arthurs and Templeton, 2009). Inquiry and cooperative learning are both examples of active learning strategies (Arthurs and Templeton, 2009).

The word *inquiry* is used extensively in science education literature, but an exact definition is harder to come by (Windschitl, 2001; Anderson, 2002; Buck et al., 2008). Inquiry-based education can describe both the process of teaching students how scientists use inquiry, and also having students use inquiry to learn science content (National Research Council [NRC], 1996; Colburn, 2000; Clough, 2006). Guiding definitions for the curricular reform efforts described here come from the descriptions found in Weaver et al. (2008) and the NRC (2000) texts: inquiry is "involving students in the discovery process" (Weaver et al., 2008, 577) and engaging students "in many of the same activities and thinking processes as scientists" (NRC, 2000, 1). The NRC also outlines five crucial components of inquiry: (1) students engage in scientifically oriented questions, (2) students give priority to evidence in responding to questions, (3) students formulate explanations from evidence, (4) students connect explanations to scientific knowledge, and

Received 6 May 2015; revised 16 February 2016 and 18 February 2016; accepted 19 February 2016; published online 22 February 2016.
[1]Department of Geological and Atmospheric Sciences, Iowa State University, 253 Science Hall, 2237 Osborn Drive, Ames, Iowa 50011-1027.
[a]Author to whom correspondence should be addressed. Electronic mail: cinzia@iastate.edu. Tel.: 515-294-7583. Fax: 515-294-6049.

TABLE I: Inquiry rubric from Buck et al. (2008).

Characteristic	Level 0: Confirmation	Level 1/2: Structured Inquiry	Level 1: Guided Inquiry	Level 2: Open Inquiry	Level 3: Authentic Inquiry	Description from Text
Problem/Question	Provided	Provided	Provided	Provided	Not Provided	Does the student formulate the question under investigation, or does the lab text provide it?
Theory/Background	Provided	Provided	Provided	Provided	Not Provided	Does the lab text provide all prior knowledge necessary to the investigation?
Procedures/Design	Provided	Provided	Provided	Not Provided	Not Provided	Does the lab text provide the experimental procedures students are to execute?
Results/Analysis	Provided	Provided	Not Provided	Not Provided	Not Provided	Does the lab text tell students how data are interpreted and analyzed?
Results communication	Provided	Not Provided	Not Provided	Not Provided	Not Provided	Are students given options on how to communicate results, or does the manual prescribe a specific method?
Conclusions	Provided	Not Provided	Not Provided	Not Provided	Not Provided	Are students provided with a summary or list of observations and results that should have been obtained in the laboratory?

(5) students communicate and justify their explanations (NRC, 2000). The new lab activities engage students in these five components of inquiry, and often have students mimic the discovery process scientists experienced for a given topic.

In order to clarify the definition of inquiry and make comparisons between different labs or courses, Buck et al. (2008) put forth a quantitative rubric designed to assess the level of inquiry in labs (Table I). They selected six categories to evaluate within each lab: problem/question, theory/background, procedures/design, results/analysis, results communication, and conclusions. Table I also provides a summary from Buck et al. (2008) for what each category addresses.

Describing how inquiry was incorporated into the lab activities is the primary focus of this paper, but inquiry was not the only focus of reform for the labs. Cooperative learning was also incorporated into the lab activities. Research has shown that cooperative learning strategies are effective at helping students learn science content (e.g., Yuritech et al., 2001). A common cooperative learning technique is the jigsaw activity, first described by Aronson et al. (1978). Jigsaw activities generally start by breaking students into small groups. Each group of students learns a piece of important content (e.g., what characterizes a sedimentary rock), and as such become "experts" in that topic. For the second portion of the activity, one student from each expert group forms a new small group in which each student is charged with conveying the material he or she learned in his or her expert group to the other students in the group. Once each student has shared their content, the small group completes an application activity (e.g., identifying different types of rocks). Jigsaw activities give each student a critical role in learning and conveying information to other students in the class, keeping them engaged in the material (Aronson et al., 1978). As we transformed the geology labs, TAs relied heavily on the jigsaw technique as a basis for structuring the lab activities.

COURSE OVERVIEW

Geology 100L is an introductory physical geology lab taught at a large U.S. midwestern university with a total enrollment of some 35,000 students. The lab is independent from the introductory lecture course, and the two can be taken concurrently or in different semesters. It is also possible for a student to take only the lab if they completed an introductory geology course elsewhere without taking the associated lab, and if their current major requires the lab. The lab consists of three to four sections, each with up to 25 students; each lab meets 2 h once per week for 15 weeks. The lab includes a required field trip to a local state park that is scheduled on a Saturday during the semester. Geology 100L is offered fall and spring semesters and is taught by graduate TAs that vary from semester to semester. Approximately two-thirds of the students are nongeology majors and non-STEM majors, ranging from freshmen to seniors, with the majority (usually two-thirds) being freshmen and sophomores. Most students are enrolled in the class to fulfill the general education requirement for a natural science laboratory course. There is usually an even split between female and male students, and minority students represent at the most 10%–15% of the population.

TABLE II: Results from survey of 32 introductory geology lab syllabi.

Topic	Number of Schools Covering Topic
Sedimentary rocks	32
Igneous rocks	32
Minerals	32
Metamorphic rocks	31
Topographic maps	26
Geologic hazards	19
Geologic time	19
Field trips	17
Rivers and flooding	16
Geologic structures	14
Deserts and glaciers	13
Groundwater	11
Plate tectonics	11
Oceans and shorelines	9
Energy use/carbon usage	6
Weathering and erosion	5
Soil	5
Rock cycle	3
Rain	3
Region-specific labs	3
Climate	2
Geophysics	2
Waterfalls	1

Inquiry was added into the lab activities to not only align them with the NRC's inquiry standards, but also to reinforce the process of scientific inquiry that we were trying to communicate through a 6-week authentic research project that had also been added to the course. Students design and implement a research project that focuses on local groundwater and surface water issues. They have access to a hydrology research station close to campus that includes eight monitoring wells and a stream gauge to collect data on water level and water quality. Each group of students develops a research question, collects and interprets their data, and presents their findings during a poster session attended by faculty and graduate students from the department. This research project is outlined in detail in Moss et al. (in preparation).

Students prepare for this project during the 2-week mini research lab, when they explore surface water and groundwater flow using a stream table and ant farm model. The 6-week research project allows students to engage in all steps of the research process: TAs provide feedback throughout the process, but this project is an "authentic inquiry" activity.

In order to accommodate the research project, some lab topics had to be removed from the course. No firm guidelines for what should be taught in college-level, introductory geology labs exist locally or nationally. A random sample of 32 introductory geology lab syllabi shows some consistent patterns in what is taught, but much variety as well (Table II). Syllabi were gathered from a variety of 4-y North American universities and colleges. Total enrollments varied from 1,300 to 54,000 students, and two universities were located in Canada. Both public (60%) and private (40%) institutions were sampled. Only seven institutions did not offer graduate degrees, and they were private institutions. Lab meeting schedules and lengths varied, but the majority of the courses surveyed were offered once a week for 2 h, with three outliers that lasted approximately half an hour and one that lasted 3 h. Most courses spent an average of 1 week on each topic; however, many of these courses combined igneous, sedimentary, and metamorphic rocks into 1 week.

The goal of this selection process was to find a balance of what should be covered at this stage for geology majors and what were the perceived needs of the larger population of students enrolled in these labs. Labs on glacial processes and climate change, geologic structures, and earthquakes, and one of the weeks spent on mineral identification were eliminated (Table III). In our first iteration (Spring 2011), geologic structures were taught for 1 week of the lab. However, it was determined that a lab on topographic maps was needed because of the assumption and expectation from several upper-level geology courses that students have basic map reading skills. In Fall 2012, a topographic maps lab replaced the geologic structures lab.

Assessing Level of Inquiry

For this study, it was necessary to modify the inquiry rubric put forth by Buck et al. (2008) to better fit the labs covered in this course. Buck et al.'s (2008) rubric is focused on chemistry lab exercises that involve an experiment as the central activity. Chemistry tends to be an experimental science, whereas geology is often an observational science, and when experiments are involved, they differ from benchtop experiments typical of chemistry. The wording of the original rubric was, therefore, adjusted to fit the needs of the observation-based geoscience lab activities. The six original categories were preserved, but the description of what each category addressed was carefully modified to maintain the original meaning of the level of inquiry (Table IV).

In addition, a "transitional" score was added to the rubric to help represent curricular changes that are in the right direction, but might not be full inquiry yet. For example, in the mineral identification lab, students complete an activity at the beginning of class that introduces them to the concept of a classification scheme and helps them develop characteristics to classify minerals prior to being told the characteristics scientists use to classify minerals. This is an improvement over a traditional lecture-then-identify lab format, but not a true inquiry scenario. This transition is part of the process of scaffolding students' knowledge of inquiry and a means to strike a balance between incorporating more inquiry and minimizing the frustration of students accustomed to being told the "right" answer right away.

The constraint of bottom-up removal of guidance put forth in Buck et al.'s (2008) rubric was also eliminated. This allowed us to clearly document labs that included inquiry at different steps of the lab, rather than having labs that provided every component of the lab and those that only provided some guidance in the procedure or in the communication of results all score as confirmation activities.

TABLE III: An example of the weekly lab schedule before, during, and after changes to the curriculum. Classes devoted to the research project (Moss et al., in preparation) are in bold and inquiry-based labs are shown in italic.

	Before 2011	Spring 2011	Fall 2012
Week 1	Introduction to Measurements and Earth Processes	Introduction + *Mystery Tube Activity*	Introduction + *Mystery Tube Activity*
Week 2	Plate Tectonics	Plate Tectonics (from lab manual)	***Introductory Field Activity***
Week 3	Earthquakes	Earthquakes (from lab manual, with additional data)	***Streams and Groundwater (practice investigation)***
Week 4	Mineral Identification	*Streams and Groundwater (investigation about flooding)*	***Streams and Groundwater (practice investigation)***
Week 5	Mineral Identification	*Streams and Groundwater (investigation about flooding)*	*Mineral Identification*
Week 6	The Rock Cycle + Igneous Rocks	*Rock Cycle (using chocolate as a model)*	*Rock Identification*
Week 7	Sedimentary Rocks	*Rock and Mineral Jigsaw*	*Rock Identification*
Week 8	Metamorphic Rocks	*Rock and Mineral Jigsaw*	*Rock Cycle*
Week 9	Geologic Time	*Rock and Mineral Jigsaw*	**Field Day**
Week 10	Stream Processes	*Spring Break*	*Plate Tectonics*
Week 11	Groundwater Processes	Glaciers and Climate Change (from lab manual)	*Pangaea*
Week 12	Geologic Structures and Maps	*Geologic Structures (paper folds)*	**Work Day**
Week 13	Topographic Maps	Geologic Time	*Topographic Maps*
Week 14	*Thanksgiving Break*	**Work Day**	*Thanksgiving Break*
Week 15	Glacial Processes and Climate Change	**Work Day**	**Poster Presentations** + Virtual Volcano Activity
Week 16	Quiz	**Poster Presentations**	*Geologic Time + Capstone Activity*

In many cases, theory or background was not provided to the students, but some guidance on the procedure (e.g., a worksheet to guide them through the content) was provided (see, for example, the Pangaea lab described below). Because this is an introductory lab, students are expected to understand basic and fundamental concepts of geology. While it is arguable whether or not students truly learn these concepts, it is nonetheless important to present them. The new curriculum focuses more on encouraging the students to get to an answer on their own rather than focusing the majority of time and attention on what the right answer is. For example, more emphasis is placed on students gaining the knowledge of how to use the physical characteristics of a mineral to determine its identity than on students being able to walk out of the lab having memorized the physical characteristics of quartz, mica, or feldspar. This teaching philosophy builds more inquiry into the middle levels of the rubric categories, while still providing students with an accepted answer at the end of class. The revised rubric is designed to show when and where students are given flexibility, and even a taste of inquiry, in their labs. Not every lab can be open inquiry—for the students' sake, the TAs' sake, and logistical constraints. Finally, the revised labs are meant to support the research project embedded in the course while still enabling students to learn basic geoscience concepts.

Three persons independently evaluated and scored the labs using this rubric, the first author and two TAs who taught the lab more than two semesters and who were not involved in the revision. Categories within labs that were scored differently were discussed until consensus was reached on the final score. Categories in which guidance is provided score zero points, transitional categories score 0.5 points, and categories without guidance provided score one point.

The total points earned for each lab are matched with the corresponding ranking from Buck et al. (2008). Confirmation activities provide students with all six of the categories, and earn 0/6 points. Structured inquiry activities provide students with four of the six categories and earn 2/6 points. Guided inquiry activities provide students with three of the six categories and earn 3/6 points. Open inquiry activities provide students with two of the categories and earn 4/6 points. Authentic inquiry activities do not provide students with any of the categories and earn 6/6 points.

In order to compare Buck et al.'s (2008) rubric and the revised rubric, the plate tectonics lab from the revised curriculum was evaluated using both rubrics (Table V). The revised lab scores as a confirmation lab on the Buck et al.'s (2008) rubric because students are presented with the accepted information (a map with plate boundaries) at the end of the lab. However, using our rubric, which removes the bottom-up constraint from the rubric scoring, the lab scores 2.5 points, or as a structured inquiry lab. Without removing the bottom-up constraint, the lab would score as a confirmation lab on our rubric as well. Two other labs (Mystery Tube and Introductory Field Activity) also scored higher on the revised rubric than the Buck et al. (2008) rubric because of transitional categories or because the bottom-up constraint was removed. Additionally, the plate tectonics lab from the NAGT/AGI lab manual (Busch, 2015) was evaluated using both the Buck et al.'s (2008) rubric and the

TABLE IV: Inquiry rubric category summaries and scoring guide.

	Buck et al. (2008)	Our Description	Provided (0 pts)	Transitional (0.5 pts)	Not Provided (1 pt)
Problem/ Question	Does the student formulate the question under investigation, or does the lab text provide it?	Do students formulate their own questions during the lab exercise? Is every student/group answering the same question?	Students are given a question to frame the lab and answer within their lab activity.	n/a	Students are not given a question to frame the exercise. They are told to explore the content, but not given a question to explore.
Theory/ Background	Does the lab text provide all prior knowledge necessary to the investigation?	Is a lecture given prior to students engaging in the exercise?	Students are given background information via a lecture prior to completing all components of the lab.	Students engage in an introductory activity prior to receiving background knowledge.	Students receive no background knowledge about the topic of the lab.
Procedures/ Design	Does the lab text provide the experimental procedures students are to execute?	Are students told how to go about completing the lab exercise?	Students follow a worksheet with questions to complete the lab exercise.	Students have some guiding principles outlined in the handout, but also have flexibility in completing components of the activity.	Students have no guidelines on what steps to take to complete the activity.
Results/Analysis	Does the lab text tell students how data are interpreted and analyzed?	Are students told how to interpret, categorize, or analyze any data they see in the lab exercise?	Students are presented with data and told how to analyze and interpret the data.	Students are presented with data and have some flexibility in categorizing, analyzing, or interpreting the data, but also are given some guidelines.	Students are presented with data and given no guidelines on how to interpret or analyze the data OR students collect their own data.
Results communication	Are students given options on how to communicate results, or does the manual prescribe a specific method?	How do students communicate results to the class? Is there any flexibility in how they communicate these results? Will every student or group communicate their results in the same way?	Students are given specific questions to answer in the lab manual. Students may or may not communicate with their peers.	Students have some flexibility in how they communicate their results, but all students are looking at similar data, so what and how data are communicated is very similar.	Students have full control of what data they present and how they present their data. Groups are looking at different types of data, so what is communicated varies.
Conclusions	Are students provided with a summary or list of observations and results that should have been obtained in the laboratory?	Do students get a list of "right" answers or conclusions to draw from the lab? Are any results they find novel?	Students' answers or conclusions are compared to values or ideas that have been well established and accepted by the scientific community.	n/a	"Accepted" results do not exist or are not provided to the students.

revised rubric. Both rubrics score the lab manual activity as a confirmation activity.

LAB ACTIVITIES: BEFORE AND AFTER

The lab structure prior to the curriculum changes was largely based on lecturing by the TA and individual, noncollaborative student work. In addition to the lab format being unengaging for the students, the weekly lab content was usually disconnected from other labs and presented as isolated units. The content and its order were chosen by the instructor who supervised the lab TAs each semester. Since the lab is a separate course from the introductory lecture and students could take the lab after the lecture, lecture content and lab content were not covered concurrently.

When Buck et al. (2008) did their assessment, they evaluated 46 introductory geoscience labs in addition to the chemistry labs that were the focus of their study. These labs were taken from lab textbooks commonly used in introductory geoscience courses; 11 of the labs were from an older version of the NAGT/AGI manual (Busch, 2006). They found that every lab scored a zero, or as a confirmation lab,

TABLE V: A comparison of using the Buck et al.'s (2008) rubric and the revised rubric to evaluate the plate tectonics lab from the revised curriculum and the NAGT/AGI lab manual (Busch, 2015). For a full explanation of the scores for each category for the revised lab, see Table XV.

Rubric	Plate Tectonics Lab (Revised Curriculum)		Plate Tectonics Lab (NAGT/AGI Lab Manual; Busch, 2015)	
	Buck et al. (2008)	Revised Rubric	Buck et al. (2008)	Revised Rubric
Problem/Question	Provided	Provided	Provided	Provided: Every student answers the same questions in the lab. The lab text provides "Think about it" questions in the chapter's table of contents page.
Theory/Background	Not Provided	Not Provided	Provided	Provided: The lab text provides all necessary background information.
Procedures/Design	Provided	Transitional	Provided	Provided: Students answer questions in the lab handout.
Results/Analysis	Provided	Transitional	Provided	Provided: Students are presented with a variety of different data (such as plate boundary lengths, or maps) and are guided through analyzing and interpreting each type of data via the lab handout.
Results communication	Provided	Transitional	Provided	Provided: Little group communication is needed. Students communicate their findings with the TA via the lab handout.
Conclusions	Provided	Provided	Provided	Provided: Each answer to the lab questions has an accepted answer.
Score	*Confirmation*	*Structured Inquiry*	*Confirmation*	*Confirmation*

meaning that all components were provided to the students in the lab manual.

All of the redesigned labs incorporate some amount of inquiry and/or utilize some form of the jigsaw technique with the intent to engage the students in meaningful activities for the full lab time. Each lab is structured so the emphasis is on students discovering the content instead of being told about it by the TA or course packet. Students are asked to use observations and other evidence to answer questions during the lab, and groups are asked to present their findings to the rest of the class. The schedule for the labs is more cohesive and connections between lab content are built throughout the curriculum. For example, the mineral and rock identification labs are a 4-week series that culminates in an application activity (see Table III). The original lab manual has been replaced by a course packet (created by the first author and available as a pdf file upon request from the second author), which contains the exercises and supplementary information students need for each lab and is available for purchase at the university bookstore. As a result of the reform, six of the 10 labs are now no longer confirmation activities; the four labs that were scored as confirmation labs now include collaborative learning and some components of inquiry (Table VI). What follows is a description of the reformed laboratory activities as implemented in Fall 2013 and an analysis of their inquiry level using our inquiry rubric modified from Buck et al. (2008). Tables that break down and evaluate each component of the lab in terms of inquiry and compare their score to how they would have scored with Buck et al.'s (2008) rubric are available as an electronic supplement.

TABLE VI: Inquiry scores for the reformed labs. All labs were confirmation activities prior to the reform.

Lab	Score	Inquiry Level
Mystery Tubes	4	Guided
Introductory Field Activity	1.5	Structured
Mini Project	5	Open
Mineral Identification	0.5	Confirmation
Rock Identification	0.5	Confirmation
Rock Cycle	1.5	Structured
Plate Tectonics	2.5	Structured
Pangaea	1	Confirmation
Topographic Maps	1	Confirmation
Geologic Time	2.5	Structured

Mystery Tube Activity

This lab is completely new to our curriculum. It is based on the activity outlined by Debbink and Brown (2010). Students are presented with a heavy cardboard tube (e.g., carpet tube) with strings sticking out the sides (see Fig. 1). The ends of the tube are capped with duct tape so students are unable to see inside the tube. They are asked to make observations about the tube and then form hypotheses about what is inside the tube. The class discusses proposed hypotheses and eliminates those that are not possible based on their observations. Students then make models of the

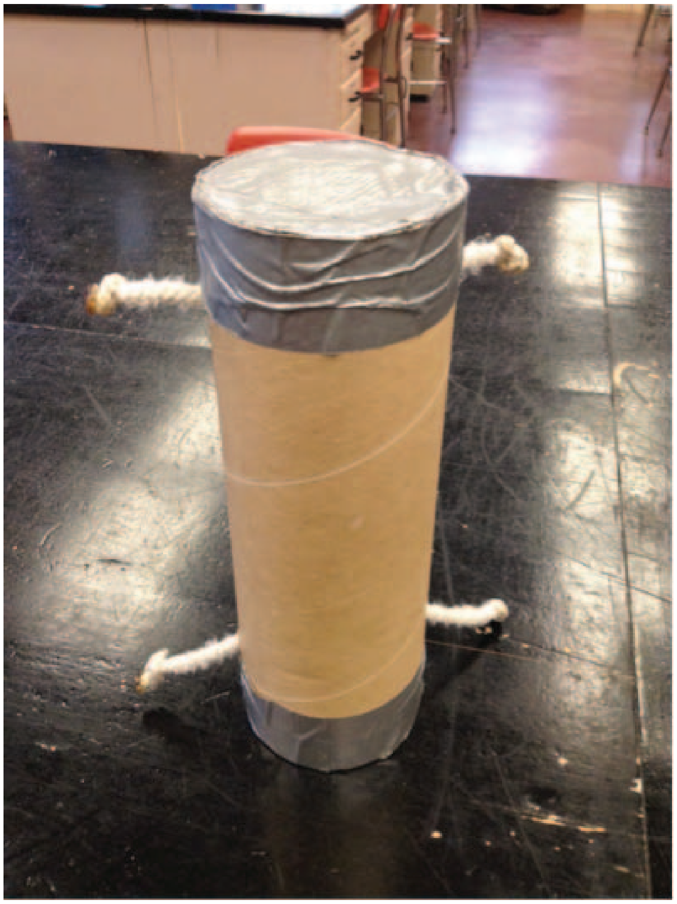

FIGURE 1: Tube used in Mystery Tube activity.

tubes using toilet paper tubes and string to test the remaining hypotheses. TAs discuss how this activity relates to the nature of science, making comparisons between the activity and real-life situations; for example, in the same way students are unable to cut open and see inside the tube, scientists are unable to "cut open and see" inside the Earth. This lab is designed to teach students about science and scientific inquiry and scores 4/6 (as an open inquiry activity) using our revised rubric (Table VII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). The TAs provide some guidance to the students throughout the lab, but the majority of the activity is left open-ended for the students.

TABLE X: Example of student instructions for the rock identification jigsaw activity.

Igneous Rock Instructions
• What is an igneous rock?
• How do igneous rocks form?
• What are the different locations where igneous rocks form and how does this affect their characteristics?
• Define extrusive and intrusive.
• What does the composition of a rock say about how the rock formed?
• What is Bowen's reaction series?
• How do scientists classify igneous rocks?

TABLE XIV: Fossil and rock evidence provided in the Pangaea exercise.

Group	Evidence
1	*Cynognathus* and *Glossopteris* fossils
2	*Mesosaurus* and *Lystrosaurus* fossils
3	*Nothofagus* tree fossils; the location of the Appalachian mountain belt in the United States and Europe
4	Ancient and modern day coal deposits
5	Evidence of ancient glaciation

Introductory Field Activity

The Introductory Field Activity is our equivalent of a chemistry course's Introductory Glassware Manipulation lab. This lab introduces students to the research site, the equipment available to them, and basic concepts about groundwater and surface water. This lab prepares the students for the 6-week research project they complete in the course (Moss et al., in preparation). This lab scores 1.5/6, or as a structured inquiry activity (Table VIII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). Inquiry is incorporated into the lab by an introductory activity in which students brainstorm how they might answer the question "Is the water here safe to drink?" and by leaving open ended questions for the students to explore at the end of the lab.

Mini Research Project

The week after students complete their introductory activity in the field, they spend two weeks reviewing the concepts they have learned about groundwater and surface water and performing a mini version of their semester-long research project. They choose a research question (e.g., "How does rainfall affect the movement of contamination from a leaky underground storage tank?" or "How does groundwater level vary with the addition and removal of a dam?") and plan how they can collect data to answer that question using two physical models, a groundwater ant-farm model (Fig. 2), and a stream table. Students collect data during the first and second week of the lab and then present their findings to the class after completing their research during the second week. This lab scores 5/6 on our rubric, or as an open inquiry activity (Table IX, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). TAs provide some guidance to keep the students on track, but students are left to design their experiment as they wish.

For one project, students explored the influence of rainfall on the movement of contaminant from a leaky underground storage tank using the ant farm model. They pumped water with food coloring into the leaky storage tank on the ant farm (Fig. 2) and then observed the movement of the dyed water during normal conditions (input on both sides, stream flowing), taking notes on the relative rate of movement. Following this step, students poured water on the surface of the ant farm to simulate rainfall and observed how this influenced the flow of the dye. They then flushed the dye from the system and repeated their experiment. After forming their conclusions, students presented their findings to the class, giving a demonstration during their presentation. Completed during two lab periods, these mini

FIGURE 2: Students using the ant farm groundwater model. In the background, students working around the stream table.

projects are rudimentary and basic, but provide scaffolding for their semester-long research project.

Mineral Identification, Rock Identification, and the Rock Cycle

Prior to the curriculum reform, mineral and rock identification was taught over 5 weeks. Two weeks were dedicated to mineral identification. Igneous, sedimentary, and metamorphic rocks were taught in three separate weeks. Each lab included a lecture by the TA on the topic followed by hand sample identification.

In the revised curriculum, 1 week of mineral identification was removed and identification pared down to 15 common minerals instead of 30+ minerals. Students begin the mineral identification lab by working in groups to create a classification scheme for 12 unknown mineral samples

TABLE XIX: Student evaluation scores for the TA and the lab, and amount learned before the reform (three semesters, Fall 2009 to Fall 2010), during the reform (Spring 2011 and Fall 2011), during the refinement of the lab content (Spring 2012 and Fall 2012), and during the continued implementation of the reformed labs (Spring 2013 to Fall 2014). *Note*: Evaluations were administered on paper during the lab period prior to Fall 2011. Since Fall 2011, evaluations are submitted electronically, and the submission rate has declined.

	Average TA Evaluation (SD)	Average Course Evaluation (SD)	Amount Learned (SD)	*n*
Fall 2009–Fall 2010	4.62 (0.55)	4.19 (0.81)	3.77 (0.84)	203
Spring 2011–Fall 2011	3.89 (0.95)	3.08 (1.01)	3.11 (0.93)	106
Spring 2012–Fall 2012	4.05 (0.97)	3.60 (1.07)	3.38 (1.11)	88
Spring 2013–Fall 2014	4.23 (0.85)	3.72 (1.08)	3.76 (0.96)	150

FIGURE 3: Mineral samples from sets A and B.

(Fig. 3). There are two sets of mineral samples (A and B) that each contain the same 12 minerals, but the forms of some of the minerals differ between the sets (e.g., set A has specular hematite and set B has oolitic hematite, set A has calcite showing its cleavage and set B has calcite showing its crystal form, set A has milky quartz and set B has rose quartz). After working with their set, groups switch sets with another group and test how their classification scheme works with the new samples. The differing forms of minerals between the sets cause problems in students' self-created schemes. The paired groups compare their results and classification schemes, discussing where and why any discrepancy arose. This is followed by a whole class discussion on the problems that students encountered, followed by a brief overview of the physical characteristics (e.g., luster, hardness, streak) geologists use to identify minerals and the commonly accepted classification scheme. This allows students to see the rationale behind the accepted classification scheme instead of just memorizing it. Finally, they use what they learned about how minerals are classified, and identify 15 new mineral samples.

At the beginning of the second week of this series, students spend a few minutes identifying the 12 minerals from the previous week's introductory classification activity, allowing them to review and apply what they learned. The rest of the lab is spent on a rock identification jigsaw activity. Students break up into three groups and each group is assigned a different rock type (igneous, sedimentary, or metamorphic) on which to become experts. They are given a list of concepts to describe and understand, and basic resources that provide that information (Table X). Each group presents what they have learned to the rest of the class. The presentations usually occur at the end of the second week of the series. In the third week of the series, one member of each expert group is placed in a new identification group of three experts and the three students identify a selection of igneous, sedimentary, and metamorphic hand samples.

This series of labs culminates in the fourth week with a two-part activity on the rock cycle. For the first part of the activity, groups of students are given an igneous, sedimentary, and metamorphic rock and are asked to describe and identify each rock. In addition, they are asked to identify the minerals present in the rock and match those minerals to the hand samples they saw in the first week of the series. They then "transform" the rocks into a rock of a different type (e.g., transform an igneous rock into a sedimentary rock). They describe the process(es) of how the original rock can be transformed into the new rock, and identify what rock would result from the process. For the second part of the lab, students move a rock of their choosing through the rock cycle, creating at least one igneous, one sedimentary, and one metamorphic rock. For example, a group of students could start out with gneiss and transform it into granite, then sandstone, and finally quartzite. They are again asked to describe the processes by which they change their rocks. Each group presents their rock cycle to the rest of the class, and students are asked to write personal reflections on how each rock cycle was different and whether or not there are many paths through the rock cycle.

The Mineral Identification lab scores 0.5/6 on our rubric, or as a confirmation activity (Table XI, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). The Rock Identification lab is also a confirmation activity, scoring 0.5/6 on our rubric (Table XII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). In both of these labs, inquiry activities (such as the introductory activity in the Mineral Identification lab) and cooperative learning activities (such as the Rock Identification jigsaw) were incorporated when possible. The third lab in this series, the Rock Cycle lab, scored 1.5/6 on our rubric, or as a structured inquiry activity (Table XIII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). More flexibility was available in removing guidance for the students in this lab than in the identification labs.

Plate Tectonics and Pangaea

The Plate Tectonics lab used prior to the reform consisted of a series of questions that guided students through the current understanding of plate boundary location, convection, and plate tectonic theory. Students explored hypotheses about plate motion (e.g., expanding Earth, shrinking Earth, sea-floor spreading) and tested these hypotheses by analyzing the location and relative amounts of the different types of plate boundaries that were given to them.

The first lab in the new two lab series is a jigsaw activity that has been slightly modified from the Discovering Plate

TABLE XX: Results from the paired t-test of student GCI data. Fall 2011, $t(48) = 5.121$, $p < 0.0001$; Spring 2012, $t(32) = 4.651$, $p < 0.0001$.

Term	n	Pretest Mean	Posttest Mean	t Ratio	Degrees of Freedom	95% Confidence Interval	Standard Error of the Mean
Fall 2011	49	7.78	9.04	5.12	48	(0.77, 1.76)	0.25
Spring 2012	33	8.24	9.85	4.65	32	(0.90, 2.31)	0.35

Boundaries activity from Rice University (Sawyer et al., 2005). Each group of students uses one type of physical evidence that is shown on large world maps (earthquake depth and location, ocean floor age, topography, or volcano location) to describe the patterns that they can use to identify plate boundaries. Each group then classifies the identified boundaries based on these data. For example, the earthquake group might classify one type of boundary as having shallow, sparse earthquakes, and classify another type of boundary as having numerous earthquakes that occur at increasing depth. Once the groups have classified all of the boundaries on their map, one member of each group forms a plate group, wherein they combine their data and classifications, and seek to create a new classification scheme for the boundaries. It is only after they have created their own plate boundary map that they see an "official" plate boundary map. This exercise allows students to understand what characterizes the different types of plate boundaries.

The second lab focuses on reconstructing the past arrangements of the continents based on geologic deposits and fossils, and uses the past location of the continents to explain the plate boundary distributions we see today. The class is divided into five groups, each receiving a map showing the present day continents with the locations of various fossils and rock formations with their ages (Table XIV).

Each group uses their information to reconstruct where the continents were 250 and 125 million years ago. Once each group has made their reconstructions, groups 1, 2, and 3, and groups 4 and 5 combine to share their evidence to further refine their reconstructions. The larger groups then compile a history of how the continents moved from Pangaea to where they are today. Students are asked to use their knowledge of plate tectonics and the location of different plate boundaries (developed in the previous lab) as they create their history, as well as cite evidence to support their ideas. The whole class combines their information and students further refine and outline the history of the continents, again using evidence from the geologic record and modern-day plate boundaries to support their claims. Each student turns in a written copy of the history for credit.

The Plate Tectonics lab scored 2.5/6 points on our rubric, or as a structured inquiry activity (Table XV, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). Though students are provided with a map of where the plate boundaries are located, they are not told what kind of plate boundaries are where. The Pangaea lab scored 1/6 on our rubric, or as a confirmation activity (Table XVI, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). Students are largely guided through this activity but are required to interpret what each type of rock or fossil tells them about the climate of that location in the past.

Topographic Maps

Prior to the curriculum changes, the questions in the Topographic Map lab asked students to explain the symbols used in topographic maps and answer a few basic questions about a variety of topographic maps of locations across the U.S. Students who live in an age in which ubiquitous GPS devices provide directions often did not see the usefulness of understanding how to read a map, causing many of them to find this activity irrelevant.

Instead of using maps from various parts of the country, the inquiry lab uses local maps to teach students the same concepts that were originally covered. The first part of the lab begins with pairs of students exploring and familiarizing themselves with the USGS Ames (Iowa) West topographic maps of the campus and surrounding area. Students are asked to point out and describe the basic features of the map (e.g., map scale, contour intervals). Students are then shown the peak stage level of the nearby river during the 2010 flood. The river crosses the city and the stage was measured at a USGS stream gauge just south of the city. Students are asked to map the areas affected by the 2010 flood on tracing paper. Students compare their maps with the ones produced by other groups in the class.

In the second part of the lab, students create a contour map of a nearby state park where the students were taken on a 3-h field trip a few weeks beforehand. They are given a map (created in ArcGIS) of the park with 60–80 different elevation points and are asked to draw 20-ft contours on the map. Using this map, students mark what areas of the park would be affected by different flood stages, including mapping the areas affected by the 2010 flood. Students then compare their contour and flood maps with a map created in GIS by a TA. This lab scores 1/6 on our rubric, or as a confirmation activity (Table XVII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). Students are guided through the lab via the lab handout, but need to use creativity as they use elevation data to create their contour map.

Geologic Time Activity

The last lab activity of the semester focuses on Geologic Time, a concept often hard for students to grasp (Dodick and Orion, 2003; Libarkin et al., 2007; Cervato and Frodeman, 2012). This lab was originally centered on understanding relative and absolute dating methods, having students apply these methods to date cartoon drawings and photographs of stratigraphic sections. At no point students were asked to conceptualize the vast amount of time in geologic history.

The new lab focuses on applying relative and absolute dating measurements to rock and fossil samples representative of the local geologic history and stratigraphy, as well as mapping out the extent of geologic time. The lab begins with an activity that uses pennies to teach the concept of radioactive decay. Pairs of students are given a set of 20 pennies and told that the heads side of the penny represents the parent isotope and the tails side the daughter isotope. Initially, all of the pennies are heads up, representing a 100% composition of the parent isotope. The TA leads the students through a series of half-lives, in which students toss the pennies in the air and drop them onto the table. Each penny that lands heads up represents a parent isotope and each penny that lands tails up represents an atom that has decayed into the daughter isotope. Each pair counts the number of heads and tails, and the TA graphs the total amounts on the chalkboard. Daughter isotopes, or pennies that were tails up, are removed before the students repeat the same process for four or five half-lives. This exercise generally models decay simply and also elucidates why radiometric dating becomes less accurate when very small proportions of the parent isotope remain.

After the introduction to radiometric dating, students begin an activity that asks them to reconstruct the local geologic history using two series of hand samples representative of local geology, but not necessarily from the area. Each student is assigned a role as one of five different geoscientists (geochronologist, petrologist, paleontologist, paleoclimatologist, or stratigrapher), and is provided with different information and tasks in identifying the samples. Each student does not have information for every sample, but the group must work as a whole to understand the samples. Geochronologists are given the ratio of parent–daughter isotopes and are asked to calculate the age of some of the samples. Petrologists are asked to use their experience with rock identification to identify some of the samples. Paleontologists are given an overview of various types of fossils they might encounter and are asked to identify different fossil samples. Paleoclimatologists are given background information on what types of rocks form in different climate areas, and are asked to identify the environment in which the fossil or rock was deposited. Stratigraphers are tasked with combining all of the groups' information and ordering the samples from oldest to youngest. After the group identifies the two series of samples (one focusing on the shallow marine history of the area and the other focusing on the most recent glaciation of the area), they write out a history of the area using evidence to support their conclusions. Students are then presented with short summaries of the commonly accepted geologic history of the area with which they compare their own stories.

To end the lab period, students draw a geologic time scale with chalk on the lab tables using one millimeter to represent one million years. They mark each geologic period (provided) on their scales, and mark where the samples from the history activity fall. They are also given small figurines of different life forms (e.g., brachiopods, horses, different dinosaurs) and asked to place those on the timeline after finding out the range of these organisms on a geologic time scale. This activity allows them to visualize the geologic time scale, as well as the relatively small proportion of that geologic time scale that life has been present on Earth.

The revised Geologic Time lab scores 2.5/6 on our rubric, or as a structured inquiry activity (Table XVIII, available in the online journal and at http:dx.doi.org/10.5408/15-096s1). Students are not given much guidance as they synthesize their data and create their reconstruction for the area.

ASSESSMENT

Observations of students in the lab by the first author show that they are engaged for the majority of the class period—a significant change from the previous curriculum—and are all spending the full lab period working in class. Students actively collaborate for every lab activity. Each activity allows students to engage in scientific inquiry in a fun way. Anonymous comments from students in the official lab evaluations suggest that the students enjoy the labs.

A comparison of TA and lab evaluation scores before (Fall 2009–Fall 2010) and after the reform (Spring 2013–Fall 2014) shows a slight decline in both categories, but within the standard deviation (Table XIX). On the other hand, the self-reported amount learned is virtually identical. The evaluations during the two semesters (Spring 2011–Fall 2011), when the majority of the transition between the old curriculum and the new curriculum took place, have the lowest scores. Student feedback during these two semesters was used to improve the lab activities. Student evaluations show that there is no significant difference in their perception of their TA, the lab, or how much they learned in spite of the significant increase in workload. However, these values have limited significance since they are influenced by factors, like the likeability of the TA, that are highly subjective (see, e.g., Gravestock and Gregor-Greenleaf [2008], for a review of literature on student course evaluations). In fact, there is a strong correlation between the evaluations of individual TAs and the course evaluation and amount learned reported by students in the section (R^2 of .82 and .79, respectively).

Since so many variables have changed from before the reform and after (e.g., TAs, quiz content, grading scale), it would be meaningless to compare quantitative learning outcomes (such as final lab grades) before and after the transformation. In Fall 2011 and Spring 2012, we used a 15-question subset of the Geoscience Concept Inventory (GCI; Libarkin and Anderson, 2005) to measure change in conceptual understanding in the students. This is the same subset used to assess learning in introductory labs at North Carolina State University (McConnell, pers. comm., 2011). The questions focus on plate tectonics and geologic time (Appendix A, available in the online journal and at http://dx.doi.org/10.5408/15-096s1).

A paired *t*-test was performed on the statistical platform JMP (SAS, CARY, NC) for the statistical analysis of the student data. This type of analysis is commonly used to assess before-and-after studies. A paired *t*-test will calculate the difference between each pair (a student's pretest and posttest score), determine the mean of these changes for the class, and provide insight into whether or not these differences are explained by random variation or by the treatment being tested (the new curriculum). There was a statistically significant increase in students' scores from the pretest to the posttest in both semesters (Table XX). This change represents about a 1–2 question total increase on the score and signifies improvement in conceptual understanding. The pretest and posttest scores, as well as the statistical significance of the students' improvement, are consistent with the results published by Libarkin and Anderson (2005), as well as with other studies that used the GCI to assess student learning before and after instruction (e.g., Elkins and Elkins, 2007; Petcovic and Ruhf, 2008).

Normalized gains (Hake, 1998) were also calculated on the students' scores for each semester. Normalized gains determine how much a student improved given the room they had to improve, and is described by the equation $G = (\text{Post\%} - \text{Pre\%})/(100 - \text{Pre\%})$, where Post% and Pre% represent the students posttest and pretest scores as percentages. Normalized gains reveal subtle changes in scores because small shifts in scores by students with higher pretest scores produce the same relative gain as larger improvements in students with lower pretest scores. Normalized gains for Fall 2011 were 18.6% ± 27.9%; normalized gains for Spring 2012 were 17.6% ± 41.9%.

CHALLENGES AND REFLECTIONS

One of the biggest challenges in implementing this style of lab is to ensure that the TAs buy in into the new concept and to give them a basic training in inquiry-based teaching (e.g., Young and Bippus, 2008). Some TAs believe that it is easier and less time-consuming to prepare a short lecture and assign students questions instead of engaging them for 2 h. The questions that students ask during inquiry activities are not predictable, and can thus be intimidating or challenging for the graduate TAs who themselves have only a few years more experience than the students they teach in the lab. We have found that having a presemester training and weekly meetings with the TAs to discuss how the previous lab went and discuss the plan for the upcoming lab helps them feel more comfortable teaching the inquiry labs. They also have access to lesson plans for each lab, outlining what materials are needed, approximate times for each activity, and possible questions that students might ask, or questions that the TA might want to ask the students. Additionally, one TA, usually a more experienced one, is tasked with lab coordination and is in charge of preparing all of the materials needed for each lab and ensuring that all TAs are ready.

In another study analyzing the reform of an introductory lab at another research institution, Ryker and McConnell (2014) modified the grain size of the Buck et al. (2008) rubric, but used a different approach in their analysis of each lab. After scoring each lab using the rubric, they then weighed the inquiry levels by the percentage of total lab time spent on each activity by the TAs. They found that teaching strategies and student-centered learning teaching techniques varied among the TAs, with more experienced TAs being more likely to teach in a more reformed matter. In our implementation, there was no systematic plan to observe the TAs while they were teaching, but we did observe the TAs prepare for labs and reflect on the success of labs in the weekly lab meetings. The TA who was lab coordinator for Fall 2013 through Fall 2014 continued to follow the reformed lesson plans, providing insight to the other TAs on what questions may arise and ways to encourage students to explore the material during the lab. Reflection on the previous week's lab during the meeting suggests that all TAs are implementing the curriculum, and, like Ryker and McConnell (2014) observed, the less experienced TAs do not employ as many reformed teaching practices as the more experienced TAs.

Transforming the introductory geology lab from cookbook labs to inquiry and jigsaw labs is a gradual and ongoing process. In the first semester (Spring 2011), about half of the labs were revised and some were left as they had been taught for years (Table III). Starting in Fall 2011, all of the labs were reformed and small adjustments have been made at every new offering. While it is possible to completely transform a curriculum in one semester, we found that making the transition more gradual helped reduce TA anxiety. As the changes to the lab have solidified, more TAs are willing to teach this lab. We carefully select TAs each semester, giving preference to those interested in teaching this lab and those with previous experience. Their ease and willingness to teach have also improved as we have worked out some of the initial kinks: corrected typos in the course packet, established equipment checkout procedures, clarified reasonable expectations of how much work we can expect from students, developed detailed lesson plans, smoothed out logistics of preparing lab materials (by moving from printed handouts to a course packet), assembled an online database of quiz questions, established realistic deadlines for students, and created grading rubrics and policies.

The authors have limited their involvement in the lab since Fall 2013. The first author has attended weekly lab meetings both Fall 2013 and Fall 2014, but has left the coordination of the lab to the TA coordinator. Putting together a course packet that students purchase through the university bookstore has been helpful in sustaining the changes beyond the influence of the authors. It also helps to have a PhD student as coordinator since he or she can be involved for more semesters than an MS student.

Using a rubric to gauge the level of inquiry of laboratory activities is helpful in assessing what labs need to be updated or can be improved. A rubric is also helpful in assessing the progress that has been made in converting labs toward inquiry-based activities. However, this rubric does not tell the full story of the improvements and level of student engagement in the labs. For example, more open-ended activities have been incorporated in the Mineral Identification lab, yet these changes do not appear as a significant change in the rubric. The Mineral lab in Ryker and McConnell's (2014) study was their lowest scoring lab. Teaching students how to identify minerals limits the level of freedom for the students: the opening activity shows that students lack some of the background knowledge of physical properties (e.g., streak) necessary for identifying minerals. Also, there is an accepted way to identify hand samples and there is a correct answer to the identity of each hand sample. Mineral Identification labs will likely always contain low levels of inquiry, but including inquiry when possible can better align the lab with an inquiry-based curriculum. Student engagement and active learning practices can be applied to labs that do not lend themselves to open-ended activities, but this still aligns them with best teaching practices. Currently, each of the 10 lab sessions includes collaborative learning, and six incorporate at least some level of inquiry.

In many instances, some guidance is also necessary in order to maximize student learning and make sure they grasp the key concepts of the lab. For example, after a few semesters of implementing the revised lab, a handout was added for the mini research project lab to guide students through the experiment process (Fall 2013). It was found that they needed direct guidance in this lab in order to be prepared for their semester-long research project. Although this decreased the score on the inquiry rubric, it increased students' understanding and success in their semester-long project.

CONCLUSIONS

Scientific inquiry is at the forefront of science education standards and discussions. Definitions of inquiry vary from teaching students the process of scientific inquiry to having students engage themselves in the process of scientific inquiry. A modified version of the rubric developed by Buck et al. (2008) can help instructors gauge how effective they have been in incorporating scientific inquiry into their lab exercises. Evaluation of the revised introductory geology lab curriculum shows that there have been improvements to the level of inquiry present in the labs. Prior to the revisions, all of the lab exercises were confirmation activities. With the reform, only four labs remain as confirmation activities, with each of those labs incorporating active learning techniques. Four labs score as structured inquiry, one as guided inquiry, and one as open inquiry.

The buy-in and support of the TAs was crucial to the success of the curriculum reform. We have found that weekly TA meetings, established lesson plans, and an experienced TA lab coordinator helped TAs feel comfortable with the more open-ended structure of each lab. Three years after the first full implementation of the new curriculum, the changes continue to be implemented and appear to be self-sustaining, and are still well received by students.

Acknowledgments

We would like to thank Tom Parham, Sarah Day, and Joe Kohlhaas for their help in developing the revised lab activities, and Maddie Mette and Derrick Vaughn for help with evaluation of the labs with the rubric. We also want to thank the TAs who patiently worked with us through this extensive curriculum revision. We are grateful to two anonymous reviewers, an associate editor, Curriculum and Instruction editor Heather Petcovic, and editor-in-chief Kristen St. John for their valuable and careful feedback that helped us significantly improve the manuscript.

This project was supported in part by a grant to Iowa State University from the Howard Hughes Medical Institute through the Science Education Program.

REFERENCES

Anderson, R.D. 2002. Reforming science teaching: What research says about inquiry. *Journal of Science Teacher Education*, 13:1–12.

Aronson, E., Blaney, N., Stephan, C., Sikes, J., and Snapp, M. 1978. The jigsaw classroom. Beverly Hills, CA: Sage Publications.

Arthurs, L., and Templeton, A. 2009. Coupled collaborative in-class activities and individual follow-up homework promote interactive engagement and improve student learning outcomes in a college-level environmental geology course. *Journal of Geoscience Education*, 57:356–371.

Bransford, J.D., Brown, A.L., and Cocking, R.R., eds. 2000. How people learn: Brain, mind, experience, and school. Washington, DC: National Academies Press.

Buck, L.B., Lowery Bretz, S., and Towns, M.H. 2008. Characterizing the level of inquiry in the undergraduate laboratory. *Journal of College Science Teaching,* 38:52–58.

Busch, R.M., ed. 2006. Laboratory manual in physical geology, 7th ed. Upper Saddle River, NJ: Pearson.

Busch, R.M., ed. 2009. Laboratory manual in physical geology, 8th ed. Boston, MA: Pearson.

Busch, R.M., ed. 2015. Laboratory manual in physical geology, 10th ed. Boston, MA: Pearson.

Cervato, C., and Frodeman, R. 2012. The significance of geologic time: Cultural, educational, and economic frameworks. *In* Kastens, K., and Manduca, C., eds., Earth and mind II, GSA Special Paper 486, p. 19–27.

Clough, M.P. 2006. Learning science as and through inquiry. *Iowa Science Teachers Journal*, 332.

Colburn, A. 2000. An inquiry primer. *Science Scope,* 23:42–44.

Debbink, A., and Brown, K. 2010. Mystery tubes. Understanding Science Lesson. University of California Museum of Paleontology. Available at http://undsci.berkeley.edu/lessons/mystery_tubes.html (accessed 1 September 2010).

Dodick, J., and Orion, N. 2003. Measuring student understanding of geological time. *Science Education*, 87:708–731.

Elkins, J., and Elkins, M. 2007. Teaching geology in the field: Significant geoscience concept gains in entirely field-based introductory geology courses. *Journal of Geoscience Education,* 55:126–232.

Gravestock, P., and Gregor-Greenleaf, E. 2008. Student course evaluations: Research, models and trends. Toronto, Canada: Higher Education Quality Council of Ontario.

Hake, R. 1998. Interactive engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses. *American Journal of Physics*, 66:64–74.

Handelsman, J., Miller, S., and Pfund, C. 2007. Scientific teaching. New York: W.H. Freeman and Company.

Libarkin, J.C., and Anderson, S.W. 2005. Assessment of learning in entry-level geoscience courses: Results from the Geoscience Concept Inventory. *Journal of Geoscience Education*, 53:394–401.

Libarkin, J., Kurdziel, J., and Anderson, S. (2007). College student conceptions of geological time and the disconnect between ordering and scale. *Journal of Geoscience Education*, 55:413–422.

Moss, E., Cervato, C., Ogilvie, C., and Ihrig, L., 0000. Authentic research in an introductory geology laboratory: effects on nature of science understanding and science self-efficacy. *Journal of Geoscience Education*, In Preparation.

National Research Council (NRC). 1996. National Science Education Standards. Washington, DC: National Academy Press.

National Research Council (NRC). 2000. Inquiry and the National Science Education Standards. Washington, DC: National Academy Press.

Petcovic, H., and Ruhf, R. 2008. Geoscience conceptual knowledge of preservice elementary teachers: Results from the Geoscience Concept Inventory. *Journal of Geoscience Education,* 56:251–260.

Ryker, K., and McConnell, D. 2014. Can graduate teaching assistants teach inquiry-based geology labs effectively? *Journal of College Science Teaching*, 44:56–63.

Sawyer, D.S., Henning, A.T., Shipp, S., and Dunbar, R.W. 2005. A data rich exercise for discovering plate boundary processes. *Journal of Geoscience Education,* 53:65–74.

Weaver, G., Russell, C., and Wink D. 2008. Inquiry-based and research-based laboratory pedagogies in undergraduate science. *Nature Chemical Biology*, 4:577–580.

Windschitl, M. 2001. Inquiry projects in science teacher education: What can investigative experiences reveal about teacher thinking and eventual classroom practice? *Science Education*, 87:113–143.

Young, S.L., and Bippus, A.M. 2008. Assessment of graduate teaching assistant (GTA) training: A case study of a training program and its impact on GTAs. *Communication Teacher, 22*(4):116–129.

Yuritech, R.F., Khan, S.A., Leckie, R.M., and Clement, J.J. 2001. Active-learning methods to improve student performance and scientific interest in a large introductory oceanography course. *Journal of Geoscience Education*, 49:111–119.