Assessing Inquiry in Physical Geology Laboratory Manuals

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ABSTRACT

Many agencies, organizations, and researchers have called for the incorporation of inquiry-based learning in college classrooms. Providing inquiry-based activities in laboratory courses is one way to promote reformed, student-centered teaching in introductory geoscience courses. However, the literature on inquiry has relatively few geoscience examples and features an array of modifiers that complicate instructor efforts to identify or adapt inquiry-based activities for their courses. We review several measurement protocols developed to assess inquiry in laboratory activities. We apply one of these to assess the level of inquiry present in four published physical geology laboratory manuals. While the majority of activities used in the published manuals were classified at low levels of inquiry, these manuals also contained examples of higher-level activities that were not identified in previous analyses. We describe the development of inquiry-based lessons for inclusion in a freshman-level physical geology laboratory course at a large public research university in the southeast U.S. and apply the same protocol to assess the laboratory course activities and discuss how some activities were adapted to increase inquiry levels. We discuss how other instructors or laboratory course developers can adapt existing activities to incorporate higher levels of inquiry in their laboratory courses, matching them with the type of information or skill they want students to learn.
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Key words: inquiry, physical geology, laboratory courses, undergraduates

INTRODUCTION

Calls for science education reform have been widespread in the U.S. for decades (e.g., Schwab, 1962; Novak, 1988; AAAS, 1990; DeBoer, 1991; NRC, 1996) and have targeted university and college science professors, who play a critical role in how society will learn its science (Siebert and McIntosh, 2001, ix). Reform that incorporates inquiry in the classroom is recognized as one way in which we can improve conceptual knowledge and attitudes in a variety of science, technology, engineering, and mathematics (STEM) fields (e.g., Prince, 2004; McConnell et al., 2006; Beichner et al., 2007; Wood, 2009; Singer et al., 2012). Inquiry learning parallels the process of scientific inquiry and focuses on the students' role in asking and investigating scientific questions and constructing a strong conceptual understanding of science (NRC, 2000). The National Science Education Standards describe five essential features of inquiry that involve the learner: (1) engaging in scientifically oriented questions; (2) giving priority to evidence in responding to questions; (3) formulating explanations from evidence; (4) connecting explanations to scientific knowledge; and (5) communicating and justifying explanations (NRC, 2000, 29). In this context, inquiry is characterized as a continuum of learner self-direction (NRC, 2000). The more recent Next Generation Science Standards (NGSS) stress scientific practices that align with these principles, including asking questions, analyzing and interpreting data, constructing explanations, and obtaining, evaluating, and communicating information (NGSS Lead States, 2013).

Inquiry-based classrooms are characterized by student-centered, rather than teacher-centered instruction (Buck et al., 2008). While research validates the incorporation of inquiry-based learning into science courses (e.g., Singer et al., 2012), there continue to be calls for more research on student learning in science laboratory courses (Singer et al., 2012). Further, relatively little guidance has been provided for geoscience instructors about what constitutes an inquiry-based exercise and how they might adapt existing activities to increase the level of inquiry. In addition, the terminology surrounding inquiry is inconsistent from study to study, further complicating efforts to make practical changes to classroom assignments. We became interested in practical measures of inquiry for laboratory activities during reflection about the contrasts among weekly laboratory classes in our physical geology laboratory course.

We had revised our physical geology laboratory course to take advantage of local geological resources and create what we interpreted as inquiry-based activities. Each of the 11 weekly laboratory classes lasts 2 h and 45 min, and students complete between three and seven activities in an average laboratory class period. The classes featured a minimum of instructor lecturing and were based around a series of small group activities. The activities were either created for the course or were borrowed and/or adapted from colleagues, published articles (e.g., Hall-Wallace, 1998), or online sources such as those available at the Science Education Resource Center (SERC, http://serc.carleton.edu). As we developed and incorporated the materials, we made no explicit effort to classify the student activities on the basis of levels of inquiry or specific pedagogical strategies (e.g., peer learning, problem-based learning). Over the first 2 y of the course, 20–30 sections of the course were taught by graduate teaching assistants (GTAs) each semester. We used their feedback and comments on student surveys to guide

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revisions. These revisions included adding preclass assignments, modifying activities for clarity and ease of grading, improving resources and materials, adding end-of-class assessment tasks, creating postclass online quizzes, and distributing short "suggestion sheets" for GTAs for each week's class to guide their instruction. We began to investigate instructional practices used by GTAs approximately 4 y after starting to teach the revised course (Ryker and McConnell, 2014). During this research, we sought a method of assessing the characteristics of the laboratory classes and belatedly discovered a rubric for assessing the level of inquiry in laboratory materials published by Buck et al. (2008).

The goals of this study were to assess the level of inquiry used in topics commonly covered in physical geology laboratory courses, and to provide a framework that instructors can readily apply to measure the degree of inquiry in their own laboratory courses. Buck et al. (2008) evaluated materials in 22 college science laboratory manuals, including three physical geology manuals. They rated laboratory classes in all three manuals at the lowest level of inquiry (Buck et al., 2008). In this paper, we seek to revisit their assessment of physical geology laboratory manuals by completing a more fine-grained analysis of individual laboratory activities rather than estimating the inquiry level for the laboratory class as a whole. Next, we discuss how we applied the rubric to analyze our home-grown laboratory courses to determine which laboratory classes, and which activities within those laboratory classes, should be modified in an effort to try to create a consistent level of inquiry throughout the course. Finally, we make some recommendations for other instructors on how to increase the level of inquiry included in laboratory activities, discuss how to scaffold the incorporation of higher-inquiry activities so that students have the greatest opportunity for success, and identify when it is appropriate to use different levels of inquiry.

Benefits of Inquiry-Based Laboratory Courses

Inquiry-based classrooms are beneficial for a number of reasons. Inquiry plays an important role in attracting, engaging, and retaining students (Moskal et al., 2004; Bopegedera, 2011). While students may initially be reluctant to take control of their learning and apply the extra effort required by inquiry-based instruction, these tasks can help them better identify and explain erroneous results, experience a sense of content mastery, and improve their communication skills (Deters, 2005). Students in classrooms utilizing these activities show higher achievement (Schneider et al., 2002; Deters, 2005; Kanter and Konstantopoulos, 2010) and deeper understanding of the nature of science than their peers in traditional classrooms (NRC, 2000). Middle and high school students in inquiry laboratory courses exhibited greater knowledge gains and retention than those in traditional, verification-style laboratory courses (Blanchard et al., 2010). This was especially true for more senior students and for classrooms where teachers used more reformed teaching techniques (Blanchard et al., 2010). At the college level, students in physical geology laboratory courses had better conceptual models of sand-sediment transport when taught in an inquiry-based learning module compared to a traditionally structured, workbook-style laboratory exercise (Miller et al., 2010). A study that used a modified version of the Buck et al. (2008) rubric found that students in a physical geology laboratory had greater learning gains after participating in higher-inquiry laboratory courses (Moss and Cervato, 2016). Students in this study also awarded the laboratory similar course evaluations, indicating that there was no negative impact of moving from more traditional laboratory courses. Preservice teachers who experience inquiry-based instruction demonstrated increased knowledge and more reformed teaching practices than their colleagues (Bransford and Donovan, 2005).

Not all laboratory activities need to be inquiry-based for maximum learning gains. Timmerman et al. (2008) used a mix of inquiry-based and traditional laboratory activities in an introductory college biology class. They found significant student learning gains on abstract topics (such as evolution) when inquiry-based activities were used. However, more descriptive, concrete topics (such as anatomy) could be taught effectively using traditional didactic methods (Timmerman et al., 2008). Lawson et al. (2000a, 2000b) found similar results in an introductory biology course where students mastered abstract, theoretical concepts more effectively than descriptive topics when taught using inquiry-based pedagogies. Several researchers advise careful scaffolding of a mix of inquiry levels to help students achieve success (Volkmann and Abell, 2003; Eick et al., 2005).

Challenges of Incorporating Inquiry

There are several challenges to incorporating inquiry-based teaching strategies in introductory geoscience classrooms. These include the availability of resources (e.g., educational materials, instructional preparation time), situational factors (e.g., class time constraints, large class sizes, disconnected lecture and laboratory classes), teacher awareness of instructional practices, and teaching beliefs and values that support change (Edelson et al., 1999; Sundberg et al., 2000; Anderson, 2002; Barab and Luehmann, 2003; Gess-Newsome et al., 2003; Zion and Mendelovici, 2012). Trumbull et al. (2005) argued that laboratory activities should integrate content knowledge about the subject at hand and inquiry to maximize the impact of inquiry-based materials. This means that an instructor must be familiar with both the content and methods of inquiry-based teaching.

This raises another important challenge: the lack of consistent definitions for what constitutes inquiry. Inquiry has been used to refer to the way we teach, a method for conducting research (how we "do science"), or the way students learn (Flick, 1995; Colburn, 2000; NRC, 2000). Additionally, the term "inquiry" has been given numerous modifiers, such as traditional, guided, and structured, which lack a common meaning (Buck et al., 2008). This makes a direct comparison of study results difficult. The ability to classify the level of inquiry present in an activity is an important first step in determining whether the degree of inquiry in which students engage affects increased content mastery, interest, and skill development.

Assessing Inquiry

Early methods for characterizing the type of inquiry present in a lesson evaluated laboratory exercises on whether they provided students with (1) a question to be answered, (2) the data collection methods needed to answer the question, and (3) the ability to interpret the results

TABLE I: Rubric used to characterize inquiry in the undergraduate laboratory (modified from Buck et al., 2008).

Characteristic	Corresponding Essential Feature of Inquiry (NRC, 2000)	Level 0: Confirmation	Level ½: Structured Inquiry	Level 1: Guided Inquiry	Level 2: Open Inquiry	Level 3: Authentic Inquiry
Problem/ question	Engaging in scientifically oriented questions	Given by teacher	Given by teacher	Given by teacher	Given by teacher	Open to learner
Theory/ background	Giving priority to evidence in responding to questions	Given by teacher	Given by teacher	Given by teacher	Given by teacher	Open to learner
Procedures/ design		Given by teacher	Given by teacher	Given by teacher	Open to learner	Open to learner
Analysis of results	Formulating explanations from evidence	Given by teacher	Given by teacher	Open to learner	Open to learner	Open to learner
Communication of results	Communicating and justifying explanations	Given by teacher	Open to learner	Open to learner	Open to learner	Open to learner
Conclusions	Connecting explanations to scientific knowledge	Given by teacher	Open to learner	Open to learner	Open to learner	Open to learner

(Schwab, 1962; Herron, 1971). The level of inquiry was determined by which of these features were given to students and which were open for exploration. All elements of an activity were provided in low-level inquiry activities, whereas high-level inquiry exercises were characterized by the student acting independently to create their own question, collect the necessary data, and interpret their results (Schwab, 1962). Domin (1999) and Bell et al. (2005) both described a similar four-level method for classifying inquiry, with different aspects, such as outcome, approach, and procedure, being provided to the students. The method described by Bell et al. (2005; attributed to Rezba et al., 1999) renumbered Schwab's four levels (from 0, 1, 2, and 3 to 1, 2, 3, and 4) and renamed them confirmation, structured, guided, and open, respectively. Pyle (2008) provided examples of Earth Science activities that matched the division outlined by Bell et al. (2005) but also incorporated aspects of geoscience thinking. Kastens and Rivet (2008) defined six modes of Earth Science inquiry (e.g., use of physical models, observation of change over time) but did not attempt to define different levels of inquiry within these modes.

Wenning (2005) expanded on these and other early rubrics (including Herron, 1971; Staver and Bay, 1987; Colburn, 2000) by incorporating the concept of intellectual sophistication. Higher levels of intellectual sophistication were interpreted to require a shift from concrete to abstract reasoning. Wenning (2005) proposed a hierarchy of nine different types of inquiry that he positioned along a continuum of intellectual sophistication and locus of control. This continuum included three specific inquiry levels dedicated to laboratory courses: guided, bounded, and free. The distinctions among guided, bounded, and free inquiry laboratory courses was again based on the amount of independence given to students in identifying the question to be asked and the procedures to be used and echoed Schwab's (1962) definitions of his levels 1, 2, and 3.

Brown et al. (2006) developed a similar inquiry continuum that categorized activities from more to less student guidance. A unique aspect of the Brown et al.'s assessment protocol is that it allows activities to be described as a high level of inquiry while still being teacher-directed. An activity is labeled full, partial, or no inquiry on the basis of the extent to which the essential features of inquiry described by the NRC (2000) are included.

While the inquiry classification schemes of Schwab (1962), Bell et al. (2005), Wenning (2005), and Brown et al. (2006) each provide a framework for analysis, they often lack practical definitions of each level of inquiry and thus are challenging to apply to characterize laboratory activities. Further, the use of the continua by Brown et al. (2006) makes consistent application of labels difficult, resulting in activities that could be labeled as "guided" in one study and "structured" in another (see discussion in Buck et al., 2008).

The quantitative rubric developed by Buck et al. (2008) provides concrete definitions for five levels of inquiry in laboratory activities. These are: confirmation (level 0), structured (level ½), guided (level 1), open (level 2), and authentic (level 3; Table I). The inquiry level is determined on the basis of the following six elements of each activity: (1) problem/question, (2) theory/background, (3) procedures/ design, (4) analysis of results, (5) communication of results, and (6) conclusions. The more of these elements that are provided by the instructor or laboratory manual for the student, the lower is the inquiry level (Table I). For example, an activity at the lowest inquiry level (confirmation; Buck et al., 2008) would provide students with a task and direct them through the steps necessary to complete the task effectively (Table I). A student following instructions to identify a mineral or read an elevation from a topographic map would be completing a confirmation task. A structured inquiry activity would ask students to come up with their own method of communicating their results, but it would provide the question, background information, procedures, and method of analyzing results. For example, a geologic time laboratory could provide students with background information on radioactive decay and a graph plotting parent and daughter isotopes over time. Students would be provided with the half-life of several radioactive elements, and they would have to identify which would be the best to use to obtain an accurate date on rocks of different ages. An example of a guided inquiry activity would be to have

students decide how they could estimate the size of a drainage basin when provided with a topographic map. A kilometer grid already overlaid on the map would give students a hint as to the procedures to use. However, they would not be given explicit instructions on how to analyze the results of their observations. An inquiry activity that only provides students with the question and background would be classified as open. For example, students could be are presented with three hypotheses that describe earthquakes as periodic, time-predictable, or random and then instructed to design and conduct an experiment using a physical model (Hall-Wallace, 1998) to determine which of these hypotheses best describes the model's movements. They would come up with the experimental procedures and decide how to analyze and communicate their results. Authentic inquiry activities would require students to generate their own research question and design a method for testing and analyzing the results (Buck et al., 2008).

The Buck et al. (2008) rubric provides a range of levels that allow an instructor to readily distinguish between varying degrees of student independence in laboratory exercises. The discrete labels tied to that independence, plus the descriptions in the original article, bring clarity to a wide number of inquiry modifiers and provide an opportunity for this protocol to be consistently applied. The characteristics that Buck et al. (2008) used to define the levels of inquiry reflect the NRC's definition of inquiry (Table I; NRC, 2000).

Buck et al. (2008) applied their rubric to evaluate 386 laboratory experiments in undergraduate science laboratory manuals. Each laboratory topic was counted as a separate experiment, and Buck et al. (2008) assigned a single inquiry level to an entire laboratory class. The majority of these were rated as confirmation (29.8%) or structured (62.2%). Buck et al. included 46 laboratory courses from three geology laboratory manuals, all of which they rated as confirmation, the lowest level of inquiry. Ryker and McConnell (2014) applied this rubric to individual activities in physical geology laboratory courses in an analysis of inquiry and teaching practices at a single institution. In that study, the majority of activities were rated at structured (43.1%) or guided (35.1%) inquiry levels. Here, we extend that analysis to characterize laboratory activities from multiple laboratory manuals (including more recent editions of two of the manuals cited in Buck et al., 2008), complete a detailed review of our own laboratory materials, and discuss how instructors can incorporate inquiry-based exercises into their laboratory courses.

METHODS

We analyzed laboratory activities from five physical geology laboratory manuals. One of the manuals (NCSU Physical Geology Laboratory Manual, 2013) was developed specifically for the inquiry-based physical geology laboratory course at the authors' institution. These materials were created and collected by the authors with assistance from several graduate students. Several activities are publically available from the SERC or were shared by colleagues.

The other four manuals are commercially published by multiple companies and are used in physical geology laboratory courses across the country. These are referred to herein as the American Geological Institute (AGI)/National Association of Geoscience Teachers (NAGT) (Busch, 2011), Zumberge (Rutford and Carter, 2014), Jones and Jones (Jones and Jones, 2013), and Ludman and Marshak (Ludman and Marshak, 2012) laboratory manuals. (Buck et al. [2008] included ratings of earlier editions of the AGI/NAGT and Zumberge manuals.) The Ludman and Marshak, Jones and Jones, AGI/NAGT, and Zumberge manuals are in their 2nd, 8th, 9th, and 16th editions, respectively. Only the Ludman and Marshak text specifically refers to the inclusion of inquiry-based exercises, although the AGI/NAGT manual describes an activities-based approach. Ludman and Marshak (2012, viii) include a statement in their preface that, "students learn best by doing science… [and] are guided through real geologic puzzles so they understand concepts more deeply and learn to think like a geologist." The 9th edition of the AGI/NAGT manual was revised to have a "new activity-based user-friendly format… with each lab's specific learning objective correlated to an activity within the lab" ((Busch, 2011, vii). The manuals sampled were selected to represent the most recent edition of laboratory manuals from multiple large publishing companies, and we assume that these are reasonably typical of other published geology manuals. We selected six topics that were covered in all five laboratory manuals: minerals, groundwater, streams, earthquakes, geologic time, and plate tectonics. Each laboratory was broken up into activities, usually composed of multiple questions; we examined a total of 806 questions in 210 activities.

We used the rubric from Buck et al. (2008) to characterize the level of inquiry for each of the activities. Examples of activities used in physical geology laboratory courses that are representative of the different levels of inquiry are described in Table II. The nonparametric Kruskal–Wallis test and Mann–Whitney post-hoc paired-comparison test were used to compare and contrast the level of inquiry for similar laboratory topics among different laboratory manuals.

For each activity, an inquiry score was calculated using the scale and numeric levels provided by Buck et al. (2008). The five levels are: confirmation (0), structured (½), guided (1), open (2), and authentic (3). Each laboratory activity was assigned an inquiry level, and we determined the proportion of each laboratory composed of activities at each level. We multiplied those values together and added the resulting scores for each level to determine a total inquiry score. For example, if we were to evaluate a laboratory with eight separate activities, six of which were structured and two of which were guided, we would calculate the score for the laboratory as 75% structured (75×0.5) and 25% guided (25×1), for a total inquiry score of 62.5. This differed from the original method used by Buck et al. (2008) of assigning a single inquiry level to an entire laboratory topic, and it allowed for a more fine-grained examination of the laboratory courses.

Coding of inquiry levels began with two researchers (the first author and a reviewer external to this project) independently coding 43 laboratory activities using the Buck et al. (2008) rubric. This was done to ensure the rubric was used consistently, as well as to minimize potential confirmation bias. The researchers began with a subset of 12 activities and explained their reasoning for each activity on which their coding did not match and negotiated agreements on interpretations of those items to ensure consistent assessments. They then evaluated all 43 activities based on

the revised interpretations. Through this process, the co-coders established good interrater reliability on the 43 separate items ($K = 0.898$; Cicchetti and Sparrow, 1990). An analysis of the inquiry level of laboratory activities was also conducted with two additional researchers unaffiliated with North Carolina State University (NCSU), again to minimize confirmation bias and ensure the rubric could be applied independently by other geoscience instructors without discussion. After reading the original article by Buck et al. (2008), the researchers independently evaluated a subset of activities from all five laboratory manuals ($n = 40$, including eight from the *NCSU Physical Geology Laboratory Manual*). Without discussion, this resulted in a good interrater reliability ($K = 0.827$; Cicchetti and Sparrow, 1990), making us confident that this rubric can be applied by instructors with fidelity. (The original rubric established an inter-rater reliability value of 83% agreement with 36 laboratory activities in three laboratory manuals [Buck et al., 2008, 54].) The first author subsequently characterized the level of inquiry for the rest of the laboratory exercises.

The nonparametric Kruskal–Wallis test was used to determine whether there were statistically significant differences between inquiry scores for activities in the five laboratory manuals and for activities associated with the six laboratory topics (Kruskal and Wallis, 1952). A nonparametric statistic test was selected because the inquiry scores were not normally distributed among the laboratory courses analyzed in this study. If a significant difference was identified at $p < 0.05$, a post-hoc paired-comparison test was used to determine which groups differed from one another.

RESULTS

What Do the Levels of Inquiry Look Like in the Four Physical Geology Laboratory Manuals?

In contrast to reports in Buck et al. (2008), each physical geology laboratory in the four manuals we evaluated contained at least two levels of inquiry (Fig. 1). Most (19 of the 24) of the laboratory courses contained at least one guided inquiry exercise, and all laboratory courses contained confirmation and structured activities (Table II). Only two laboratory courses contained open inquiry activities (plate tectonics in Jones and Jones; groundwater in Ludman and Marshak). None contained authentic inquiry activities. The average proportion of exercises at each level of inquiry in these four laboratory manuals was: 39.9% confirmation, 48.1% structured, 10.9% guided, and 1.1% open, producing an average inquiry score of 37.1.

There was no statistically significant difference between the inquiry scores assigned to the activities in the four published laboratory manuals ($H[3] = 1.556$, $p = 0.669$; Fig. 2). Average inquiry scores by manual were 44.4 (Ludman and Marshak; median of 41.3), 37.2 (Jones and Jones; median of 35.0), 35.8 (AGI/NAGT; median of 40.4), and 31.1 (Zumberge; median of 25.7).

There was a statistically significant difference between the inquiry scores assigned to the activities in the different laboratory topics in the published laboratory manuals ($H[5] = 21.933$, $p < 0.001$; Fig. 3). Post-hoc paired-comparisons revealed statistically significant differences between some of the laboratory courses. The activities in the minerals and streams laboratory courses received significantly lower inquiry scores than those in the plate tectonics, geologic time, earthquakes, and groundwater laboratory courses ($p < 0.05$).

The average inquiry scores for the two low-scoring laboratory topics were 23.0 for minerals (median of 23.3) and 21.6 for streams (median of 20.6). These laboratory courses were characterized by predominantly confirmation and structured inquiry exercises (Figs. 2 and 4). Few guided activities were identified in these laboratory courses (Fig. 1). The laboratory topic with the highest average inquiry score was groundwater (53.3; median of 46.9; Fig. 3). The groundwater laboratory courses had the highest percentage of open activities of all the laboratory topics (4.5%; Fig. 1).

Characterizing Inquiry in NCSU Physical Geology Laboratory Courses

We anticipated that the activities in these laboratory courses would exhibit higher levels of inquiry than commercially produced laboratory manuals, but we were unclear about how inquiry would vary within and among different laboratory courses. Our analysis revealed that all six laboratory courses incorporated activities featuring guided inquiry, and two (earthquakes, groundwater) had open inquiry tasks (Fig. 4). The average proportion of exercises at each level of inquiry in the NCSU laboratory manual was: 16.5% confirmation, 40.1% structured, 36.6% guided, and 6.7% open, producing an average inquiry score of 70.1. The highest-scoring laboratory courses were earthquakes (93.8) and plate tectonics (91.7; Fig. 4).

Analysis reveals a similar variation in scores among laboratory topics, with the minerals topic once again earning the lowest inquiry score (23.8). The inquiry scores given to the activities within the minerals laboratory were significantly lower ($p < 0.05$) than those in all the other laboratory courses except for streams. We subsequently revised both the minerals and geologic time laboratory classes to increase their inquiry scores (see Grissom et al., 2015).

DISCUSSION

Ideally, what levels of inquiry would we want to see in physical geology laboratory manuals, and what does this mean for geology laboratory development? As scientists and instructors, we might wish our students to develop a mix of technical skills (such as map reading or mineral identification) and scientific reasoning skills (such as interpreting the geologic history of an area from a cross section). Creating activities at a range of inquiry levels is one way to address this goal. We can apply some lessons from the analyses described here to produce a more diverse array of inquiry activities in physical geology laboratory courses. Our experience is that increasing inquiry levels of key activities in the NCSU laboratory courses can result in improved student performance on graded assignments (Grissom et al., 2015).

Scaffolding Inquiry Based on Concepts To Be Learned

It is not recommended that all activities should be at high levels of inquiry, as this can cause students frustration (Volkmann and Abell, 2003; Deters, 2005). For example, students may not be ready to formulate their own questions or establish experimental controls at the beginning of a semester. However, by starting out at lower levels of inquiry and increasing the level of student independence within and across laboratory courses, students can be made to feel more

TABLE II: Sample activities for each laboratory topic at differing levels of inquiry.

	Level of Inquiry			
	Confirmation (Level 0)	**Structured (Level ½)**	**Guided (Level 1)**	**Open (Level 2)**
Characteristics provided for students:	Problem/question; theory/background; procedures/design; analysis of results; communication of results; conclusions	Problem/question; theory/background; procedures/design; analysis of results	Problem/question; theory/background; procedures/design	Problem/question; theory/background
Minerals	Students sketch samples of quartz and halite before and after breaking them with a hammer. They use these to say whether the minerals display cleavage or fracture (NCSU Physical Geology Laboratory Manual, 2013, 8).	After categorizing an unknown set of minerals and rocks into groups based on their own criteria (see guided example), students are asked to compare their results with those of others in the class, and say what this comparison tells them about the process of classification (Ludman and Marshak, 2012, 51)	Students collect and compare interfacial angles of clear quartz, amethyst, and smoky quartz. They then decide what their data indicates about the underlying chemical composition and atomic architecture of each (Jones and Jones, 2013, 15).	None identified.
Plate tectonics	Students are provided with a map showing the relief of Earth's surface features and are asked to copy over the boundaries of the tectonic plates from another map. Students then answer questions like: Which plates do not contain significant areas of continental landmasses? Or, name the plates bounded by the East Pacific Rise (Zumberge; Rutford and Carter, 2014, 257)	Students connect magnetic anomalies around the Pacific-Antarctic Ridge and explain whether their results support the seafloor-spreading hypothesis (Jones and Jones, 2013, 331).	Discovering plate boundaries activities, as described by Sawyer (http://plateboundary.rice.edu/). In these activities, students are asked to make observations based on four global data maps. They then work together in a jigsaw activity to describe multiple plate boundaries on the basis of their observations (problem/question). Students are not given explicit instructions on how to analyze the results of their observations (NCSU Physical Geology Laboratory Manual, 2013, 2–7).	None identified.
Geologic time	Students are given a picture that they are told is of inclined beds with a crosscutting feature and are asked to determine which is younger. In the preceding text, students are told that "if one rock cuts across another, it must be younger than the rock that it cuts" (Ludman and Marshak, 2012, 419–420).	Students apply the principles of relative dating to a cross section diagram to place the rocks in the correct sequence from youngest to oldest (Jones and Jones, 2013, 253–254).	Students are asked why zircon sand grains found on a modern beach would not yield modern age using absolute age dating. Using their answer, they define a rule geologists should follow when they date rocks according to radiometric ages of crystals inside the rocks (AGI/NAGT; Busch, 2011, 190).	None identified.
Earthquakes	Students outline areas on a map to indicate different surface materials (bedrock, mud and fill, unconsolidated alluvium). These materials are already color coded on the map (Jones and Jones, 2013, 318).	Students are given the time interval between the arrival of P and S waves and asked to explain how the interval changes with distance from the epicenter (AGI/NAGT; Busch, 2011, 357).	Students make a prediction about why different seismic waves make the ground shake differently at an earthquake epicenter versus far from it (Ludman and Marshak, 2012, 396).	Using an earthquake simulation machine, students must design and conduct an experiment to determine whether the movements that occur with the model are best described as periodic, time-predictable, or random (Physical Geology Laboratory Manual, 2013,, 7).

TABLE II: continued.

	Level of Inquiry			
	Confirmation (Level 0)	**Structured (Level ½)**	**Guided (Level 1)**	**Open (Level 2)**
Streams	Students determine the elevation of multiple points on an idealized hypothetical topographic map. They also determine the direction of stream flow, with a reminder that water flows downhill (AGI/NAGT; Busch, 2011, 261).	Students are asked to calculate the stream discharge using a stopwatch, a tennis ball, and a meter stick. They are told to make measurements in several places across the stream in order to account for lateral variations in depth. Each group is asked to share their results with the class, but must come up with their own way of communicating their results (Physical Geology Laboratory Manual, 2013,, 8–9).	Using a map with two modern stream systems, students are told to sketch a series of maps that show the progressive changes that will occur as erosion continues around some of the map's features (Zumberge; Rutford and Carter, 2014, 114–115).	None identified.
Groundwater	Students are given a table of subsidence by year and asked to calculate the total subsidence for a given time range (AGI/NAGT; Busch, 2011, 289).	Using the relationship of flow lines to water table contours, students sketch a network of flow lines on a map. Students are told how to represent these lines on the map, but results are not immediately obvious (Zumberge; Rutford and Carter, 2014, 130–131).	Based on the flow lines drawn (see structured example), students determine whether there is reasonable evidence to conclude whether seepage from a dump contaminated a well (Zumberge; Rutford and Carter, 2014, 130–131).	Students are given a case involving a dispute between a farmer and two local companies whose pumping he suspects are responsible for his wells running dry. The students act as consultants to determine why the farmer's wells have run dry based on depth to water data before and after commercial pumping (Ludman and Marshak, 2012, 293–294).

comfortable taking control in the laboratory environment. In describing how instructors might vary levels of inquiry over time, Fay and Bretz (2008) proposed four possible inquiry trajectories, featuring slow, rapid, or linear increases, as well as an oscillating level of inquiry. The strategy used in the NCSU physical geology laboratory courses most closely matches the oscillating level of inquiry by concentrating lower-level inquiry activities at the start of each laboratory and building toward higher-level activities toward the end of the laboratory course. The confirmation and structured activities in these laboratory courses are often set up to scaffold students toward the higher inquiry levels, much like how lower-level questions on Bloom's taxonomy may scaffold a student's ability to answer higher-order questions (Eick et al., 2005).

We suggest that lower-level inquiry exercises should be used to help students master descriptive topics (Lawson et al., 2000a, 2000b; Timmerman et al., 2008) or to build to activities that develop higher-order thinking skills. For example, mineral identification may be described as a more descriptive, concrete topic. Mineral identification received the lowest average inquiry score compared to the other laboratory topics. If this is the only skill that we intend for students to get out of this laboratory activity, then lower-inquiry activities are an appropriate selection. However, if the highest level of inquiry students experience is structured (as defined by Buck et al., 2008), then they are not learning how to ask their own questions, design their own experiments, and analyze their results. This creates the illusion that geology, and science in general, is about confirming a set of known ideas, rather than creatively investigating how the world works (Herman, 2008).

If the intended purpose of an exercise is for students to master more abstract, theoretical topics or develop authentic scientific reasoning skills, then higher-inquiry-level activities are needed. For example, the groundwater laboratory courses received the highest average inquiry score of the six topics among the laboratory manuals. The five groundwater laboratory courses analyzed used different activities to get students to envision how water moves through subsurface materials, an abstract concept that students cannot observe directly. Some laboratory courses had students use maps to determine the relationship between the water table and surface topography; others had them taking depth-to-water measurements to complete three-point problems to determine flow direction. The open activities in these laboratory courses required students to apply their knowledge of groundwater movement to solve hypothetical disputes over groundwater pollution or wells running dry (Table II). Here, the inquiry level matches the topic being addressed: The higher-level inquiry activities support the learning of an abstract concept. The streams laboratory courses also asked students to tackle an

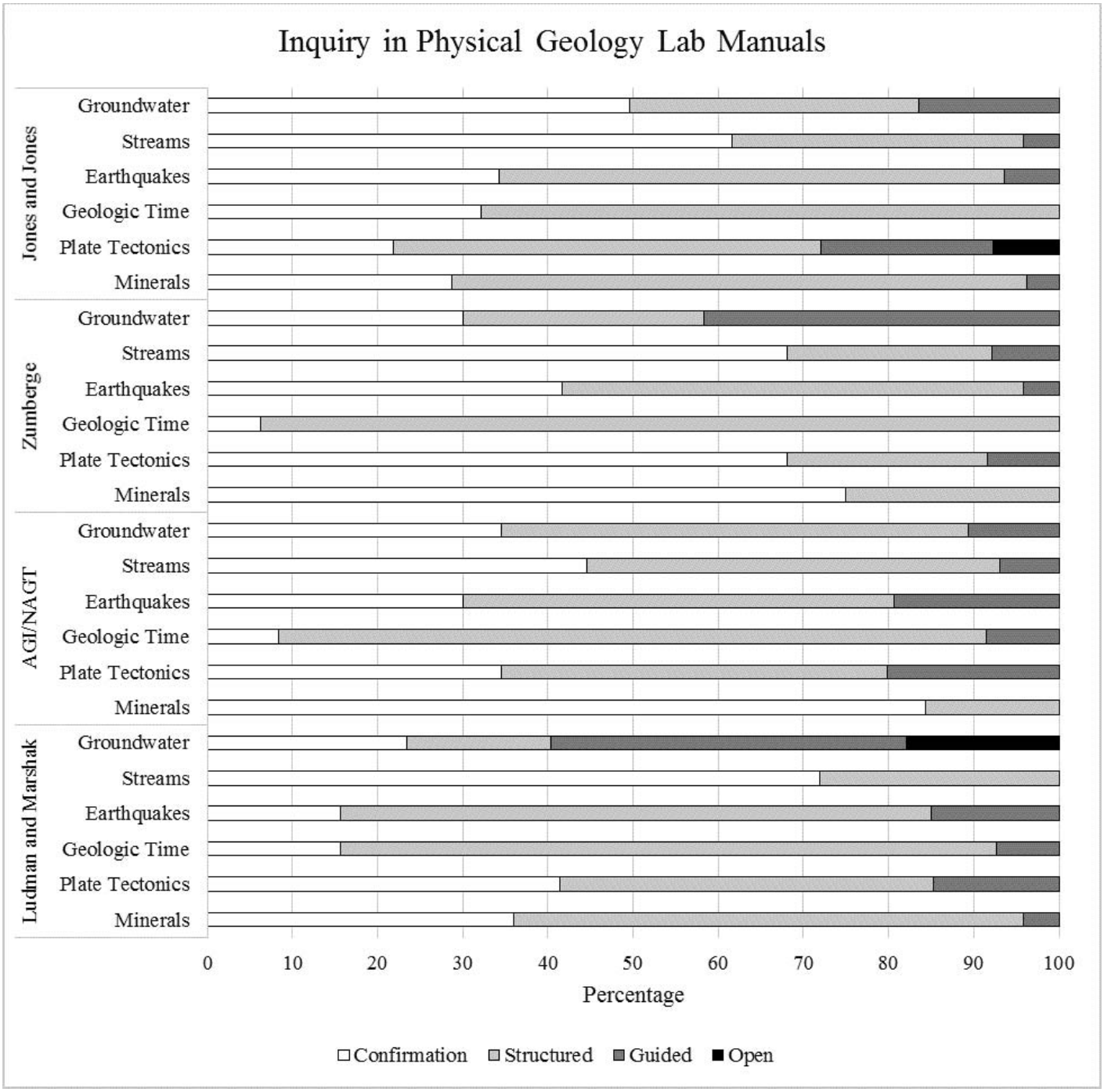

FIGURE 1: Proportion of each laboratory analyzed from the published laboratory manuals that can be attributed to each level of inquiry. No authentic inquiry activities were identified in any of these laboratory courses.

abstract concept: How does surface water affect landscapes over geologic time? However, these laboratory courses received an average inquiry score closer to minerals (a descriptive topic) than groundwater (an abstract concept). If instructors know which laboratory courses contain content out of alignment with inquiry levels (low inquiry for an abstract concept; high inquiry for a descriptive concept), it allows them to target those laboratory courses for development. This guidance may be especially useful in cases when time and resources are limited for curricular reform.

Increasing the Level of Inquiry in a Physical Geology Laboratory Course

While large-scale changes take time, some small changes can be readily made to increase the level of inquiry present in physical geology laboratory courses. To illustrate this, we will use a short example from the Ludman and Marshak groundwater laboratory topic. Though this particular example is a confirmation inquiry question, the overall laboratory had the third highest inquiry score of all of the laboratory courses analyzed, so this should not be seen as

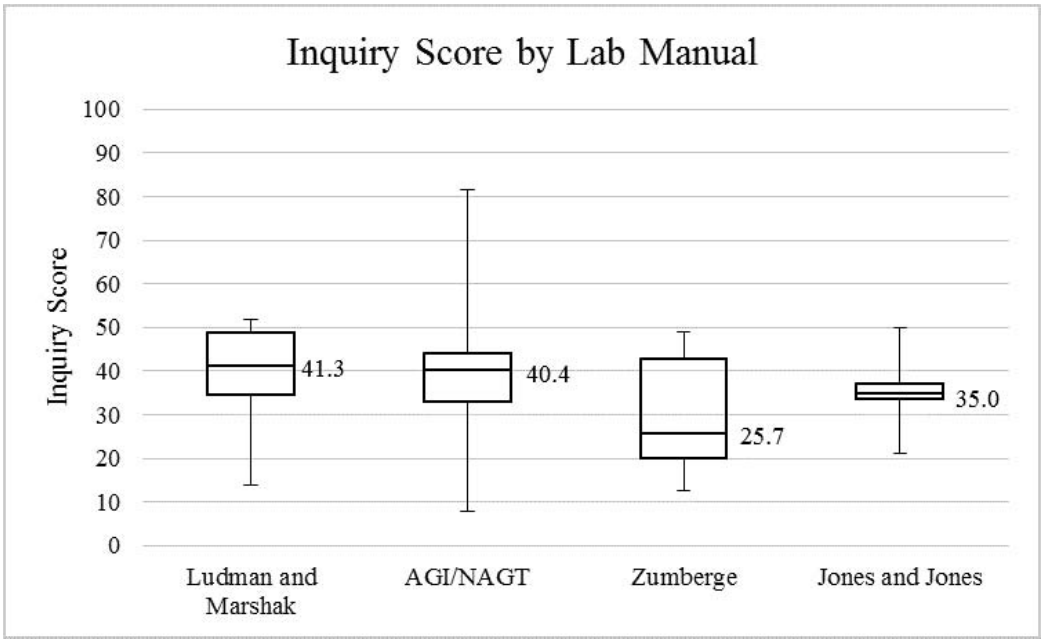

FIGURE 2: Range of inquiry scores for each of the four published laboratory manuals analyzed. Numbers represent median scores (compare with average scores in text). Inquiry scores for the laboratory manuals did not differ significantly from each other ($p > 0.05$).

representative of the laboratory as a whole. Students were given the following question (emphasis added):

> *"Are all porous rocks aquifers? Hold pieces of* ***highly porous pumice and scoria*** *above two beakers or rest them on the rims as shown in Figure 12.3. Slowly drop or sprinkle water onto the rocks and observe what happens. Are pumice and scoria porous? Permeable? Explain."* (Ludman and Marshak, 2012, 283)

A review of the reading material associated with this activity reads:

> *"Pumice and scoria are very porous, but their pores are not connected. Pore spaces must be connected for water to move from one to another—a property called permeability."* (Ludman and Marshak, 2012, 283)

Students are given the answer to whether these two rocks are porous by the question itself and the reading

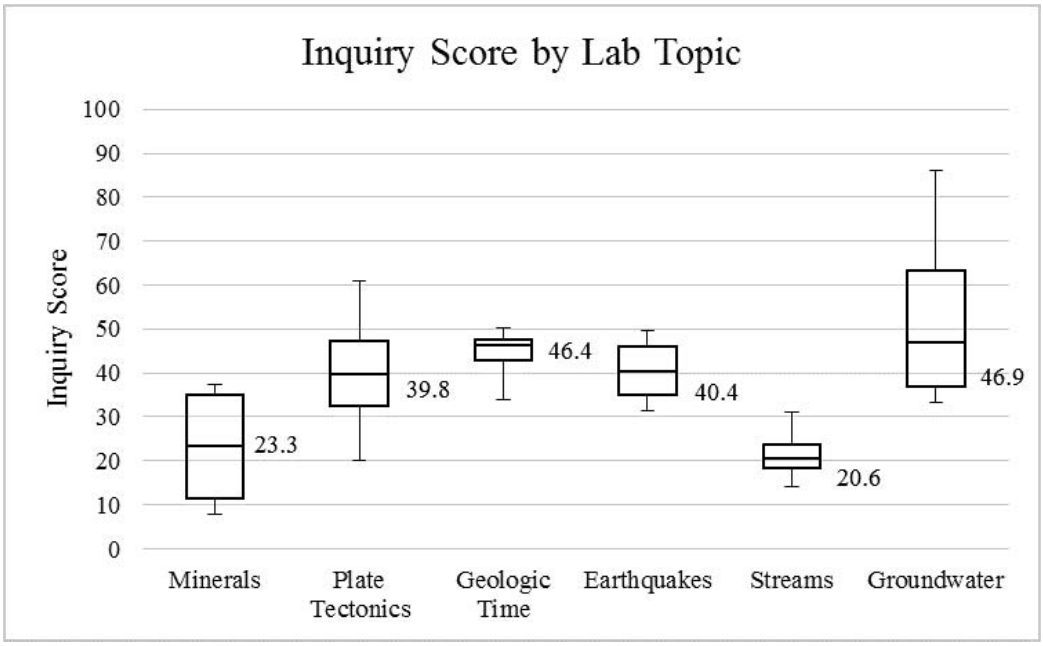

FIGURE 3: Range of inquiry scores for each of the six laboratory topics analyzed within the four published laboratory manuals. Numbers represent median scores.

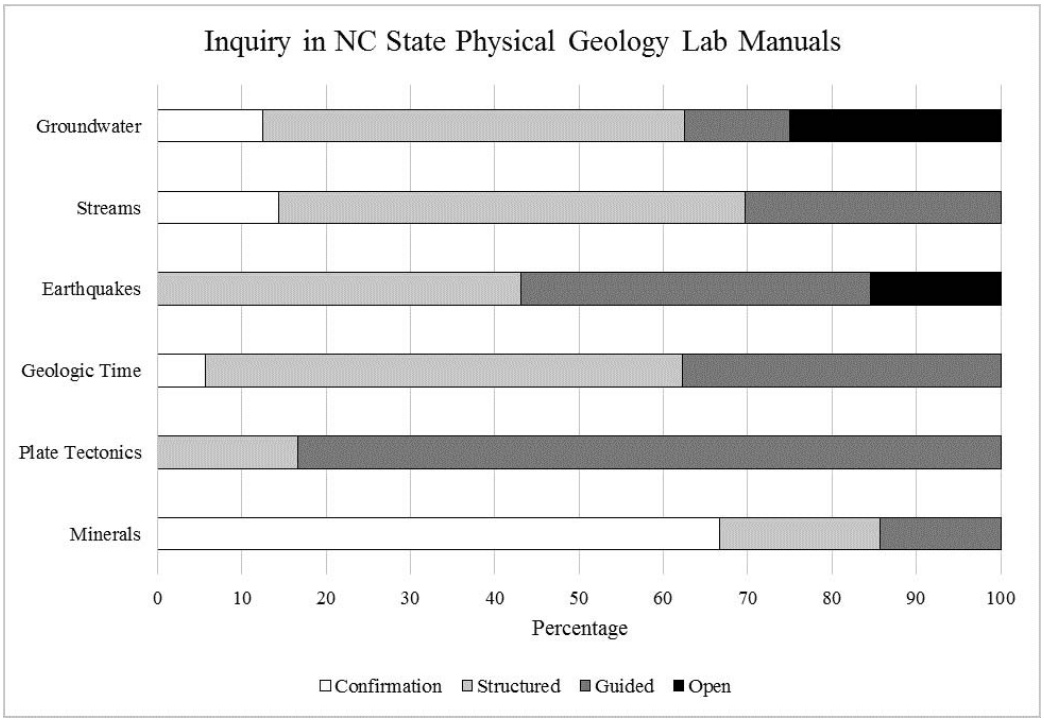

FIGURE 4: Proportion of each laboratory analyzed from the NCSU laboratory manual that can be attributed to each level of inquiry. No authentic inquiry activities were identified in any of these laboratory courses. Total scores for each laboratory were as follows: groundwater 87.5; streams 57.9; earthquakes 93.8; geologic time 66.0; plate tectonics 91.7; and minerals 23.8.

beforehand. This is an example of a confirmation exercise: The correct answer is "immediately obvious from statements and questions in the laboratory manual" (Buck et al., 2008, 54). In order to increase the level of inquiry to structured, the authors could change the rocks used as examples, remove the "highly porous" descriptor of the rocks in the question, and provide students with the explanation after the exercise is completed, rather than before it. This would give students the opportunity to learn something that has not already been described in the manual. To convert the activity to a guided exercise, the authors could ask the students to devise their own method of analysis (if water moves through the rock, the pore spaces are connected, and the rock is permeable). To turn this into an open inquiry activity, the instructor could still start by providing samples of several different types of sediment or rocks, along with the definitions for porosity and permeability. They could then ask students to come up with an experiment to put the rocks in order from highest to lowest porosity or permeability, rather than providing them with the procedures.

Multiple resources have been developed with the goal of providing support for instructors who wish to modify their existing laboratory courses to include higher levels of inquiry (e.g., Clark et al., 2000; Peters, 2005; Grady, 2010; Lott, 2011; Gooding and Metz, 2012). Volkmann and Abell (2003) laid out 10 adaptation principles to guide instructors away from cookbook laboratory courses. They reported that high school teachers have found this easy to use in transforming their instruction. Russell Laboratories (2013) offered five questions to consider for any instructor looking to "uncook" their cookbook laboratory activities, along with examples of phrasing and techniques that instructors can use. The Buck et al. (2008) rubric is not the only one available for instructors (see previous discussion of other inquiry rubrics), but it is a straightforward method of classifying and comparing different laboratory activities.

Limitations

We selected the four published manuals to represent successful publications from multiple companies. The assumption was that these would be reasonably typical of other published geology manuals. However, there may be other physical geology laboratory manuals that we did not come across that include activities featuring higher levels of inquiry.

In the NCSU laboratory manual, minerals were grouped with igneous rocks into one laboratory topic. In the Ludman and Marshak laboratory manual, minerals were split into two laboratory courses: one on identifying minerals on their own, and one showing their relationship to the rock cycle. To allow comparison with the other laboratory manuals, we examined only the exercises on mineral identification for the "minerals" topic. In the Jones and Jones laboratory manual, minerals were also split into two chapters: one on their properties, and one on their identification. Since both properties and identification were covered together in the other manuals' mineral laboratory topic, activities from both chapters were treated as one laboratory topic.

Rocks and the rock cycle, a very common topic for physical geology laboratory courses, were divided up several different ways. The Ludman and Marshak and AGI/NAGT manuals had three separate laboratory courses for each rock type, and a separate laboratory for the rock cycle. The Zumberge and Jones and Jones manuals had one laboratory

on all three rock types. The NCSU laboratory manual had one laboratory on minerals and igneous rocks, one on sedimentary and metamorphic rocks, and one on the rock cycle. Because the number of exercises associated with rock identification varied so widely between manuals, we did not choose to use them as a topic in this study.

We note that there is some potential for bias in our analysis because we were assessing inquiry-based laboratory courses that we had created. We endeavored to address this by co-coding two different selections of laboratory activities with colleagues who were not affiliated with this research project. The first colleague was also from NCSU, but the second two colleagues were from other institutions and had no discussion of the application of the rubric before coding laboratory activities. In both cases, we found good interrater reliability with these colleagues; therefore, we anticipate that our application of the Buck et al. (2008) rubric to the NCSU laboratory courses and the laboratory courses in the four published laboratory manuals was valid and reliable.

We calculated inquiry scores using the scoring scheme of Buck et al. (2008). We recognize that the progression of scoring from 0 (confirmation) to ½ (structured) to 1 (guided) and 2 (open) is unusual in comparison to other inquiry scales that step up in whole numbers (0, 1, 2, 3 or 1, 2, 3, 4), but we decided to remain true to the rubric. The statistical analyses presented here produced similar results when recalculated with whole numbers (0, 1, 2, 3 or 1, 2, 3, 4); that is, there is no statistically significant difference among the four published laboratory manuals. In our view, the absolute scores are less important than the distinction between inquiry levels.

CONCLUSIONS

The benefits of inquiry-based instruction are many, from improving attitudes to maximizing student learning. The physical geology laboratory manuals analyzed here exhibit a wider range of inquiry activities than that interpreted by Buck et al. (2008). However, they incorporate mostly low-level inquiry activities (confirmation, structured), and this may indicate that inquiry may not be one of the underlying philosophies being used in their development (Siemens, 2002). Activities in the NCSU laboratory manual illustrate that it is possible to take publicly available resources and combine them with activities based around local geology to incorporate higher-level inquiry activities in introductory laboratory courses.

While some departments utilize published laboratory manuals, many use a mix of activities developed in-house with those adapted from other resources, including published manuals. The development of inquiry activities requires time and effort on the part of the person designing the laboratory courses. We found the rubric from Buck et al. (2008) to be straightforward to apply in our analysis, and we believe it could be a valuable resource for faculty making decisions about the activities to include in their own laboratory courses. To provide additional assistance, we share the most recent versions of the NCSU laboratory courses at the following Web site: https://sites.google.com/site/geosciencelearning/research/ncsu_mea110_labs.

We do not intend to imply that the goal is to offer only higher-level inquiry laboratory activities. The level of inquiry should be matched to the task at hand. Higher-inquiry-level activities are more appropriate for abstract topics. Lower-level inquiry activities are more suitable when the task is descriptive or to scaffold to higher-level inquiry activities. By providing a mix of high- and low-inquiry activities in introductory geology laboratory courses, students can develop a better understanding of geology and the nature of science. Additional studies are needed to better understand how higher-level inquiry activities could benefit students in terms of their learning and perceptions of science, especially geology.

Asking students to limit themselves to low-inquiry activities may influence their views of the nature of science as a primarily confirmatory, fact-gathering activity, and may negatively influence their perceptions of geology (Herman, 2008). Students who have positive experiences with science are more likely to persist and take a second course in the discipline, improving student retention rates (Brainard and Carlin, 1998; Moskal et al., 2004). While asking students to complete higher-level inquiry activities from the beginning of a laboratory may cause frustration, scaffolding learning for those students to the point where they can take on these activities can lead to a sense of accomplishment, improved theoretical understanding, and a view of science as a creative process by which we investigate the world around us.

Acknowledgments

The laboratory courses related to minerals, rocks, and geologic time have undergone revision to incorporate higher levels of inquiry since the analysis presented in this paper. Other researchers have reported those changes, and related improvements in student performance, perceptions of relevance, and situational interest (Grissom et al., 2015). We thank the reviewers of an earlier version of this manuscript for their thoughtful comments. We are grateful to all the students enrolled in the physical geology course at North Carolina State University for their useful feedback and to the graduate teaching assistants who have often been the source for improvements to the laboratory courses.

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