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ABSTRACT

Inquiry-based research is recommended as a method for helping more students understand the nature of science as well as learn the substance of scientific knowledge, yet there is much to learn about how teachers might adapt inquiry for science teaching and what teachers need to know in order to do this. This case study of an exemplary teacher's wisdom of practice presents a portrait of possibility for the effective implementation of inquiry-based teaching in a high school science class. The teacher had an extensive understanding of the discipline of oceanography, including substantive content, how oceanographers carry out research, and how they establish new knowledge claims in the discipline. She used this understanding in conjunction with reflection on her students' learning to transform her traditional teaching into inquiry. This research has implications for preservice science teacher education and professional development for inservice teachers. (Contains 34 references.) (Author/YDS)

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A Science Teacher's Wisdom of Practice in Teaching Inquiry-Based Oceanography

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Abstract: Inquiry-based research is recommended as a method for helping more students understand the nature of science as well as learn the substance of scientific knowledge. Yet there is much to learn about how teachers might adapt inquiry for science teaching, and what teachers need to know in order to do this. This case study of an exemplary teacher's wisdom of practice describes an portrait of possibility for the effective implementation of inquiry-based teaching in a high school science class. The teacher had an extensive understanding of the discipline of oceanography, including substantive content, how oceanographers carry out research, and how they establish new knowledge claims in the discipline. She used this understanding in conjunction with reflection on her students' learning to transform her traditional teaching to inquiry. This research has implications for preservice science teacher education and professional development for inservice teachers.

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Introduction

"Go into this with that questioning mode. Say I wonder why, why could this be. . . . Your first task is to kind of look and question." These were the instructions from a high school oceanography teacher to her students as they headed out onto the beach for a first attempt at developing their own research project. I was along, in a questioning mode myself, to try and understand how a teacher uses inquiry-based science teaching to engage students in doing and learning science. What does inquiry mean—is it the same as discovery or hands-on learning? Would there be substantive learning by students? Does inquiry let the teacher off the hook, so to speak, as students become responsible for finding out for themselves? What does a teacher have to know and do to use inquiry in a meaningful way?

There are many questions associated with the contemporary call for infusing inquiry into science classrooms. Inquiry is promoted in contemporary science education reform as a way to help more young people understand scientific principles and concepts as well as the nature of science—its social and epistemological characteristics (American Association for the Advancement of Science, 1990; National Research Council, 1996). Yet, inquiry-based teaching and learning "is not easily described" (American Association for the Advancement of Science, 1990). While more images of inquiry in K-12 classrooms are emerging in the literature (see, for example Minstrell & van Zee, 2000; National Research Council, 2000), there is still much to understand about how teachers might adapt inquiry for science teaching and what teachers need to know in order to do this.

In undertaking this study of a secondary science teacher, Liz Dietrich[1], I hoped to learn more about what inquiry might look like in a high school classroom. Also, based on the theory that inquiry might bring more students into science, I explored her engagement of girls who have done poorly in other science courses. That work is reported in another paper (Holmlund Nelson, 2000). In this paper, I focus on the knowledge base this teacher drew upon in order to implement an inquiry approach to teaching and learning oceanography. Liz's teaching provides "an image of the possible" (Shulman, 1983) for the effective implementation of inquiry-based teaching in a high school science class. As Liz taught for years in a traditional manner, relying upon textbooks, lectures, and recipe-like laboratory activities, understanding the knowledge base she drew from to transform her teaching can inform professional development related to helping teachers shift to inquiry-based teaching.

In this paper I report on the following two research questions:

1. What is the knowledge base this high school science teacher drew upon in order to teach an inquiry-based oceanography course?
2. How did she transform this knowledge to develop and implement an authentic and engaging inquiry-based oceanography curriculum?

Background

The current call for the incorporation of inquiry into K-12 classrooms focuses on inquiry as a "constellation of teaching strategies that can facilitate learning about scientific inquiry,

[1] All participant names are pseudonyms

developing the abilities of inquiry, and understanding scientific concepts and principles" (Bybee, 2000, p. 37). Thus, classroom inquiry is not only a teaching method, it is an approach to learning about scientific knowledge as well as the nature of science (American Association for the Advancement of Science, 1990). In order to engage their students in authentic ways of learning about science and scientific content teachers themselves must possess an understanding of the nature of science—how scientists go about constructing and accepting scientific knowledge.

Inquiry-Based Teaching and the Nature of Science

Exemplary teachers understand not only the content of their subject matter, but its culture and context, its particular discourse, and how it is practiced (Wilson & Wineburg, 1993). Exemplary science teachers, therefore, know more than scientific principles, facts, and concepts. They also understand the nature of science—for example, how scientists do their work, how scientific knowledge comes to be accepted, or when and why scientific knowledge is subject to change. Medawar (cited in Shapiro, 1996) emphasizes the difference between "the procedures of science—adventures of thought and strategies of inquiry that go into the advancement of learning—and, on the other hand, the substantive body of knowledge that is the outcome of this complex endeavor" (p. 536). Shapiro (1996) points out that most students learn the substantive body of knowledge, what Latour called "science that knows (ready-made science)" and get little, if any, opportunity to engage in the science "that does not yet know (science in the making)" (Latour, 1987). Understanding "science in the making," or the nature of science, as well as being deeply familiar with the substantive body of knowledge in a scientific discipline are facets of scientific literacy. Teachers themselves must be scientifically literate in order to help their students achieve this goal.

The nature of science refers to "the epistemological commitments underlying the activities of science" (Abd-El-Khalick, Bell, & Lederman, 1998, p. 418). It is generally accepted in the literature that there is no one scientific method that all scientists employ in their pursuit of knowledge about the natural world (Finley & Pocovi, 2000, in Minstrell). Instead, scientific inquiry is recognized as a diverse process, "from mental introspection to electronic computation, from quantitative measurement to speculative inference" (Ziman, 2000, p. 14). Yet, traditionally the enacted K-12 science curriculum focuses predominantly on the transmission of scientific knowledge and memorization of this by students. Duschl speaks to the importance of helping students learn not only scientific knowledge, "the prevailing knowledge claims or views of science" (p. 56), but also "why science believes what it does and how science has come to think that way" (p. 57). An understanding of the nature of science contributes to the transformation of teaching centered around the traditional, step-wise scientific method to inquiry-based teaching (Bybee, 2000).

Teachers' understandings of "the processes by which scientists validate knowledge" (Gallagher, 1991, p. 125) are shaped by the ways in which they learn science. Work by Palmquist and Finley (1997) with preservice (i.e. prospective) teachers supports the idea that teachers have few opportunities to experience and discuss the nature of science, and this affects how they teach science. Gallagher (1991) concluded from his study of preservice and practicing teachers that their images of science teaching and their understanding of the nature of science were largely built upon their experiences as students in college science courses. Unfortunately, the focus of instruction in most college science classes is on the rapid transmission of established knowledge.

Very little, if any, time is devoted to learning how scientific knowledge develops and comes to be accepted. This has serious implications for the implementation of inquiry-based curricula.

Inquiry in the Science Classroom

Inquiry-based teaching can be implemented from different points along a continuum, from structured or guided inquiry to open exploration (National Research Council, 2000; Sutman, Schmuckler, Priestley, & Priestley, 2000). Although a clear understanding of how to translate scientific inquiry into meaningful classroom activities is ill-defined, essential components can be identified (Marx, Blumenfeld, Krajcik, & Soloway, 1997; Moscovici & Holmlund Nelson, 1998). Whether the inquiry is highly structured by the teacher or more open-ended, scientific questions emanating from observations of phenomena or personal experiences are primary. Time must be provided for students to work with possible hypotheses or generate their own, and to develop experiments or conduct research to test these. Students should be encouraged to reflect on their evidence to understand its significance and the further questions it poses, as well as rely on their evidence to develop explanations and examine the limitations of their study. Wells (1995) emphasizes that reflection on their research helps students organize and construct meaning. Collaborative group work and whole class discussions or presentations create authentic opportunities for students to share their findings, question each others' results, and reflect on their knowledge, organize it, and construct personal meaning (Wells, 1995).

Conceptual Framework

Wisdom of Practice: An Examination of Teacher Knowledge

Teachers possess, as do all professionals, a knowledge base from which they develop their professional behaviors and decisions (Shulman, 1987; Wilson, Shulman, & Richert, 1990). Shulman (1986) poses three questions that frame this investigation of knowledge in science teaching: (a) What are the sources of teacher knowledge? (b) What does a teacher know and when did he or she come to know it? (c) How is new knowledge acquired, old knowledge retrieved, and both combined to form a new knowledge base? A teacher's "wisdom of practice" (Shulman, 1987) is built as she integrates her various types of knowledge, from multiple sources, to develop meaningful learning experiences, then transforms these based on the knowledge gleaned from implementing them.

Three categories of knowledge are of primary interest in this research: (a) disciplinary content knowledge, (b) knowledge about teaching and learning, (c) the fusion of these into pedagogical content knowledge. Disciplinary content knowledge includes an understanding of the facts, concepts, and organizing principles as well as the epistemology of the discipline. In science, teachers should know not only their own specialty area (biology, oceanography, physics, earth science) but have a good understanding of the interconnections amongst the many branches. Knowledge of the historical context and the interconnections to other disciplines is also important. A clear understanding of the epistemology or nature of science is essential; this focuses on the general question, "how does a scientist know?" (Ryan & Aikenhead, 1992, p. 567). Ryan and Aikenhead (1992) designate the following as relevant to an epistemology of science: (a) the meaning of science, (b) scientific assumptions, (c) values in science, (d) conceptual inventions in science, (e) the scientific method, (f) consensus making in science, and (g) characteristics of the knowledge produced in science. The sources of disciplinary knowledge often come from a teacher's undergraduate studies and from continued scholarly pursuits.

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Knowledge of teaching and learning also comes from a variety of sources and includes many different components. Sources used by teachers to build knowledge about teaching and learning includes teachers' experiences as students (Grossman, 1991; Lortie, 1975) and their formal studies (both completed and ongoing) in education. As teachers enter the field, other knowledge sources arise. These include professional organizations, committees within their schools and districts, curricular materials, and ongoing classroom experiences (Shulman, 1987).

The third category, pedagogical content knowledge, is of particular importance to this study. Pedagogical content knowledge involves a synthesis of all types of teacher knowledge to develop effective learning activities. Teachers should understand the commonly difficult constructs and misrepresentations in their discipline. Teachers should also know the learners in their classrooms, drawing upon "what there is in the child's present that is usable" (Dewey, 1902/1990, p. 201) as a referent for helping the student construct an understanding of the subject under study. Developing a repertoire of representations that serve to bridge the gap between students' inexperience and conceptual understanding involves pedagogical content knowledge (Shulman, 1987; Wilson et al., 1990). A science teacher develops particular activities and examples to help students understand abstract ideas such as the structure of matter. As students encounter these examples, the teacher will note what proves problematic and causes students' to form or reinforce previous misconceptions. She then must have at hand other examples or provide further experiences to help students attain a more scientifically accurate conceptualization. A teacher's pedagogical content knowledge enables her to transform disciplinary concepts and principles into accessible learning experiences that reflect the nature of the discipline as well as the content.

Pedagogical content knowledge becomes richer as teachers gain more experience and reflect on that experience in light of students' understandings. Shulman talks about the pedagogical reasoning and actions of a teacher and how these may be—should be—affected by her "wisdom of practice" (1987). Through reflection on students' work, discussion, and questions in relation to the learning activities provided, the teacher develops new understandings about learners and subject matter. This "accumulated lore of teaching experience" (Shulman, 1986, p. 10), i.e. the wisdom of practice, transforms pedagogical decisions and acts related to planning, instruction, and evaluation.

Schwab (1978) lays a foundation for the wisdom of practice work. He states: "*How* we teach will determine *what* our students learn" (p. 242). How a teacher represents the subject matter in the classroom affects the meanings students construct about the discipline itself (Wilson et al., 1990). An exemplary teacher transforms her subject matter knowledge into representations the students can relate to, without causing them to construct misleading conceptions. Schwab explains that knowledge should not be imparted to students as "truths out of nowhere but as conclusions from evidence, or decisions from thought about alternatives and their consequences" (p. 270). Related to this, students in science classes should be engaged in talking science. Lemke (1993) describes this as "observing, describing, comparing, classifying, analyzing, discussing, hypothesizing, theorizing, questioning, challenging, arguing, designing experiments, following procedures, judging, evaluating, deciding, concluding, generalizing, reporting, writing, lecturing, and teaching in and through the language of science" (p. ix). An exemplary teacher models the language of science while at the same time making it accessible. Thus, through reflection on the connections between how a lesson is taught and what students learn, teachers construct and refine their wisdom of practice. This new comprehension provides additional knowledge for pedagogical decisions and actions.

Shulman (1987), in delineating the aspects of "pedagogical reasoning and action" (p. 15) provides a more focused frame through which to view teachers' work. He provides six categories in his model of a wisdom of practice:

(a) Comprehension of disciplinary ideas and practices, within the discipline and in the context of a larger world.
(b) Transformation of these ideas and practices into meaningful classroom activities, appropriate to student characteristics. This involves four areas of decision-making:
   - preparing the relevant knowledge into forms accessible to students;
   - developing appropriate representations of the concepts;
   - selecting instructional strategies that will best assist students; and,
   - adapting the above to meet specific needs of specific students.
(c) Instruction.
(d) Evaluation of student understanding and of the instruction.
(e) Reflection on the students' and on the teacher's own learning and efficacy.
(f) New comprehensions that provide for deeper understanding of teaching and learning.

Shifting to inquiry involves much more than implementing a prescribed series of steps. Structuring opportunities for students to pose genuine questions about natural phenomena, design experiments, or learn to question ideas and scientific claims involves a different conceptualization of what is important to learn, how people learn, and how to teach for this type of learning. This sort of transformation is a process stemming from reflection and new understandings (Schon, 1983; Zeichner & Liston, 1996). A true transformation to inquiry-based teaching will result in authentic learning experiences that scaffold students' learning about scientific concepts as well as "science in the making."

Method and Analysis

This is a case study of an exemplary oceanography teacher, Liz Dietrich, and her students in three different classes over the course of two semesters: the second semester of 1999 and the second semester of 2000. This was a purposeful sampling of an unusual case, as is suggested for case studies (Creswell, 1998). This study provided an opportunity for an in-depth analysis of a science teacher who used inquiry-based teaching strategies and who was identified as exemplary by her principal, by receipt of numerous competitive grants and fellowships, and a state award for "Excellence in Education."

Data sources included: thirty-seven hours of participant observation and direct observation in one of the teacher's regular and two of her advanced oceanography classes; twenty seven hours plus two full days accompanying two different advanced classes on field trips; three semi-structured interviews and numerous informal interviews with the teacher over a period of one year; semi-structured interviews with thirteen students from the three different classes; documents such as scientific articles and study guides given by the teacher to the students; and, students' laboratory and project reports, journals, and other class work.

Classroom and field trip observations provided a picture of this teacher's pedagogy. Interviews and informal conversations with the teacher provided a forum for her to explain her goals for her students and her philosophy of teaching and sources of knowledge. These also provided a means to clarify my questions about the purposes of various activities, about her conception of inquiry, and her epistemology of science. Observations allowed me to see how she transformed her scientific knowledge into learning activities and how she nurtured relationships with her students. Interview questions with the students centered around what they found useful about the class, their conceptualizations of science, past experiences with formal and informal science, and how the teacher contributed to their learning. This study is limited by the inherent difficulty in eliciting the tacit knowledge a teacher possesses and determining how she then employs that knowledge in classroom practice.

Data were analyzed using Spradley's (1979) suggestions for domain searches to "isolate the fundamental units of cultural knowledge" (p. 142). From this, themes emerged and were developed into codes with major categories focusing on the sources and substance of the teacher's knowledge base. Subcategories included her substantive knowledge about science, her epistemology of science, her knowledge about pedagogy, and her knowledge and beliefs about learners. Another major category focused on the transformation of all types knowledge into pedagogical reasoning and actions. Coded data were sorted into various matrices and conceptual maps for analysis, as described by Miles and Huberman (1994).

Findings

Liz Dietrich's understanding of the nature of science and her deep knowledge about oceanography proved to be quite important to her ability to structure effective inquiry-based learning experiences. She integrated this scientific knowledge with her understanding of learners and pedagogy to facilitate her students' learning of oceanography concepts and scientific processes. Her pedagogical methods changed over the years as her wisdom of practice and her scientific knowledge became more extensive. Her wisdom of practice was built not only from her twelve years of teaching science, but also from her position as a novice researcher during summer field work with scientists, and insights gleaned from her work in developing curriculum for her classroom and a marine science center.

In the following sections I will describe Ms. Dietrich's knowledge in detail, both the sources she attributed to each type of knowledge and examples of the substance of that knowledge as evidenced in her teaching. Specifically, I will explore the sources and content of her substantive knowledge in science, her understanding of the nature of science, and her knowledge about teaching and learning. Once her knowledge base is established, I will show how she transformed this into an inquiry-based oceanography curriculum. In this sense I am using transformation to encompass all the elements she employed in her pedagogical decisions and actions—developing the curriculum, implementing and assessing it in view of her students' achievements, and reflecting frequently on its appropriateness and effectiveness. The synthesis of her various forms of knowledge into pedagogical decisions and actions reflects her pedagogical content knowledge as employed in the development of the regular and advanced inquiry-based oceanography courses.

Sources and Substance of Liz Dietrich's Knowledge Base

Disciplinary content knowledge. Through interviews Liz and I tracked the development of her substantive knowledge of science, in general, and oceanography, in particular. Her extensive understanding of science was also evident in her teaching and classroom discourse.

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Early in high school she developed a passion for science and took as many courses as were available. When she exhausted all the school had to offer, including biochemistry, she contracted to do an independent study with one of her teachers. She graduated as salutatorian of her class and was awarded an academic scholarship for girls going into science. She entered a large research university to study science and become a science teacher. She obtained a Bachelor of Science degree in biology, although by this point her interest centered on marine biology. After completing a fifth year to receive her teaching certification, she obtained her first position, teaching general science and biology. She maintained her interest in marine biology by taking on a summer job as director and instructor at a nearby marine science center. After four years she moved to a new job in a high school that allowed her to develop oceanography, geology, and astronomy courses. As she felt her understanding of geological and astronomical concepts was shallow, she took summer courses at nearby colleges to increase her knowledge. During this time she taught marine biology courses to adults at a local college and to children through summer institutes. She also obtained a Master's degree in science education.

The development of Ms. Dietrich's subject matter knowledge was not confined to college courses. To cultivate her own "passion for the natural world, especially the marine environment and its inhabitants" and to enrich her teaching, she jumped at every summer opportunity to work with scientists. This brought her to Hawaii to study volcanoes with vulcanologists and to the mid-Pacific on a NOAA ship to conduct research on game fish. She spent time in Florida studying coral reef ecology, and sailing in the San Juan Islands for further research on marine habitats. She spent two weeks at sea as a novice researcher working alongside biochemists, oceanographers, and geologists studying deep sea vents, and continues to be involved with this research. She currently is learning to use geographical information systems (GIS) in order to incorporate this tool into her classroom. Liz felt her experiences working with scientists and taking summer science courses improved her teaching, and gave her a richer understanding of how scientists do their work and a deeper understanding of oceanographic and geologic knowledge. When asked about what helped her improve as a teacher, she replied, "I guess the fact that I do continuing science education. . . . My first nine years of teaching I did something science-oriented every summer. I think it makes me a better teacher."

She went on to say that deep content knowledge is important to facilitate the shift from traditional, recipe-like labs to inquiry-based science:

> I'll never forget [my student] said oceanography was so much harder than geology because, since I knew more I expected them to know more. That was before all my geology experience [with scientists]. But I found that really enlightening to think about, because it is, I mean, you have to understand. I mean, there's some basic things—like I think you have to have a degree in what you teach, because just to have a discussion has many facets. I think you need to have a pretty good understanding.

This is very similar to Grossman's (cited in Shulman, 1987) findings that teachers who had less confidence in their subject matter knowledge were more controlling in their classrooms than in the subjects where their subject matter knowledge was more extensive. In the first case, they used fewer questions, let students voice their own ideas less, and stuck more closely to the textbook. Liz recognized this phenomena in her own teaching, and pursued disciplinary knowledge so that she could structure her other courses as she did oceanography. In her inquiry-based oceanography courses she was able to scaffold students' efforts to develop research questions and design experiments, avoiding the prescriptive tendency of most textbook based science labs that tell students what to do and how to do it (and imply there is a particular outcome that should result). In the advanced class, especially, she drew on her knowledge of scientific content to guide students toward fruitful investigations. This also took pedagogical skill; I will discuss this further in the final section on her wisdom of practice.

Liz supported her continued work with scientists and her "constant wondering why" through scholarship. To prepare for advanced oceanography and to answer her personal questions, she read current research on such topics as the bleaching of coralline algae or the increased mortality of Orca whales, or theoretical work such as Jared Diamond's Guns, Germs, and Steel (1999). She emphasized she devotes time to these activities as it "satiates my own interest in science." Talking about an article she read on the settling of zooplankton, she exclaimed over the challenge it presented to her previous understanding:

> I *totally thought* that it was "Yeah, they drift in on the high tide and if they're too high they dry out, if they're too low they get eaten and boom, that's the band of barnacles! Which is how I'd been teaching for many years! And so then I pull out, I found this article on preferential settling on most of the zooplankton in the intertidal zone, where they can choose where they settle. And most of their settling is where adults, particularly where the adults got scraped off. And so they could even, once they start, when they're tasting their way, I mean they're literally tasting for, it appears to be just molecules. When they made slurry, a milkshake out of the barnacle glue, the babies were still able to find it. It's just totally a trip.

I watched her subsequently share this article with her students, helping them interpret "the techiness of reading that article, that's written by scientists so deciphering the language is harder for them" and sharing her excitement over this new idea.

It was obvious that Liz drew upon multiple sources for her scientific knowledge. Importantly, her knowledge was not stagnant. She did not rely solely on the content of her college courses or on available textbooks for her subject matter knowledge. By keeping up to date on current research in her areas of interest she brought new questions, findings, and scientific debates to her students. Wineburg (1997) spoke about this as generative knowledge, important to exemplary teaching. Not only did this better ensure that her students would encounter the most recent thinking in the discipline, her ongoing learning served as a model for her students. As Wineburg discussed, subject matter knowledge goes beyond breadth and depth. Liz Dietrich's knowledge of oceanographical concepts encompassed more than knowledge of a broad array of facts about oceanic processes or relationships. It included more than a large amount of understanding about any one particular topic, say Orca whales in the Pacific Northwest. Her knowledge base was dynamic, continually changing as she learned more about the topics she thought she knew deeply, or when she learned about the nature of science through her immersion in scientific research.

From her early foundations in high school to her ongoing summer experiences working as a teacher/researcher with scientists, the foundation of her knowledge was firmly grounded in understanding how scientific questions are pursued and, especially, how new scientific knowledge becomes established as part of the canon. She attributed her work with scientists in the field to her deeper conceptualization of the nature of scientific inquiry:

> It was just very powerful, seeing science. [I've learned] that there are no right answers. Doing science myself and working with scientists who, basically their hypotheses are wrong and their questions lead to more questions. You don't get the right, definitive

answer, you get more data. How you interpret it is where you go next. [Science is] a way of posing questions. I look at it not as answers but more questions. And then it's a strategy to try and answer those questions.

Her ongoing association with research scientists contributed to her understanding of the nature of science:

I think that there are some scientists who are very entrenched in their beliefs. I mean, you look at Alfred Wegener, for example, going against the current accepted theory can take a while. So, as open as they seem, they are as entrenched as what they believe. So, being with the U in this deep sea/potential life originating at vents, as opposed to the shallow seas, it's very hotly contested right now among the scientific community. And so it was interesting to read some of the literature on that hotly debated topic.

She realized the political and economic ramifications on scientific research:

The way science is funded . . . it is very competitive and I don't think that you get the best outcomes of science. Because they don't have time to do it. They have to write grants to get money to do the project, but then they very rarely have time to look at the actual data. They get so much data, but they don't have time, and then they have to publish again in order to get the money so they can fund their research. It's a vicious cycle.

Her epistemology reflected many elements of a non-naïve (Ryan & Aikenhead, 1992, p. 561) conception about the nature of science. As reflected in the above examples, she held an authentic basis for understanding how scientific hypotheses and theories are constructed and the social process of consensus making through peer review. Based particularly on her work with scientists studying deep sea vents, she understood the tentative and often paradigm-bound characteristics of scientific knowledge.

Her knowledge of the discipline included extensive and continually growing subject matter knowledge, as well as a well-developed understanding of the nature of science. She stated her goals for her students were for them to learn something about cause and effect, relationships, and processes in the marine environment; to use their own empirical data and also the prior work of others to inform their interpretations and conclusions; and to develop a wondering attitude toward the natural world. From these it can be inferred that she understands how scientific knowledge is qualified; for example, a recognition that scientific propositions emerge from probabilities rather than uncovered truths, and that the paradigm under which one works shapes the interpretations one makes (Kuhn, 1970; Ziman, 2000). She realized that science is used to answer particular kinds of questions, that there are limitations to science —"the answers aren't out there waiting to be discovered"—and that science involves interpretations based upon data, past understandings, and social negotiation and values.

Knowledge on teaching and learning. Understanding how Liz's pedagogical knowledge evolved over her twelve years of teaching illuminates the difficulties teachers may face when trying to shift to inquiry-based teaching. Liz admitted that as a "rookie teacher I did what I would call cookbook labs" from the textbook. Her college professors, to a large extent, modeled this type of teaching. She described how her college science experiences did not serve her well as an example for science pedagogy:

Doing your science as an undergraduate and then having to teach it—I still don't think you have the connection. By the time you figure out how to be a good teacher the science that you did is four years old. And you never really did it . . . it was always something

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somebody handed to me to do. You know, we have this outcome that we had to achieve. And there was a right or wrong answer. So even undergraduate science was very much science in a box.

Strong role models did exist in her learning experiences. These provided an enduring image for Liz's conceptualization of good science teaching that facilitated her gradual shift to an inquiry-based approach. One of her high school science teachers structured an experiential approach to science education to which she often referred:

I loved [chemistry] in high school. Particularly the biochemistry, because it was so—I'm very much an experiential learner and I like the hands-on. In biochemistry, we made, in studying all our chemical equations, we made aspirin, we made nylon, we made pheromones, we made alcohol. And so, in order to do that you totally had to understand the equations, but it was never just the equations like kids are expected to memorize in some classes.

University chemistry undermined her confidence in herself, and reinforced her appreciation of an experiential approach:

Chemistry was so daunting. I had to keep taking Spanish to counteract the Cs I would get in the chemistry and then I'd 4.0 Spanish so I could keep my grade point. So, I really questioned one, had I been misled, and two, you know, your confidence, I think. But I knew, end result, that that's what I wanted to do in real life, that I had to get through these weeding out classes, I mean that's what they called them, "weeding out classes" for engineers and doctors. . . . I mean I liked it [science], but I didn't like that. . . . It didn't connect to me, it didn't make sense that I had to listen to this disconnected lecture and read something totally unrelated, and then regurgitate that on a test, but never knowing which were the most important facts.

Then, in her junior year at college, Liz experienced another "phenomenal, phenomenal educator. He just made marine biology come alive!" This teacher took science back "out of the box" and immersed her in investigating ideas and phenomena. He reinforced her early conception of effective science teaching and impacted the evolution of her teaching career.

Even while teaching in a very traditional form during her first job, she continued to explore this experiential approach to teaching and learning in her work at the marine science center. She described this experience as "paramount in my evolution as an educator. One of the amazing directors would always ask 'why do you think that is?' and was the first person in charge that got you questioning, thinking. And leaving you in control." She explained how her co-instructors influenced her ideas about teaching and the use of questioning and inquiry:

Why I give the science center such a powerful point in my life is that most of teaching is very isolated, but that place was very open. We planned together, there were three of us teaching. . . . And [another teacher], I would say maybe she guided us to asking a question, you know, an open-ended question with just the kids dialoguing about it. And then how to solve it.

Based on her memories of what she refers to as "experiential learning" and the excitement she found at the marine science center in using questions and discourse to explore scientific concepts, Liz began to seek ways to change her pedagogy. She considered her facilitation of classroom discussions centered around important questions to be some of the most important knowledge she held. She said that "knowing how to ask a question is one of the most valuable tools . . . You know, how do you facilitate a discussion." Using questions to get students to think about cause and effect relationships, or to problem-solve ways to get the data pertinent to their own questions was very typical in both her regular and advanced classes. Even in the regular class, where many students had very little initial interest in oceanography or science, students would find themselves engaged in a problem-solving discourse where they were leading the direction of the conversation. Much of the discourse in her advanced oceanography classes, especially, centered on students' questions, and involved students talking to students and the teacher, rather than the traditional "teacher question-student response-teacher evaluation" pattern seen so often in classrooms (Lemke, 1993). Through this involvement in a scientific discourse situated in authentic problem solving, Liz sought to immerse her students in a community of practice to help them understand scientific content as well as how science is done.

This was important to Liz, as she believed that "regardless of whether or not you go into science as a career, science is for everyone." She was clear in her belief that the learning experiences she provided were useful for *all* her students:

> The questioning, the problem-solving, the thinking will carry over. I mean, the whole thing I give them on their outline the first day is if you can communicate effectively, both written and orally, if you can analyze a problem, work together and come up with an answer, you're going to be successful, regardless of what you go on in, be it business or science.

As we will see in the next section, Liz's extensive disciplinary understanding, her pedagogical strategies, and her belief that all her students can find personal value in learning science came together to provide rich and engaging learning experiences for the students in her oceanography classes.

Transformation of Her Knowledge Base for Effective Science Teaching and Learning

Shulman's (1986) third question about teacher knowledge asks how new and old knowledge is combined to form a new knowledge base, a wisdom of practice. Having a well-developed understanding of the scientific discipline she taught and understanding the nature of science did not ensure that Ms. Dietrich would be able to teach this to her students. While her vision of good science teaching, based on her experiences as a learner, led her to create experiential courses that involved her students in active learning, decades of research demonstrate that hands-on science activities do not themselves guarantee student learning. A teacher must transform what she knows about science into appropriate classroom activities by selecting the information that is of most importance, choosing the best way to engage students in learning this (lecture? demonstrations? discovery?), determining how to represent ideas, and adapting these models and activities to her specific students' abilities and needs. Yet, a teacher's decisions do not always result in the expected student outcomes; as Wilson, Shulman, and Richert (1990) point out, sometimes it seems a teacher must know her subject matter in 150 different ways in order to reach all her students. Thus, reflection on what students are learning, whether they are building misconceptions or are unable to grasp the concept at hand, causes a teacher to revise or develop additional ways of representing the material and different means for engaging students in the ideas at hand. This pedagogical content knowledge is constructed and reconstructed through experience and new understandings.

Reflection on teaching effectiveness with respect to changing goals in science education can also create a need for transformation of instructional strategies or ways in which disciplinary

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knowledge is represented. Additionally, a teacher may need to transform past practices in light of new disciplinary understandings. As Liz learned more about the nature of scientific inquiry and knowledge, she saw inadequacies in her teaching. Liz wanted her students to learn more than scientific facts. She was quite concerned about students' conceptualizations of science:

I hated the fact that they're like "our data's wrong, we didn't get the right answer." And what really, here's what really springboarded me into this, is doing science myself and working with scientists who do science and who, basically, their hypotheses are wrong and their questions lead to more questions. You don't get the right, definitive answer, you get more data. And you data's your data and how you interpret it is where you go next. And so, really working with kids, working with scientists, was paramount for this. I mean, I've been working toward getting to experiential inquiry, but really that's what science is. That you design your own experiment, you build the materials you need to do your own experiment, you collect your data, and then you interpret it, and then you build something else.

Thus, she wanted to develop learning experiences that challenged her students to use questioning, analysis, and communication skills as well as build understanding of scientific principles and concepts. Liz felt that the critical thinking employed in scientific investigations would serve her students in many aspects of their lives.

In the following section, observational and interview data provide evidence that key to the effectiveness of Liz's teaching and her students' gains in scientific understanding was her ability to draw from her extensive scientific knowledge and pedagogical wisdom to engage them in authentic communities of scientific practice. I will show how she integrated her scientific and pedagogical knowledge into pedagogical content knowledge that included her use of probing questions and student discourse to help students construct their own knowledge. It will be seen that she continued to build her pedagogical content knowledge through reflection on her understanding of the nature of science and on her students' achievements in light of her goals for them.

An image of inquiry in oceanography. In order to understand how Liz transformed her teaching, from her early to her current practice, I will begin by describing the elements of inquiry observed in her regular and advanced classes. Her students were encouraged to make observations and, from these, generate questions for further investigation. Out of these questions, they learned to develop hypotheses that were testable, and to plan their own experiments to get data that would inform their ideas. They were encouraged to develop their own explanations and models from their evidence, and present these to an audience of their peers or, in advanced oceanography, an audience including scientists and other adults. While this sounds very similar to the so-called scientific method, in practice it was a creative process that challenged students to go beyond following directions to think for themselves, invent methods and equipment, access sources of information beyond a textbook, and employ critical thinking in order to analyze their data and represent it for others. As Liz Dietrich said:

> So traditionally, teachers just say this is what we expect, this is what you should get. Instead of "your data's your data, how are you going to interpret it?" At the beginning of the year, my first semester oceanography kids are like "why won't you just tell us?" So my kids are going to get to the point where whenever I ask them, it's like "hypothesize why", and they're "so it's okay to be wrong?" I say "yes!" They're like "we can be wrong?" and it's like "yes, I expect you to be wrong because most hypotheses are."

As a result of this understanding that doing science does not mean finding right answers, Liz used probing questions to get her students to think about their own questions. This was very obvious during classroom observations. I asked students to talk about how they felt when Ms. Dietrich didn't answer their questions. Joel and Lacey, two advanced oceanography students explained what it means to them:

> Joel: Ms. D is so good at never answering our questions with answers, but with more questions. This is good, I learn so much more, because I have to figure things out.
> Lacey: I think it's self motivation. All our classes should be like this. Because rather than being given a whole bunch of facts we don't care about, we want to find these things out and use them. This definitely makes a difference in my learning, because I might not remember the exact fact, but in the process I'll know how to figure things out when I need to.

Jill, a student in regular oceanography, replied in a similar fashion, saying:

> This is so different from the science classes I've had recently, I haven't had a teacher like this since 7th grade. She actually asks questions a lot, most of my other classes the teacher just lectures and you write it down, and I just zone out because you've heard it once and then you're seeing it again and you don't have to think. But she [Liz] asks questions, like about barnacle reproduction, that get you thinking, and then she usually gets to an answer somewhere down the road, but by then you've had time to think about it and I usually get to the answer myself.

Liz's use of probing questions and her engagement of students in authentic scientific discourse where ideas are voiced, supported with evidence, questioned and challenged by others was supported by her extensive disciplinary knowledge. Her teaching strategies helped motivate students to think about what they knew and what they needed to find out. This constant questioning of students to get them to verbalize their ideas was a powerful example of her pedagogical content knowledge, as the questions she asked were rooted in disciplinary knowledge.

Liz not only used questions herself, she encouraged students to formulate their own. One of Liz's goals for her students was that they would develop a curiosity about the natural world, a capacity and inclination to "wonder why" when faced with anomalies between what they thought they knew or understood and what they observed. In regular oceanography, students moved from common conceptualizations of barnacles as inert, sharp, white things on rocks to see them as living organisms responding to stimuli in their environment. In the advanced class, students moved from their general understanding that there are five significant elements to life in the intertidal zone (dessication, predation, reproduction, movement, nutrition) to a deep understanding of how a particular organism, say Hemigrapsis nudus, is adapted to these elements, or how a physical feature, such as the breaking waves on a particular shoreline, affects the substrate composition and therefore the distribution of organisms.

Students were encouraged to develop ways to investigate their questions. Liz assisted them, through engaging them in group conversations, in translating their multitude of questions into a testable hypothesis for which data collection would be possible. In this, she again drew on her subject matter knowledge to steer them toward non-trivial investigations. She provided multiple opportunities for data collection, ranging from experiments during which they collected quantitative data, to conversing with scientists she arranged to accompany them, to supporting them as they developed their own equipment to get the kind of data they wanted. For example,

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one group invented a "centrifugal force plankton sorter" as a way to sort plankton according to size as they collected it in a swirling current. While this device wasn't very successful, the effort reflected information a visiting scientist had provided about the need to invent new equipment when working on cutting edge science in the deep ocean.

Groups' analyses and conclusions were always shared with the whole class. In regular oceanography this often took the form of class discussions. In advanced oceanography, each of their four major projects were presented as oral reports or poster presentations. The latter modeled scientific conferences, where the research question, background research, data, and analysis are displayed on a poster and a short presentation is given. The audience, composed of students' peers as well as invited scientists and other adults, were encouraged to question the presenters' regarding any aspect of their work. In this way, Liz was providing students an authentic forum where they were the experts on their work, yet also continuing to learn in the process. As Pam, a student in advanced oceanography, told me:

> When you're presenting stuff like that not everyone's going to remember the content that you tell them, so you have to, like show pictures and diagrams and creativity helps them remember, also. I guess it's a lot like learning, teaching, learning.

Overall, Liz attempted to involve them in a process of scientific inquiry authentic as possible in a school setting. These opportunities helped students develop understanding of both content and the nature of scientific work and knowledge.

Building a wisdom of practice. The teaching strategies Ms. Dietrich selected and refined over her years of teaching reflected her increased understanding of the nature of science, scientific inquiry, and learning in science. Whereas she began her career using "cookbook labs" and lectures, she came to understand that while she might be teaching scientific content, she wasn't providing her students opportunities to learn about the nature of scientific inquiry and scientific knowledge. She moved away from this approach in her teaching, saying, "I mean what are we teaching them when we use cookbook labs? We teach them how to follow directions, not to think, not to problem-solve." She realized the difficulty students' had with learning in a different way, and employed pedagogical reasoning integrated with her understanding of scientific inquiry to help them:

> So, the hardest part is them coming up with their own question. So I really, and I think I have to work on guiding them even more to the question and then how to, for one, pose the question, and then two, what information is, what kind of information do they need to help solve their question or solve their problem.

Contrasting her epistemology of science with what often happens in science classes—the emphasis on following directions, getting the right answer, memorizing vocabulary, and regurgitating facts—she explained that the "cookbook science" so often implemented in schools doesn't build the problem-solving skills required for "figuring out why." This recognition emerged over her twelve years of teaching as she continually reflected on her students' accomplishments in her courses. It caused her to transform lessons she and others had previously developed at the marine science center:

> I did [in my early years of teaching] many of the things I do now, but there was a lab sheet that gave them the directions, you know, "count the number of times the cirri comes out in a minute." You know, "do this three times, take the average." Whereas now that would be "well, what should we measure, is there something we could measure?" And they're like "we could count the number of food particles, we could find out how

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much plankton is in the water before and we can measure how much plankton is in the water after." Now I ask them "How?" "What might be an easier way?" Now the kids advance ideas like "what if I timed how long these came out?"

Liz attributed her pedagogical shift from "cookbook labs" to inquiry-based investigations to her wisdom of practice—what she called her "maturity, once you see what works or what doesn't work." She said this change "involved my role as a facilitator, or my ability to give up, I don't want to say the power in the classroom, but to give up the control in the classroom. To allow them to do it." "Doing it" referred to thinking and speaking as well as putting their hands on materials. She wanted students to actively use scientific language and ways of thinking about phenomena rather than passively follow textbook instructions. In regular oceanography she started them off the first week with the question "what is the most successful intertidal organism?" This began a series of observations and experiments with oysters, barnacles, and shore crabs. Students were directed to observe barnacles in a beaker of water, develop hypotheses based on these, and design a series of tests to ultimately determine what their natural environment is like and why barnacles are so successful in that environment. Over the next two days students moved from comments like "oh wow, see that little crack, and that black thing comes out" to "yesterday we noticed the cirri on the bottom were going slower than those on the top. Then when we flipped the clump [of barnacles] over, those on top were faster. Our hypothesis is it's either light or pressure. We'll test both."

Liz set up this five day investigation to be student-directed, within the parameters she presented: collect initial data on your control, make inferences based on observations, formulate an hypothesis and an experiment to test it, collect qualitative and quantitative data, develop some conclusions and support these with evidence. As she roamed the class and responded to students' questions, she modeled the use of scientific language as well as process, as in this exchange:

Student: Should we try to get the same barnacles as yesterday?

Ms. Dietrich: That would be great, it's one way to rule out some experimental error.

Student: [as he looks down into the beaker of barnacle-encrusted rocks] Look at this, Ms. D. What do you think this guy [barnacle] is looking for?

Ms. Dietrich: Well, what do you think?

Student: I don't know, don't you?

Ms. Dietrich: Well, we can hypothesize. [and she went on to question the student about why the barnacle might be extending its "feathery things" into the water.]

In this conversation she introduced the idea of experimental error as a concept connected to the student's own actions. As well, she used "hypothesize" in context, again directly related to the student's question and interest. Hypothesizing became an action the student engaged in, rather than merely a word set down in a lab report. Through this sort of discourse at the beginning and end of class and with individuals and lab groups, Liz provided access information that would help them in their investigation and would build an understanding of how scientific work is done. By using scientific terminology in context during these conversations she provided opportunities for them to hear how specific terms are used, like experimental error, to learn scientific names for things, such as barnacle cirri (the "black thing" that emerges from the barnacle's shell), and to practice using these terms and practices themselves.

Based on her evaluation of what her former students learned through "cookbook labs" and what they learned through this type of guided inquiry, Liz shifted her original lecture/lab approach to science teaching to a more inquiry-based pedagogy. She taught her students to ask questions rather than ask her for correct answers. In the barnacle investigation she asked them for their observations, then used probing questions such as "why do you think that is?" rather than merely provide factual answers. She reported:

> So I never, we never answer the question "what are the barnacle cirri doing?" because by the time they've done it I don't have to. They don't need a right or a wrong answer. And they have enough evidence before them that they can figure it out on their own.

In the end, the students were still somewhat sloppy in their procedures. Liz reported that "they were taking three different barnacles for three trials, rather than one barnacle for three trials." They were still using colloquial terms more frequently than scientific, and they had mixed success in using evidence to support their claims. But this was only the first week of many opportunities to design and carry out experiments, and to think carefully about what it means to use data to support a conclusion and to learn scientific content and processes in the context of pursuing their own questions.

In advanced oceanography, Liz extended the knowledge and inquiry skills built in the introductory class. She reflected on the achievements of her students and sought ways to make their experiences and their results more authentic. One of her main concerns in advanced oceanography was that the students did not collect enough data to make valid conclusions. Upon realizing this, she enlisted the help of the statistics class. Students in advanced oceanography teamed up with students in statistics, who ran statistical tests on the data. Students then better understood what kind of research effort was needed in order to be able to make conclusions from their data. Further pondering the students' lack of data and therefore limited ability to draw conclusions, Liz considered restructuring the procedures in advanced oceanography.

> I realized that I want a theme for Advanced that goes through every field site. I want their questions to evolve while they're getting the same data at every site. I want them to— because our data's the weakest point. I tried to look at why their data is so weak. You know, they have five samples. So why do they only have five samples? Because of our time constraint. Having two days to design the project, go out and collect the data and come back. And so, I thought, okay, how can I help them have better questions before they go out? So that's when I thought of the idea of everyone doing the same project at the first field site. Say, these are the basic parameters of the intertidal zone, these are the criteria for how to collect scientific data, and these are the sheer numbers that are involved, of any sample size. You need to have significant data, I mean, that's what the stats kids told us, our data isn't significant. So how do we get more? And so everybody's starting on the same page, and then their question evolving at each site, but with similar data. I think this will allow us to get more significance. And probably help them a little bit in their overall understanding.

Overall, Liz wanted her students to understand scientific concepts such as tidal fluctuations, intertidal zonation, and ocean currents. She also believed it important that students learned to pose questions and determine "what kind of information they need to help solve their question or solve their problem." She explicitly recognized that more often than not there are no definitive answers or solutions to these questions and problems, that science doesn't imply a set of answers exist somewhere and a person must only be clever enough to unearth them. Instead, she hoped students learn that "your data is your data and how you interpret it is where you go next." She believed traditional science labs misled students as to what scientists do:

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> I mean, if we refer to the cookbook labs, I mean there is an end result that they expect, that the kids expect to get. And what I try and do is, there's no end result, your data is your data, and then how you interpret it might be not even right or wrong. I mean, that's never a term that I use. You could have supported your data better, or you could have come up with another idea.

Students confirmed that they were learning differently in oceanography. Laura, an advanced oceanography student told me:

> Biology, it was different because it's just like, you're told, you're like told everything, like you know, oh this works this way, and this works this way, study and take test, blah. And then like, with oceanography, like when we went out here, you know, and she just wants us to look around for stuff and ask questions and, to start us off with things, and just that question just hit me, it was just like, whoa, you know!

Through the sequence of learning activities described in the previous section, beginning with guided inquiry in regular oceanography and culminating in poster presentations on their own research in advanced, Liz assisted her students in learning that scientific assertions require evidence and that scientific knowledge is based on interpretations of empirical data, theoretically shaped, and ultimately limited by the researcher's time, tools, and knowledge. Liz wanted her students to learn the tenets of oceanography and also about how that knowledge was established and how it changes. Thus, Liz provided her students with opportunities to learn about basic oceanographic concepts through reading, talking, and conducting experiments. Understanding that a main purpose of science is to generate new knowledge for it's own sake, she engaged students in wondering about phenomena and posing questions to which possibly no one knew the answer. Pam, a student in the advanced class, commented, "Yeah, you can't even find this in books, you know when you're out there you see things that nobody has ever written about or maybe ever even found out before."

Liz's pedagogical decisions and actions evolved over time as she reflected on what her students were not learning through her use of cookbook labs and lectures, and as she developed a deeper understanding about how scientists do their work. This doesn't mean she never used lectures again; she understood that there is much in science that one needs to know in order to be able to pose questions and proceed with research. She realized that she couldn't teach all that her students should learn through inquiry. As such, she utilized other teaching strategies such as lectures and structured activities. The key to her wisdom of practice, to her ongoing refinement of how she involved her students in learning, was her own questioning of how her instructional strategies correlated with her students' learning and her goals for their accomplishments. These goals were solidly rooted in her knowledge about oceanography and about scientific research.

Conclusion and Implications

Liz Dietrich drew from her impressive knowledge base about oceanography and the nature of scientific inquiry to transform her traditional lecture and lab dependent teaching to an inquiry-based approach. Coming out of college with a B.S. in biology and years of experience in both "experiential" and traditional, lecture-based courses, she implemented the traditional model, yet felt uncomfortable with her approach. She saw the emphasis on memorization and the focus on right answers over understanding caused her students to develop misunderstandings about the nature of science. While she used hands-on labs, having students work with materials as a way to facilitate conceptual understanding, she saw they were still concerned mainly with getting expected results rather than seeing their data as evidence to support scientific claims. Her growing understanding of the nature of science, developed through her interactions with scientists as they conducted their research, as well as her ever deepening knowledge of the substantive content of the discipline, and her reflection on what and how her students learned in the classroom and at the marine science center, motivated her to move away from the cookbook labs.

The portrait of inquiry in both the regular and advanced oceanography classrooms was more than a series of steps such as described by the traditional scientific method. Due to the way Liz Dietrich immersed students in doing and talking science, these students were learning more than scientific facts and concepts. She involved her students in an authentic community of scientific practice, where they learned and used scientific vocabulary and practices in the context of their genuine questions about natural phenomena. In this way, students learned about the nature of science, how scientific knowledge is established and defended, as well as about the body of established scientific knowledge that traditionally serves as the content of school science. Importantly, students were involved in "science in the making" (Latour, 1987). This moved them from the traditional school science model of verifying knowledge through the replication of others' experiments (which usually translates to following the directions to get a predetermined result) to one in which they undertook investigations to which there were no right answers. In this way, they had opportunities to construct a richer notion of science, involving an understanding of the nature of scientific knowledge.

While some studies have postulated that a teacher's content knowledge does not influence classroom practice (Lederman & Gess-Newsome, 1992), this study suggests that a rich understanding of oceanography and the nature of science substantially contributed to the teacher's effective adaptation of inquiry-based teaching. As well, translating her knowledge into practice required a pedagogical content knowledge enriched through her reflection on her practice as well as her knowledge base. This speaks to science teacher education and the experiences that might assist novice teachers shift from the traditional models most know well to an inquiry-based approach.

This study informs professional development for practicing teachers, as well. Many professional development programs isolate pedagogy from scientific practice or vice versa. The evolution of Liz Dietrich's wisdom of practice implies that teachers may need to undertake scientific inquiry themselves in order to bring authentic experiences and richer knowledge to their students. It also speaks to the role of reflection in transforming practice. Liz's experiences with research scientists were more than stories she related to her students. She developed an understanding of how scientists do their work, compared that to how and what her students learned in school, and found her practice of school science lacking. Her attempts to bring a more authentic practice into the classroom stemmed from an integration of her growing pedagogical and scientific understanding. In this way, Liz Dietrich's use of inquiry in oceanography can provide a model for integration of scientific inquiry and pedagogical inquiry in professional development. Her practice can also serve as inspiration, a portrait of possibility, for science teachers interested in transforming their practice to engage students in authentic communities of practice and enhance their understanding of scientific knowledge and inquiry.

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