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At the Elbows of Scientists: Shaping Science Teachers' Conceptions and Enactment of Inquiry-Based Instruction

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Abstract This study stemmed from concerns among researchers that reform efforts grounded in promoting inquiry as the basis for teaching science have not achieved the desired changes in American science classrooms. Many science teachers assume that they are employing inquiry-based strategies when they use cookbook investigations with highly structured step-by-step instructions. Additionally, most science teachers equate hands-on activities with classroom inquiry and, as such, repeatedly use prepackaged, disconnected activities to break the monotony of direct instruction. Despite participation in numerous professional development activities, many science teachers continue to hold misconceptions about inquiry that influence the way they design and enact instruction. To date, there is very limited research exploring the role of inquiry-based professional development in facilitating desired changes in science teachers' conceptions of inquiry. This qualitative study of five high school science teachers explores the ways in which authentic inquiry experiences with a team of scientists in Panama shaped their conceptions and reported enactments of inquiry-based instruction. Our findings suggest that professional development experiences engaging science teachers in authentic research with scientists have the potential to change teachers' naïve conceptions of inquiry, provided that necessary supports are provided for reflection and lesson design.

Keywords Inquiry-based instruction · Professional development · Paleontology · Science practices · Panama

Introduction

Inquiry has been the cornerstone of reform efforts in science education over the last several decades and will continue to be a central factor in improving the status of science teaching and learning in American K-12 classrooms. Despite the heightened attention that inquiry has

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received in national reports (National Research Council [NRC] 2000, 2012) in the USA, there is very little evidence to suggest that inquiry-based instruction (IBI) is the mainstream approach in science classrooms (Capps et al. 2012; Meyer et al. 2013). Researchers indicate that without professional development (PD) support that provides science teachers with opportunities to participate in scientific inquiry, and to reflect on their experiences, IBI will continue to be at the periphery of conventional classroom practice (Capps and Crawford 2013; Lederman and Lederman 2012). Science teachers also need support in developing strategies for creating an inquiry-based learning environment, as well as an understanding of subject matter and the nature of science (NOS). Most science teachers earn subject matter credits in science departments where science is rarely taught within the contexts of the NOS and scientific inquiry (Kennedy 1990; Keys and Bryan 2001). As such, it is extremely challenging for teachers to teach subject matter using an approach that they were not previously exposed to as students.

A promising approach to developing skills necessary for IBI lies in PD opportunities that expose science teachers to authentic scientific investigations (Crawford 2012; Nugent et al. 2012). In support of this approach, reform documents such as the new *Framework for K-12 Science Education* (National Research Council [NRC] 2012) call for PD opportunities that (1) are themselves inquiry-based and (2) support teachers as intellectual reflective practitioners. Indeed, if teachers are expected to teach science as inquiry, they should be provided with opportunities to develop a deep understanding and appreciation of the way scientists collaborate to develop new theories (Morrison and Estes 2007). The successful implementation of IBI by science teachers will require a significant shift in our approach to PD. Science teachers will have to be involved in learning experiences that not only familiarise them with authentic inquiry but also support them in integrating these experiences with their actual teaching practice (Capps and Crawford 2013). Capps et al. (2012), who reviewed science PD research, reveal that very few opportunities are being provided for teachers to participate in authentic inquiry experiences. These experiences are necessary to support teachers in the design and implementation of scientific investigations in the classroom (Jarrett and Burnley 2003; Tal 2001).

There is some indication that many science teachers hold naïve conceptions regarding the NOS and IBI, which is promoted among K-12 students (Capps et al. 2012; Lederman and Lederman 2012). This inaccurate view is reflected in the scientific method, which emphasises the use of linear steps that all scientists allegedly use to make their discoveries (Windschitl 2003). This view is so entrenched in science teachers' ideas about science teaching that even highly qualified teachers would indicate that they were teaching science as inquiry when in reality they were not (Capps and Crawford 2013). So far, there is very little research regarding the role of PD in facilitating a change in science teachers' conceptions of IBI (Fazio et al. 2010; Keys and Bryan 2001; Lederman and Lederman 2012). Our study aimed to address this gap by focusing on the role of authentic inquiry experiences in shaping science teachers' conceptions of IBI. These inquiry experiences were embedded within a larger PD program that was designed to support science teachers' learning of scientific inquiry and the nature of science. The purpose of this study was to investigate science teachers' professional learning as they participated in authentic paleontology fieldwork with a team of scientists in the Panama Canal. Specifically, we wanted to determine how these inquiry experiences shaped teachers' conceptions of IBI. The study is guided by the following research question: How were science teachers' conceptions and enactment of inquiry-based instruction shaped by authentic research experiences with scientists? We used the theoretical constructs of inquiry and professional development to guide our investigation and subsequent discussion.

Theoretical Constructs

Inquiry

Inquiry is defined by the National Science Education Standards (NSES) as “the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an appreciation of how scientists study the natural world” (National Research Council [NRC] 1996, p. 23). This definition highlights a complex interaction between doing science, learning science concepts, and learning about the nature of science. These three facets of inquiry are embedded within the constructs scientific inquiry, inquiry-based learning, and inquiry-based instruction (Anderson 2007; Keys and Bryan 2001), which are often confused by science teachers. A disambiguation of these terms may prove essential in addressing some of the misconceptions about inquiry held by science teachers and students alike.

Scientific inquiry refers to “the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work” (National Research Council [NRC] 1996, p. 23). In other words, when scientists carry out investigations in order to construct scientific knowledge, they are actually engaging in scientific inquiry. Scientists study natural phenomena by making careful observations, collecting and analyzing empirical data, and providing scientific explanations for their findings (Keys and Bryan 2001; Minner et al. 2010). While science teachers are not expected to replicate this complex form of inquiry in the classroom, an understanding of the processes involved in the development of scientific knowledge will likely promote students’ interest in science. Furthermore, the central premise of IBI is that students approach learning in a way that parallels the strategies used by scientists and the attitudes demonstrated during scientific inquiry (Bass et al. 2009). In order to develop these skills and attitudes in students, it seems reasonable to expect science teachers to become familiar with the processes of science as practiced by scientists. Exposing science teachers to authentic inquiry experiences, therefore, facilitates the design of classroom inquiry experiences that simulate the practices of science (Capps et al. 2012). Classroom inquiry experiences will likely engage students in an inquiry-based approach to learning.

Inquiry-based learning refers to skills, knowledge, and dispositions that are to be developed in students as a result of their engagement with classroom inquiry. Central to reform documents is the content standards, which emphasise three components of the educational outcomes of student learning in science (National Research Council [NRC] 1996, 2012). These include (1) knowledge and understanding of core scientific concepts, (2) abilities to do science, and (3) understandings about the NOS. As such, students learn science by seeking to answer questions about the natural world through science processes such as observing, predicting, and making inferences. Embedded in the notion of inquiry-based learning is the understanding that students engage in some of the same activities and thought processes as scientists who are constructing scientific knowledge. It is generally acknowledged that engagement in inquiry practices contributes to effective learning, motivation, and increased interest in science as a human endeavor (Michaels et al. 2008; Sandoval and Reiser 2004; Windschitl 2003). Teachers play a critical role in implementing the kind of instruction that will facilitate such learning.

Inquiry-based instruction has recently been reconceptualised in the new *Framework for K-12 Science Education* (National Research Council [NRC] 2012) as those practices scientists engage in during the development of scientific knowledge (Capps and Crawford 2013). Teachers implementing IBI, therefore, are expected to guide students through inquiry processes that mirror the practices of scientists. Inquiry-based instruction is, therefore, characterised by students who are (1) engaging with scientific questions, (2) planning and conducting investigations, (3) generating explanations by connecting evidence and scientific knowledge,

(4) applying scientific knowledge to new problems, and (5) participating in critical discourse and argumentation with their peers (Bass et al. 2009; National Research Council [NRC] 2000). These features of IBI reflect the responsibilities of science teachers as they help students to construct their own knowledge while developing the skills and dispositions characteristic of scientists (Minner et al. 2010). Teaching science as inquiry is a rather complex task that challenges the majority of teachers, who will require considerable PD and support (Crawford 2012; Luft 2001). Researchers agree that engaging science teachers in authentic PD activities will improve confidence and expertise in the enactment of IBI (Blanchard et al. 2009; Dresner and Worley 2006; Rahm et al. 2003; Windschitl 2003).

Professional Development

Researchers note the importance of PD in ensuring that teachers develop the appropriate skills, knowledge, and instructional strategies needed to help students achieve meaningful science experiences (Desimone et al. 2002; Hewson 2007; Opfer and Pedder 2011). Capps et al. (2012) confirmed the importance of designing inquiry-based science PD to support science teachers' enactment of classroom inquiry. Inquiry-based PD is defined as "one that consists of activities that support teachers in creating classroom environments in which students learn science concepts and principles through inquiry as well as learn about what science is, and how scientists work" (Capps et al. 2012, p. 296). These activities should ideally provide teachers with authentic experiences that will provide the context for learning about scientific inquiry and the NOS (Nugent et al. 2012). According to Crawford (2012), a focus on authenticity during science teacher PD will enhance teachers' abilities to design and implement IBI. Furthermore, teachers who engage in experiences that they will subsequently be required to enact typically translate these experiences as they introduce scientific concepts to their students (Capps et al. 2012).

Professional development activities outside of the school, such as museum visits or field trips, can provide teachers with authentic experiences (Falk 2005; Neathery 1998) that could enhance their practice. While these contexts are not readily considered as a means of teacher PD, research has indicated that field trips for science teachers can contribute to the enrichment of science learning environments for their students (Nugent et al. 2012; Tal 2001). Field experiences can be highly effective especially if they are designed to engage participants in real-world phenomena that enable them to think like scientists. This idea is supported by National Research Council's [NRC] (1996) call for teachers to "experience learning in a variety of places where effective science teaching can be illustrated and modeled, permitting teachers to struggle with real situations and expand their knowledge and skills in appropriate contexts" (p. 62). Additionally, authentic PD experiences will allow science teachers to draw from their own learning experiences (Melber and Cox-Peterson 2005) as they attempt to facilitate similar learning in their students (Rennie et al. 2003).

One promising opportunity for inquiry-based PD lies in the formation of partnerships between classroom teachers and practicing scientists. Collaborative partnerships involving scientists and science teachers, such as Research Experiences for Teachers (RETs), have potential to promote an instructional model that parallels the way scientists solve problems in the real world (Jarrett and Burnley 2003; Morrison and Estes, 2007). Additionally, these experiences provide science teachers with opportunities to integrate their research experiences into classroom activities (Blanchard et al. 2009; Dresner and Worley 2006). In addition, opportunities for reflecting on their inquiry experiences allow science teachers to critically examine their classroom practices in light of new experiences and knowledge (Capps and Crawford 2013; Tseng et al. 2013). As such, fostering teacher reflection during these authentic inquiry experiences will contribute to the successful implementation of IBI, especially if the experiences were directly connected with teachers' curriculum materials. If teachers are not supported in translating their experiences into practice, they will be less likely to transform their science pedagogy into one that facilitates students' learning about science as inquiry.

Purpose of the Study

This study stemmed from concerns among researchers that reform efforts grounded in promoting inquiry as the basis for teaching science have not achieved the desired changes in American science classrooms (Meyer et al. 2013). Many science teachers assume that they are employing inquiry-based strategies when they use cookbook investigations with highly structured step-by-step instructions. Additionally, most science teachers equate hands-on activities with classroom inquiry and, as such, repeatedly use prepackaged, disconnected activities to break the monotony of direct instruction (Moscovici and Nelson 1998). Despite participation in numerous PD activities, many science teachers continue to hold misconceptions about inquiry that influence the way they design and enact instruction. Lederman and Lederman (2012) indicated that very little research exists that explores the role of PD in facilitating the desired changes in science teachers' conceptions. Furthermore, Capps et al. (2012) reported that very few authentic inquiry experiences are provided through science teacher PD due to difficulties in large-scale inquiry-based interventions. The purpose of this study was to explore the ways in which authentic inquiry experiences with a team of scientists in Panama influenced science teachers' conceptions and enactment of IBI. The PD activities spanned two locations, USA and Panama, and involved a small group of highly motivated high school science teachers.

Research Context

The PD activities were designed to provide teachers with the opportunity to develop conceptual knowledge in geosciences, understandings in scientific practices, and views about NOS. The activities were part of a larger National Science Foundation (NSF)-funded project called the Panama Canal Project–Partnership for International Research in Education (PCP-PIRE), which aims to advance the knowledge of extinct faunas and floras of the ancient Neotropics based on new fossil discoveries along the Canal. The PCP-PIRE also seeks to develop the next generation of globally competent scientists by engaging STEM faculty, other early career professionals, university students, and science educators in paleontological, geological, and biological research.

During the initial excavations for the Panama Canal a century ago, the Smithsonian Institution made natural history and geological collections that documented modern and ancient biodiversity in the New World Tropics. A century later, in 2009, Panama initiated extensive excavations to expand the Canal over the next decade. Consequently, highly fossiliferous 10–22-million-year-old deposits are now being uncovered that potentially yield important clues to ancient Neotropical biodiversity. Over the next 5 to 10 years, these new excavations and related activities will form the basis of the development of a long-term, sustained international research and education program. The study presented in this paper focused on integrating this research experience as part of a PD activity for high school science teachers.

California Teachers Project

The goal of the California Teachers Project is to increase teacher content knowledge through direct experience and interaction with researchers, interns, and students, with the expectation that teachers will integrate that knowledge and experience into their lesson plans and curricula. It focuses on using research experiences with scientists in the Panama Canal as part of a PD activity where science teachers collect fossils from the rich exposures of the late Miocene (10-million-year-old) Gatun Formation, for use in planning and implementing of classroom activities. Several science teachers from different high schools in CA volunteered to participate in a two-week-long field experience working alongside the PCP-PIRE team in Panama. Prior to the trip, the teachers participated in a daylong content workshop led by STEM faculty aimed at developing an understanding of the interconnectedness of the paleontological, geological, and biological concepts necessary for teaching about fossils. They were also provided with previously collected fossil samples from the Gatun Formation to familiarise them with the types of fossils they were likely to find during field activity.

Our study focuses on the core activity of the project, which took place over a two-week period during July 2012 in and around Panama City, Panama. This activity was designed to ensure that teachers gain practical experience collecting fossils, participate in scientific inquiry with the team of scientists, learn about the NOS through the framework of paleontology, and acquire content knowledge related to ancient biodiversity, climate change, and evolution. It involved formal presentations or “talks” led by scientists from the Smithsonian Tropical Research Institute (STRI), during which scientists communicated portions of their research while fielding questions and alternative explanations from peers within the audience. Teachers also participated in guided tours of the facilities at STRI, the tropical rainforests at Barro Colorado Island, and the new BIOmuseo. In concert with scientists and interns, teachers prospected for and excavated fossils in the field sites within the Panama Canal and the rich exposures of the late Miocene Gatun Formation nearby. In order to provide the context for fossil collection, scientists shared with teachers the ecological and geological history of the area and explained the significance of the work they do. Every weekday evening, the teachers met with the K-12 STEM education coordinator assigned to the project in order to debrief the day’s activities with the scientists and brainstorm ways in which the field experiences may be translated back into the classroom. In order to provide follow-up and to mark the end of the project for the teacher cohort, the research team visited the teachers in CA to observe the various ways in which their professional learning experiences were translated into practice in the classroom. Table 1 summarises the professional development activities and indicates how each activity contributed to enhanced understanding of IBI.

Research Design

Using a qualitative research design, we examined ways in which an authentic inquiry experience influenced high school science teachers’ conceptions and enactment of inquiry-based instruction. The collection and analysis of the data was shaped by a constructivist grounded theory approach (Charmaz 2006), which allowed us to give priority to the participants’ voice and to focus on how and why teachers constructed meanings during their inquiry experiences. Additionally, we connected their shared experiences with additional data sources collected during the study. Our data, therefore, focused on how teachers described their experiences while working with a multidisciplinary team of scientists in Panama and their perceptions of how the experiences influenced their enactment of classroom inquiry. Our analysis, which was embedded in the interpretative tradition (Crotty 1998), sought to establish reasons for why our teacher participants viewed their inquiry experiences the ways they did.

Table 1 Professional development activities and their relevance to inquiry-based instruction

	Activity	Goals	Relevance to inquiry-based instruction
Phase I	Content-based workshop (CA, USA); duration 1 day	To strengthen teachers' content knowledge of cross-cutting concepts relating to fossils	Knowledge of the subject matter enhances science teachers' abilities to enact inquiry-based instruction (Kind 2009)
		To provide information regarding culture of Panama and research scientists are conducting there	
Phase II	Field activities (Panama); duration 2 weeks		
	Prospecting and excavating fossils	To allow teachers to work alongside scientists in the Canal as they dig for fossils	The authentic experiences provide teachers with a more accurate depiction of scientific inquiry that they can promote with their students (Nugent et al. 2012)
		To develop teachers' conceptual knowledge of geological features of the excavation site	Teachers are learning about concepts within a situated context (Brown et al. 1989). For instance, they learned about faults at a site with very conspicuous fault lines
	"Tupper Talks"	To allow teachers to participate in forums scientists use to communicate their findings	Teachers experienced firsthand the development of scientific knowledge as scientists presented current findings and used existing knowledge to generate new explanations. Teachers gained an appreciation for the nature of science that is important to teach students (Lederman and Lederman 2012)
	Guided tours	To engage teachers in informal learning about culture and history of Panama	Informal learning opportunities allow teachers to draw from their professional development experiences as they work to improve the quality of learning for their students (NRC 2009). The experiences also allow them to plan similar informal learning opportunities for their students
	Daily debriefing	To encourage teachers to reflect on their experiences and possible changes to pedagogy	Reflection is a valuable tool for teacher learning and teacher change (Capps and Crawford 2013)
Phase III	Online community of practice		
	Brainstorming sessions	To provide pedagogical support for teachers as they integrate experiences into their curriculum	Supporting teachers in developing inquiry-based lessons from their experiences is essential for successful integration (Capps et al. 2012)
	Lesson/artifact share	To provide a forum for teachers to learn from each other's experience with inquiry-based instruction	Promoting sustained, reflective collaboration that is embedded within the context of teachers' practice is characteristic of effective PD programs (Duncombe and Armour 2004). Teachers are required to establish similar learning communities in their science classrooms

Study Participants

Five high school science teachers were recruited by the superintendent of a school district in southern CA to participate in this program. These teachers were highly recommended as well-qualified and motivated teachers. Teachers had to commit to participating in all the activities of the PD that spanned a period of 8 months (May–December 2012) and took place both in the USA and Panama. Information regarding the participants is summarised in Table 2. Glenda[1] has 20 years of experience teaching general biology and AP biology. Dave has 8-year teaching experience in general biology but has taught AP biology for approximately 5 years. Sara has been teaching chemistry and AP environmental science for 7 years, and Mark has 2 years of experience teaching general and AP biology. All participating teachers were certified by the state, and each has attained a master's degree. The fifth teacher, Monica, holds a Ph.D. in plant pathology and has been teaching agriculture and biology for 8 years. Prior to teaching, she worked as a molecular biologist in Uganda. The five teachers attended the content-based workshop 6 weeks before the international field experience, which consisted of interactive lectures led by two STEM faculty members from a university in southeastern USA. They were then flown to Panama to participate in a 2-week-long field trip to work alongside the PCP-PIRE research team.

Data Sources and Collection

For this study, we investigated how science teachers' thinking about IBI was shaped by authentic inquiry experiences with a team of scientists in the Panama Canal. Additionally, we explored science teachers' perceptions of the various ways in which their conceptions regarding inquiry were reflected in their teaching practices. Our primary data sources were derived from semi-structured interviews and teacher journal entries, while researchers' notes and teacher artifacts were supplementary sources used for triangulation. Additionally, we conducted limited classroom observations to confirm teacher reports of inquiry enactment. Semi-structured interviews, which were audiotaped and subsequently transcribed, were conducted before and after the inquiry experiences. The first phase of the interviews was conducted by phone prior to the trip, lasted approximately 50 minutes, and was designed to acquire information regarding teachers' professional qualifications and experience, their teaching contexts, and instructional practices. The second phase of the interviews was conducted in Panama towards the end of the two-week-long field experience. This interview lasted on average 55 minutes and was designed to elicit information about what teachers learned as a result of their participation in authentic research as well as their thoughts about its relevance to practice. The interview protocol included prompts such as: Please share some of the significant moments you have experienced during this trip and tell me why they were important to you? Were there any portions of the experience where you thought about teaching activities for your students and if so what are they? What do you think is the best way to share these experiences with your students and why?

Another primary source of data included teachers' journal entries, which documented teachers' reflections at the end of each day's activity. In order to guide their reflection, they were provided with prompts such as: What parts of the experience stood out for you today? How did the experience affect you? What connections, if any, can you make between your experience and your instruction? Although prompts were provided to guide their reflection, teachers were encouraged to write freely and not to feel limited or restricted in what they

[1] All names included are pseudonyms.

Table 2 Profile of study participants

Name	Age	Course(s) taught	Years of experience	Education
Glenda	Early 50s	General and AP Biology	20	BSc (Marine Sciences) M. Ed
Dave	Late 30s	General and AP Biology	8	BSc (General Biology)
Sara	Mid 30s	AP Chemistry and AP Environmental Science	7	BSc (Chemistry) M. Ed
Mark	Late 20s	General and AP Biology	2	BSc (Ecology and Evolutionary Biology) M. Ed
Monica	Early 50s	Agriculture and General Biology	8	Ph.D. (Plant Pathology and Nematology)

documented in their journals. We provided journals for teachers to write in, but several teachers stated their preference for electronic journaling. Again, we consented to the forms of documentation that teachers were more comfortable with. Two of the five teachers mailed a print version of their journals to the first author within a month of the trip to Panama, while the other three teachers sent their electronic journal as an email attachment several weeks after their return.

Another important source of data included researchers' field notes. Notes were taken throughout all phases of the PD program, and included those taken during meetings, video-conferences, and debriefing sessions with the participants. Notes were also taken during field activities and during classroom observations made before and after field activities in Panama. The primary purpose of these notes was to document teachers' comments during formal and informal interactions that may have relevance to the research questions. These data also provided a means of triangulating the aforementioned primary data sources. Instructional artifacts such as lesson plans and worksheets were also collected to support observation notes collected during our classroom visits. Teachers voluntarily submitted lessons and worksheets that they believed best reflected their conceptions of inquiry-based instruction.

Data Analysis

The data were analyzed in three phases. First, we focused on primary data generated directly from the participants' voice, including the interview transcripts and journal entries. Second, we examined all researcher notes, including classroom observations and meetings notes. Third, we analyzed all classroom artifacts, such as lesson plans and worksheets that were designed by teachers both before and after the inquiry experiences. During all three phases, the data were coded on three different levels as we collectively made sense of the emergent ideas from our sources. As we refined our ideas, the process of constant comparison allowed us to determine similarities and differences across data sets. In the paragraphs below, we present a more detailed explanation of the analysis.

The interviews were transcribed and together with the teacher journal entries were coded in order to identify initial open codes for subsequent analysis. During initial coding, we examined fragments (Charmaz and Mitchell 2001) of the transcripts and journal entries that directly addressed teachers' perspectives, their reflections on field experiences and classroom practice, and plans for modifying their instruction. These initial codes were compared across the two data sources (transcripts and journal entries) and used to frame subsequent analysis. Where necessary, in vivo codes, such as "science is messy," were used to preserve participants' innovative terms that captured the meanings they attached to their experiences (Charmaz 2006). The initial codes were then subjected to a more focused examination as we further synthesised these codes in order to generate themes related to our research question (Holton 2007).

All researchers' field notes were subjected to a similar system of coding. Fragments of the data were coded to identify incidents or statements that related to the codes identified during the first phase of data analysis (Charmaz and Mitchell 2001). These initial codes were further examined for new themes, which were then consolidated with the emergent themes from phase one of the analysis. The artifacts, such as lesson plans and students' worksheets designed by the teachers, were carefully examined in order to identify the features of inquiry instruction that were evident in their design. Guided by the characteristics of inquiry instruction and learning published by the NRC (2000), we determined whether or not teachers' changing conceptions of inquiry were reflected in their pedagogy. Information acquired through examination of artifacts also corroborated some of the themes that emerged from interview transcripts, teacher journal entries, and researchers' field notes. In order to ensure reliability of our analysis (Charmaz and Mitchell 2001), we asked an independent science education researcher to repeat the analysis using the steps outlined above. Findings were consistent with our description below.

Findings

The purpose of this study was to identify ways in which science teachers' participation in scientific inquiry shaped their thoughts about inquiry-based instruction. We analyzed data collected over a period of 8 months (May to December 2012) including teacher interviews, journal entries, and field notes to describe and interpret teachers' experiences working with scientists in the Panama Canal. From analysis of teachers' reflections on their research experiences as well as confirmatory observations of classroom enactment and artifacts, we were able to determine how teachers' participation contributed to their developing conceptions of inquiry teaching. This is summarised in Table 3. The findings below represent the emergent themes from the grounded theory analysis described in the preceding section. These three themes suggest that teachers' interactions with scientists during authentic fieldwork in Panama prompted reflection on practice, which resulted in new conceptions about classroom inquiry.

"Science is messy"

While in Panama, teachers attended talks by scientists during which they presented research findings as well as current understandings regarding some of the processes that led to the distribution of flora and fauna in North and South America. In the first of these talks, one paleontology professor spoke in length about the Great American Biotic Interchange (GABI), a phenomenon that has fascinated paleontologists and biologists since the mid eighteenth century. The simple and classic story of GABI describes an event during which land and freshwater fauna migrated from North to South America via Central America and vice versa as a result of the tectonic formation of the Isthmus of Panama. During the talk, various explanations regarding the biotic and geologic dynamics of GABI were presented, and the subsequent verbal exchanges among different scientists with contradicting theories about dispersal patterns suggested that current understandings of GABI were still a bit unclear.

Although the teachers were on the periphery of the discussion that ensued, they witnessed for the first time scientists debating issues of scientific importance for which no one had clear answers. For one particular teacher, this had somewhat of a significant impact as reflected in her journal entries several days later:

Table 3 Shifts in teacher conceptions of science instruction

Participant	Course taught	Reported instructional practice	Most profound aspect of field experience	Developing conceptions as a result of field experience	Lesson/artifact(s) observed
Glenda	Biology/Ocean Ecology	Lab activities, note taking, quizzes, lectures	Participating in paleontology digs with the team of scientists	Less emphasis on lectures and direct instruction. More emphasis on exploration of concepts, discussion, and justification of claims	Enactment: students used popsicle sticks to generate possible gametes in a lesson on dihybrid crosses
Dave	Biology	Warm-up quizzes, student stations, lab activities, field trips	Communicating/ interacting with the scientists	More emphasis on data gathering analysis and communication of findings among peers	Plan: students conducted a virtual exploration of plants species in Panama and neighboring surroundings. They were expected to communicate findings during poster board sessions
Sara	Chemistry/ Environmental Science	Warm up quizzes, lecture, practice problems/ worksheets	Experiencing the process of science	More emphasis on NOS and the processes involved in constructing scientific knowledge	Plan: students were expected to critically examine claims made in real-world scientific research articles
Monica	Agricultural Science/ Biology	Lectures, interactive activities, projects, field trips	Learning about science concepts outside current field of study	More emphasis on highlighting interconnectedness of disciplines, example ecology, agriculture, and forensic paleontology	Enactment: did not reflect reported conceptions
Mark	Biology	Guided inquiry	Interacting with scientists as they carry out research	More emphasis on “question-asking, mistake making, critique back and forth”	Plan: students designed experiment to determine the purpose of the moth’s antennae

> "Bruce has named two dozen species and he edits an important journal in his field, but he is still not clear about GABI. His whole talk the other night was about how messy our understanding of GABI is. When dealing with scientific law, it is not like God comes to you and says, 'yes my child, you have figured out my law of gravity. Good work or whatever.' We get confirmation. Our peers (original emphasis) confirm our ideas by recreating our results but no one is ever able to say, 'yes, you are right!' So why doesn't the way we teach science reflect this uncertainty and ambiguity?" (Sara, 07/15/2012)

Sara, who teaches AP chemistry, admitted that during her 7-year experience teaching the subject, her inquiry-based classes consisted of the use of cookbook-style laboratory worksheets. For each laboratory designed for her students, including titration labs where students are trying to determine the precise endpoint of a reaction and hence the quantity of a specific solution, she still knew the right "answer." She noted that the predictability of her cookbook activities resulted in the fabrication of data by her students as they attempted to conform to existing patterns within the knowledge base.

> "I started thinking about how often kids want to make up data. Why is that? Well, for years they have done cookbook labs made to demonstrate something that I already know. There is a trend in the data and an obvious answer at the end. So of course they can make up the data…it has such an obvious pattern. But science is not really like that. Science is messy. Working in the field is messy." (Sara, journal, 07/15/2012)

During the final interview of the study, she indicated, "I think my students have this idea that if a question is hard or if a problem is hard and they can't answer it right away, then they have done something wrong." She noted that the presentation of laws and theories in school texts contributes to students' misconceptions about the nature of science because of an inherent emphasis on successes of scientific experiments while neglecting the failures or errors that were important to the process. She opined during an interview,

> "I think the fact that our students come into the classroom…I think they are led to believe that all science…the big scientific discoveries were made by some brilliant guy who had this beautiful hypothesis. He somehow perfectly designed an experiment and boom! His ideas are confirmed in our textbook." (Sara, 07/24/2012)

Subsequent presentations made by other scientists and interns currently conducting research in Panama, as well as contradictory comments and complex questions that emerged from the audience, reinforced Sara's developing conceptions of scientific inquiry and inquiry teaching. She reflected that none of the presentations was conclusive and that "there are these big overarching questions that we are still struggling to answer." As Sara reflected on the idea of unanswered questions in science, she advanced her concerns to her peers during one of our regular debriefing sessions.

> Another teacher participant, Dave shared a 'mystery box' activity he had heard about previously where students were encouraged to determine the content of a box without opening it. The other teachers, who had similar concerns about the predictable nature of their classroom investigations, shared other pedagogical ideas that would provide a more realistic representation of inquiry. Sara shared the possibility of having her AP environmental science students conduct research on complex and controversial issues that do not have known or specific solutions. In one journal entry she asked, "How can I incorporate this into chemistry too? What are the big issues still plaguing chemists? I need to keep thinking about this." (Sara, 07/15/2013)

Other teacher participants alluded to the “messy” nature of scientific inquiry as they reflected on the fieldwork they conducted in Panama. Teachers worked with scientists and student interns to dig for fossils in the newly exposed regions of the Canal. Dave indicated that the actual digging experience “dispelled a lot of the glamour” that is typically associated with being a scientist. He reflected on his first encounter with Brian, the paleontologist who had shared some of his research on fossils found in Panama, and how his study was “cool and captivating.” However, Dave indicated that being in the field and using a hammer to chip away at the soil in hopes of finding “a hip bone of a bear dog or something like that” with “the sun beating on you” is messy work that requires “a tremendous amount of patience.” Another teacher, Glenda, also commented on the nature of the fieldwork noting, “It takes a tremendous amount of patience and persistence to be a paleontologist.” She revealed that she found many rocks that looked like fossils, but scientists and interns in the group confirmed that they were not. Despite the challenging circumstances under which teacher participants worked, they all commented on the feeling of excitement and the sense of pride experienced when they found a fossil. Monica mentioned a feeling of thrill when Glenda found the fossil of a turtle shell after a very long day of digging. She wrote, “Oddly felt a sense of personal pride despite having nothing to do with the find.”

Sara reported that changes in her conceptions of inquiry instruction were reflected in the instructional approach she employed at the beginning of the ensuing school semester. She started by using her personal experiences in Panama to stimulate conversations about what it means to do science, hoping to convey the “messiness” that is characteristic of the development of the scientific body of knowledge. For her AP environmental science, she provided students with brief articles from the journal *New Scientist*. She was careful to select those articles that reflected uncertainty about the outcomes of scientific research, for example, “Flawed stem cell data withdrawn” (Aldhous and Reich, February (2007) and “Climate is too complex for accurate predictions” (Giles 2007). The purpose of this exercise was to expose students to some of the complex questions being researched by scientists, specifically those that are challenged by other scientists in the field, in order to demonstrate the non-linearity of the process of doing science. When they were reading the articles, she wanted students to identify how scientists are conducting their research, what uncertainties or complexities make the research difficult or challenging, what steps are taken to address these challenges, and whether or not other scientists are in agreement about the best way to proceed (Sara, lesson outline, 08/2012). She challenged students to think about some of the experiments they would conduct if they were part of the research team.

For her chemistry lesson, she reported using the “mystery box” activity to allow students to develop a better understanding of key aspects of the nature of science. Students were expected to conduct at least three different procedures that would allow them to test and retest their original hypothesis and to draw reasonable conclusions as to what was inside the mystery box. They were instructed to make observations, to record their data, and to draw conclusions based on evidence. Sara observed that students became frustrated because they were unable to determine definitively what object was in the box. She indicated that students seemed to have forgotten how to explore or be curious and the activity, which was a departure from the usual cookbook labs, was a lesson in perseverance. At this point, she was able to share anecdotes of her research experience with the team of scientists in Panama to demonstrate the often uncertain and complex process involved in “doing science.” Toward the end of the lesson, and after scaffolding by the teacher, students became more open to a scientific exploration of their “mystery box”, in one instance using magnets to determine whether or not the object was magnetic.

Another teacher, Mark, indicated that as a new teacher (2 years of experience) teaching AP biology, inquiry-based learning was emphasised during his credential program. He initially characterised inquiry as "question asking, mistake making, critique back and forth" but indicated that the actual field experience allowed him to develop a more authentic perspective on inquiry instruction. He explained that the approach to learning inquiry through experience was a lot more effective than being told about it. After the trip to Panama, Mark indicated that he now places a greater emphasis on scientific practices by being more explicit in his discussions about data gathering and using evidence to inform conclusions with the use of "if…then…because" statements. He explained that the subtle change in his approach to teaching was accompanied by a concurrent change in his students' approach to learning. Students, he said, "wanted to change data that didn't fit with their expectations" and would often claim "have no data" if the results of their experiment fell short of that predicted in the text.

In an attempt to change his students' view of the linearity of the scientific process, Mark adopted a guided inquiry approach to explore questions that relate to the concepts being taught but that are more aligned with students' interests. He shared a sample lesson plan, in which his students collectively designed an experiment aimed at determining the purpose of a moth's antennae. In their experiment, students removed the moths' antennae and allowed the moths to move through a choice chamber in which pheromones were used as a means of attraction. Their control experiment involved moths with intact antennae. For both the experimental and the control experiments, students measured the speed of the moth as it travelled through the chamber and compared results to interrogate their hypotheses. The guided inquiry approach employed by Mark allowed students to become involved in a process of asking questions and planning investigations in an attempt to address their observations about a natural phenomenon. In so doing, the classroom activities reflected the inquiry process of scientists rather than the methodical steps from a cookbook worksheet.

"Seeing the community of scientists"

In addition to attending formal talks and participating in digs for fossils, teachers were given multiple opportunities to interact informally with scientists who were involved in various projects at the Smithsonian Tropical Research Institute in Panama. These included biologists, ecologists, paleontologists, chemists, and geologists from North, South, and Central America. As part of these interactions, teachers were witnesses to the construction of scientific knowledge as scientists provided evidence to support their findings and occasionally defended their position on the ideas they advanced. Teacher participants reported that the observations of interactions within the scientific community contributed to subtle shifts in the way they approached their instruction after the Panama experience. During one of the interviews, Dave shared his excitement about being a part of the group of scientists:

> "First of all, I've never been to Central America and seeing the community of scientists…when Doug[2], Chris, and Bruce were talking. It's such an international group. There are a lot of South Americans and Central Americans but it's still so exciting. You look at that and say, these are scientists!" (Dave, 07/23/2013)

Glenda, an AP biology teacher, indicated during one of the videoconferences that she made "subtle but profound" changes to her instruction because of her interaction with scientists. She shared that she now placed a greater emphasis on discussion, and justification of arguments

[2] Doug is a chemistry professor at a university in a southeastern state in North America, and Chris is a geologist and native of Columbia who conducts research at the Smithsonian Research Institute in Panama.

advanced during these discussions. Most of her lessons now have a standard format: she asks an open-ended question and have students talk about it in small groups and present their ideas to the class, in each case justifying their arguments. In one observed lesson about dihybrid crosses, she gave students Popsicle sticks and asked them to generate gamete possibilities based on discussions they had had in previous classes. During the post-observation talk, Glenda reflected that there had been a deliberate shift in her teaching strategies as she uses direct instruction less often and facilitates more discussions where students provide evidence to support their claims. The students, she observed, responded much better, and her lessons were more dynamic and reflective of an authentic scientific community.

Dave admitted that he was very impressed by the way scientists communicated their findings within the scientific community. He indicated that he intended to integrate more of the scientific practices, specifically data gathering and analysis as well as communication of findings, in his general biology courses. One of the lesson plans he submitted toward the end of the project reflected the integration of technology to conduct virtual ecological explorations of plant species in Barro Colorado Island in Panama and on a nearby university campus. In the lesson, which had been partially implemented, groups of students were engaged in a comparative study of plant species in both localities with specific emphasis on adaptations to climatic and other abiotic factors, symbiotic relationships with other organisms, and species distribution and frequency. For the assignment, students were expected to use technological applications such as Google Earth to enhance a poster, which was to be created and presented by each group. The lesson plan was quite comprehensive, aligned with local state and district standards, and integrated technology in an authentic way that will likely contribute to meaningful learning experiences for his students. Moreover, students were expected to use evidence from their exploration to draw conclusions about their comparisons. Dave indicated that students were very excited about the project not only because they were using applications from their smartphones (Google Earth and Leaf Snap[3]) but also due to the authentic nature of the assignment, which required integration of real scientific data. During his discussions with his students, he encouraged collaboration and group work, frequently using anecdotal information about his own interactions with “a great community of scientists that has shaped the whole field of ecology and our understanding of it.”

Mark, an AP biology teacher, noted that his students get more involved when working in groups to gather data, and since his return from Panama he has made more deliberate steps to create and foster a learning community where students are involved in argumentation as they become more aware of the importance of providing evidence to support their ideas. During our meeting at the end of the project, Mark indicated that he has a “new classroom scenario” and a “new space” for sharing and communicating knowledge collaboratively constructed during instruction.

The Multidisciplinary Approach

The information gleaned from the multidisciplinary team of scientists highlighted the interconnectedness of disciplines and provided the impetus for teachers to reexamine the adequacy of their subject matter knowledge. Dave indicated that although he was a biology teacher, he felt that he needed to learn more about the fundamentals of geology in order to provide context for teaching about how fossils are distributed in certain environments. He lamented the fact that although some biological concepts are related to other disciplines, gaps in knowledge

[3] Leaf Snap is an electronic field guide app for plant species in certain geographic regions. It can be used on iPhones, iPads, and iPod Touch.

contributed to limitations in the way he presented his content. He admitted that background information allowed for greater coherence in the presentation of the subject matter, indicating that the multidisciplinary approach he experienced while in Panama facilitated more meaningful understanding of the concepts presented during some of the talks.

Another teacher, Monica, who teaches agricultural science, indicated that the experience uncovered connections among disciplines that she had previously overlooked. In her personal investigations and informal chats with various members of the interdisciplinary team, she identified forensic paleontology as having some level of application with certain concepts in agriculture. She indicated that the experience allowed her to look at her course from another perspective.

> "I don't think that is a direction I would have gone with this and I don't know that I would have simply because of my own background and my own perspective. I do not know that I would have gone through with the necessary amount of effort to look at paleontology as a discipline." (Monica, 07/22/2012)

Glenda, in one of her journal entries, wrote about her plans to include a paleontology lesson on the giant extinct shark Megalodon in her ocean ecology class at the end of the shark unit. During our summative meeting with teacher participants at the end of the project period, she provided an account of the enactment of her lesson. She described the excitement her students displayed about "doing paleontology" and learning about a prehistoric shark that they had become vaguely familiar with through pop culture. As part of the activities for this lesson, students were asked to hypothesise about the diet of the shark whose fossilised tooth they observed, as well as possible tooth location in the jaw based on tooth morphology. In reflecting on her decision to integrate paleontology with ocean ecology, she maintained that she was able to engage students in scientific processes such as observing, hypothesising, inferring, and measuring.

The other teachers reported that they found very creative ways to integrate their research experiences into the subject they taught. They agreed that finding connections stretched their imaginations and stimulated the desire to think or read more about new knowledge domains, which allowed for greater coherence in the presentation of concepts. Researching connections to make her lessons more relevant, Glenda stated, inspired her "to encourage students towards research" thereby creating enthusiasm towards the subject while also fostering a culture of lifelong learning.

Conclusions

The authentic inquiry experiences provided for the science teachers allowed them to participate in paleontological digs with a multidisciplinary team of scientists in the Panama Canal. Rather than creating a highly structured program that simulated scientific inquiry, we provided opportunities for science teachers to work at the "elbows of scientists" in authentic explorations of fossils in newly exposed areas in the Canal. The activities and interactions were, therefore, natural rather than staged. We made the following conclusions after consolidating our findings with current literature in the field.

A Distorted View of Inquiry

Research indicates that many science teachers hold inaccurate conceptions of scientific inquiry, inquiry instruction, and the NOS (Lederman and Lederman 2012; Meyer et al. 2013). This distorted view of inquiry has created formidable barriers to the enactment of IBI in K-12 classrooms. Many teachers believe that cookbook investigations and other hands-on activities implemented to break the monotony of lectures or PowerPoint presentations are reflective of inquiry instruction. Consequently, our teacher participants' reported that they were enacting IBI when in actuality they were not. The lack of congruence between teachers' enactment and the requirements outlined in reform documents is due in part to teachers' misconceptions of inquiry and inquiry instruction. Furthermore, other challenges including lack of time and poor subject-matter preparation (Capps et al. 2012) contribute to low levels of inquiry-based enactment in the classroom.

Our findings confirmed reports that authentic inquiry experiences that allow science teachers to participate in the investigation of real-world phenomena with scientists help teachers conceptualise science as a creative process (Keys and Bryan 2001; Nugent et al. 2012; Webster-Wright 2009) rather than as a body of knowledge. Our teacher participants were given opportunities to collaborate with a team of scientists in Panama who are involved in documenting ancient biodiversity of the Neotropics. Not only were teachers immersed in scientific experiences with the scientists, they were also a part of discussions during which scientific knowledge was constructed through argumentation. According to self-reports, these experiences had a profound impact on the ways our teacher participants thought about science.

Lederman and Lederman (2012) documented characteristics of scientific knowledge that were used as a frame of reference to support our findings. According to this framework, scientific knowledge is tentative, empirically based, subjective, involves human inference and creativity, and is socially and culturally embedded (p. 24). Our teacher participants came to appreciate science as a process that is inherently unpredictable, and the knowledge created as a result, tentative and heavily reliant on evidence and theories. Furthermore, teachers' participation in the construction of scientific knowledge facilitated an understanding of science as a human enterprise that is embedded within the culture of science, and the scientists with whom they interacted are the product of that culture (Lederman and Lederman 2012). Knowledge of the NOS contributes significantly to the enactment of IBI (Capps and Crawford 2013; Lederman and Lederman 2012) and as such is key to shaping teachers' conceptions of inquiry.

Inquiry Experience Is Essential

Our findings indicated that authentic immersion experiences in scientific inquiry are essential if teachers are to change their conceptions of IBI. Despite attending workshops and seminars about inquiry, our teacher participants were reportedly unclear about the processes involved in the development of scientific knowledge. During the inquiry experiences, the teachers learned as they participated in the discourses and practices of the scientific community (Putnam and Borko 2000). Through their experiences, observations, and interactions (Luft 2001; Skilbeck 2006), teachers learned the requirements of the scientific community in which they participated and began to assimilate its values and practices. This enculturation into the community's ways of thinking (Putnam and Borko 2000) is essential to the process of teachers becoming knowledgeable in and about their practice (Borko 2004; Marlow et al. 2003). As a result, the simulated inquiry experiences that typify some PD opportunities for science teachers do not adequately convey the practices of scientists as they collaborate to develop scientific knowledge. Immersion in authentic inquiry experiences with scientists, therefore, has the potential to shape teachers' conception of inquiry-based instruction especially if teachers are provided with opportunities to reflect on their practice.

Reflections on Practice

Our findings demonstrated that science teachers' experiences with inquiry, coupled with informal interactions with scientists and other teachers, stimulated a reflective process that yielded new understandings and insights (Rennie and Johnston 2004) into teaching and learning. Through reflection on practice, teachers became aware of their flawed conceptions of IBI and explored various ways to modify their practice in light of new ideas. Unless teachers' perceive their practices to be ineffective in generating student interests, they are unlikely to make attempts to change. The reflection process allowed teacher participants to critically examine their practices in light of their new experiences and information. Consequently, reflective action resulted in deliberate changes in instruction as teachers experimented with strategies that aligned more closely with scientific practices they observed in Panama. Reflecting on practice engaged teachers with their preexisting beliefs about IBI. Several studies have established an inextricable link between teacher beliefs and the teaching strategies employed in the science classroom (Gunel 2009; Haney and McArthur 2002; Mansour 2009). Changes in teachers' beliefs or conceptions are central to the shift towards IBI and must be adequately addressed in science PD programs (Luft 2001).

Discussion

Despite the fact that inquiry is the dominant paradigm in science reform efforts, science classrooms in the US are still not characterised by IBI (Meyer et al. 2013; Wilson 2013). This suggests that teachers may be experiencing difficulties in establishing and maintaining a culture of inquiry in the classroom. Several studies have suggested that science teachers hold naïve conceptions of what constitutes scientific inquiry (Capps and Crawford 2013; Lederman and Lederman 2012; Tseng et al. 2013). There is very little research regarding the role of PD in shaping teachers' conceptions of inquiry, and our research has contributed to this emerging area of study. Our investigation provided empirical evidence that engaging teachers in authentic inquiry is a powerful tool in stimulating teacher reflections on IBI and NOS. Our findings support calls within the science teacher education community to expose teachers to authentic research experiences as a means of content and pedagogical enrichment (Almquist et al. 2011; Buck 2003; Jarrett and Burnley 2003; Martin 2004; Melber and Cox-Peterson 2005; Tal 2001). Professional development activities that are authentic and situated in practice "empower teachers to make better decisions about science instruction by increasing their understanding of community resources available, science content, scientific processes, and pedagogical models" (Melber and Cox-Peterson 2005, p. 118).

The PD experience designed for these high school teachers addressed several features of highly effective programs as prescribed by teacher education researchers. These included (1) opportunities for science teachers to reflect on existing conceptions about inquiry (Loucks-Horsely and Matsomoto 1999) in light of the cognitive dissonance created as a result of experiences with scientists, (2) immersion in scientific practices that will likely foster the development of an instructional repertoire consistent with teachers' new understandings (Supovitz and Turner 2000), and (3) ongoing support as teachers grapple with establishing and maintaining a new classroom culture (Luft 2001). However, this small-scale study was exploratory in nature and could benefit from additional refinement informed by evaluations of the program and current research in PD of science teachers. Additionally, studies of this nature require partnership with practicing scientists, some of whom may not be willing to accommodate teachers during their research endeavors. Identifying scientists with current projects relating to specific topics in the school curriculum is essential to ensure the success of similar programs.

Future research will focus on enhancing the structure of the activities within the program so as to propose a model for science teacher PD that could be applicable outside the field of geosciences. Our research investigated science teachers' conceptions and enactment of IBI after participating in authentic research experiences with scientists. Based on our findings, we contend that authentic PD experiences involving teachers in research with scientists have the potential to change teachers' naïve conceptions of inquiry, provided that necessary supports are provided for reflection on practice. Additionally, if carefully designed, these experiences provide teachers with opportunities to create learning experiences for their students that reflect their own learning experiences in the field.

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