Teaching the content and context of science: The effect of using historical narratives to teach the nature of science and science content in an undergraduate introductory geology course

by

David Winston Vanderlinden

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Education

Program of Study Committee:
Michael P. Clough, Co-Major Professor
Joanne K. Olson, Co-Major Professor
A. Geoffrey Abelson
James T. Colbert
Jennifer R. Seymour

Iowa State University

Ames, Iowa

2007

UMI Number: 3274879

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

This work represents not only my own effort, but also the efforts of many others who supported and encouraged me through the process of completing this work and the doctoral degree. I owe a debt of gratitude to these individuals and will always be thankful for their patience and their guidance.

I would like to acknowledge my co-major professors, Dr. Michael Clough and Dr. Joanne Olson. I can still remember the first day when I heard Mike talk about the nature of science; this was the same day when realized that there were many NOS aspects which I had not previously contemplated. I have learned so much from Mike since then, both from listening to what he has offered and from observing his modeling of how to teach about the nature of science. Joanne has truly been a mentor throughout this process, guiding and coaching me through the development of research questions, the experimental design, and the research and writing processes. She has offered assistance when I needed it, and allowed me room to explore and learn on my own when I was capable. Both Mike and Joanne challenged me to learn and grow while providing the needed support to make the process manageable and enjoyable.

I greatly appreciate the contributions and suggestions of my committee members, Dr. A. Geoffrey Abelson, Dr. James Colbert, and Dr. Jennifer Seymour. Each of them provided insight which has helped me to learn more about the research process and to contemplate the significance of this work.

I am grateful to my partner, Steve Betz, who supported my efforts throughout this long journey and who helped me edit this document. When I thought I could go no further, he inspired me to continue on to the end and to succeed in the face of many obstacles.

My colleague in graduate school, Crystal Bruxvoort, forged the way before me in the doctoral program and I often relied on her advice and insight. My friends Julia Rahn and Mary Beth Wilk offered consistent encouragement and helped me to believe in my own abilities. Each of these individuals helped me laugh when I needed relief and helped me focus when I needed to take each step forward. The knowledge that they were watching and supporting me, with full appreciation of all that the process involved, provided inspiration and motivation to me on a daily basis.

I acknowledge each of you for your contributions, truly too numerous to mention here, and I look forward to celebrating this achievement together through our memories of both the good times and the bad. Because of your support, I can look back on this long road with a true sense of accomplishment.

ABSTRACT

This study reports the use of historically accurate narratives (short stories) to simultaneously teach geology content and the nature of science in an introductory, undergraduate geology course. The stories describe key events involved in the development of geologists' ideas about continental drift/plate tectonics and deep time/the age of the Earth. The design of the stories provides a highly contextualized setting which is designed to promote NOS and geology understanding by explicitly attending students to fundamental concepts and requiring students to reflect on the short story content. Evidence is reported to support the conclusion that students using these short stories constructed a better understanding of 1) the variety of processes involved in the construction of scientific knowledge, 2) the subjective nature of data that allows it to be interpreted differently by different scientists, and 3) the roles that culture and society play in determining the way in which scientific work is conducted and scientific ideas are constructed, while maintaining equal levels of understanding of geology content when compared to students who did not use the short stories. In some cases, students' preconceptions about objectivity in science, the degree to which scientific ideas can be considered as "proven" or "true," and the role of discovery in science appear to have adversely affected their ability to interpret the short story content in the ways intended. In addition, students' misconceptions about differences in how oceanic and continental plates were formed and geologists' use of relative and absolute dating techniques, especially the appropriate uses of radio-isotopic dating, are described.

This study has implications for science instructors as they make efforts to efficiently use class time and curriculum resources to teach about the both the content and context of

science and for geology instructors as they consider students' misconceptions about plate tectonics and deep time. In addition, this study presents a method for addressing concerns about many students' disinterest in science and the need to prepare a scientifically literate population.

CHAPTER 1: GENERAL INTRODUCTION

Background

Science is a field that invokes a wide array of responses from students, commonly including excitement, awe, apathy, and fear. Science instructors usually attempt to dispel students' fears and combat their apathy by relying on the elements of science that invoke excitement and awe. Still, the end effect often is perceived by students to be more a task of memorizing known facts than achieving an appreciation for the ways in which scientific knowledge is built. In fact, students often have significant misconceptions about the nature of science (NOS), or "what science is, how it works, the epistemological and ontological foundations of science, how scientists operate as a social group and how society itself both influences and reacts to scientific endeavors" (Clough, 2006, p. 463).

By the time when students enter college, they have often encountered multiple implicit and explicit messages through education, interaction with media, and everyday usage of science terms that have instilled deep-rooted misconceptions about the nature of science (McComas, Clough, & Almazroa, 2000). For example, students often perceive science to lack any element of creativity or imagination, to be a static and purely objective body of knowledge rather than a dynamic understanding of the natural world that is influenced by factors related to those who participate in building the knowledge and the society at large, and to be a process where all scientists follow the same methods, allowing them to reach common conclusions (Lederman, Abd-El-Khalick, Bell & Schwartz, 2002; Rudolph, 2000; Songer & Linn, 1991). A study of the NOS can reveal fallacies in each of these perceptions. Unfortunately, "for most science students, a description of the NOS is relegated to a few paragraphs at the beginning of the textbook quickly glossed over in favor of the facts and concepts that cram the remainder of the book and generally fill the course" (McComas, et al., 2000). This approach is not only inadequate at providing detailed and well-contextualized messages about the nature of science, but the heavy focus on memorizing and applying science content also sends implicit messages that convey a contradictory message (Clough, 2006).

The Value of History of Science Materials to Illustrate NOS Concepts

One method that has been proposed to dispel nature of science misconceptions and to integrate NOS materials throughout science courses is the incorporation of history of science (HOS) materials into traditional science curricula (Conant, 1957; Klopfer & Cooley, 1963; Lin & Chen, 2002; Lonsbury & Ellis, 2002; Stinner, McMillan, Metz, Jilak, & Klassen, 2003). These materials provide historically accurate details about how science concepts developed in the context of particular scientific, social, and political settings. Materials involving the history of science often demonstrate the human side of science – the idea that emotions, political and social pressures, and subjective decision-making influence scientific findings. Also, historical descriptions of science can show how scientific knowledge comes into being and what is required for the body of scientific knowledge to undergo change – two areas that are commonly misunderstood due to the "textbook-centered presentation of the finished products of science" in science classes (Stinner et al., 2003, p. 618). By using examples from the history of science to explicitly describe and explain the epistemological nature of science, it is hoped that students will experience growth in their views of what science is all about.

A more human view of science may help to allay some of the fear and apathy students feel concerning science. Seeing the human side of science may have the effect of encouraging more students to see it as an accessible means of gaining understanding about their world, and perhaps even as a potential career path. In addition, the views concerning science held by the population at large can influence social decisions about what types of scientific studies should be funded and pursued; consequently, the view that citizens have concerning science can have wide societal effects. Detailed portrayals of science as a way of knowing may encourage more citizens to feel able and compelled to engage in discourse concerning science decisions at both individual and public levels. Intentions similar to these have been voiced by national science education policies and standards, which have identified a goal of increased science literacy and have related science literacy to topics typically considered part of the nature of science (National Research Council [NRC], 1996).

Many reasons have been proposed to explain why inclusion of science history can make a valuable impact on NOS understanding. Lonsbury and Ellis (2002, Using Science History to Teach the Nature of Science section, ¶ 1) state that “science history can provide concrete examples to help students understand difficult science and/or nature of science concepts.” Matthews (1994) asserts that incorporating science history allows for more interdisciplinary understanding – showing connections both within different fields of science and also between science and the humanities. Stinner et al. (2003) propose that history of science materials provide opportunities to make students explicitly aware of nature of science concepts, an approach that Abd-El-Khalick and Lederman (2000) demonstrated to be more effective than the implicit approach of assuming that students will pick up on these ideas just by studying science content.

In addition, science history provides an added focus on epistemology (how we know) rather than just on science content (what we know). Stinner et al. (2003) describe that a typical classroom practice is to present scientific ideas, such as Newton's law of gravity, "as if they were self evident and came full-blown to the mind of the great man" (p. 618). Such a presentation leaves out the human, social, political, and economic aspects of science epistemology, but inclusion of more details of the historical perspective could help to fill in the picture, particularly if attention is explicitly drawn to the significance of these details.

Finally, Harding (1991) cautions against using the versions of science history that currently predominate and that assume "that histories of intellectual structures can be independent of the histories of the economic, political, and social environments in which the intellectual structures emerge" and thus "[seek] simultaneously to reconstruct the logical development of science and also provide a historical explanation for it" (pp. 221-222). Science history, to be used effectively as an illustration of the nature of science, must emphasize accurate portrayals of the economic, political, and social perspectives in which scientific knowledge was framed.

While previous attempts to use HOS materials to teach science concepts and to address NOS understanding have met with some success (Klopfer & Cooley, 1963; Lin & Chen, 2002; Lonsbury & Ellis, 2002; Solomon, Duveen, Scot & McCarthy, 1992), little work with college-level students enrolled in science classes has recently been documented. In addition, many of the materials that have been developed have either focused on primary or secondary level science or on teacher-education courses, and the few that have focused on college science are largely out of print. A need exists for new materials that can be incorporated into college science classes and that effectively address key science content while simultaneously providing accurate descriptions of the NOS.

Purpose of Study

This study involves the use of materials specifically designed for a college-level introductory geology course. This study and the development of these materials have been supported, in part, by a grant from the National Science Foundation (Clough, Olson, Stanley, Colbert & Cervato, 2006). The purpose of the study is to describe the NOS views of a group of typical college-level introductory geology students and how these views may change due to specific instructional strategies that attend the students to NOS ideas using stories from science history. In addition, students' understanding of the key science content areas addressed in the short stories will be examined, with a hope that better understanding how the ideas were developed may also improve students' understanding of and ability to apply the associated science content. The specific geology concepts focused on within this study are the theory of plate tectonics and the concept of deep time as it relates to the age of the Earth. The primary nature of science concepts addressed within the stories involve: the variety of processes involved in the construction of scientific knowledge; the subjectivity involved as scientists' interpret data from their unique theoretical perspectives; the tentative, yet durable, character of scientific knowledge; and the effects that culture and society have on science, scientists, and the process of constructing scientific knowledge.

Materials

The materials used in this study consist of 1) four historically accurate short stories that describe the development of scientists' ideas about continental drift/plate tectonics and deep time/the age of the Earth, and 2) a quiz designed to examine students' understanding of the geology and NOS concepts emphasized within the short stories. The short stories describe the historical and social context in which the ideas were developed, scientific debate that ensued at the time of development, and the processes involved as these ideas eventually became accepted by the scientific community at large. The science concepts involved are described through the use of scientific terms and descriptions that cohere with the type and level of knowledge commonly expected in an undergraduate, introductory geology course. Embedded within the stories are specific statements and open-ended questions that attend students to and prompt students to reflect on the science and NOS concepts illustrated. In this study, students read the stories and submitted written responses to the embedded questions to fulfill a required homework assignment. Toward the end of the semester, the students completed the quiz, which consisted of open-ended questions designed to examine the students' understanding of the science and NOS concepts emphasized in the short story assignments.

Research Questions

This study will focus on answering three research questions.

1. How are geology students' views of NOS affected by the use of history of science materials in an introductory-level course?
2. How are geology students' understanding of plate tectonics and deep time affected by the use of history of science materials in an introductory-level science course?
3. What NOS misconceptions appear to interfere with learning as students interact with the history of science materials?

Overview of the Methods

A mixed methods study was conducted utilizing qualitative methods to describe students' level of NOS and geology understanding, and quantitative methods to examine changes in students' understanding. The qualitative part of this work could best be described as an interpretive study of the NOS and geology views that students have and how these views may change while interacting with history of science materials in their coursework. In particular, the misconceptions about the nature of science that students exhibited as they answered questions related to the history of science materials are described and characterized. The quantitative portion of the study involved making comparisons between students' views and contemporary accepted views about the NOS and geology to rate the ideas held by these individuals, and then to measure to what extent use of history of science materials generates statistically significant changes in the students' ideas. A control/treatment application was used, with control group students having no exposure to the HOS materials, but being assessed for their NOS and geology content understanding toward the end of the course. The treatment group was required to interact with the HOS materials as part of two homework assignments during the course, and these students also responded to the same NOS and geology content assessment questions toward the end of the course.

Terms

To ensure clarity about the meanings of some specific terms used in this study, the following glossary is offered. Several of these terms will be discussed further in subsequent chapters, but brief definitions are presented here.

The *nature of science* field is one that focuses on concepts such as the attributes of science, characteristics of scientists, the processes used by scientists, characteristics of scientific knowledge, and how the scientific community and society at large interact.

Although debates exist among various nature of science specialists concerning some details of the various aspects of the NOS, in this work the terms *more informed views, currently accepted views,* and *contemporary views* are used to describe NOS views that are largely agreed upon among those who study the nature of science.

The terms *misconceptions, alternative conceptions*, and *naïve views* are commonly used in the literature to describe ideas about the NOS or about science concepts that contradict with currently accepted views. In this work, the term misconceptions will most often be used to describe these types of views, but citations from and descriptions of the literature will often include these other terms also.

The term *science educators* is used to refer to specialists whose primary work is the preparation of future science teachers, while the term *science instructors* is used to refer to those who teach science courses (i.e. geology).

Historians of science are specialists who study science history, particularly examining influences of socio-political influences on the scientific community, scientific work, and the types of ideas considered by science within a particular historical context.

The *participants* in this study are students enrolled in an undergraduate, introductory geology course; consequently, the terms participants and *students* are used interchangeably.

Interpretive qualitative research is a type of study intended to identify and describe how the participants assign meaning to various ideas – in this case, ideas about the nature of science and about essential concepts in the field of geology.

Coding is the particular method used in this study to examine writing samples of the participants, looking for common themes and grouping together similar students' responses under descriptive category headings (open coding) and then defining relationships between the various groupings (axial coding), as described by Strauss and Corbin (1998).

CHAPTER 2: LITERATURE REVIEW

The Nature of Science

Over the past several decades, science education has increasingly emphasized the importance of including nature of science instruction in science classes (American Association for the Advancement of Science (AAAS), 1993; National Science Teachers Association (NSTA), 1962; NSTA, 1990). In addition, nature of science issues have received attention from philosophers of science, historians of science, and theorists engaged in critical reflection on science (Abd-El-Khalick, Bell, & Lederman, 1998; Harding, 1991; Munro, 1993.) In fact, McComas and Olson (2000) have described that the nature of science consists of a hybridization of the overlapping fields of the philosophy, history, sociology, and psychology of science. Together, these fields help us to understand who scientists are, how scientists work, general characteristics of scientists, the social traditions of science, epistemological and ontological bases for science knowledge, and how science interacts with the rest of society.

As might be expected based on the wide variety of individuals concerned with NOS issues, there is no one single definition of NOS that can be applied in all situations. Some aspects of the nature of science are contested, based on differences in the philosophical underpinnings used, the field of science being studied (biology, geology, physics, etc.), and an array of other factors (Alters, 1997; Rubba & Anderson, 1978; Wandersee & Roach, 1997). Alters (1997) surveyed a sampling of philosophers of science and found that eleven different philosophical positions (comprised of varying degrees of reliance on *a priorism*, conventionalism, positivism, and realism) could be delineated within the opinions of the philosophers. Briefly, *a priorism* was described as the view that reason (separate from observation or experience) can be used to determine what constitutes truth in science; conventionalism suggests that truth does not independently exist, but is determined by the individual as they set conventions around which they will conduct their work; positivism is based on the idea that, if concepts are defined appropriately, experiment and observation can lead one to find valid ideas; and realism is based on the idea that truth exists independent of our thinking but we can never know for certain if what we have described is equivalent to reality. Alters (1997) interpreted these results to mean that new instruments are needed to characterize the NOS views of students and teachers based on the degree to which they adhere to each of these four philosophical underpinnings. However, Smith, Lederman, Bell, McComas, and Clough (1997) responded, arguing that general agreement about many aspects of the NOS does exist, and Efflin, Glennin and Reisch (1999) described that this is the case for the following NOS concepts: the main purpose of science is to acquire knowledge about the physical world, science attempts to describe an underlying order to the world, science is dynamic, changing, and tentative, and there is no one universal scientific method. Consequently, these authors contend that most of the detail of various philosophical underpinnings can be avoided both in teaching about and in characterizing students' understanding of the NOS. While they acknowledged that areas of disagreement exist, especially related to the extent to which social and historical factors impact science and whether or not there is an external reality that represents truth that scientists can describe/attain, they also asserted that discussions about these ideas are better left primarily to the philosophers of science and that NOS instruction can acknowledge these differences but should place primary emphasis on areas of broad agreement. They contend that the history of science provides a rich source of examples that can illustrate these aspects of the nature of science.

Lin and Chen (2002) describe a potential cause for these types of disagreements within the area of NOS education.

> Because the philosophy and sociology of science is a conceptually rich field and the field is represented by an evolving body of knowledge, there is disagreement both about the nature of science and about appropriate attributes for students to learn about the nature of science. (p. 774)

In fact, Abd-El-Khalick and Lederman (2000) described an evolution of ideas related to the NOS – from a focus on science processes (observation, inferences, etc.) in the 1960s to a focus on the status of scientific knowledge (e.g. tentative, public, etc.) in the 1970s, and to the addition of psychological and social factors, such as the roles of creativity and of social discourse in science, in the 1980s. Keeping in mind that these differences of perspective and of focus exist, a majority of NOS researchers seem to agree with the idea that a broad description of the ideas represented by the nature of science that are of primary concern to today's science educators can still be outlined. Such a view is presented by Lederman et al. (2002): "NOS refers to the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (p. 498). Within this broad context several areas of general agreement exist, as demonstrated by their appearance in multiple sets of international science education standards (McComas & Olson, 2000). These areas include the ideas that there is a significant human side to science; that scientists make ethical decisions; that characteristics of individual scientists, political and social pressures, and subjective decision making have influence on scientific findings; that scientific knowledge has a tentative, yet durable, nature – allowing it to simultaneously be subject to revision and/or rejection at some future point and also essential to our current ability to describe and predict scientific phenomena; and that the work of scientists requires creativity at multiple levels. Even where there are areas of disagreement, many feel that the best approach is to educate students about the perspectives that exist and the reasons for the differences rather than focusing on indoctrinating one particular view (Clough, 2006; Matthews, 1998).

Measuring and Describing Individuals' NOS Conceptions

Over the past 50 years a wide variety of instruments have been used to describe students' and teachers' conceptions concerning the nature of science. Many of these views have been shown to be in sharp disagreement with contemporary descriptions of the nature of science (Lederman, 1992; Lederman, Wade, & Bell, 1998). Similarly, research scientists have also been shown to hold inadequate NOS conceptions (Kimball, 1968). Examples of inadequate conceptions include seeing "science as a search for objective truth and [an emphasis on] empiricism to the exclusion of personal and subjective attributes and factors, such as opinion, interpretation, speculation, and human bias and values," the failure to view "creativity and imagination as integral to science," and inadequate understanding of how "politics, economics, and religion, that affect the kind of science that is done, … [are] mediated by various factors including funding for science, and gender and racial issues" (Lederman, et al., 2002, pp. 507-508). Schwab (1964) described that science is taught as an "unmitigated rhetoric of conclusions in which the current and temporal constructions of scientific knowledge are conveyed as empirical, literal, and irrevocable truths" (p. 24). In addition, McComas, Almazroa, and Clough (1998) contend that science teaching focuses on knowing the end-products of science (facts) and neglects the process of how this knowledge came into being. These types of views are problematic in that they have the potential to adversely affect public decision making on science and decrease interest in pursuing careers in science, particularly among groups that are already underrepresented in science careers (Seymour & Hewitt, 1997; Tobias, 1990).

Rationales for Teaching the Nature of Science

Shamos (1995) suggests that understanding NOS is pre-requisite to scientific literacy. Lonsbury and Ellis (2002) also describe a link between NOS ideas and science literacy, or the ability for individuals to understand, interpret, and evaluate publicly presented scientific ideas and arguments. The skills of science literacy have the potential to impact multiple aspects of our society – including the economy, government policies, medical practices, etc. McComas, et al (1998) describe that an accurate knowledge of the NOS is needed for public decision making regarding science funding, formation and evaluation of public policies about science, and legal decisions based on science matters. However, a lack of understanding of how scientific findings are politically, socially, and culturally situated can lead to a high degree of apathy in regard to public decision-making on science. Particularly, if science knowledge is seen to be objective truth, debate of this knowledge will likely be seen as meaningless. “At the foundation of many illogical decisions and unreasonable positions are misunderstandings of the character of science” (McComas, et al, 1998, p. 511). In a more positive light, Lonsbury and Ellis (2002) propose that “knowing how scientific knowledge is constructed, how it is justified, and how it changes will help individuals make informed decisions related to the validity and application of science-derived knowledge” (The Nature of Science section, ¶ 2.) Further, McComas et al. (1998) describe that accurate teaching concerning the NOS encourages a realistic understanding of both the durable nature of well-supported scientific ideas and the historically tentative character of scientific knowledge, and consequently combats the tendency some individuals have to dismiss an entire field of study if they learn that a fundamental idea has been changed or rejected. Driver, Leach, Miller, and Scott (1996) also describe that accurate NOS understandings allow people "to make sense of the science and manage the technological objects and processes they encounter, …to make sense of socio-scientific issues and participate in the decision making process, … [and] to appreciate science as a major element of contemporary culture" (pp. 16-19).

In addition, incorporating appropriate NOS content into science classes has been described as having a positive impact on students' interest in science. Tobias (1990) has described that the second tier of college students, high achieving individuals who choose not to pursue science majors, desire more of the history, sociology, and philosophy of science to be represented in the college science curriculum. These students often opt for non-science majors due to the absence of this type of material in the typical college science courses. This view is also represented in the research of Seymour and Hewitt (1997), who explored the question of why students who begin science majors either do or do not complete the major. Among all the students surveyed (including male, female, white, non-white, students who did and did not choose to complete a science major) views were found to describe that the narrowness of the science curriculum, with regard to social and philosophical views of science, was perceived as a detriment. The words of the two following students represent this view quite well.

> I think my four years would have been terrible if I only focused on science classes, because everything would have been facts, and regurgitation of facts – no real conversation, no studies of civilization or culture. (p.180)

> I came in here dead set on becoming a chemist. But there's not too much creativity at the lower levels. And that concerned me. I took some German, then some linguistics classes, and the next thing I know I'm graduating in linguistics. I came in very techie, and ended up very fuzzy. (p. 181)

Both of these students happened to be white males; however, other work has revealed that this issue is also problematic for female and non-white students.

Feminist and multi-cultural critiques of science have also focused on the importance of adequate NOS understanding. Bruning (2003), in a review of the literature, described that girls and minority students view science as being "objective, rational, masculine, and mechanistic" (p. 28). This view became part of a rationale for students to see science as not being interesting or connected to their lives. Rossiter (1982) describes the opposition between stereotypical science ("tough, rigorous, rational, impersonal, masculine, competitive, and unemotional") and stereotypical womanly activities ("soft, delicate, emotional, noncompetitive, and nurturing") (p. xv). This socially created juxtaposition can discourage the recruitment of women into science and create an unwelcoming feeling in science for women. A more accurate description of science (and of "womanly activities") could begin to make changes in these societal definitions, thus paving the way for more women to explore fields of science as career choices.

Describing feminist views about what might bring about the entry of more women into science, Harding (1991) suggests, "Scientists must acknowledge that their values and beliefs influence their scientific practices and learn to identify the effects" (p. 299). Munro (1993) offers agreement from a multicultural perspective, stating that "What would science from a multicultural perspective look like?" is an inappropriate question; instead, we should be asking “How can science not be cultural?” and “Why and how has it come to be that science is considered value neutral and not a cultural construction?” (p. 11).

Producing individuals within and outside the scientific community who understand the social, political, and cultural aspects of the NOS could go a long way toward achieving these goals. In fact, Munro (1993) proposes:

> If we acknowledge that science can only be fully understood when socially and culturally situated, then one direction that ‘multicultural’ science education could take would be to ‘historicize’ science …., [addressing questions such as] How has science shaped human social relations and consciousness? .... [and] How can different epistemological perspectives (those of women and other cultures) help to generate new ways of looking and seeing that can enrich and expand the process of inquiry that is the heart of science? (p. 13)

A final rationale for including NOS instruction in science teaching is provided by several experts on the nature of science who suggest that it enhances students’ ability to learn the typical content of science courses (Driver, et al., 1996; McComas, et al., 2000). Songer and Linn (1991) found that students with more accurate views of NOS were better able to integrate content knowledge on the topic of thermodynamics. Furthermore, Matthews (1989) acknowledged similar positive results leading to an increased understanding of science and interest in the subject.

Aspects of the Nature of Science Studied

For the purpose of this research study, the following aspects of the nature of science have been the primary focus: scientists employ creativity in multiple aspects of their work, including the interpretation of data and the construction of new scientific knowledge; ideas in science have a tentative, yet durable, nature; and science knowledge is constructed within a social context. A brief discussion of each of these concepts follows.

Lederman et al. (2002) describe that “science, contrary to common belief, is not a lifeless, entirely rational, and orderly activity. Science involves the invention of explanations and theoretical entities, which requires a great deal of creativity on the part of scientists” (p. 500). As noted above, college science students often lament the lack of creativity represented in science throughout their studies; obviously, the creative aspects of science that Lederman et al. describe must not be adequately represented in college science courses. Ryan & Aikenhead (1992) conducted a study of secondary science students in which they reported that only 17% of these students were certain of the inventive character of scientific knowledge, indicating that secondary science classes are no better at accurately describing the role of creativity in science. In developing and testing a new instrument to gauge level of NOS understanding, Lederman et al. (2002) solicited expert opinions about the creative nature of science. “Expert group participants … reflected the belief that creativity permeates the scientific process, from the inception of a research question to setting up and running an investigation to the interpretation of the obtained results” (p. 508). Relatively naïve views related to the role of creativity in science are demonstrated by the following example statement. “A scientist only uses imagination in collecting data … But there is not creativity after data collection because the scientist has to be objective” (p. 515).

Another NOS feature that is essential to this study is the tentative, yet durable, characteristic of scientific knowledge.. This aspect of the nature of science has been well-described by multiple experts in the field (Duschl, 1994; Lederman, et al, 2002; McComas, 2000). Science ideas are described as durable because they work in multiple settings to allow scientists to make accurate predictions and explanations of phenomena as well as to help guide new forms of scientific inquiry and they fit together cohesively with other ideas in science to form an inter-related network of knowledge. At the same time, these ideas are tentative due to the way in which knowledge is constructed by humans as they attempt to interpret the actions and order of the natural world – as such, these ideas are always subject to change as new information becomes available or as old information is reinterpreted in light of new ideas and/or perspectives. Efflin et al. (1999) propose that "students benefit by considering the idea that different paradigms compete with each other, and that [students] can easily understand some of the ways in which theoretical commitments and social issues can influence the development of science" (p. 114). Again, such an understanding would provide a context for science information that seemingly would be more satisfactory to those who thirst for more than just the memorization and categorization of a group of accepted scientific ideas during their education. Unfortunately, the current presentation of science material does not emphasize this aspect of science. Consequently, naïve views predominate, as exemplified by the following statements: "If you get the same result over and over and over, then you become sure that your theory is a proven law, a fact." and "Compared to philosophy and religion … science demands definitive … right and wrong answers" (Lederman et al., 2002, p. 515). To combat ideas such as these, Efflin et al. (1999) propose that

> educators should discuss the idea of empiricism more generally [including] discussion of the many and different ways that experience and the use of experiments informs scientific beliefs, and also the important fact that scientists often argue about how to understand and interpret the results of measurements and experiments. (p. 114)

Science ideas are constructed within a social context, and this context has an impact on what ideas are proposed, investigated, and accepted in science. This social context involves both the accepted ideas of the scientific community and the ideas of the overall social community (Lederman et al. 2002). Duschl (1994) reports that "the standards used to assess scientific explanations are closely linked to the then-current beliefs of the scientific community" (p. 446). Because science ideas and methods are socially developed, the views of other scientists will impact how science is done by individual scientists. In addition, science comprises a part of our larger collective society, and Driver et al. (1996) propose that NOS instruction can be useful "in order to appreciate science as a major element of contemporary culture" (p. 19). In this dynamic interaction, science both impacts and is impacted by the larger cultural setting in which it operates. Through the political process, social values are used to guide areas of scientific investigation, with public funding, or the lack thereof, playing a major role in this guidance. In addition, basic research in science can later lead to applications that alter social constructs towards ideas such as disease, warfare, and the use of technology.

The Current State: Typical Misconceptions about the Nature of Science

In a description of the views of college students about these aspects of the nature of science, Kurdziel & Libarkin (2002) found much room for improvement. They describe that students in introductory, college-level geology classes typically view science as a static body of facts; lack an appreciation of the roles of evidence, creativity, and subjectivity in scientific inquiry; fail to view science as a creative endeavor; and fail to appreciate how theories guide scientific research and influence scientists' observations & interpretations of data. They further describe that these ideas are resistant to change without explicit NOS instruction, possibly coupled with inquiry based experiences or examples from the history of science.

Although students' NOS views are clearly in need of change to more accurately reflect our contemporary understanding of the nature of science, effective instruction about the NOS does not frequently occur at any level of education. This lack of effective instruction can be accounted for by a number of factors. First, teachers' views of the NOS have been demonstrated to be as far out of line with contemporary views as are their students' views. Lederman (1992) described several deficiencies that commonly exist in teachers' NOS understanding and that have been documented repeatedly since the 1950s. Despite many attempts to improve teachers' conceptions of NOS, these findings have remained relatively unchanged. The results of these initial studies have been validated and added to by many others in the ensuing years.

One area where teachers' conceptions of the nature of science do not accurately reflect contemporary NOS views is the tentative nature of scientific information. Many teachers view scientific information as part of a relatively fixed body of knowledge that does not change (Akerson, Abd-El-Khalick & Lederman, 2000; Brickhouse, 1990; Lederman, 1992; Murcia & Schibeci, 1999). Other areas of deficiencies in teachers' conceptions of the NOS include positivist views about the objective nature of science, a lack of appreciation for the role of creativity in the development of abstract ideas, a lack of appreciation for the role of critical questioning within the processes of examining and evaluating scientific ideas , a lack of appreciation for the social and cultural context of scientific work, and a hierarchical view of the relationship between scientific hypotheses, theories, and laws (Abd-El-Khalick & BouJaoude, 1997; Akerson et al., 2000; Murcia & Schibeci, 1999). It would be desirable for teachers to explicitly model accurate NOS views of these concepts throughout their teaching and to promote the development of accurate NOS views by their students, but these studies point out that teachers frequently model or implicitly convey inaccurate views instead.

An area of consistency between several of these studies is the idea that teachers' views do not seem to be consistently "naïve" or "accurate" across the population. Even within an individual respondent some NOS topics seem to be better understood than others. Palmquist and Finley (1997) found similar results in their study of fifteen pre-service teachers. Most participants' views were categorized as mixed, indicating that they varied in their agreement with either contemporary or traditional views of the NOS depending on the idea or topic rather than having an over-riding theme to all of their views.

A further finding from the many studies of teachers' conceptions of the nature of science is that the teachers' conceptions do not seem to be linked to their academic or science background and aptitude. Carey and Stauss were among the first to point this out in their 1968 study in which they concluded that "there seems to be little, if any, relationship between an understanding of the nature of science … and the academic variables used in this study" (p. 363). These variables included high school science units, college science units separated by field of study, total college science units, grade point average by field of study, science grade point average, and overall college grade point average. Also Kimball's (1968) study has shown that there is no notable difference between scientists and science teachers, including comparisons based on year of graduation, school of graduation, and time since graduation. It can be concluded that scientists, including those involved in post-secondary education, commonly have mixed views that include some misconceptions about the nature of science. With teachers at all levels of the educational system commonly possessing inaccurate views of the NOS, it is no wonder that effective instruction to alter students' views is not widespread.

Another factor that can be used to explain why effective NOS instruction is not common is that a number of teachers express beliefs that it is not essential to teach about the nature of science (Clough, 2006; McComas, et al., 1998). Many of these instructors believe that students will learn about the nature of science simply by learning science content. Clough (2006), however, describes that while it is true that students do learn lessons about the nature of science regardless of whether or not it is explicitly addressed during instruction, most of the lessons that students learn in this manner lead to misconceptions about the NOS.

> Teachers' language (Dibbs 1982; Benson 1984; Lederman 1986b; Zeidler & Lederman 1989), cookbook laboratory activities, textbooks that report the end products of science without addressing how the knowledge was developed, misuse of important words having special meaning in a science setting, and traditional assessment strategies are just some of the ways students develop conceptions about the NOS. Ever present in science content and science teaching are implicit and explicit messages regarding the NOS. The issue is not whether science teachers will teach about the NOS, only what image will be conveyed to students. (Clough, 2006, p. 464)

Especially for post-secondary students who have encountered these types of implicit messages about the nature of science throughout numerous science lessons during their primary and secondary education, deep-rooted ideas about the nature of science that do not conform to the desired understanding are likely to be present.

Barriers to Effective NOS Instruction

Even when teachers possess an accurate understanding of the nature of science and are convinced that it is valuable to address the NOS through their teaching, time and institutional constraints – related to pressure that teachers often feel to cover a large quantity of science content specified in the course curriculum – and a lack of resources can prevent these teachers from engaging in significant work to address their students' NOS conceptions (Allchin, 1990; Brickhouse & Bodner, 1992; Solomon, et al., 1992). In response to material presented at The First International Conference on the History and Philosophy of Science in Science Teaching, a group of teachers wrote a summary of their views that included the following statements.

> As our goals as science teachers widen, there will be a growing need for supplementary resources to use in the classroom. At the most specific level for example, we will find use for: collections of excerpts from original documents with appropriate commentary (e.g. Brush, 1987; Matthews, 1989; Bakker & Clark, 1988); … guides to historically based experiments (e.g. Conant, 1948); and material for recreating debates in the classroom (e.g. Solomon, P1; Lockhead & Dufresne, P1). Historians and philosophers can contribute, perhaps in collaboration with teachers, by selecting appropriate episodes or topics and organizing the essential information. (Allchin, 1990, p. 168)

While the inclusion of NOS goals in science standards documents at the K-12 level (AAAS, 1993; NRC, 1996) has helped to spur the development of some new curricular materials to address the NOS, less attention has been paid to developing materials for post-secondary science courses. Kurdziel and Libarkin (2002) have described that many college faculty do not know how to address NOS in their instruction and what materials to use. Without resources to teach about the NOS, it is likely thay many college faculty rely on the assumption that simply learning science content will instill accurate NOS conceptions in their students; however, as previously described this method is largely ineffective. Consequently, a further look at what is wrong with relying on implicit messages about the NOS and a description of what types of instructional strategies are most likely to meet with success is needed.

Requirements for Effective NOS Instruction

While a wide variety of specific activities and lessons can be used to accurately convey NOS concepts, some common features of the most successful strategies have been described by various researchers. General features that are more likely to lead to success at altering students' NOS conceptions involve using an explicit (rather than implicit) approach, engaging students in reflection about specific NOS concepts, and using lesson formats that present NOS concepts in both decontextualized and contextualized settings. Each of these ideas will be discussed in more detail below.

Reflective Strategies

Shapiro (1996) conducted a study of pre-service elementary teachers where pairs of students were asked to design and conduct an experiment to investigate a question of their own choice as part of their elementary science methods course. During this assignment, students maintained a journal – recording the work they put into developing a question to study, how they selected methods to address the question, and their findings. The method of data collection involved the use of a repertory grid. Students used the grid structure to record their ideas about various elements involved in the assignment. Students were administered the repertory grid both before and after the assignment and changes in their constructs on each element were noted. Significant changes in student constructs were followed up with interviews to further describe what caused these changes. The interview aspect of the study required students to reflect on their own changes in personal constructs within the repertory grid. Another aspect of the study discussed during the interviews involved a definition of science written by the students on the first day of the class and a review of this statement conducted by the students following the assignment.

Results from this study showed a shift toward views that are more consistent with the contemporary understanding of the nature of science. Shapiro (1996) concluded that this type of activity can increase students understanding of the nature of science in two ways. The fact that students were involved in authentic investigations allowed them to make observations about how science worked. This alone was not enough, however. Deep reflection on the students' changing ideas was a second essential feature, both in terms of making these changes notable to the researcher and also in terms of making these changes notable to the students. Reflection was encouraged in this study through the use of student journals during the process, through the use of the repertory grid to record changes that the students might not have otherwise noticed, and finally through the use of interviews to focus attention on these changes and discuss how involvement in the experience caused these changes to take place for the student.

Khishfe and Abd-El-Khalick (2002) also found, in their study involving sixth grade students, that requiring students to reflect on their NOS understanding while they were engaged in activities designed to accurately convey the nature of science was effective at helping students to adopt more accurate NOS views. In this case students were engaged in open-ended scientific inquiry activities, followed by post-activity discussions that explicitly attended students to relevant NOS concepts and required students to reflect on these concepts in relation to their own experiences during the activities. Clough (2006) summarizes the idea of reflective instruction as using “pedagogical approaches that help students make connections between the activities they are experiencing and targeted NOS issues” and suggests examples such as “raising questions and creating situations that compel students to consider NOS issues inherent in laboratory activities, readings, and other science education experiences” (p. 466).

Implicit vs. Explicit Strategies

Shapiro’s (1996) conclusions also can be used to describe a philosophical division that exists on nature of science instruction. Some researchers have conducted experiments with the assumption that NOS ideas can be absorbed implicitly if the participants are placed in a situation where NOS ideas should be useful either to discussion about science or to investigations in science. Other researchers have worked under the premise that, to facilitate changes in NOS conceptions, the appropriate aspects of NOS must be explicitly pointed out to participants during these discussions and investigations. Both of these ideas have been tested during attempts to improve teachers' conceptions about NOS, and the majority of research indicates that explicit attempts are more successful than are implicit attempts (Abd-El-Khalick & Lederman, 2000).

The following ideas have been used to further distinguish implicit vs. explicit attempts to improve teachers' conception of NOS (Abd-El-Khalick & Lederman, 2000). Implicit attempts involve little or no attending of the students to NOS ideas. Instead, an emphasis is placed on presenting information or a situation where the nature of science is correctly utilized with the assumption that the students will pick up on this correct interpretation of the nature of science and incorporate it into their own understanding. Explicit attempts specifically attend students to how the nature of science is portrayed in a particular setting, and usually ask students to reflect on this portrayal of NOS. The Shapiro (1996) study can be used as an example of both implicit and explicit attempts to portray the nature of science. Students were asked to journal their own thoughts on their scientific investigation during the process; this exemplifies an implicit approach in which any increases in NOS understanding that occurred through journaling would have required students to transfer ideas about how their investigation was proceeding into an understanding of NOS on their own. The repertory grids and reflective interviews were used together to create an explicit attempt at improvement in NOS understanding; here students were required to reflect on the changes in their thinking and articulate how participating in a scientific investigation caused them to think differently about several aspects of the nature of science.

While the degree of merit for implicit instruction is still open to some debate, it has generally been agreed upon that explicit instruction in NOS can produce statistically significant gains. Abd-El-Khalick and Lederman's (2000) review of several studies that have been conducted is helpful in illuminating this idea. Nine separate studies that utilized a primarily explicit approach for NOS instruction were reviewed. The reviewers found that in all of the studies that presented sufficient numerical data to make a quantitative measure of the participants gains (eight of the nine studies), statistically significant gains were shown. These gains ranged from a 3% to 11% increase in understanding as measured by instruments such as the Test on Understanding Science (TOUS) and the Nature of Science Test (NOST). The ninth study was Shapiro's (1996) study that has already been described and that was qualitative in nature rather than quantitative, but that also showed gains in understanding of NOS.

Abd-El-Khalick and Lederman (2000) have pointed out that even though these explicit attempts to improve teachers' conceptions of the NOS showed statistically significant gains, the practical significance of the gains must be called into question. Because relatively small percent changes were noted (3% to 11% increase), it seems that more work is needed to make a large enough impact on teachers' conceptions to bring their overall view of NOS in line with the currently accepted views. According to their review of a number of studies, while explicit attempts are more successful than implicit attempts even the explicit attempts leave room for improvement.

Contextualized vs. Decontextualized Strategies

One possible reason for the statistically small gains that have been measured, even when explicit instruction has been used, has been presented by Clough and Olson (2001). In their study of attempts to improve teachers' conceptions of the NOS, the researchers focused on the difference between contextualized and decontextualized explicit approaches. Contextualized explicit approaches draw "students' attention to important NOS issues entangled in science content and its development", while decontextualized explicit methods isolate and emphasize "fundamental NOS issues in familiar concrete ways that are not complicated by science content" (Clough, 2006, pp. 473-474). Clough and Olson (2001) suggest that contextualized NOS teaching strategies may be more effective both at teaching NOS ideas and at convincing teachers that they can and should implement these ideas into their own teaching. Shapiro's (1996) study can be seen as an example of the use of contextualized explicit methods of teaching about the nature of science. In this study, the main focus was on the design and implementation of an authentic scientific investigation. Consequently, the students were primarily focused on science content, even though they were not pursuing this content in a science course. At least two studies designed to improve science teachers' NOS understanding (Akerson et al., 2000; and Brickhouse, 1990) have proposed that nature of science ideas should be included in the college level science courses required for pre-service teachers. Such a setting would more easily facilitate the use of contextualized explicit study of NOS since science content is already being emphasized in these courses. One notable comment about this idea comes from Akerson et al. (2000).

> We believe that developing science teachers' views of NOS would be achieved best in the context of science content courses. An explicit, reflective approach to NOS instruction embedded in the context of learning science content would not only facilitate developing science teachers' NOS views, but might go a long way in helping teachers translate their NOS understandings into actual classroom practices. (p. 297)

History of Science Materials

Implementing explicit, reflective strategies that are highly contextualized due to their reliance on key content of introductory science courses could help a wide array of students (future scientists, future teachers, and future citizens who will not necessarily be involved in science or teaching) to achieve more accurate conceptions about the nature of science. Stories from the history of science are particularly well suited to provide the type of material that could be useful in the context of introductory science courses to teach about the nature of science.

History of science materials provide a rich array of sources for addressing key NOS concepts. Duschl (1994) has described that George Sarton – a key founder of the discipline of the history of science in the U.S. – developed "a set of guidelines for doing history of science that sought to characterize and understand the choices scientists made in the pursuit of scientific explanations and the conditions, social-political or otherwise, under which the choices were made" (p. 445). Because of this guideline, most of the materials produced by historians of science emphasize many of the social aspects of science, the epistemology of science, and the status of scientific knowledge. The ways in which historians of science emphasize epistemological concepts are revealed through the following words of Duschl (1994).

> Over time, what the collective critical histories and sociologies of science discovered was that the growth of scientific knowledge was not an activity that grew without disruption, upheaval or alteration to central ideas. Close scrutiny of historical events in science indicated that science was better characterized as a discipline in which dynamic change and alteration were the rule rather than the exception. The view of science as an inductively logical process – a process of moving from empirical fact to the development of scientific theory – was not supported by these historical studies either. (p. 445)

Because of these characteristics of historical works, many researchers have described reasons why history of science materials can be useful in conveying key NOS concepts.

Ways in which History of Science Materials Accurately Convey the NOS

Leite (2002) has described how history of science materials have been used to stimulate interest in science and humanize the study of science. Parallels between the intellectual development of the individual and the historical development of science – progressing through phases of wonder, utility, and systematizing motives – can be illustrated through the use of history of science materials. The first two of these stages are often only demonstrated in the history of science, while much of science focuses on the third. History of science materials have also been used to demonstrate human activities in science, that science is a living, collective enterprise whose past exerts influence on the present, and perceptions of how science influences and is influenced by our way of life – that science is both internally and externally influenced. Leite (2002) also contends that it can help with appreciation of science concepts themselves and can help reveal students' misconceptions about science that are similar to earlier views from science. These misconceptions, if revealed both to students and teachers, can allow students to recognize the faults of these views and teachers to anticipate potential resistance to adopting more accurate views.

Clough (2006) contends that the use of history of science materials allows for the production of highly contextualized NOS lessons that

> illustrate the complexities and challenges individual scientists and the scientific community experience in constructing ideas and determining their fit with empirical evidence. In addition to enhancing understanding of science content, these examples exemplify important epistemological and ontological lessons that are bound up in that content and central to understanding the NOS, and place the science content in a human context. (p. 474)

Martin and Brouwer (1991) voiced a similar idea: “the kernel of many of the ideas about the epistemology of science can be communicated – at least tacitly – through story and anecdote” (p. 713). Clough (2006) also describes that history of science materials help to avoid the problems commonly encountered when using decontextualized activities alone, when students are more likely to dismiss the activity as misrepresenting how science really works because it as seen as not related to science or as different from how real scientists work.

Finally, Seymour and Hewitt (1997) have described that students who chose to quit majors in science, mathematics, and engineering describe their loss of interest partly based on the narrowness of the educational experience, particularly related to areas that are essential to the nature of science such as the creative and social aspects of the ways in which science knowledge is constructed. Clough and Olson (2004) describe that “integrating scientists’ personal thoughts humanizes science and science education because it presents scientists as real people – with motives, prejudices, humor and doubts – a view not always shared by students” (p. 31). Based on this description, it would seem that history of science materials would be very useful at combating the loss of interest in science. In fact, Stinner et al. (2003) suggested that history can serve as motivation and interest for students to learn more about science, to illustrate areas of disagreement in science – thus demonstrating the dynamic nature of scientific knowledge, and to illustrate interdisciplinary concepts that transcend the bounds of individual fields of science.

Cautions Concerning the Use of HOS Materials

Several researchers have also described cautions to be considered when using history of science materials in science courses. Leite (2002) cautions against portraying history in such a way that distorts it as “glorious successful progress from ignorance to truth” or that reduces history to biographies consisting of names and dates (p. 333). In many ways, current portrayals of the history of science in science textbooks are inadequate. Leite (2002) describes many of these inadequacies. Typical textbook presentations include biographies and mention of key advances, but they do not support the goal of illustrating NOS concepts such as "the dynamic nature of science, the role of the human mind in the creation of theories, the co-operation between scientists and the influence of the contexts [in which science is done]" (p. 355). Further description of how textbooks often misrepresent the nature of science is provided by the following statements.

> The way science discoveries are often presented and the way most scientists are characterized may lead to the idea that science is just hidden somewhere, waiting for a genius to find it out in a moment of insight …It does not show how science depends on the construction of new concepts and technological devices, on thought and hard work, as well as on external factors like culture, religion, politics, economics, etc. Thus it can give a false idea of independence of science from the rest of the world. (p. 355)

Similar ideas are also presented by Tao (2003) who reported a preponderance of textbook stories that describe how "heroes of science single-handedly made discoveries and inventions through diligence, perseverance, and ingenuity without depicting the ideas that developed and evolved in the process" (p. 148). Clough (2006) has also described that textbooks, along with many other common sources for instructional materials, often inaccurately portray the NOS. These images become increasingly troubling when viewed in light of the words of Kuhn (1970), who has asserted that "more than any other single aspect of science, [the textbook] has determined our image of the nature of science and of the role of discovery and invention in its advance" (p. 143). Even in cases where accurate portrayals of the NOS are included, textbook history of science presentations are usually non-compulsory, often being relegated to a separate essay that readers can easily skip over and that lack related learning activities/exercises. The result is that the format in which history of science materials are presented by textbooks promotes student indifference (Leite, 2002).

Leite (2002) also describes that when developing more appropriate history of science materials, one must balance between including enough and too much information; because these materials are designed for use in science classes, they should not take focus and time away from study of science. Matthews (1998) has suggested that "it is unreasonable to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science" (p. 168). The emphasis must be placed on materials that relate to relevant science content and that illustrate key components of the nature of science, but not on an expectation of expertise for the various philosophical vantage points from which science can be viewed. In addition, the materials must balance the competing goals of instilling an appreciation for the stability/utility of science knowledge and an appreciation for ways in which science knowledge changes (Leite, 2002). Students should be able to draw from the materials to see how each of these attributes of science is illustrated.

Solomon et al. (1992) and Tao (2003) each made attempts to use history of science materials in 7th grade science classes to illustrate aspects of the nature of science. These researchers reported some further cautions that future researchers should be aware of. Solomon et al. (1992) found that it was common for students to express a "dismissive attitude toward early, superseded theories" that was "often supported by references to our superior instruments [technology]" (p.416). These students had "difficulty empathizing with the thinking of scientists whose theories they knew to have been superseded" (p. 417). In these instances, even when history of science materials illustrate aspects of how scientists work and how scientific knowledge undergoes change, students may dismiss the lessons as not being relevant to today's science based on a view that current science is much more advanced.

Tao (2003) also described that students use their prior understanding to filter the information presented in the stories, an idea that is consistent with constructivist learning theory. "Prior to instruction, students possessed certain inadequate views of NOS. They brought these views to bear upon the science stories and focused their attention on aspects of the stories that matched these views" (p. 169). These results present another way in which students' views of the NOS may not be affected in the ways in which researchers and curriculum developers might expect. Much in the same way that scientists' can interpret data differently based on their background, theoretical lens, and prior knowledge, so students can interpret history of science materials differently. In some cases, Tao (2003) found that students used their interpretation of history of science materials to bolster their pre-existing misconceptions about the nature of science. These misconceptions often involved the use and meaning of specific vocabulary from science; Clough and Olson (2004) have suggested that "words such as law, theory, prove, and true should be used carefully and students should be made aware of the importance of these words' meanings" when teaching about science and the nature of science (p. 29). These findings and descriptions together present the realistic view that history of science materials do not present a magic bullet that will automatically help students form accurate conceptions about the nature of science, but they do provide fertile ground for teachers to use as they actively address nature of science issues with their students.

Past Attempts to Use HOS Materials to Improve NOS Understanding

Multiple attempts have been made to improve students' NOS understanding by using history and philosophy of science materials to more accurately demonstrate the nature of science, and several of these studies will be described in more detail here. In the 1950's James Bryan Conant developed the Harvard Case Histories in Experimental Science and in the 1960's Klopfer and Cooley introduced the History of Science Cases (Conant, 1957; Klopfer & Cooley, 1963). Both of these sources relied on links between the history of science and key NOS concepts; however, both are now out of print and are not readily available to teachers. Solomon et al. (1992) developed short accounts of history of science for use with seventh grade students. The stories were accompanied by activities designed to encourage students to examine the text and extract desired information about the nature of science. Solomon et al. (1992) found that HOS materials were effective at moving students "away from serendipitous empiricism and toward an appreciation of the interactive nature of experiment and theory" and that "helping the pupils to focus on the reasons for accepting one theory rather than another was more effective than just teaching accepted theory" (p 418-419). The degree of effectiveness reported was based on the durability of students' learning of the accepted scientific idea, determined by year end interviews and responses to questions asking the students to recall a scientific theory. Consequently, this study has been used to demonstrate that students' understanding of science content and NOS concepts can simultaneously be aided through the use of short historical narratives about key developments in science. Solomon et al. (1992) also found that "studying the history of a change in a theory may make the process of conceptual change a little easier" (p.419). The authors reported that the students found it encouraging to know that even scientists struggled with changing their ideas, especially at times when the students were being asked to change their own ideas about science content.

Roach and Wandersee (1995) developed short stories that interwove history and fiction to illustrate and emphasize attributes of the NOS. They chose to use the format of short stories because they believed that stories provide meaningful ways for students to connect new ideas into their conceptual framework, thus facilitating conceptual change. These stories, referred to as interactive historical vignettes (IHV), are designed to be read aloud by teachers to their students and have questions interspersed, that are intended to engage the students in the story and require the students to actively consider the science and NOS concepts involved. Wandersee (1985) also contends that this type of approach can help science teachers become familiar with and anticipate students' misconceptions about science. Further, he describes that students may become aware of their own misconceptions because "the misconceptions of the past can be found in the conceptual frameworks of today's students" (p. 594). However, other researchers view this as unlikely. Solomon et al. (1992) describes that "the scientific thinking of ancient philosophers and that of untutored children have very little in common" (p. 410).

Lin and Chen (2003) worked with pre-service teachers to demonstrate ways in which chemical concepts can be taught by using history of science materials. They found that the teachers who participated in this study had enhanced understanding of the NOS, particularly related to creativity, the theory-based nature of scientific observations, and the function of theories. In addition, these teachers were able to explain their understanding of the NOS by using examples from historical cases.

Finally, Tao (2003), used stories in an attempt to implicitly convey accurate NOS conceptions related to the intentions of scientific investigation and experimentation, the need for creativity in scientific work, and the knowledge status of scientific theories, etc. The use of implicit strategies has already been described as potentially problematic, and through interviews with students after they interacted with the stories, "it soon became apparent that after students had read the stories, they only picked up one or two aspects or features of the stories in their discussion" (Tao, 2003, p. 158). This can be interpreted as further evidence for the importance of employing strategies that explicitly attend students to how historical stories convey the nature of science and how these portrayals contrast with common misconceptions about the NOS.

Implications for Teacher Implementation

Based on many of the findings reported here, it can be interpreted that the ways in which NOS curriculum is implemented by teachers is as important as the curriculum itself. As described previously, implicit means alone are not effective at conveying an accurate understanding of the nature of science (Abd-El-Khalick & Lederman, 2000; Clough, 2006). A variety of different explicit and reflective strategies based on history of science materials have been shown to be effective at altering students ideas to more accurately reflect the NOS (Klopfer & Cooley, 1963; Lin & Chen, 2002; Lonsbury & Ellis, 2002; Solomon, et al., 1992). In a description of the Project Physics Course developed by Gerald Holton of Harvard University, Matthews (1989) describes that fifteen percent of US students taking physics courses in the 1970's were exposed to this curriculum and as a result learned that scientists use a diverse range of approaches to solving problems rather than always adhering to what is commonly described as a step-wise universal scientific method. In addition, these students' knowledge of physics was equal to that of those who studied under other curricular packages. Matthews (1989) also states that reviews of the Project Physics Course indicate that the teacher's role is critical to the effectiveness of the curriculum, as evidenced by the fact that only about five percent of the variance in student achievement could be linked to differences in curriculum but the majority of variance appeared to be a factor of differences in teachers.

An examination of four studies (Lin & Chen, 2002; Lonsbury & Ellis, 2002; Solomon, et al., 1992; Tao, 2003) in light of teacher implementation strategies may be useful to illuminate common features that are related to greater success in altering students' views to more accurately reflect the nature of science. While thorough discussion of all the teacher implementation strategies used in these four studies is not always provided in the literature, the description that is provided appears ample to determine that three of the studies (Lin & Chen, 2002; Lonsbury & Ellis, 2002; Solomon, et al., 1992) relied on significant explicit attempts to illustrate the nature of science through HOS materials, while Tao (2003) relied on more implicit strategies. Since implicit strategies have already been described as less useful, the emphasis here will be on the three explicit strategies used, but some useful information can still be gained by contrasting the Tao (2003) study with the other three.

Solomon et al. (1992), Lonsbury and Ellis (2002), and Tao (2003) all worked with middle or secondary students enrolled in science classes, while Lin and Chen (2002) worked with pre-service chemistry teachers nearing the end of their undergraduate program. All four studies asked students to read texts that relayed information from the history of science related to key science content that was part of the required curriculum. The subjects in the Lin and Chen (2002) study were enrolled in a chemistry teaching methods class and had previously completed significant college-level chemistry coursework, so although the chemistry content involved in the stories was not directly a part of the curriculum of their methods course it related to their prior coursework and to projects in the methods class that required them to develop teaching units and lesson plans for chemistry classes. In this sense, all four studies were attempting to simultaneously teach required science content and also teach NOS concepts through the use of HOS materials.

All four studies also built in additional activities that required the students to actively engage with the materials. Lin & Chen (2002), who used researcher edited materials that emphasized how scientific understanding develops and that presented scientists' original debates, discussions, and experiments, required students to engage in group discussions and debates, observe demonstrations, and participate in project assignments and hands-on experiments to simulate scientists' work. Small group cooperative learning activities were utilized for some assignments and simulations. A major assignment required students to use HOS materials in the design and development of a case study that they would be able to use as future teachers.

Lonsbury & Ellis (2002) used lectures, small group work, and discussions to address the HOS related to genetics – a required topic of study for their subjects, who were enrolled in a high school biology course. Activities included asking students to evaluate some specific historical views of genetics and to describe how a specific set of views would affect the ways in which scientists viewed the natural world, and discussions of factors related to how and when paradigm shifts take place. The researchers also describe use of an activity intended to show how scientists work together to develop ideas and add to their current understanding, and how paradigms guide lines of inquiry, types of questions formulated, and ways in which data is interpreted.

Solomon, et al., (1992) used researcher developed resources to emphasize areas of NOS where the perceived need was the greatest and that related to science content already in the curriculum (seventh grade science in the UK). An example of these resources is a sequence of eight short lessons to “show how the telescope was discovered and then used by Galileo.” These lessons involved descriptions of pre-Galilean development of the use of lenses and described historically accurate social contexts, such as the recommended use of the telescope for military purposes (p. 411). Descriptions of how the use of the telescope altered scientists’ views about the landscape of the moon were also included. During the study, the students read the stories, and different groups made posters to describe the content of sections of the story. Students also engaged in making models of the moon and using lights to illuminate it from different angles to view and make measurements about the effect of viewing shadows cast by mountains that would be visible through a telescope. Other units involved similar readings and active learning activities (including sequencing a set of statements, performing an activity, or engaging in a role play) designed to require students to actively engage with the reading and extract relevant information about science and the NOS.

Common to all three of these studies is a heavy reliance on the teacher to intercede in the activities. For Lin and Chen (2002), the teachers of the science methods course led class discussions, presented demonstrations, and introduced portions of the history of science materials in class. Similarly for Lonsbury and Ellis (2002), the teacher (who was also the primary researcher) presented lectures, led classroom discussions, and expressed concern in the report that he “may have put too much emphasis on the idea of paradigm shifts”

(Discussion section, ¶ 4) – all of which indicate a significant role for the teacher as a guide to the students as they engage with HOS materials. In the Solomon et al. (1992) study the researchers indicate awareness of the important effect that teachers' views of the NOS have on students' perceptions and the teachers were included as co-researchers. Although specific teacher-student interactions during the instruction are not described, it is noted that a portion of the study was considered to be action research, where the primary researchers worked with teachers to recognize and bring about good practice. Due to the relatively intense integration of the HOS materials into other classroom activities and this description of action research, it is assumed that the teachers did actively engage in drawing students' attention to key aspects of the NOS and helping them to accurately interpret this information.

By contrast, in the Tao (2003) study, although the teacher was described as "keen to teach the NOS," it is also noted that "the teacher purposely did not actively teach or draw students' attention to the various aspects of NOS in the stories; students were left to find out about the themes of the stories for themselves in their collaborative engagements" (pp. 155-156). In this case, it appears that the approach taken was to allow the materials to speak for themselves, in the hopes that students would draw accurate conclusions about the NOS from them – a strategy that is consistent with implicit methods for teaching the nature of science. It must be described that this study was not designed to measure the effectiveness of the curriculum at altering students' ideas, but instead to elicit students' NOS understanding and investigate how students react to the stories. However, pre/post-test measures were made as well as a qualitative analysis of student discussions, and these results showed that students often interpreted the content of the stories in ways different from how it was intended and sometimes used the stories to either reinforce inaccurate NOS conceptions or to shift from one inaccurate conception to another. While in a few instances students did appear to shift toward more accurate NOS views, the most common result was the reinforcing of inaccurate views.

Clearly, requiring students to read and reflect on HOS materials alone is not sufficient, but methods employed by other researchers to help attend students to NOS concepts and accurately interpret these concepts have been more effective. Not surprisingly, active learning strategies appear to be important parts of the most effective ways in which students can engage with NOS materials, and methods that require students to internalize and apply their knowledge may comprise some of the best methods. Lonsbury and Ellis (2002) describe having students reflect on previous paradigms, explain how they influenced scientists' views, and even why different views can flounder for years before a paradigm shift occurs. Solomon et al. (1992) required students to interpret and present key ideas using posters and reflect on the ideas through building models and making calculations. Lin and Chen (2002) report that in the context of asking the students (pre-service teachers) to design instructional units using HOS materials, the researchers emphasized the need to "describe the important part of the history related to the concepts they planned to teach, and more important, to integrate discussion, role-playing, demonstrations, or hands-on activities in designing their own historical teaching methods" (p. 779). This task was especially challenging for students, but significant text-based resources were provided and suggestions and extra help from teachers were frequently required. The researchers report that "when the preservice chemistry teachers in this study finally did the generative work of designing a historical teaching material, they began to internalize the lessons they learned from chemistry courses, historical case, and teaching methods class" (p. 785). Evidently, the more that students actively engage in not only reading HOS of science materials, but also interpreting the materials, using them to answer other questions related to science or describe science content, and applying them to the context of how scientists work and how science knowledge is constructed – all under the active direction of teachers – the more likely they are to adopt accurate NOS views.

The types of learning described in these four studies can also be examined in light of learning theory concerning conceptual change. Clough (2006) describes that HOS materials should be used to illustrate NOS concepts in light of the body of knowledge related to conceptual change framework, as described by researchers such as Strike and Posner (1992) and Appleton (1997). Appleton describes that students can exit instruction intended to result in conceptual change in three ways: interpreting new ideas as fitting with their current conceptions, interpreting new ideas as approximately fitting their current ideas, or interpreting new ideas as an incomplete fit that presents cognitive conflict. The first two of these generally result in no conceptual change and sometimes in reinforcement of the student's current conceptions – outcomes that appear to be consistent with the description of the majority of participants in Tao's (2003) study. The third can result in conceptual change if the student engages with the conflict and tries to fit new ideas, represented by an alternative explanatory framework, into their mental constructs. The types of activities employed by Solomon et al. (1992), Lin and Chen (2002), and Lonsbury and Ellis (2002) can be seen as efforts to engage students in conceptual change via ongoing teacher-monitored strategies.

Assessing the Effectiveness of HOS Materials

When using HOS materials to address NOS concepts, it is also important to consider how to measure the effectiveness of the materials. Since the intent of the materials is to alter students perception of the nature of science, a focus on quantifying and /or describing the students' NOS understanding is necessary. While numerous instruments have been developed to measure NOS understanding, a majority of these are standardized instruments that employ forced choice and/or Likert-based design, a method that has been characterized as often inaccurately describing students' views. These problems were summarized by Lederman et al. (2002) based on the ideas that respondents do not necessarily understand and interpret the questions and the potential responses from which they must select in the same way as the writer's of the instrument and that forced choice instruments, to some degree, end up imposing the views of the instrument's developers on the participants rather than giving the participants an opportunity to express their own views. For these reasons, Lederman et al. (2002) suggest that using open-ended types of questions in either a written or interview format would be more likely to result in accurate characterization of respondents' views. These researchers further contend that open-ended questions get at students' own thinking about NOS and their reasoning behind this thinking, generate data that can be used to discriminate between naïve and more informed views about NOS, and allow for assessment of changes in views due to the use of novel instructional strategies. Aikenhead and Ryan (1992) also describe that paragraph type responses provide less ambiguity to what the students actually think than do Likert-type responses; however some ambiguity will still remain due to the possibility of incomplete or inarticulate writing being submitted by participants.

Both of these research groups have developed instruments that can be used as a source for open-ended questions for NOS assessment. Lederman, et al, 2002 developed the Views of Nature of Science Questionnaire (VNOS) and Aikenhead & Ryan (1992) developed the Views on Science, Technology, and Science (VOSTS) instrument. Although in its final form, the VOSTS instrument is a forced-choice instrument, during the development phase each question was presented in an open-ended format to ascertain how students would interpret the question and to construct a list of choices that accurately represented the variety of views present in the student population. The questions from the VOSTS can either be administered using the forced-choice format, or they are also still quite suitable to administration as open-ended questions.

CHAPTER 3: METHODS OF THE STUDY

Overview

Over the past several years, students' misconceptions regarding the nature of science have been well documented (Lederman, 1992; Kurdziel & Libarkin, 2002; Ryan & Aikenhead, 1992). Although efforts to address these misconceptions have been made at the primary and secondary levels, consistent messages about the nature of science are also needed at the post-secondary level. Kurdziel and Libarkin (2002) have described that "as administrators at universities and colleges attempt to implement reform efforts [to improve students' conceptions of the nature of science], science faculty are faced with the huge task of transforming the rhetoric of reform into classroom practice" (p. 322). A significant limitation on reform efforts is caused by a shortage of resources that simultaneously allow college faculty to address the required science content and NOS concepts. Without these types of resources, college instructors may be tempted to sacrifice NOS instruction to focus only on the large body of required science content. In addition, as has been previously described, efforts to address NOS concepts that draw on contexts from science tend to be more effective than the use of decontextualized efforts alone (Clough, 2006; Clough & Olson, 2001). Students need to be able to see strong illustrations of how the nature of science is reflected in the scientific ideas they are studying and is portrayed through the work of real-life scientists.

This study comprises one portion of a larger study funded by the National Science Foundation and intended to explicitly teach NOS concepts and fundamental science ideas through history of science materials (Clough et al., 2006). A research team comprised of faculty members from science education, history of science, and geology, as well as graduate students from science education and history of science worked to simultaneously develop curricular materials related to the study. This work comprised: 1) researching and writing short stories (4-6 pages in length) that exemplify the nature of science by providing historically accurate descriptions of scientific work in the fields of continental drift/plate tectonics and deep time/age of the Earth; 2) writing statements and questions that became embedded into the short stories and were designed to draw students' attention to geology and NOS concepts – particularly key elements of plate tectonic theory, evidence used by geologists to determine the age of the Earth, the variety of processes involved in the construction of scientific knowledge, the ways in which data must be interpreted by scientists, the tentative, yet durable, nature of science knowledge, and the effects that prior experience, culture, and society have on science, scientists and the process of constructing scientific knowledge (subjectivity); and 3) researching and writing assessment (quiz) questions that are aligned with relevant science content understanding and nature of science understanding promoted in the short stories. This study examined the effect of using these short stories in an introductory geology course, and as such this researcher's focus involved the researching and writing of assessment questions (item 3 above), coordinating the implementation of the short stories, conducting assessments of student learning using the materials described (collecting student responses to questions embedded within the short stories and to the quiz questions), and analyzing the findings from the assessments.

Research Questions

This study was designed to answer three research questions.

1. How are geology students' views of NOS affected by the use of history of science materials in an introductory-level course?
2. How are geology students' understanding of plate tectonics and deep time affected by the use of history of science materials in an introductory-level science course?
3. What NOS misconceptions appear to interfere with learning as students interact with the history of science materials?

Development of HOS Materials Used in the Study

HOS Short Story Development and Content

The development and intended use of the HOS materials was informed by a review of the literature related to the usage of historical materials for science teaching. Heilbron (2002) has suggested that a useful way to incorporate HOS materials into science classes would be to design case studies that can easily be inserted into courses where the scientific ideas are discussed. In so doing, he suggested that the case studies should be written in a modular format, so that they can be presented in whole or in part, and they need to convey useful scientific information that goes beyond what the students would otherwise encounter and that strengthens the students' understanding of the key principles presented in textbooks. To accurately portray NOS concepts within the context of learning about science, he states: "Whenever possible the case studies should carry epistemological or methodological lessons and dangle ties to humanistic subject matter. But never should the primary purpose of the cases be the teaching of history" (p. 330). Finally, he suggests that these case studies should be written by teams of historians, philosophers, scientists, and teachers.

In light of these suggestions, the stories were written and edited by a collaborative group of science educators, historians of science, and geologists and were focused on two key areas of geology – plate tectonics and deep time. The rationale for focusing on these two concepts is threefold. First, these concepts represent foundational ideas in our modern understanding of geology, with multiple other ideas being related to and understood only in relation to plate tectonics and/or deep time. King (2000) describes that "plate tectonics is now a cornerstone of our understanding of the Earth, from local to global range" (p. 60) and Trend (2001) describes that an understanding of deep time is essential to understanding of multiple other concepts in geology (i.e. mass extinction, glaciation, continental fragmentation). Second, the geology instructor suggested that students often have difficulty developing a sufficiently detailed understanding of these two concepts and that additional resources related to these topics would be useful. Third, a review of the literature reveals that misconceptions about these two areas are quite common. Philips (1991) constructed a list of common geology misconceptions, including the idea that the continents do not move. Barrow and Haskins (1996) conducted a study to describe college students' understanding about earthquakes at the beginning of an introductory geology course. Based on the response of the students in their study (n=186), 41.8% of students reported that they did not know whether or not earthquakes were caused by the movement of plates and 4.7% said that this was not the cause. When asked why earthquakes and volcanoes are studied together, only 9% of students referred to plates in their answers; an additional 10% referred more vaguely to "surface and subsurface movement" (p. 145). The remaining 81% of students relied on misconceptions to describe the relationship. The most common responses were that the two both involved underground pressure (31%) and that earthquakes cause volcanoes (17%). Barrow and Haskins (1996) concluded that “overall, students lacked a broad understanding about the theory of plate tectonics” (p. 145).

King (2000) administered a questionnaire about the composition of the Earth to 61 science teachers at an Earth science workshop. From the results, it was noted that misconceptions about the state of matter (liquid, solid, or mixed) present in the mantle and core were very common. The researcher also described that these ideas are misrepresented in some high school textbooks and UK national exams. These types of misunderstandings are important because “if pupils are to gain a scientific understanding of the evidence concerning the structure and properties of the Earth, and of the explanations we have for these characteristics, then a knowledge of their states is critical” (p. 58). An understanding of the states of matter in the various layers of the Earth promotes an understanding of how the plates move, of seismic waves, and of the generating mechanism for the Earth’s magnetic field.

Marques and Thompson (1997a) described continental drift and plate tectonics as “ideas that are central to a modern view of Earth as a very dynamic, ever-changing planet, of whose environment humankind is hopefully a more-than-temporary guardian” (p. 195). These researchers used interviews and questionnaires to examine the perceptions of 280 students (age 16/17) in Portugal. They reported the following common misconceptions: the same boundary serves to demarcate where plates meet and where continents meet the ocean; the wandering of magnetic poles causes the motion of plates; continents arose from the bottom of the oceans due to vertical forces (an idea quite similar to that held by

Permanentists in the 19th century); oceanic currents cause the continents to move; continental drift is caused by forces related to the rotation of the Earth; plates are arranged in stacked layers; plates rotate around an axis; and the same plate tectonic mechanisms cause the formation of continental and ocean mountain ranges.

In the area of deep time, Trend (2001) described that "people conceive and perceive major natural events through deep time ("geo-events") in different ways … These cognitive deep time frameworks may differ greatly from the scientific consensus" (p. 192). He also described that prior to his work minimal research had been conducted to describe students' understanding of deep time. Trend (2001) studied in-service primary teachers in the UK to determine what their conceptions of deep time were and described that teachers had better ability to apply relative time (ranking in order a series of occurrences across the history of the Earth) than ability to accurately attach absolute dates to these occurrences. While the teachers usually understood the relative order in which events occurred, they often had widely varying degrees of inaccuracy related to the actual amount of time that passed between the events. One other study conducted to describe misconceptions about deep time reported that about half the sample (10-11 & 14-15 year olds) believed that life and the Earth originated at about the same time (Marques and Thompson, 1997b).

Clearly, students do have a wide variety of misconceptions about plate tectonics and the Earth's history. Consequently, curriculum designed to address these concepts should be beneficial to geology instruction. Especially when considering how these concepts provide foundational groundwork for much of the rest of our knowledge about the Earth, it is important for students to engage in activities that will solidify and deepen their understanding. Based on Heilbron's (2002) suggestion that HOS materials should strengthen students' understanding of key scientific principles, the descriptions of misconceptions about plate tectonics and deep time found in the literature, and the interest of the geology instructor involved in this study to use materials related to these topics, the concepts of plate tectonics and deep time were deemed as excellent subject matter for the short stories.

A further suggestion for how to incorporate HOS materials into science courses is provided by Tao (2003) from a study that employed implicit methods to teach NOS concepts through short stories about the history of science. Tao concluded that it would be more effective to "actively scaffold students' understanding. The teacher can do this by holding whole-class discussion after each story during which they query students' views and direct their attention at the various aspects of NOS presented by the story" (p. 169). Based on the context of large, lecture-based classes in university lecture halls, a setting where it would be challenging to find time for and to motivate students to actively engage in discussions about the stories, the materials for this study were developed with a variety of explicit, embedded statements and questions intended to model correct interpretations of how the stories illustrate NOS concepts, to draw students attention to specific examples of NOS concepts, and to ask students to describe how NOS concepts are illustrated by the story. For example, Duschl (1994) has pointed out that scientific ideas are the products of creative scientific thinking of a culture at a given time, so one embedded question asked students to describe how the story illustrates the influence of wider culture and prevailing ideas on people investigating the natural world.

Theoretical Underpinnings for Development of Quiz Questions

To examine the degree to which the history of science materials used in this study affected students understanding of the targeted concepts, quizzes were written using open-ended questions intended to elicit students' views related to the geology concepts (continental drift/plate tectonics and deep time/age of the Earth) and NOS concepts (the variety of processes involved in the construction of scientific knowledge; the ways in which data must be interpreted by scientists to reach conclusions; the tentative, yet durable, nature of scientific knowledge; and the effects that culture and society have on science, scientists, and the process of constructing scientific knowledge). The design of these assessment questions was informed by the work of researchers in science education. As previously described, Lederman et al. (2002) reviewed the literature to describe research that supports the importance of using interviews and open-ended forms of assessment to accurately describe individuals' NOS understanding. The findings identified that forced-choice instruments are based on two risky assumptions: 1) that the respondents interpret the items in the same way that the developers intended, and 2) that it is the respondents' views rather than the developers' views that are being reflected by the results. Follow-up interviews with respondents have demonstrated that these two assumptions are often not valid–the respondents often failed to glean similar understanding of the questions to that held by the developers, and the descriptions derived by analysis of the responses was related to the theoretical frameworks held by the developers but did not fully represent the views held by the respondents. For these reasons, the use of open-ended assessment questions was selected for this study.

Lederman et al.'s (2002) summary was partially based on the work of Aikenhead and Ryan (1992) who used open-ended questions with follow-up interviews to develop an empirically-based set of multiple choice responses to questions about the nature of science. The empirically-based choices that they used in their Views on Science-Technology-Science

(VOSTS) instrument represented the typical ideas proposed by high school aged Canadian students. Working in this manner, Aikenhead and Ryan (1992) found that while "Likert type responses offer only a guess at student beliefs, and the chances of an evaluator guessing accurately are very remote" such that "ambiguity often reached the 80% level," the use of "the empirically derived, multiple-choice responses mode reduced the ambiguity to the 15 to 20% level" (p. 479). Because this study was conducted using college age students in the US (rather than high school age students in Canada), it was not assumed that the same empirically-based multiple choice responses would represent all of the views that might be present in the population studied. Lederman et al. (2002) have reported that when using the VOSTS instrument in Lebanon several Lebanese science teachers indicated that

> their views on the NOS issues elicited by some VOSTS items were either not represented among, or were combinations of, the provided viewpoints. Other teachers chose to express viewpoints totally different from the ones presented in the VOSTS. (p. 503)

One of the quiz questions used in this study was derived from the VOSTS; consequently, this question was converted to an open-ended format so that all student views present in the population could be documented.

Even in their use of open-ended questionnaires, Lederman et al. (2002) and Aikenhead and Ryan (1992) described that follow-up interviews were essential to developing accurate descriptions. In many cases, researchers either attempt to infer too much from the questionnaire responses or are not able to infer concrete conclusions at all. These researchers found that by using follow-up interviews, which asked the participants to read their responses and then provide explanation and justification, more accurate descriptions of the participants' NOS understanding were derived. In addition, the respondents' reasons for developing such an understanding could be uncovered. During a pilot study, to be described later in this chapter, follow-up interviews were used to ensure that respondents interpreted the questions as the researchers intended and that the researchers interpreted the responses in the ways that respondents intended. Also, most open-ended questions included a portion that asked the participant to use examples from science to further explain or describe their views.

Two key sources were used to provide examples of open-ended questions which target NOS concepts: Lederman et al. (2002) and Aikenhead and Ryan (1992). In some cases, quiz questions were taken almost verbatim from these sources; in other cases the stylistic presentation of questions and the description of NOS views described as naïve or expert were used to design new open-ended questions.

Quiz Questions Intended to Elicit Students' NOS Conceptions

Question NOS-A: Consider that a gold miner discovers gold, but a musician creates a song. Some people think that science knowledge is discovered while others think that scientific knowledge is created. (a) What do you think? (b) Provide evidence using your knowledge of science.

This question was derived from Aikenhead and Ryan (1992) who used a similar question in their VOSTS instrument. The primary intent of the question is to obtain a description of the respondents' views about the processes involved in the accumulation of scientific knowledge. Ryan and Aikenhead (1992) suggest that this type of question is a way to ask:

> Does scientific knowledge tell us what is really out there in the universe (ontology) or is scientific knowledge 'mind stuff' (epistemology)? The question delineates two camps within the philosophy of science: (1) an ontological perspective consistent with logical positivism …; and (2) an epistemic perspective consistent with contemporary views. (p. 565)

The results from Ryan and Aikenhead's (1992) study using the VOSTS instrument with Canadian high school students demonstrated that only 17% of participants had ideas that exclusively aligned with the contemporary view that ideas are invented because they are mankind's interpretation of nature. Another 40% acknowledged some degree of invention as necessary for the formation of ideas in science, but also relied on a description that scientists sometimes have chance discoveries of ideas, described by the researchers as a "classic but erroneous notion that many discoveries occur by accident, a notion heralded in the media and by popular writers of the history of science" (Ryan & Aikenhead, 1992, p. 566). The remaining 37% of participants relied exclusively on descriptions of science ideas as being discovered. This view is the most problematic in that it fails to acknowledge the inventive nature required to interpret indirect evidence, which is necessary in the field of geology when developing ideas related to processes that cannot be directly observed such as plate tectonics or the history and origin of the Earth, and to assign meaning to direct observations, such as interpretation of what types of natural forces could have caused geological strata to accumulate in a particular arrangement.

Questions NOS-C: Evidence can be used to support the idea that about 65 million years ago the dinosaurs became extinct. One group of scientists suggests that a huge meteorite hit the Earth 65 million years ago and led to a series of events that caused the extinction. A second group of scientists suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these different conclusions possible if scientists in both groups have access to and use the same set of data to derive their conclusions?

This question is a slightly modified form of a question used by Lederman et al. (2002) in their development of Version C of the VNOS instrument. The primary intent of the question is to obtain a description of the respondents' views about the need for scientists to interpret data and the tentative, yet durable, nature of scientific knowledge. Lederman et al. (2002) conducted extensive testing of all items on the VNOS to determine the reliability of the questions; this testing involved administering the instrument to undergraduate and graduate college students and to elementary and secondary teachers with accompanying interviews. They determined that the participants' written responses were congruent to the more-detailed responses expressed during interviews, and consequently they concluded that the participants interpreted the questions in the ways intended by the researchers and that the questions provided reliable measures of the NOS concepts involved. The researchers also assessed the validity of the VNOS by administering the instrument to an expert group, composed of individuals with doctoral degrees in science education or history and philosophy of science, and to a novice group, composed of individuals with doctoral degrees in other fields such as American literature and history. Distinct differences between the responses of the two groups were noted, such that "the expert group's responses … reflected current NOS understandings at a rate nearly three times higher than those of the novice group" (p. 506). On questions designed to assess the tentative nature of scientific knowledge, more naïve views were exemplified by statements such as "compared to philosophy and religion … science demands definitive … right and wrong answers" while more informed views were exemplified by statements such as "everything in science is subject to change with new evidence and interpretation of that evidence. We are never 100% sure about anything because … negative evidence will call a theory or law into question, and possibly cause a modification" (Lederman, et al., 2002, p. 515). Similar differences were described for multiple other characteristics of the NOS, including the theory-laden nature of scientific work due to the different types of interpretations that can be derived from data depending on the theoretical framework adopted by the scientists. Based on these findings, this question was determined to provide an adequate means of measuring the respondents' views about the need for interpretation of data and the tentative, yet durable, nature of scientific knowledge.

Question NOS-D: In what ways, if at all, do the culture and society have an effect on an individual scientist's work? Include an example to explain your reasoning.

Question NOS-E: In what ways, if at all, do currently accepted scientific ideas have an effect on an individual scientist's work? Include an example to explain your reasoning.

These questions were written by the researcher, but a question that targets the same concepts was used by Lederman et al. (2002) in the VNOS. The VNOS question asked respondents whether science reflects "social and cultural values" and the "political values, philosophical assumptions, and intellectual norms of the culture" or whether it is "universal" and consequently is not affected by these types of factors (p. 509). Lederman et al. (2002) reported that members of the expert group commonly addressed two different types of cultural influences: ones from the external culture of society at large and ones from the internal culture of science. Based on these findings, two separate questions were used in this study to address the influence of the internal scientific culture and the external social culture.

Together these two questions are intended to obtain a description of the respondents' views about the effects that prior knowledge and experience, culture, and society have on science, scientists and the process of constructing scientific knowledge – with implications for the degree to which respondents feel that science and scientists are able to maintain pure objectivity in their work. From the findings of Lederman et al. (2002), the expert group participants described that the internal culture of science acts to establish rules of practice and evidence and to limit subjectivity through processes such as peer review and group consensus. These participants also described the role of the external culture of society at large as having influence on what kind of science is done through funding, gender, and racial issues. Only one-third of the novice group made any reference to any types of influences from culture and society.

It should be emphasized that these four questions alone are not sufficient to produce an understanding of the participants' views on all aspects related to the nature of science; the intent of this study is only to describe the participants' views as they relate to the targeted aspects of NOS and the degree to which the HOS materials used can have a positive impact on the students' understanding of these NOS concepts.

Quiz Questions Intended to Elicit Students' Conceptions about Geology

In addition to teaching NOS concepts, the short stories were also designed to promote a greater understanding of science content. The developers focused on fundamental geology concepts that are typically difficult for students to understand and used the history of science to illustrate how these ideas were developed. Selection of geology content questions used on the assessment was influenced heavily by the content being taught in the geology course and illustrated by the short stories. The instructor expressed strong desires to ensure that the wording and overall emphasis of the questions would be consistent with the types of ideas presented in lectures and textbook readings for the course, with the intention that this would enable students in both the control and treatment groups to see strong links between the course content, the content of the stories, and the assessment items. As such, the context and wording of the four geology content questions were negotiated between the researcher and the geology instructor, and explicit outside sources were not consulted in the construction of these questions. The full text of these four questions can be viewed in Appendix A. The focus of the questions was intended to examine students' understanding of plate tectonics and deep time – particularly related to the movement of continental and oceanic plates, methods used for relative and absolute dating of geological materials, and the geological evidence about the age of the Earth. The short stories were centered on the development of these ideas and included descriptions of the key scientists' work, alternative explanations that were considered before these ideas were accepted by the scientific community, and the evidence used to support the ideas. Consequently, strong links were present between the content of the short stories and the NOS and geology concepts examined in the assessments.

Research Subjects and Context

The subjects of this research project were students enrolled in a one-semester, undergraduate, introductory-level geology course at a large, public, midwestern U.S. university. Because the instructor of the course was using the short stories and assessment questions as part of her regular instruction, the study was classified as exempt by the university's Internal Review Board and informed consent documentation was not required. All of the data gathered were considered to be a typical part of the class structure and assignments. The participants were informed, however, that their responses to questions related to the short stories and in class assessments would be viewed by the research team.

The introductory geology course involved in the study consists of a one-semester overview of primary factors that describe the composition of the Earth, the natural forces that influence the Earth (movements of plates, climate, ocean currents, etc.), and how the Earth changes through time. The class had high student enrollment (approximately 250 students per section) and the primary mode of teaching involved a lecture format from PowerPoint presentations, which consisted of instructor-developed information and images as well as publisher-developed supplements to the course textbook. Students were able to download all materials from the lectures in advance of each class period. During most class sessions, approximately 75% of the students enrolled were in attendance.

Fall semester students served as a control group, while spring semester students served as a treatment group. For the control group, the fall semester of 2004 (n = 281) was used to administer six of the eight assessment questions and the fall semester of 2006 (n = 328) was used to administer the remaining two assessment questions. One other assessment question (NOS-B) had been administered to the fall 2004 group, but during a pilot study this question was found to have low alignment with the short story concepts and consequently it was omitted from this study. Further discussion of the pilot study appears later in this chapter. The two questions used with the fall 2006 group consisted of NOS questions (NOS-D and NOS-E) introduced to replace question NOS-B. All treatment group students were enrolled in two sections of the geology class during the spring semester of 2007. The treatment group completed the short stories and related homework questions; the control group had no short stories, but completed their regular homework assignments based on the textbook readings.

It was the intention that treatment group students would complete the short story assignments in place of some homework assignments. In the actual implementation of the study, however, the geology instructor chose to use the continental drift/plate tectonics stories in addition to a regular homework assignment and the deep time/age of the Earth short stories in place of only a portion of a homework assignment. Consequently, treatment group students spent more time completing required homework than did the control group. Based on a survey of the students, treatment group students spent an average of approximately 30-45 minutes more time working with the continental drift/plate tectonics material when compared to control group students. From the survey results and discussion with the instructor, it is estimated that the treatment group students spent an average of 15-30 minutes more time working with the deep time/age of the Earth material than the control group students.

The fall 2004 and spring 2007 sections of the geology class were taught by the same instructor. This instructor was not able to teach the class during the fall 2006 semester; consequently, control group data for the two replacement questions (NOS-D and NOS-E) was gathered from sections of the geology class that were taught by a different instructor. Although a different instructor was involved during fall 2006, the basic structure and content of the course was consistent with those used in other portions of the study. In addition, because only NOS control group data was gathered during fall 2006 and because instructional efforts to impact NOS understanding at the college level are rare and are often ineffective (Lederman, 1992), it was deemed acceptable to gather the needed data in this manner. The fall 2006 instructor was aware that her class was being used as a control group for NOS questions and of the importance of maintaining the integrity of the data by refraining from offering any explicit NOS instruction to the class. Figure 2 shows an overview of the three semesters involved, the quiz questions used, and the geology instructors who were teaching the class.

	Fall 2004	Fall 2006	Spring 2007
Geology Instructor	Dr. X	Dr. Y	Dr. X
Quiz questions for which control group data was gathered	NOS-A, NOS-C, GEOL-A, GEOL-B, GEOL-C, GEOL-D	NOS-D, NOS-E	
Quiz questions for which treatment group data was gathered			NOS-A, NOS-C, NOS-D, NOS-E, GEOL-A, GEOL-B, GEOL-C, GEOL-D

Figure 1: Description of the instructors involved and quiz questions responded to by the control and treatment groups

Use of Quizzes to Assess NOS and Geology Content Understanding

During fall 2004 and spring 2007, students were randomly assigned two assessment questions: one geology question and one NOS question; during fall 2006 each students was randomly assigned one NOS question. All of the NOS and geology content questions were open-ended, requiring students to write a response that could be analyzed for accuracy and/or level of sophistication. The geology questions targeted information related to 1) utilizing plate tectonic theory to compare mineral deposits on previously connected continents (GEOL-A), 2) describing appropriate usage of absolute and relative dating methods (GEOL-B), 3) determining the age of a layer of sedimentary material (GEOL-C), and 4) relative ages of continental and oceanic crust material (GEOL-D). The NOS questions targeted information related to 1) the ways in which new knowledge gets added to the body of science

(NOS-A), 2) the use of disagreements between scientists to illustrate the tentative nature of science and the causes and results of necessary subjectivity in science (NOS-C), 3) the effects that culture and society have on the work of scientists (NOS-D), and 4) the effects that currently accepted scientific ideas have on the work of scientists (NOS-E). As previously described, question NOS-B was used in the pilot study but was omitted from this study. The complete text of the eight assessment questions can be viewed in Appendix A. A summary of the number of control group students responding to each question is shown in Table 1 below. During the coding process, some students' responses could not be clearly interpreted or classified; these instances are noted in Tables 1 & 2 and were excluded from analysis.

Table 1: Number of students from control group responding to each quiz question

Geology questions	GEOL-A: Mineral deposits & continental drift	GEOL-B: Absolute and relative dating methods	GEOL-C: Layering of sedimentary rock	GEOL-D: Ages of continental vs. oceanic rocks – plate tectonics
# of students	69	69	70	72/73

NOS questions	NOS-A: Inventing vs. discovering scientific ideas	NOS-C: Tentative nature of science – multiple interpretations of data	NOS-D: Effects of culture and society on the work of scientists	NOS-E: Effects of currently accepted scientific ideas on the work of scientists
# of students	55/70	130/138	137/174	121/154

(Numbers represent "classifiable responses"/"all responses")

During the spring semester of 2007, the treatment group (n = 298) students participated in the research study by completing the homework assignments and taking the quiz. The timing used to administer the treatments and quiz is illustrated in Figure 1.

Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
			X	1						X	2	Quiz			

Treatment Group only:
X = in-class discussion of homework questions, preceding homework due date
1 = Homework 1 due (continental drift/plate tectonics short story)
2 = Homework 2 due (deep time/age of the Earth short story)

Control and Treatment Groups:
Quiz = In-class assessment of students' NOS and geology understanding conducted

Figure 2: Timing used to administer treatments and to assess students' understanding of NOS and geology concepts in the control and treatment groups during each semester

Treatment group students read a pair of short stories describing the development of geological ideas about continental drift/plate tectonics and a pair of short stories describing the development of geologists' ideas about the age of the Earth and the related concept of deep time. These stories comprised socially-situated descriptions of 1) Wegner's development of continental drift theory; 2) the efforts to develop the mechanism of plate tectonics, which accounts for how continental drift occurs; 3) Hutton's ideas about how geological formations are generated and what this means concerning the age of the Earth, and 4) the work of multiple scientists to provide further evidence about the age of the Earth. As two separate required homework assignments, the students answered questions that were embedded within the short stories and that required the students to consider relevant social, political, and economic factors that influenced the incident under study. Consistent with other course requirements, students were expected to work primarily alone to complete each of these homework assignments, although approximately ten minutes was allotted to in-class discussions related to the stories and the embedded questions. The students were not accustomed to engaging in small-group discussions in the context of this geology class, and observations of student interaction patterns were interpreted to indicate that for most students substantial fruitful discussion did not occur. Less than 10% of the students acknowledged having already worked on the questions and many students were observed engaging in activities other than discussing the short stories. During part of the time allotted to discussion, the instructor discussed her views on some of the homework questions and asked students questions such as “Do you think scientists are objective?” Students usually replied to these questions in one or two words and did not offer explanations to further describe their thoughts.

Near the end of the semester (using the same timing as occurred during the fall semester), students were required to provide written responses to the same quiz questions as were used with the control group. Again, students were randomly assigned one geology question and one NOS question. In addition, the quiz asked treatment group students to report the amount of time they had spent completing the homework assignments involving the short stories. Table 2 shows the number of treatment group students responding to each question. Only students who submitted at least one of the homework assignments involving the short stories and also participated in the in-class quiz are considered as treatment group participants.

Table 2: Number of students from treatment group responding to each quiz question

Geology questions	GEOL-A: Mineral deposits & continental drift	GEOL-B: Absolute and relative dating methods	GEOL-C: Layering of sedimentary rock	GEOL-D: Ages of continental vs. oceanic rocks – plate tectonics
# of students	70/78	77	71	72

NOS questions	NOS-A: Inventing vs. discovering scientific ideas	NOS-C: Tentative nature of science – multiple interpretations of data	NOS-D: Effects of culture and society on the work of scientists	NOS-E: Effects of currently accepted scientific ideas on the work of scientists
# of students	67/71	75/78	66/72	70/77

(Numbers represent "classifiable responses"/"all responses")

Data Reduction and Analysis

Analysis of the data obtained during this study involved examination of students' responses to both the questions embedded within the short stories (submitted as homework assignments) and the questions administered during the in-class assessments (quizzes) toward the end of the course. Qualitative methods were used to describe and characterize the students' views on key NOS and geology concepts, including misconceptions about the nature of science, while quantitative methods were used to measure the impact that the HOS materials had on the students' understanding of NOS and geology, as reflected on the quizzes. The intent was the development of grounded theory, defined as the process of systematically gathering and analyzing data to arrive at ideas throughout the research process (Strauss & Corbin, 1998). The methods used to develop grounded theory involved careful study of students' responses to homework and quiz questions and the development of categories that described common themes present in the responses, a process referred to as open coding. Throughout coding, the focus was on providing conceptual order to the data by organizing it into discrete categories and attaching appropriate descriptions that elucidate students' thinking.

Homework Analysis

Due to the quantity of data involved, three researchers participated in analyzing the data obtained from students' written responses to the homework questions embedded in the short stories. The first researcher, the author, holds a master's degree in education and a secondary teaching license. He has taken a graduate-level course in the nature of science, has two years of research experience with the NOS, and has 13 years of post-secondary science teaching in the field of chemistry. The second researcher holds a PhD in science education and has over 10 years of experience with NOS research. The third researcher was a master's degree student in science education, holds a secondary science teaching license, has taken a graduate-level course in the nature of science, and is a former student of the geology course and instructor involved in this study.

These three researchers met together after reading a sampling of 15-20 responses for each homework question and decided on a rubric that would be used to code students' responses. The basic template for all questions included five categories: 1) accurate and detailed response; 2) accurate but less detailed response; 3) mixed view, containing both some accurate and some inaccurate ideas or a response that is too vague to be labeled as completely accurate; 4) all inaccurate views; and 5) unclassifiable because students' ideas cannot be clearly determined based on the response provided. Any inaccurate views in students' responses are also commonly referred to as misconceptions from here forward. The inclusion of an unclassifiable category is supported by the work of Aikenhead and Ryan (1992) who reported that, while the use of open-ended type responses provides less ambiguity to what the students actually think than do Likert-type responses, some ambiguity still remains due to incomplete or inarticulate paragraphs. In cases where sufficient ambiguity was present that the researchers felt that accurate interpretation of the participant's views was not discernable, the response was coded as unclassifiable. This type of coding allowed for the number of students in each category to be quantified. In addition, students' responses categorized as type 3 or 4 were examined in more detail through an open-coding process to develop categories for the types of misconceptions present.

Quiz Analysis

For the quiz questions more detailed coding was desired; consequently, students' responses were coded in a manner that would allow the interpretation and indexing of major themes present in the data with the intention to note similarities, differences, and relationships between ideas (Bogdan & Biklin, 2003; Krathwohl, 1998). To anticipate potential themes that could be notably present or absent, the researcher wrote detailed, accurate responses for each quiz question (afterwards referred to as the comparison key). Comparison key entries for the geology-specific questions (related to continental drift and deep time) were discussed with a faculty member from the geology department to ensure accuracy in the responses. Similarly, comparison key entries for the nature of science questions were discussed with faculty from science education to ensure accuracy in the responses. Students' responses were then read and examined for themes – the presence or absence of key concepts from the comparison key, as well as the presence of alternative/novel ideas were noted and coded. Emerging themes from the responses were recorded and a constant comparative method (Glaser & Strauss, 1967) was used to group similar responses to form an initial coding scheme. (See Appendix B to view the final coding rubrics.)

Krathwohl (1998) suggests that it is useful to select examples of verbatim narrative from the data for each of the categories.

> If you are seeking to view the situation as perceived by those it in, select material in the informant's own words. Write a definition of the code; delineate what falls under the code title. The definition shows its generality and also helps to define the boundaries of what is included. Constructing definitions is likely to help you see other relationships among the codes and the necessity for further refinement and revision of the structure. (p. 310)

In adherence to this methodology, students' responses were reread and coded using the scheme, with revisions to category definitions and descriptions being made as needed to ensure that the categories accurately reflected students' views and that students who had similar ideas would be coded in the same way. Throughout the process, quotations from students' responses were listed alongside each category to serve as exemplars and to ensure that each new response placed in the category would be consistent with others placed in the same grouping. During this part of the coding process, it was important to make theoretical comparisons, defined by Strauss and Corbin (1998) as "an analytic tool used to stimulate thinking about properties and dimensions of the categories" (p. 73). The researcher compared categories and students' responses within the categories to make interpretations about what facets of students' conceptual frameworks may have caused the different types of responses involved. In so doing, the process of making theoretical comparisons helped to further delineate the differences between each category in the coding scheme.

Krathwohl (1998) also suggests that qualitative researchers should check for objectivity, "defined as consistency between the way other observers would view the evidence and how the researcher did" (p. 340). Consequently, a representative sample of 20 student responses from each quiz question was read and coded by the two other researchers who participated in coding the homework questions to ensure inter-coder agreement and to further revise and clarify the coding scheme. Any discrepancies in coding that involved less than 85% agreement were resolved through further discussion and recoding of the data.

At this point the coding scheme constituted nominal levels of measurement. These nominal levels of measurement provide informative descriptions of the views that are prominent among the group of students and can provide useful qualitative information both for the purposes of describing the population and also for planning future instruction to strengthen accurate views and address/combat inaccuracies; however, they had not yet been ranked to compare the level of accuracy and/or sophistication in each category.

To make comparisons between the control and treatment groups, it was necessary to transform these codes into a measure on an ordinal scale. This transformation was accomplished through the development of a hierarchical relationship between the categories, a process that was greatly aided by the ways in which theoretical comparisons between coding categories had been made throughout the coding process and by use of the comparison keys. Comparisons keys helped to gauge the level of understanding demonstrated in each student's written responses, and individual categories were ranked for level of accuracy and sophistication based on the theoretical comparisons that had been made between categories. Accuracy was defined as the degree to which students' views adhered to the understanding of geology and nature of science concepts described in the comparison key. Sophistication was defined as the level of clarity and ability to use multiple forms of evidence to defend/illustrate the views expressed by the students. In some cases two or more categories were combined if they described views that were different in their nature but equal in their degree of accuracy and/or sophistication. This ranking became a numerical score that could be applied to each student's response and could serve as an ordinal scale for measurement of the degree of accuracy and level of sophistication exhibited in each response. Statistical comparisons (t- and Mann-Whitney tests) were made between control and treatment groups to determine whether or not exposure to the short stories and embedded questions had a measurable impact on students' understanding of each geology and NOS concept addressed in the quiz questions. In addition, one way analysis of variance (ANOVA) and Kruskall-Wallis tests were conducted to determine to what degree students' scores on the quiz questions were dependent on the amount of time spent working on the short story assignments and the number of short story assignments completed.

Assumptions, Limitations, and Delimitations

This work is based on several key assumptions, three of which relate to the participants involved. First, it is assumed that the students provided honest responses and were motivated to provide adequate descriptions of their thoughts. To bolster this assumption, the geology instructor assigned the reading of the short stories and the submission of written responses to the embedded questions as required homework assignments and provided written and oral directions that the answers provided should show careful consideration of the topics involved. Homework scores were assigned based on the degree to which students' responses appeared to reflect honest effort and sincere thought rather than based on the correctness of the responses. Similar oral directions were provided for the quizzes, with extra credit points being awarded for participation. A second assumption related to the participants is that the control and treatment group were equivalent in their understanding of NOS and geology before the study. The large sample size, the use of sections of the same introductory geology class, and the consistency of the instructor between control and treatment groups (with the exception of the fall '06 group, when each control group participant answered only one NOS question) support this assumption. Finally, it is assumed that only the short stories affected students' understanding of NOS differently between control and treatment groups. While there is no way to accurately measure the effect that other factors may have had, other efforts to impact NOS understanding at the college level are relatively rare and are often ineffective (Lederman, 1992). Consequently, it is assumed that there was an equally low likelihood of external factors having measurable effects on the NOS understanding of each group.

Several assumptions apply to the qualitative methods employed in this study. First, it is assumed that the coding process accurately reflects participants' ideas – that the researcher interpreted and coded participants' responses in ways that are consistent with the participants' actual views. As described earlier from the work of Lederman et al. (2002) and Aikenhead and Ryan (1992), the use of interviews to check for consistency between the researcher's perceptions and the participants' intentions is highly desirable. During a pilot study (further described later in this chapter) interviews of this nature were conducted, with results indicating greater than 95% agreement between the researcher's interpretations of the respondents' written responses and the views that the participants expressed orally during the interviews. In addition, it is assumed that the coding schemes accurately rate NOS and geology understanding; to validate this assumption, the coding schemes were reviewed with experts (faculty) from the fields of science education and geology. Finally, it is assumed that consistent methods were employed throughout the process of coding the large quantity of data involved. Three key strategies were employed to ensure consistency in coding: the incorporation of detailed descriptions and example statements from student responses into each coding category on the coding scheme (as described by Krathwohl, 1998), the on-going use of comparisons among coding categories and among students' written responses during the coding process (as described by Strauss and Corbin, 1998), and the use of inter-coder agreement checks to ensure that other researchers would be able to use coding schemes to categorize students' responses in the same ways as are reported here.

Limitations in this study include the degree to which the HOS materials were incorporated into the overall context of the geology course, the degree to which students were willing and able to provide detailed descriptions in their responses to the embedded short story and quiz questions, and the fact that the treatment group students spent more time than the control group students working with homework assignments. While the short stories were included as homework assignments in the class, minimal referencing of the stories or the embedded questions occurred throughout the rest of the class. Students were provided with ten minutes of in-class time to engage in small group discussions concerning the embedded questions a few days before the homework assignments were due; however, the content of the stories was not included in teacher-led discussions or lectures at other times throughout the course. It is likely that further emphasis of the content and modeling of appropriate thinking from the instructor would provide for a greater impact from the HOS materials, as suggested by Tao (2003).

While students had several weeks available to read the short stories and respond to the embedded questions, it is likely that many of them procrastinated or hurried through the assignment. Varying degrees of reference to the content of the stories were found in student responses, with some responses showing significant evidence that the students had read and carefully considered the content of the stories and other responses seeming as if they easily could have been produced without examining the content of the stories at all. Again, further incorporation of the materials into the overall structure of the class could alleviate this issue. Students were provided with a limited amount of time to respond to the quiz questions – as is typical for quizzes in college-level science classes, where the focus tends to be on using all available class time to cover the required material. However, consistent timing was allocated for both control and treatment groups in an effort to ensure that neither group produced more detailed responses simply due to a factor of having more time available to write.

Although the study was originally designed with the intention that the short story assignments would replace some homework assignments for the treatment group, in the implementation of the study the continental drift/plate tectonics stories were assigned in addition to the regular homework assignment. The deep time/age of the Earth stories were used to replace a portion of one homework assignment. Due to this implementation, it is estimated that, when compared to control group students, the treatment group students spent an additional 30-45 minutes working with homework materials concerning continental drift/plate tectonics and 15-30 minutes more working with homework materials concerning deep time/the age of the Earth. For this reason, any differences in understanding of the geology content between the control and treatment groups would need to be interpreted in light of the fact that treatment group students spent more time on the topics.

Three key delimitations must be considered when examining the findings from this study. First, the findings of this study should be considered to be specific to college-level students. Further, due to the nature of an introductory geology class, most of the participants in this study are not planning to complete a degree in a science-based field. Little research has been conducted involving college students' understanding of NOS; consequently, any direct comparisons to findings from other studies must take into account differences in age, experience, and cognitive level of development of the participants involved. Second, it must be considered that the study was conducted in the context of geology. Some researchers have suggested that students may have domain-specific NOS understandings, with the likelihood that they might respond differently to questions about a particular feature of the nature of science (tentativeness, for example) in the context of different science subjects such as geology and physics (Wandersee & Roach, 1997). Consequently, it must be understood that the descriptions of NOS understanding produced from this study should be interpreted in the context of geology learning only. Finally, the probability that individual participants possess mixed views about the nature of science, exhibiting more sophisticated and accurate views with respect to some characteristics and relatively naïve or inaccurate views with respect to other NOS characteristics must be acknowledged (Lederman, 1992). Due to the large number of participants in this study, detailed profiles of individual participants' views about multiple NOS and geology concepts were not derived. Instead, the findings represent aggregate studies of the population – college-level introductory geology students.

Pilot Study

A pilot study of this project was conducted during the 2004-2005 academic year, using short stories designed for geology and biology classes. The geology stories used during the pilot study were early versions of the short stories used during the current study. Based on the results of the pilot study and subsequent additional input from reading specialists, historians of science, and geologists, the stories were modified to use a slightly lower reading level, to incorporate additional emphasis on key geological concepts and terms, and to decrease the number of embedded questions while simultaneously increasing the number of explicit statements that draw attention to accurate illustrations of the nature of science.

The pilot study used NOS assessment questions that are identical to those used in the current study, plus one additional nature of science question (NOS-B) focused on how science textbook portrayals of science change over time. Questions NOS-B was eliminated from the current study due to a lack of fit between it and the short stories, which do not specifically address how and why changes occur in science instruction or materials. During the pilot study, questions NOS-D and NOS-E (concerning the effects of culture, society, and current scientific ideas on scientists' work) were used only with biology students; during the current study these questions were used with the geology students because they were deemed to have a good fit with the NOS concepts addressed in the modified short stories. Because all geology questions and two of the NOS questions had been successfully piloted with geology students, the control group data from the pilot study for these assessment questions was used as control group data in the current study as well. For the two questions that were piloted only with biology students (NOS-D and NOS-E), control group data for geology students was collected during the fall 2006 semester using students enrolled in two sections of the same introductory geology class.

During the pilot study only the quiz questions were coded - using grounded theory to develop coding schemes that represented the ideas commonly encountered among the recipients' responses. To ensure the validity of the coding schemes, twenty percent of the biology students who participated in the pilot study were interviewed. During the interviews, these students were asked to discuss their responses and to provide additional examples/rationale that supported their responses. Based on a comparison of the interview notes with the coding of students' written responses, it was determined that excellent alignment existed between the interpretation of written responses provided by coding and the views of the participants. In the current study, the coding schemes that had been developed during the pilot study were used, but were modified when needed to account for different types of responses or different degrees of articulate discussion present in the responses.

CHAPTER 4: RESULTS AND DISCUSSION

Overview

This study was designed to examine the effects of historically accurate short stories that simultaneously address geology and nature of science concepts on students' NOS and science understanding. Students' NOS and geology misconceptions have been described by previous researchers (Barrow & Haskins, 1996; Libarkin & Kurdziel, 2001; Trend, 2001), and have the potential for long-term effects of reduced science literacy and ability to make informed decisions on science related issues common to public life. In addition, misconceptions about issues related to the nature of science negatively impact students' interest in science as a career choice (Seymour & Hewitt, 1997; Tobias, 1990). Typical textbook presentations, public perceptions of science, and teaching that focuses on the end-products of science serve to reinforce these misconceptions, so a strong need for curriculum that adequately addresses NOS concepts exists (Clough, 2006). The history of science has been described as a field which is rich in illustrations of the nature of science and which can be effectively used to confront students' NOS misconceptions while simultaneously addressing science content (Heilbron, 2002; Stinner et al., 2003).

In this study, a control-treatment design was used to examine how effective historical short stories would be at altering introductory geology students' conceptions about the nature of science, plate tectonics, and geologists' ideas about the age of the Earth. Treatment group students read the short stories and answered embedded questions, which were designed to draw their attention to and cause them to reflect on the NOS and geology concepts illustrated in the stories. To assess the impact of the short stories, both control and treatment group students completed a quiz consisting of open-ended questions about the NOS, plate tectonics, and the evidence geologists used to determine the age of the Earth.

Research Questions

This study was designed to answer three research questions.

1. How are geology students' views of NOS affected by the use of history of science materials in an introductory-level course?
2. How are geology students' understanding of plate tectonics and deep time affected by the use of history of science materials in an introductory-level science course?
3. What NOS misconceptions appear to interfere with learning as students interact with the history of science materials?

Quiz Results: Quantitative Perspective

Extensive coding of students' responses to the quiz questions was used to rate students' ideas about specific aspects of the nature of science, plate tectonics, and deep time as it relates to the age of the Earth. The scores assigned were used to make statistical comparisons between the control and treatment group, and the coding categories were used to further describe the areas in which students made significant gains. In addition, coding of students' responses to the homework questions from the short story assignments were used to describe aspects of students' understanding which appear to have negatively impacted their likelihood of adopting more informed views.

Distribution of scores for control and treatment groups

An examination of the scores assigned to the control and treatment groups for each of the eight assessment questions revealed that distributions were within or near the normal range (Table 3). George and Mallery (2001) describe that kurtosis and skewness measures between ±1.0 are considered excellent and between ±2.0 are generally considered adequate. Although scores on several questions varied slightly from the excellent range almost all were within the generally acceptable range. Two exceptions to normal distribution were noted in the descriptive statistics. The first exception was the control group for question NOS-A (invented or discovered scientific knowledge), that had a kurtosis value of 2.686 and that was not expected to be within a normal distribution range due to the high prevalence of misconceptions on this topic. The second exception involved the treatment group for question NOS-D (addressing the effects of culture and society), that had a kurtosis value of 2.941; this factor can be accounted for due to the positive treatment effect that eliminated all occurrences of student responses being coded in the lowest category.

Table 3: Descriptive statistics for the distribution of scores for the control and treatment groups on quiz questions

Geology questions	GEOL-A: Mineral deposits & continental drift	GEOL-B: Absolute and relative dating methods	GEOL-C: Layering of sedimentary rock	GEOL-D: Ages of continental vs. oceanic rocks – plate tectonics
<u>Skewness</u>				
Control	-0.532	0.295	-0.391	0.686
Treatment	-0.251	0.242	-0.322	0.875
<u>Kurtosis</u>				
Control	-1.086	-1.197	-0.810	-0.858
Treatment	-1.110	-0.854	-0.287	-0.431

Table 3 (continued)

NOS questions	NOS-A: Inventing vs. discovering scientific ideas	NOS-C: Multiple interpretations of data	NOS-D: Effects of culture and society	NOS-E: Effects of currently accepted scientific ideas
Skewness				
Control	1.694	0.885	-1.336	0.252
Treatment	0.248	0.217	1.409	0.138
Kurtosis				
Control	2.686	-0.487	1.299	-0.278
Treatment	-1.541	-1.578	2.941	-0.517

Statistical Comparisons between Control and Treatment Groups: Does the treatment have a measurable effect on NOS and geology content understanding?

Statistical tests were conducted to examine the null hypothesis that students' views on the NOS and geology concepts addressed in the assessment questions will be unchanged by exposure to the treatment. For all questions two-tailed *t*-tests were used to compare mean scores; due to the non-normal distributions found in the control group for question NOS-A and the treatment group for question NOS-D, Mann-Whitney non-parametric tests were also used to compare mean rankings for these questions (Tables 4 and 5).

Table 4: Comparison of control and treatment groups on NOS and geology items using t-tests

Assessment item	Group	N	Mean score	Standard deviation	*p*
NOS-A: Invented or discovered science ideas	Control	55	1.49	.767	<.001*[1]
	Treatment	67	2.27	1.21	
NOS-C: Multiple interpretations of data	Control	130	3.10	1.45	.019*
	Treatment	77	3.60	1.50	
NOS-D: Influences of culture and society	Control	137	2.68	.652	<.001*[1]
	Treatment	66	3.12	.373	

Table 4 (continued)

NOS-E: Influences of currently accepted scientific ideas	Control	121	2.52	.731	.586
	Treatment	70	2.46	.846	
GEOL-A: Continental drift – Minerals in Brazil	Control	69	3.55	1.39	.495
	Treatment	77	3.40	1.23	
GEOL-B: Absolute and relative dating methods	Control	69	2.19	1.06	.726
	Treatment	77	2.25	.948	
GEOL-C: Age of the Earth – Evidence in sedimentary rock	Control	70	2.50	.929	.803[1]
	Treatment	71	2.46	.734	
GEOL-D: Plate tectonics – Difference in age of ocean & continental rocks	Control	72	1.90	1.02	.806
	Treatment	72	1.86	1.01	

*Significant at α=.05

[1] Levene's test equality of variances violated, so non-homogeneous results reported

Table 5: Comparison of control and treatment groups on NOS and geology items using Mann-Whitney non-parametric tests due to deviations from normal distribution

Assessment item	Group	N	Skewness/ Kurtosis	Mean Rank	*p*
NOS-A: Invented or discovered science ideas	Control	55	1.69 / 2.69	49.91	<.001*
	Treatment	67	.248 / -1.54	71.01	
NOS-D: Influences of culture and society	Control	137	-1.34 / 1.30	91.18	<.001*
	Treatment	66	1.41 / 2.94	124.45	

*Significant at α=.05

Notably, statistically significant differences are seen in *t*-test results for questions NOS-A, NOS-C, and NOS-D. Mann-Whitney results also reveal statistically significant differences between the control and treatment groups for questions NOS-A and NOS-D. No statistically significant differences between control and treatment groups were present for question NOS- E and for all of the geology questions. With an alpha level of .05, the effect of exposure to the treatment was deemed effective at increasing the mean score on questions NOS-A, $t(113.1) = -4.30$, $p < .001$; NOS-C, $t(205) = -2.36$, $p = .019$; and NOS-D, $t(195.2) = -6.13$, $p < .001$, causing the researcher to reject the null hypothesis for these three questions. Similarly, with an alpha level of .05, the effect of exposure to the treatment was deemed effective at changing the mean ranking of scores on question NOS-A, $z = -2.23$, $p < .001$ and NOS-D, $z = -5.05$, $p < .001$. Higher scores of students' responses indicate more accurate and more sophisticated responses; consequently the statistically significant differences in mean score of 1.49 (control) and 2.27 (treatment) on question NOS-A, 3.10 (control) and 3.60 (treatment) on NOS-C, and 2.68 (control) and 3.12 (treatment) on NOS-D are taken as evidence for improvement in students' understanding of these NOS concepts when students use the short stories. Also, statistically significant differences in Mann-Whitney mean rankings of 49.91 (control) and 71.01 (treatment) for NOS-A and 91.18 (control) and 124.45 (treatment) for NOS-D are taken as evidence of improved understanding demonstrated by the treatment group on these two questions.

Non-parametric statistics for these two questions are only included due to the fact that kurtosis values indicated slight deviation from normal distributions, but as has been described above this lack of normality is expected based on the typically low-level of understanding of the NOS concepts addressed by question NOS-A in the population at large and the significant improvement, shifting participants to the higher ends of the scale, for the treatment group for question NOS-D. While the treatment group for NOS-A and the control group for NOS-D did show normal distributions, it was deemed useful to run non-parametric tests to check against the possibility that the slight deviations from normality in their complementary groups might have been the cause of the statistically significant differences seen in t-tests. The confirmation of a positive shift for the treatment group provided by the results of Mann-Whitney tests can be interpreted as evidence that statistically significant improvements were attained for the NOS concepts addressed by these assessment questions.

Students appear to have made significant gains in their understanding of the variety of processes involved in the construction of scientific knowledge (from NOS-A), the ways in which data must be interpreted by scientists, the tentative, yet durable, nature of science knowledge (from NOS-C), and the effects that culture and society have on science, scientists and the process of constructing scientific knowledge (from NOS-D). More detailed description of these types of gains can be achieved through examination of the coding rubrics used to describe students' responses and will be presented later in this chapter.

For all other questions, NOS-E and all GEOL questions, statistically significant differences in mean scores were not observed, indicating that the treatment did not significantly improve or harm students' understanding of the material and causing the researcher to fail to reject the null hypothesis of no change for these questions. While this may seem discouraging, it is useful to note the fears some instructors have expressed that spending time on NOS concepts may detrimentally affect students' understanding of the science content appears to be unfounded, especially when the NOS instruction is embedded into content-specific materials such as the short stories – thus allowing for simultaneous instruction in NOS and geology concepts.

Statistical Comparisons within the Treatment Group: Does the number of short story assignments make a measurable difference in NOS and geology content understanding?

For the three questions that were affected by the treatment, it also was considered desirable to look for further description of situations that seemed to make the treatment most effective. The researcher quantified 1) the number of students who completed only the required homework assignment related to the age of the Earth, 2) the number of students who completed only the homework assignment related to plate tectonics, and 3) the number of students who completed both assignments, and these data were used to make comparisons of scores within the treatment group. Due to the small number of students who completed only one of the two short story assignments, the non-parametric Kruskal-Wallis test was used to test the null hypothesis that the number of short story assignments which students complete does not have an impact on their understanding. The results are shown in Table 6.

Table 6: Comparison of mean ranks within treatment group based on the number of homework assignments completed using the Kruskal-Wallis test

Assessment item	Group	N	Mean Rank	*p*
NOS-A: Invented or discovered science ideas	HW 1 only	3	35.50	.955
	HW 2 only	8	5.56	
	HW 1 & 2	56	33.70	
NOS-C: Multiple interpretations of data	HW 1 only	6	25.58	.274
	HW 2 only	5	41.70	
	HW 1 & 2	56	40.02	
NOS-D: Influences of culture and society	HW 1 only	7	29.50	.411
	HW 2 only	3	40.33	
	HW 1 & 2	56	33.63	
NOS-E: Influences of currently accepted scientific ideas	HW 1 only	7	32.36	.300
	HW 2 only	6	46.83	
	HW 1 & 2	57	34.69	

Table 6 (continued)

GEOL-A: Continental drift – Minerals in Brazil	HW 1 only	7	55.57	.105
	HW 2 only	5	38.30	
	HW 1 & 2	65	37.27	
GEOL-B: Absolute and relative dating methods	HW 1 only	7	40.86	.861
	HW 2 only	6	42.92	
	HW 1 & 2	64	38.43	
GEOL-C: Age of the Earth – Evidence in sedimentary rock	HW 1 only	3	9.67	.046*
	HW 2 only	9	36.06	
	HW 1 & 2	59	37.33	
GEOL-D: Plate tectonics – Difference in age of ocean & continental rocks	HW 1 only	7	50.14	.128
	HW 2 only	3	41.00	
	HW 1 & 2	62	34.74	

*Significant at α=.05

Only for question GEOL-C are statistically significant differences observed, causing the researcher to reject the null hypothesis that the number of stories completed makes no difference in students understanding of the concepts required to answer this question. Question GEOL-C asked students to describe the types of evidence a geologist would look for in a thick column of sedimentary rock to estimate the age of the Earth. An examination of the mean ranks shows that students who completed either homework two only or both homework assignments were ranked significantly higher than students who completed only homework one. Since the emphasis of homework two was on the historical evidence that has been used to estimate the age of the Earth, these results make intuitive sense and are seen as positive evidence that students within the treatment group did learn essential science content as they engaged with the short story. While it is encouraging to see that engaging in the homework assignments was helpful within the treatment group students, it still must be noted that based on the previously reported t-test results the treatment group overall was not statistically different from the control group.

It is notable that, using an alpha level of .05, for the three NOS quiz questions where statistically significant gains in understanding were made, the number of homework assignments completed did not make a significant difference in students' scores. This result differs from a key finding of the pilot study, conducted in the 2004/2005 school year. During the pilot study completion of both assignments resulted in higher scores on question NOS-C when compared to the scores of those who completed only the assignment involving deep time/age of the Earth. It is possible that the editing of the short stories which occurred between the pilot study and the current study may account for this difference; however, it is also quite likely that the small numbers of students who completed only one assignment during the current semester does not provide sufficient data upon which to make a strong conclusion. During the pilot study, the continental drift/plate tectonics assignment was assigned as extra credit, so a sizable number of students chose not to complete this assignment. In the current study, both short story assignments were required homework; consequently, almost all participants completed both assignments. This was an unexpected result – the participants in this study were more diligent in completing the required assignments than anticipated. With 298 total participants in the current study, about eight percent of the participants completed only one story. When looking at responses to individual quiz questions, which were randomly distributed among the participants, this related to a range of 3-9 students/quiz question who only completed one homework assignment. The lack of foresight concerning the number of participants who would self-select to respond to only one assignment must be viewed as a flaw in the research design, and as a consequence no strong conclusions can be reached concerning the effect that participating in multiple HOS assignments has compared to participating in only one assignment. For this reason, it is suggested that future studies would need to build stronger methods for assigning larger groups of students to complete only one of the two stories.

Statistical Comparisons within the Treatment Group: Does the amount of time spent completing the assignments make a measurable difference in NOS and geology content understanding?

During the coding of students' homework questions (discussed in more detail later in this chapter), the researcher noticed features in some students' responses which raised questions about the amount of time the students had spent reading and reflecting on the content of the short stories. To further interpret the effects of completing the short story assignments, it was considered desirable to examine whether or not the amount of time spent completing the stories had a significant effect. When the assessment questions were administered, students were asked to report the amount of time they had spent working on each assignment, using ranges of 0 minutes, <15 minutes, 15-30 minutes, 30-60 minutes, > 60 minutes. This data was used to make comparisons of scores within the treatment group.

ANOVA analysis of the treatment group was used to test the null hypothesis that the amount of time students spend completing the two short story homework assignments does not have a direct impact on their understanding. The results are shown in Tables 7 and 8. Again, only for question GEOL-C did the amount of time spent on the short story assignments have a statistically significant effect.

Table 7: Comparison of mean scores within treatment group based on the amount of time spent working on HW1 (continental drift/plate tectonics assignment), using ANOVA

Assessment item	Group	N	Mean score	Standard deviation	*p*
NOS-A: Invented or discovered science ideas	<15 minutes	6	1.67	1.21	.189
	15-30 minutes	15	1.87	1.13	
	30-60 minutes	40	2.50	1.22	
	>60 minutes	3	2.67	1.53	
	All groups	64	2.28	1.23	
NOS-C: Multiple interpretations of data	<15 minutes	6	3.50	1.05	.908
	15-30 minutes	23	3.52	1.56	
	30-60 minutes	40	3.73	1.59	
	>60 minutes	4	3.25	1.50	
	All groups	73	3.62	1.52	
NOS-D: Influences of culture and society	<15 minutes	3	3.00	.000	.609
	15-30 minutes	20	3.15	.366	
	30-60 minutes	37	3.08	.363	
	>60 minutes	3	3.33	.577	
	All groups	63	3.11	.364	
NOS-E: Influences of currently accepted scientific ideas	<15 minutes	5	2.40	1.14	.138
	15-30 minutes	30	2.27	.868	
	30-60 minutes	27	2.74	.712	
	>60 minutes	7	2.14	.900	
	All groups	69	2.45	.850	
GEOL-A: Continental drift – Minerals in Brazil	<15 minutes	7	3.14	1.77	.715
	15-30 minutes	24	3.63	1.28	
	30-60 minutes	39	3.31	1.13	
	>60 minutes	4	3.25	.957	
	All groups	74	3.39	1.23	
GEOL-B: Absolute and relative dating methods	<15 minutes	5	2.40	1.14	.985
	15-30 minutes	31	2.23	.956	
	30-60 minutes	30	2.27	1.02	
	>60 minutes	9	2.22	.833	
	All groups	75	2.25	.960	
GEOL-C: Age of the Earth – Evidence in sedimentary rock	<15 minutes	6	2.17	.753	.012*
	15-30 minutes	17	2.24	.752	
	30-60 minutes	41	2.49	.675	
	>60 minutes	4	3.50	.577	
	All groups	68	2.46	.742	
GEOL-D: Plate tectonics – Difference in age of ocean & continental rocks	<15 minutes	4	2.25	1.50	.537
	15-30 minutes	22	1.59	.908	
	30-60 minutes	38	1.92	.997	
	>60 minutes	5	1.80	1.30	
	All groups	69	1.83	1.01	

*Significant at α=.05

Table 8: Comparison within treatment group for amount of time spent working on HW2 (deep time/age of the Earth assignment), using ANOVA

Assessment item	Group	N	Mean score	Standard deviation	*p*
NOS-A: Invented or discovered science ideas	<15 minutes	5	1.80	1.30	.073
	15-30 minutes	20	1.80	1.06	
	30-60 minutes	38	2.47	1.22	
	>60 minutes	2	3.50	.707	
	All groups	65	2.25	1.21	
NOS-C: Multiple interpretations of data	<15 minutes	8	3.25	1.28	.472
	15-30 minutes	21	3.52	1.50	
	30-60 minutes	40	3.90	1.55	
	>60 minutes	4	3.00	1.41	
	All groups	73	3.67	1.50	
NOS-D: Influences of culture and society	<15 minutes	1	3.00	.	.950
	15-30 minutes	21	3.14	.359	
	30-60 minutes	35	3.11	.404	
	>60 minutes	5	3.20	.447	
	All groups	62	3.13	.383	
NOS-E: Influences of currently accepted scientific ideas	<15 minutes	9	2.44	.882	.480
	15-30 minutes	29	2.34	.857	
	30-60 minutes	23	2.70	.765	
	>60 minutes	4	2.25	1.26	
	All groups	65	2.48	.850	
GEOL-A: Continental drift – Minerals in Brazil	<15 minutes	10	3.30	1.64	.625
	15-30 minutes	22	3.18	1.33	
	30-60 minutes	38	3.45	1.06	
	>60 minutes	4	4.00	.816	
	All groups	74	3.38	1.21	
GEOL-B: Absolute and relative dating methods	<15 minutes	10	2.30	1.16	.985
	15-30 minutes	29	2.24	.912	
	30-60 minutes	26	2.19	.981	
	>60 minutes	6	2.33	1.03	
	All groups	71	2.24	.963	
GEOL-C: Age of the Earth – Evidence in sedimentary rock	<15 minutes	5	2.20	.447	.038*
	15-30 minutes	23	2.26	.752	
	30-60 minutes	38	2.61	.679	
	>60 minutes	3	3.33	.577	
	All groups	69	2.49	.720	
GEOL-D: Plate tectonics – Difference in age of ocean & continental rocks	<15 minutes	1	3.00	.	.596
	15-30 minutes	23	1.70	1.02	
	30-60 minutes	38	1.89	1.01	
	>60 minutes	6	1.83	.983	
	All groups	68	1.84	1.00	

*Significant at α=.05

For question GEOL-C, ANOVA results indicate that the time spent on the continental drift/plate tectonics assignment had a positive effect on the participants' scores, $F(3,64) = 3.93$, $p = .012$, and post-hoc results involving least-significant difference (shown in Table 9) indicate that students who spent approximately an hour working on the assignment received better scores on this question than did any of the participants who reported spending lesser amounts of time on the assignment. Similar results can also be seen for this question when examining the amount of time participants spent on the deep time short story assignment. ANOVA results indicate that the time spent on the deep time assignment had a positive effect on the participants' scores, $F(3,65) = 2.98$, $p = .038$, and post-hoc results involving least-significant difference indicate that students who spent approximately an hour working on the assignment received better scores on this question than did the participants who reported spending half an hour or less on the assignment. These results can be interpreted to support the idea that the stories effectively address the required geology concepts – in this case, the types of evidence and understanding of geological processes that scientists use to date sedimentary materials. This type of information is essential to understanding how and why the science community has developed a timeline to describe the ways in which the Earth has developed from its origin to the present. However, in order for students to benefit from the use of the materials, they must make them a serious part of their study strategies, spending an hour or more working with the materials to critically read the story and reflect on the concepts involved.

Table 9: Post Hoc Results involving Least Significant Difference for GEOL-C: Age of the Earth – Evidence in sedimentary rock

Homework Assignment	Time spent	N	Mean score	Mean difference from those who spent >60 minutes	*p*
HW 1: Continental Drift & Plate Tectonics	<15 minutes	6	2.17	1.33	.004*
	15-30 minutes	17	2.24	1.26	.002*
	30-60 minutes	41	2.49	1.01	.007*
	>60 minutes	4	3.50		
HW 2: Deep Time & The Age of the Earth	<15 minutes	5	2.20	1.13	.028*
	15-30 minutes	23	2.26	1.07	.014*
	30-60 minutes	38	2.61	.73	.083
	>60 minutes	3	3.33		

*The mean difference is significant at the .05 level.

Quiz Results: Qualitative Perspective

What changed in students' thinking and what areas still need improvement?

Coding of students' responses to the assessment questions provides both a measure of the degree to which accurate views exist in the population and also a description of the specific types of misconceptions that exist. The categories described through the coding process encapsulate specific types of student thinking which existed in the population, and as such can be used to describe the types of differences that the treatment group exhibit when compared to the control group. These types of comparisons can be used to describe the specific changes in student thinking which occurred, allowing for the statistically significant improvements previously described. For questions where no statistically significant difference was observed between the control and treatment groups, an examination of the coding categories can be used to describe the types of thinking present in the population, thus providing ideas about the degree to which students' views do and do not reflect accurate conceptions and allowing for more informed planning of instruction designed to combat specific misconceptions.

Inaccuracies for both NOS and geology concepts were revealed, and to varying degrees persisted in the population even after the treatment. These misconceptions may be particularly important to science instructors, as they can illuminate areas that could benefit from additional instructional time. In addition, they could be used as a guide for the development of additional HOS materials. As noted previously, misconceptions about the nature of science can adversely affect students' interest in pursuing science as a career as well as how they engage in public debate and decision-making concerning scientific topics. Misconceptions concerning key aspects of geology can be important to understand, as they may act as barriers to student success in multiple areas of the geology course. A detailed description of the patterns revealed through qualitative analysis of each of the eight assessment questions follows.

NOS Quiz Questions: What changes in students' thinking about NOS issues occurred and to what degree do misconceptions persist?

Question NOS-A: Invented or discovered scientific knowledge. Question NOS-A asked students to consider whether it was more accurate to describe scientific knowledge as being discovered or invented. Participants were also asked to provide an example from science to illustrate their response.

The coding rubric, which was developed by examining student responses for prevalent themes through an open-coding process based on the work of Strauss and Corbin (1998), consisted of a continuum that ranged from students who were strongly able to identify aspects of invention (and possibly also discovery) in the development of scientific knowledge to those who relied exclusively on a description that knowledge is discovered. As such, the coding rubric can be used to illustrate differences between the control and treatment groups. Table 10 provides an overview of the coding rubric and lists the number of students from the control and treatment groups in each coding category.

Table 10: Overview of the coding rubric for quiz question NOS-A - Invented or Discovered Scientific Knowledge

Score & Frequencies*	Category Description	Example(s) from Students' Quiz Responses
4 Group n % Ctl 2 3.6% Tx 15 22.4%	Response articulately describes how aspects of invention contribute to scientific knowledge. It may also recognize aspects of discovery. No NOS misconceptions are present.	"Scientists discover things about what they are studying but they have to use the new info and prior knowledge to create an explanation, such as when geologists discovered similar fossils on different continents and created the idea of a super-continent because it fit the evidence."
3 Group n % Ctl 3 5.5% Tx 15 22.4%	Response describes how aspects of invention contribute to scientific knowledge. It may also recognize aspects of discovery. Responses may fall into this category if ideas are not as clearly articulated as above OR the supporting evidence contains at least one NOS misconception.	"Scientific knowledge is not created, it is discovered mostly. The reason I believe this way is in discovering something, we didn't know about the world previously, such as finding an archeological artifact shows that uncovering is a main part of science; however, some measure of creativity is employed when interpreting that same archeological artifact."
2 Group n % Ctl 15 27.3% Tx 10 14.9%	Response describes that invention occurs and contributes to scientific knowledge. It may also recognize aspects of discovery. However, the supporting evidence is largely inconsistent with contemporary views on NOS.	"I think that science knowledge is discovered, but the little links between them are created until proven. There has to be something found or seen to provide you with knowledge. You can't just make it up."

Table 10 (continued)

1 Group n % Ctl 35 63.6% Tx 27 40.3%	Response emphasizes discovery in the development of scientific knowledge. Supporting evidence may contain additional NOS ideas that are inconsistent with contemporary views.	"It is discovered because science is about making a hypothesis and testing different ideas over and over until you get a feasible answer." "I think that science knowledge is discovered. People (scientists) discover new things every day (such as how Pluto was not a planet). They do not make information up."

*Total number of participants for control group = 55; treatment group = 67

The coding rubric can be used to illustrate that 22% of treatment group students (compared to 4% of control group students) provided articulate descriptions of the invented character of scientific knowledge. The following examples, using students' own words, illustrate their ideas about the degree to which invention plays a role in constructing scientific knowledge.

> Scientists discover things about what they are studying but they have to use the new info and prior knowledge to create an explanation, such as when geologists discovered similar fossils on different continents and created the idea of a super-continent because it fit the evidence.
>
> Scientific knowledge is created. Scientists must interpret the data they find; a discovery by itself means nothing unless a scientist 'creates' a meaning for it by interpreting the data.
>
> I think that you create knowledge of science but you also must use tools that are found as data, such as fossils that support prehistoric animals can fly.

These students recognized factors such as the interpretation of data and the use of prior knowledge to construct a scientific understanding of data, and they also are able to differentiate between objects and ideas in science – that even when an object or artifact is found, an idea has to be generated to explain what that object is. The explanation is not self-evident within the artifact itself.

The coding rubric also can be used to demonstrate that another 22.4% of treatment group students (compared to 5.5% of the control group) described aspects of invention that contribute to the development of scientific knowledge but were either significantly less articulate or had some NOS misconceptions entangled in their rationale. As has been described by Lederman (1992), students often exhibit a mixture of views on NOS issues, with some views being relatively informed and others rooted in misconceptions. The coding rubric acknowledges this facet of students' understanding, and the categories represent a continuum ranging from low to high levels of entangled misconceptions. In the treatment group, more students' responses were categorized as exhibiting no misconceptions or low levels of misconceptions when compared to the control group. Similarly, fewer students' responses were categorized as having higher levels of misconceptions, especially the idea that science knowledge is produced only through a process of discovery.

Ryan and Aikenhead (1992) describe a reliance on the idea that knowledge is discovered as being consistent with naïve realism – an ontological view that science knowledge reflects the way that things actually are. This type of view is problematic in that it does not accurately reflect either the ways in which human interpretation influences scientific knowledge or the tentative nature of scientific knowledge. Human interpretation of nature is an inventive process, with individuals constructing explanations to account for the data – much of which is often obtained through indirect methods. Since scientists cannot prove that ideas are correct – but instead tend to accept them as long as they are useful, do not conflict with other ideas, and have not been shown to be false – all scientific knowledge should be considered as tentative. The descriptions and examples provided by Ryan and Aikenhead related to the inventive and tentative nature of scientific knowledge were used to support the ranking of student ideas in the coding rubric. For this question, 64% of students in the control group and 40% of students in the experimental group expressed views that science ideas come about exclusively through discovery. Examples include the following students' statements.

> Science knowledge is discovered. Scientific facts and theories are discovered. New discoveries are found, it's not something you can go into a lab and make for the first time.
>
> The science is always there. It is just a matter of finding it. The science is just waiting to be discovered.
>
> There really isn't a way to 'create' things like plate tectonics. Scientists studied them and proved them to be vital in the earth's movement.
>
> I think science knowledge is discovered, it is not created because the more we research about it and read about it the more we discover. It is not like one person is sitting and creating the science knowledge.
>
> Science has nothing to do with feelings, thoughts, people's interests and so on. But it has to be logical and objective.
>
> I think that science knowledge is discovered. People (scientists) discover new things every day (such as how Pluto was not a planet). They do not make information up.

These examples reveal a wealth of information about misconceptions that students hold regarding the nature of scientific knowledge. Students who voice these views fail to see the aspects of creativity, subjectivity, and humanity that influence scientists as they formulate descriptions of nature. These students' statements make one wonder how the students feel about science and how they view their own ability to contribute to the field of science. With the prevalence of these types of views, it is no wonder that so many students express little desire to study science. For them, science is a body of knowledge to be memorized and expanded upon by those who are able to repress their human side as they make pure observations and discover what nature is doing; creativity, humanity, and social interaction must be minimized. While it is acknowledged that scientists hold relative objectivity as a goal, it also must be acknowledged that the prior background, beliefs, social interactions within and outside the scientific community, and a host of other factors all affect the fields that scientists choose to study, the methods of study and interpretation they choose to use, and the way in which they filter data and draw conclusions. In fact, without using these subjective frames to guide their work, scientists would find it extremely difficult to make any sense out of their observations at all. One must have a framework from which to approach a problem or question before one can examine the data in a meaningful way.

Unfortunately these ideas were quite common not only in the control group but also in the treatment group. While a statistically significant shift was seen toward views that better align with a contemporary understanding of the epistemological aspects of scientific knowledge, there is cause for concern that still 40% of participants in the treatment group relied exclusively on elements of discovery to describe how scientific knowledge develops.

In both the control and treatment groups, a number of misconceptions were present in students' responses to question NOS-A. These misconceptions were entangled in students' rationales for why science knowledge is invented or discovered, and thus can be viewed as areas that science instructors should consider when attempting to communicate accurate views about the NOS to students. Instruction intended to promote conceptual change should be built on an awareness of the prior ideas that students' possess and should promote students' ability to see how these conceptions are less fruitful than are contemporary accepted views (Posner, Strike, Hewson & Gertzog, 1982). Although the short stories were designed to fulfill these criteria of conceptual change, some misconceptions were resistant to change. The most common misconceptions are summarized in Table 11.

Table 11: Common misconceptions represented in responses to question NOS-A

Misconception	Frequency*	Example(s) from Students' Responses
Science knowledge was always there; we just had to find it.	Group n % Ctl 24 44% Tx 10 15%	"Scientific facts and theories are discovered. New discoveries are found, it is not something you can go into a lab and make for the first time." "Although we create theories and hypotheses, make observations and conjecture interpretations, the raw data of the universe exists already. We take this data and turn it into information. We discover that this science knowledge exists by becoming more versed in the subject; however, we did not create it." "Science is discovered. Things have always been there to discover. It just took some people to look for it and encourage others to continue looking. Nothing is new."
Equating scientific knowledge with nature	Group n % Ctl 18 33% Tx 12 18%	"The properties of our world don't change for the most part (e.g., gravity) but they aren't understood until someone discovers the property." "[Scientists] discover things like new plants, minerals, species, etc. [They] could maybe create new drugs, create in the way of cloning, etc." "You can be ignorant to knowledge, but it's still there. There are scientists who study rocks, but even if they didn't, the rocks would still be there."
Sufficient investigation leads to proven scientific knowledge OR Tests and experiments produce knowledge	Group n % Ctl 7 13% Tx 8 15%	"There really isn't a way to 'create' things like plate tectonics. Scientists studied them and proved them to be vital in the earth's movement." "I do not believe that we make up scientific knowledge. We must discover it through tests and creating hypotheses." "To truly discover science, your theory must be put to the test and proven." "Discovered because everything in science is tested to see if it is true."
Equating science with technology	Group n % Ctl 6 11% Tx 1 1.5%	"I think it is discovered and created. Things that are found in earth's history are discovered, while scientists create different things in order to broaden our knowledge of the science world. Fossils, earth's history, minerals relate to discovery. New techniques, tools, and machines relate to creation."
Some examples are purely invented, others are purely discovered OR Invented ideas are predecessors of knowledge	Group n % Ctl 14 25% Tx 8 12%	"In science you must discover something new to create a theory about it." "I think the tools of scientific discovery are created (i.e., mathematics, scientific methods). However, I believe scientific knowledge is discovered using those tools. "Once [scientists] discover science, they must create hypotheses and theories to explain their findings. Therefore, scientific knowledge is both created and discovered." "While hypotheses are created, they are often created and modified around discovered evidence."

*Total number of participants for control group = 55; treatment group = 67

An examination of these misconceptions reveals some interesting aspects of students' thinking about the ontology and epistemology of science. For example, some of the most commonly encountered misconceptions were based around an interpretation of science knowledge as being equivalent to aspects of nature (gravity, electricity, etc.), objects (artifacts, fossils, etc.), or technology (light bulbs, drugs, scientific instruments, etc.) Students did not distinguish between the objects (that could be discovered or invented) and the creation of scientific principles that account for the natural phenomena under study. When students confused knowledge with nature or objects, they often contended that science was discovered because these things exist independently of humans and have been in existence for long periods of time, whether we recognized them or not. In a related way, some students did distinguish aspects of scientific knowledge such as hypotheses or theories as being invented, but they still contended that other areas of science knowledge are wholly discovered, again often relying on misinterpretations of technology or objects as being equivalent to knowledge. In some cases, they also described invented ideas as either being inferior to discovered knowledge or that it was some sort of a predecessor of scientific knowledge, i.e. a hypothesis that could only be accepted if a discovery was made to further support and define it.

Another type of misconception centered around the idea that knowledge comes directly from tests and experiments. Students who expressed these ideas usually failed to acknowledge the host of subjective factors that go into tests and experiments – that scientists base their test designs around particular ideas, that interpretation of data is required, and that scientists may disagree about what the outcome of an experiment means depending on the theoretical framework they use. This type of misconception is even more prevalent in question NOS-C, which was designed to more deeply examine these ideas.

Fortunately, the frequency of misconceptions was lower in the treatment group. The short stories appear to be effective at helping students to understand the difference between nature and scientific knowledge as the occurrence of this misconception dropped from 33% frequency in the control group to 18% in the treatment group. Equating science with technology also dropped from 11% to 1.5%. Even more dramatically, while 44% of control group participants contended that science knowledge has always existed, we just had to discover it, only 15% of treatment group participants used this type of rationale.

Question NOS-C: Multiple Interpretations of Data. Question NOS-C asked students to consider why scientists, who have access to and make use of the same data set, draw different conclusions about what caused the dinosaur extinction. Participants were provided with brief descriptions of the two conclusions that are most prevalent within the scientific community – that either a large meteor or a series of volcanic eruptions caused the extinction. The coding rubric provides a description of the array of responses which students presented, including ideas that scientists can interpret data differently, indications that disagreement occurs because there is insufficient of flawed data, and attempts to resolve the disagreement. Table 12 provides an overview of the coding rubric.

Table 12: Summary of coding rubric for quiz question NOS-C - Multiple interpretations of data (Dinosaur extinction)

Score & Frequencies*	Category Description	Example(s) from Students' Quiz Responses
6 Group n % Ctl 15 11.5% Tx 8 10.4%	Response indicates that data is subject to interpretation due to the ways that science involves a human aspect and/or an inherent degree of uncertainty. No NOS misconceptions are present.	"Both of these conclusions are possible by different scientists using the same set of data because different people/scientists interpret data differently. Data can be interpreted in several different ways based upon different levels of knowledge and different experiences."
5 Group n % Ctl 12 9.2% Tx 23 29.9%	Response indicates that data is subject to different interpretation by different scientists, without significant discussion of underlying reasons. No NOS misconceptions are present.	"Because the data can be interpreted different ways there is evidence that can support both theories."
4 Group n % Ctl 12 9.2% Tx 5 6.5%	Response indicates that different conclusions are possible, but the supporting reasons contain a mixture of ideas, some that are and some that are not consistent with contemporary NOS views	"Different scientists interpret the same results differently. Not everyone sees the same thing in the same way. Plus there is no defining evidence either way."
3 Group n % Ctl 27 20.8% Tx 12 15.6%	Response implies that if certain insufficiencies in the scientific process were eliminated, then we might be able to resolve this dilemma OR that we just can't know.	"As with anything, statistical data can be manipulated to prove or disprove the same idea. Scientists of the different theories may only be using portions of the data." "None of us were alive then so no one can possibly know exactly what happened."
2 Group n % Ctl 12 46.2% Tx 23 37.7%	Response does not address the nature of scientific knowledge; instead an evaluation of the scientific accuracy and/or plausibility of the possible explanations using geological explanations is presented.	"Both events could kick up enough debris to block out sun and lower overall temperature enough to kill them off, or [it] could have been both events together that led up to the die-off."
1 Group n % Ctl 4 3.1% Tx 0 0%	Response relies exclusively on significant NOS misconceptions	"Because they are only theories - nothing has become a fact. They haven't been able to prove anything, so it's all speculation and theorizing."

*Total number of participants for control group = 130; treatment group = 77

A relatively large number of students failed to address the nature of scientific knowledge, but instead attempted to describe the scientific evidence used to support each conclusion. (This type of response is represented by category 2 in the coding rubric.) The fact that other quizzes and tests in the course were built with an expectation that students would describe scientific evidence rather than NOS issues most likely had a significant effect on how these students responded to the question. However, it also may be true that for these students thoughts about the nature of scientific knowledge are relatively foreign and are not at the forefront of their mental processes when they consider scientific findings. It was notable that the frequency of participants in this category decreased from the control group (46.2%) to the treatment group (37.7%), indicating that the short story assignment was effective at increasing the number of students who readily recognize nature of science issues in examples such as the one provided here.

Within the remainder of the students, responses reflected a continuum consisting of four major groups: 1) responses that articulately described factors of the NOS that enable multiple interpretations of data (human interpretation of natural events, different backgrounds and/or theoretical perspectives used by different scientists, inherent uncertainty in data, etc.); 2) responses that acknowledged that data was open to interpretation but did not provide detailed description of why this is so; 3) responses that relied to varying degrees on NOS misconceptions to describe why different interpretations of data are possible; and 4) responses that were wholly inconsistent with a contemporary NOS understanding (such as discounting the value of scientific information that is not completely certain, or that if we get enough high quality data then we will be able to know for certain.) Major components of this continuum centered on the degree to which the participants acknowledged a role for some degree of subjectivity in the interpretation of data (that scientists use their backgrounds, prior learning, theoretical frameworks, etc. to help them screen data and construct meaning from it) and the degree to which participants viewed scientific knowledge as having a tentative nature (that we can never prove with one hundred percent certainty that our ideas are correct or are true reflections of nature). Students in the treatment group were much more likely to acknowledge that data is subject to interpretation by scientists (40.3% of treatment group compared to 20.7% of control group). However, most of these students did not provide a strong rationale for why this is the case, possibly indicating that the improved NOS ideas of the treatment group are relatively fragile. If students are not able to provide supporting rationales for their ideas, then these ideas have probably not been strongly built into their conceptual framework.

Lederman et al. (2002) developed the question on which this item is based in the VNOS instrument. From their use of the VNOS with NOS experts and novices, they reported that major differences could be seen between groups – novices were much less likely to acknowledge that science ideas are subject to change, particularly due to reinterpretation of existing evidence, and were much less likely to acknowledge that some degree of subjectivity plays a role in the interpretation of data. Lederman et al. (2002) offered the following examples of naïve views and more informed views (respectively) for this question.

> [Scientists reach different conclusions] because the scientists were not around when the dinosaurs became extinct, so no one witnessed what happened … I think the only way to give a satisfactory answer to the extinction of the dinosaurs is to go back in time to witness what happened.

> Both conclusions are possible because there are many different interpretations of the same data. Different scientists may come up with different explanations based on their own education and background or what they feel are inconsistencies in others' ideas. (p. 516)

The descriptions and examples provided by Lederman et al. (2002) were used to support the ranking of student ideas in the coding rubric. In addition, these examples were useful to help describe the common types of misconceptions that were present in students' responses, shown in Table 13.

Table 13: Common misconceptions represented in students' responses to assessment question NOS-C

Misconception	**Frequency***	**Example(s) from Students' Responses**
We can't know because we weren't there. (Implies that if direct observations can be made, then answer can be known with certainty.) OR Because no one knows. (Implies in other circumstances it is possible to know for certain.)	Group n % Ctl 11 8.5% Tx 7 9.1%	"It is difficult to conclude information about something that no one alive has lived through." "None of us were alive then so no one can possibly know what happened." "Because no one really knows for sure. There is evidence, but not complete step by step information for what went on."
The scientists are focusing on different data sets or are only looking at part of the data OR If scientists use the same data they should agree.	Group n % Ctl 6 4.6% Tx 2 2.6%	"It could be a combination of both so there could be data that supports both but they are each ignoring the other set when looking at what they think happened." "It is unknown to me how the same sets of evidence can lead to such varied results."
We need more or better data to make a conclusion. Current data is inconclusive. (Implies that other data could be conclusive.)	Group n % Ctl 25 20.0% Tx 8 10.4%	"There is no data showing for sure what had happened 65 million years ago – only predictions and assumptions can be made about the exact cause." "Because the rock from this period of time has dissolved or has been buried further than what scientists can get to, there isn't a lot of data from this time saying what could of possibly happened." "There is no distinct evidence one way or another. It is hard to predict what caused the extinction."

Table 13 (continued)

Due to faulty science – misinterpretation of data, extreme bias, etc.	Group	n	%	"As with anything, statistical data can be manipulated to prove or disprove the same idea."
	Ctl	6	4.6%	
	Tx	0	0%	
Because no one has proven anything and we don't have hard facts.	Group	n	%	"People assume that scientists know what they are talking about when scientists can't even prove it." "Because they are only theories nothing has become a fact. They haven't been able to prove anything, so its all speculation and theorizing."
	Ctl	3	2.3%	
	Tx	0	0%	

*Total number of participants for control group = 130; treatment group = 77

The most common misconceptions, for both the control and treatment groups, relied on the ideas that we need more or better data and that we could know if we had been there to directly observe what happened. These ideas can be seen as related because both rely on the idea that our data sources are inadequate. While it is true that limited data exists about what happened in the past, students who rely on these rationales are ignoring the fact that, no matter how much data exists, the data requires interpretation. The idea that we need more or better data was present in 20% of the control group responses but in only 10% of the treatment group responses. This shift can be interpreted to mean that the short story assignments helped students understand the tentative character of scientific knowledge and that scientists may disagree about what data means and how it should be interpreted. These concepts were illustrated in the homework assignment readings. One of the stories included descriptions of how Wegner, one of the first proponents of continental drift, presented evidence in support of the idea that the continents have moved, but his peers interpreted the data differently and even used it to support the prevailing idea of the time that the continents do not move. Tentativeness was illustrated in a companion story – eventually the prevailing ideas gave way and some of those who had used their own data to support a view of stable continents begin to reinterpret the data, using it to support continental drift and adding new details to the theory.

At the same time, the frequency of responses that indicate that if we had been there we could know was relatively stable (8.5% in the control group and 9.1% in the treatment group). This idea must be interpreted as somewhat problematic – a significant minority of the group is still focusing on the idea that direct observations are unambiguous in their meaning. These students are not considering the inherent uncertainty that exists in data, and further efforts to induce change in their thinking, perhaps using contemporary examples from science, would likely be useful.

Finally, two types of misconceptions that had been present in the control group are now absent in the treatment group: the idea that different interpretations of data only come about due to faulty science and the idea that tentativeness can be eliminated from science when concepts are proven.

The qualitative analysis described here provides essential supplementary information to further elucidate the statistically significant gains in understanding reported earlier. Overall, 40.3% of treatment group students seem to be confident in the idea that data is subject to interpretation, compared to only 20.7% of the control group. In addition, when student used the short stories the frequency of all categories of misconceptions decreased, with the exception of the view that direct observation leads to unambiguous conclusions.

Question NOS-D: Influences from culture and society on a scientist's work. Question NOS-D asked students to consider to what degree culture and society influence a scientist's work. Participants were asked to provide an example to illustrate their descriptions. Through coding, an array of responses were described – including the ideas that culture and society provide guidance for, limitations to, or have no effect on scientists' work. The frequencies of student responses for each category, summarized in Table 14, can be interpreted as evidence that most students in both the control and treatment groups see connections between cultural or societal factors and the work of scientists.

Table 14: Summary of coding rubric for quiz question NOS-D - Cultural & Societal Influences

Score & Frequencies*	**Category Description**	**Example(s) from Students' Quiz Responses**
4 Group n % Ctl 3 2.2% Tx 9 13.6%	Response describes ways in which culture and society guide <u>and</u> limit scientists' work.	"Culture and society can affect a scientist's work both positively and negatively. Problems in society can drive scientists to find solutions – such as better building materials for people in areas at risk for natural disasters, or the creation of new kinds of medicine. On the other hand, negative public opinions about issues in science such as global warming or stem cell research might cause scientists to focus their work on areas that would be better received by the public, and therefore hinder scientific improvement."
3 Group n % Ctl 98 71.5% Tx 56 84.8%	Response describes ways in which culture and society guide <u>or</u> limit scientists' work.	"People tend to explore what they believe, that is greatly influenced by culture and society." "Culture and society have a huge effect on scientist's work because if the public doesn't accept it they could try to stop the research from happening. They could try to stop it by sabotaging it or protesting. Some examples are releasing of animals that were used for testing or not giving money for stem cell research."
2 Group n % Ctl 25 18.2% Tx 1 1.5%	Response focuses only on science for the greatest good, on limitations of science due to declines in the environment, or on the role of society to demand proof from scientists.	"I think that society and culture dictate what a scientist studies. They will study what is important to the average person so that their work will benefit all of society. If the work isn't for some greater benefit, then it's kind of a waste of time." "A scientist's ideas have to go along with the beliefs of the society in order to be generally accepted as true."

Table 14 (continued)

1	Group	n	%	Response indicates that culture and society do not or should not influence a scientist's work.	"I don't think that culture and society should have an effect on a scientist's work because all the scientist is doing is researching or trying to discover/prove something. They should do their work without influence to give us the straight facts, although sometimes society does influence them. Scientists must now do things in an acceptable manner so as not to disturb the society or make society angry. I think this is dumb though, unless the scientists are doing something wrong/harmful, just let them do their work."
	Ctl	11	8.0%		
	Tx	0	0%		

*Total number of participants for control group = 137; treatment group = 66

In their VNOS instrument, Lederman, et al (2002) asked participants to comment on the degree to which science reflects cultural and social values. They described examples of naïve and more informed views. Naïve views consisted of statements like the following.

> Science is about the facts and could not be influenced by cultures and society.
>
> The society can sometimes not fund some scientific research. So in that sense it influences science. But scientific knowledge is universal and does not change from one place to another (p. 516).

More informed views consisted of statements such as the following two examples.

> Of course culture influences the ideas in science. It was more than a 100 years after Copernicus that his ideas were considered because religious beliefs of the church sort of favored the geocentric model.
>
> All factors in society and the culture influence the acceptance of scientific ideas … Like the theory of evolution was not accepted in France and totally endorsed in Germany for basically national, social, and also cultural elements. (p.516)

In a similar fashion, the coding categories for question NOS-D consist of a continuum based on the degree and types of influence that students describe for cultural and societal factors on science. Responses that describe no connection are at the lowest end of the rubric; those describing influences from culture and society that specifically guide and/or limit science are higher on the rubric. Following are some examples that demonstrate the views of students in the treatment group about how cultural and societal factors influence science.

> Society and culture affect a scientist's work because each scientist has different views on certain things. If a scientist grew up on a farm, he/she would probably be more aware of things happening in farm and rural areas.
>
> Culture and society have an affect on an individual scientist's work because they form the context in which the scientist lives and works, and they affect his world view and beliefs. As the readings demonstrated, scientists are often influenced by their beliefs and this is the starting point of their research.
>
> Scientists are apt to make their theories and ideas comply with how their culture views things. Even if a scientist tries to be indifferent they cannot completely disregard the thoughts society has given them.
>
> A scientist usually tries to find answers to problems in society at that time and that is influenced by society.
>
> An individual is the product of their society and their culture. With culture as our own lens, one can never be completely objective in reporting findings or working on experiments.
>
> Early science was heavily influenced by the Bible and other cultural/religious works. Also controversial science could be discouraged and might have trouble being accepted however right it may be.

In addition, many students voiced views about contemporary cultural and social barriers that scientists face, using examples such as global warming and stem cell research to illustrate the idea that society can limit the impact of scientists' work if social forces cause the work to be viewed as questionable, unethical, or invalid.

Two significant areas of improvement exist with the treatment group when compared to the control group. The first is the absence of responses indicating that culture and society do not or should not influence the work of scientists. The second is the increase in the types and numbers of influences that treatment group students describe. The student responses listed and described above indicate a relatively rich understanding of ways in which cultural and societal factors influence science, with virtually all of the students in the treatment group providing relevant descriptions and/or examples of these influences. These descriptions help to explain and illustrate the statistically significant differences reported between the control and treatment groups earlier in this chapter.

Question NOS-E: Influences of currently accepted scientific ideas on a scientist's work. Question NOS-E asked students to consider to what degree currently accepted scientific ideas influence a scientist's work. Participants were asked to provide an example to illustrate their descriptions. Through coding, students' responses were categorized based on varying views of whether currently accepted scientific ideas provide useful structure for, cause limitations to, or have no effect on scientists' work. Students' responses also demonstrated varying degrees of acknowledgement that currently accepted ideas are tentative. Table 15 provides an overview of the coding rubric.

Table 15: Summary of coding rubric for quiz question NOS-E – Influences of currently accepted ideas on a scientist's work

Score & Frequencies*	**Category Description**	**Example(s) from Students' Quiz Responses**
4 Group n % Ctl 11 9.1% Tx 8 11.4%	Response describes ways in which currently accepted ideas provide useful structure for <u>and</u> provide limitations to scientists' work. OR Respondent strongly embraces and focuses on the idea that currently accepted ideas are tentative and can change. No NOS misconceptions are present.	"Current ideas can shape an individual's ideas in two ways: They can agree or disagree. For example, if a scientist doesn't believe in evolution, [he] will probably be looking for evidence to the contrary, and is therefore unlikely to ever agree. However, if a scientist agrees with current ideas, he will probably only consider evidence that is consistent with current theory, shaping his ideas." "It is kind of like scientific paradigms. A way of method and reasoning affects how research is interpreted and analyzed."

Table 15 (continued)

3 Group n % Ctl 47 38.8% Tx 24 34.3%	Response describes ways in which currently accepted ideas provide useful structure for or provide limitations to scientists' work. Some degree of tentativeness of currently accepted ideas is also present. NOS misconceptions may also be present.	"When scientists are working on new ideas they use accepted scientific ideas as well. If an accepted idea is incorrect, people have spent time researching for no reason." "Widely accepted ideas will often discourage individual scientists from proposing new theories. For example, the first hypotheses regarding continental drift were rejected because they opposed the currently accepted idea."
2 Group n % Ctl 57 47.1% Tx 30 42.9%	Response describes ways in which currently accepted ideas provide useful structure for or provide limitations to scientists' work. The response is neutral with regards to tentativeness. NOS misconceptions may also be present.	"Currently accepted ideas are used as a starting point for other scientists to work off of." "Scientists apply accepted theories to their work, I believe. For example, scientists use the theory of global warming and the idea on their new and current work on the idea."
1 Group n % Ctl 6 5.0% Tx 8 11.4%	Response refers to currently accepted ideas as providing a useful framework, but the framework is seen as rigid and unchangeable. OR Response indicates that currently accepted ideas do not have an effect on an individual scientist's work.	"I think that currently accepted ideas are seen pretty much as fact, so not very many people think outside the box to come up with new ideas. All ideas researched today are based on things that were proven before." "I don't think it has that much of an effect on the individual scientist. It only makes him look better and people respect and listen to his/her ideas more."

*Total number of participants for control group = 121; treatment group = 70

Responses ranged from views that currently accepted scientific ideas either provide a rigid framework that must be adhered to by scientists or have no effect at all on individual scientists' work (at the low end) to those that described ways in which currently accepted ideas, although tentative in nature, provide guidance for and/or set limits on the work that scientists do (at the high end). The degree to which students accurately described the tentative, yet durable, character of scientific knowledge is also represented in the coding categories. Responses which acknowledged that scientific ideas have the potential to undergo change but still are highly valuable in their explanatory and/or predictive ability were scored higher than those which did not address of denied the tentativeness of scientific ideas. Examples of more naïve and more informed views, respectively, concerning the durability aspect are seen in the response to a question from Lederman et al (2002) that asked participants to consider the function of scientific theories.

> We learn scientific theories just so that scientists don't start all over from the beginning … they just can add to the old ideas.
>
> Theories set a framework of general explanation upon which specific hypotheses are developed. Theories … also advance the pool of knowledge by stimulating hypotheses and research. (p. 515)

Further, Lederman et al. (2002) describe that the culture of science itself "establishes rules of practice and evidence. These rules have a crucial role in limiting subjectivity through the application of peer review and group consensus" (p. 508). The culture of science should be considered as a key part of the currently accepted ideas that responses to question NOS-E could address.

The most common NOS misconceptions found in participants' responses were that currently accepted ideas do not necessarily affect a scientist's work or that currently accepted ideas provide a rigid network of proven information that must not be challenged by scientists as they work. Examples of these two viewpoints can be seen in the following students' responses.

> I don't think it has that much of an effect on the individual scientist. It only makes him look better and people respect and listen to his/her ideas more.
>
> None. People do what works best for them.

> There is no effect from scientific ideas on individual scientific work because there is always something that can be altered or questioned making all existing data irrelevant.
>
> Current ideas affect an individual scientist's work because they believe that those ideas are correct and base their reasons just off an idea not on a theory.
>
> Scientific ideas that are currently accepted do affect individual scientists work. An example of this is the scientific method. This idea is currently accepted and effects scientists all the time when forming ideas and experiments. Without this method scientists would not have an effective way to figure out whether or not an idea will come out as planned and can help them to prove their ideas to others. If they didn't use this they would have most of their ideas/experiments believed to not be credible or proven.

This last example relies on the assumption that all scientists always follow a universal, step-wise scientific method – a misconception that has been well-described in the literature (McComas, 2000; Ryan and Aikenhead, 1992).

Although significant improvement was not seen in the treatment group for this question (as described earlier in this chapter), the elucidation of student thinking provided by the coding rubric provides vital information about the types of ideas students possess and may be used to inform future efforts in this area. While the majority of students in both the control and treatment group were able to express relatively informed views about the ways that scientists rely on existing science knowledge to guide and/or restrict their work, further gains could be made in the degree to which students articulate the simultaneously tentative and durable nature of this knowledge. A few students at the low end of the coding continuum view existing knowledge as providing either an overly rigid structure or no structure at all. Almost half of the students' responses reflect an ambiguous middle ground due to the fact that they did not address the tentative, yet durable, character of science. Although these students were able to express ideas about how current knowledge affects a scientist's work, their epistemological and ontological ideas are not clearly expressed in their responses. Either these ideas are not at the forefront of student thinking or the question does not sufficiently prompt students to engage in discussion of these ideas. Further modification of the assessment question and curriculum designed to illustrate these concepts may be needed.

Geology Quiz Questions: What areas are best understood by students and what are their misconceptions?

Although statistically significant differences between the control and treatment groups were not measured on the quiz questions that addressed plate tectonics and the evidence geologists use to determine the age of the Earth, the descriptions of students' views which were characterized through the coding process can be used to provide unique insight into students' thinking. Typical exams in large, lecture-based university classes consist of multiple choice items, and students' responses to these exams do not provide significant insight into their thought processes. The analysis presented here can provide a more detailed view of what students do and do not understand about the concepts of continental drift, plate tectonics, deep time, and the age of the Earth. This type of knowledge could be use to geology instructors as they plan for instruction and develop curriculum intended to promote an accurate understanding of geology.

Question GEOL-A: Mineral deposits in Brazil. Question GEOL-A asked students to predict where geologists might look for mineral deposits of the same age as those formed in Brazil 200 million years ago and to explain the geologists' rationales. The coding rubric describes an array of responses, with the most informed views based around the idea that 200 million years ago the continents of South America and Africa were connected together.

Table 16 provides an overview of the coding rubric.

Table 16: Summary of coding rubric for quiz question GEOL-A – 200 million year old mineral deposits in Brazil

Score & Frequencies*	Category Description	Example(s) from Students' Quiz Responses
5 Group n % Ctl 23 33.3% Tx 17 22.1%	Response describes the idea of a super-continent (Pangaea) that existed at the time in question and refers to Africa as a likely location to look.	"A likely prediction would be Africa because the two continents were connected during the time that Earth had the large supercontinent Pangaea."
4 Group n % Ctl 19 27.5% Tx 24 31.2%	Response describes the idea of a super-continent (Pangaea) that existed at the time in question and suggests looking at areas that were connected to Brazil.	"They could look to any countries that were close or connected to Brazil during Pangea. They would have the same minerals as Brazil."
3 Group n % Ctl 7 10.1% Tx 13 16.9%	Response suggests looking for areas that have similar specific geological characteristics. No rationale based on areas that may have been linked in a super-continent is presented.	"A geologist would probably predict that these minerals occurred in more than one place, therefore they would probably use evidence such as rock layers, depth, and the general environment around the site to identify other places alike. By using evidence found at the site, a geologist has an idea where else to look."
2 Group n % Ctl 7 18.8% Tx 13 24.7%	Response suggests looking further in the same general location or nearby locations OR Response suggests looking for areas that have similar climates. No rationale based on areas that may have been linked or had similar specific geological characteristics is presented.	"A likely prediction would be to keep searching related areas in Brazil. It makes sense that if some mineral deposits were found in areas of Brazil, then its likely that there would be more mineral deposits in related areas to where this discovery was made." "Mineral deposits of a similar age will probably be found in the same area, or an area with the same climate or similar things as Brazil. They would maybe predict they found this, because some type of weather or reaction uncovered these mineral deposits."

Table 16 (continued)

1 Group n % Ctl 7 10.1% Tx 4 5.2%	Response contains only major inaccuracies or irrelevant ideas.	"Geologists would probably predict that minerals of a similar age might be found off the coast of Asia because the oceanic currents that brought these minerals to Brazil may have carried these same minerals through the Pacific Ocean and to Asia."

*Total number of participants for control group = 69; treatment group = 77

Examination of the frequencies of students' responses rated in each category demonstrates that over half of the population referred to the idea of the super-continent, Pangaea, and the concept of continental drift in response to the question. The primary difference between responses in the top two tiers of the coding rubric was based on whether or not students specifically referred to the connection that existed between South America and Africa; otherwise, responses in both categories appeared to indicate that students were well-informed of the idea of continental drift and its relevance to the question.

Within the middle two categories, however, several ideas were commonly encountered that did not rely on continental drift and that presented incomplete rationales for how a geologist would likely approach this problem. An examination of students' thinking from these categories could help illuminate areas that would benefit from additional instruction during introductory geology courses. Many of these responses referred to a general method of looking for some common feature that could be used to identify where mineral deposits of a similar age would be located. Common features included: looking further in the same general location, looking for other locations with similar climates, and looking for other locations with similar geological characteristics such as topography, depth and layering of sediment, volcanic activity, etc.

The idea that geologists could look further in the same location was considered accurate but overly simplistic – this type of response does not demonstrate an understanding that at this time in the past different continents were connected together and consequently other locations should also be examined. An example of this overly simplistic approach is provided from the following student quote. “They will probably find about the same age minerals around Brazil, because if they found minerals that old in Brazil I’m sure they will be close to the same age near places around Brazil.”

The idea that geologists would look for an area with a similar climate seems to be an indication that students do not understand what types of processes lead to mineral formation and/or that they are overlooking a fundamental principle of continental drift. A typical example is provided by a student who suggested “looking in areas with similar climates because they may have developed mineral deposits at the same time in their history.” These students may be confusing ideas used to locate fossils with ideas about minerals. If a geologist was looking for similar fossils, it could be important to consider the climate because this would be a factor that could help define the types of organisms that would be sustained in the region. Climate is not an important factor for mineral formation since most mineral deposits come from inorganic sources. In addition, looking for areas with similar climate to that which is found in Brazil today significantly overlooks the idea that climates may have changed substantially, particularly as the continents have separated and drifted to other locations on the planet. The tropical wet climate of some portions of coastal Brazil aligns quite closely with some currently arid and semi-arid coastal portions of Western Africa.

Finally, the idea that geologists would look for an area with similar geological characteristics can be considered to be only partially correct. For example, one response suggested looking “at an area with a similar erosion pattern and sea level” and another that “they might look in other regions and countries with similar topography, location, and characteristics.” These ideas appear to ignore the fact that similar geological events can occur at vastly different periods in time. Consequently, although similar geological features may be a clue that similar types of minerals could be found, these minerals may be of a very different age from those found in Brazil. Conversely, some students referred to looking for areas that are of the same age (based on depth of sedimentary layers, fossil record, or radio-isotopic dating), but ignored the idea that similar geological events would have been needed to form the mineral deposits. For these students, the only geological characteristic that was mentioned was the age of the layers. One student stated “Dig to the same depth. Generally the same stuff will be about the same level.” Ideas such as these seem to be based on an assumption that similar geological events were occurring world-wide at the same time, an idea that stands in sharp contrast to what students likely know to be characteristic of the world today.

It could be quite useful to geology instructors to realize that students have these ideas about geology and that they have not managed to connect together ideas sufficiently to adequately address the issues presented by this question. In particular, geology instructors could discern from this that students need to further develop their ideas about the differences between minerals and fossils, the implications of continental drift for climates, and the need to use multiple pieces of evidence together (i.e. dating techniques, geological features, and continental drift theory) to answer questions such as the one presented here.

Question GEOL-B: Absolute and relative dating methods. Question GEOL-B asked students to describe how geologists combine absolute and relative dating methods to bracket the age of sedimentary rocks. The most informed views demonstrated an understanding of what methods can be used for absolute dating and the limitations of absolute dating on sedimentary material. Table 17 provides an overview of the coding rubric.

Table 17: Summary of coding rubric for quiz question GEOL-B – Relative and absolute dating methods

Score & Frequencies*	**Category Description**	**Example(s) from Students' Quiz Responses**
4 Group n % Ctl 9 13.0% Tx 8 10.4%	Response provides at least one relevant example of absolute dating and one relevant example of relative dating, with reference to how bracketing can be used to describe the age of sedimentary rock.	"Absolute will use definite aging methods [by] looking at isotopes and half lives. Relative dating is more common sense. If a dike is not layered it is younger because you tell that it formed over the sedimentary rock that was already there. By taking sample of dike, you could also date it with absolute dating."
3 Group n % Ctl 19 27.5% Tx 22 28.6%	Response 1) provides only an accurate example of relative dating, or 2) provides only an accurate example of absolute dating, or 3) fails to provide description of how the two forms of dating are used to bracket the age of sedimentary rocks. An inaccuracy may be present, detracting from the quality of the answer.	"This rock layer's on top of that one therefore this one's older than that one." "They can use index minerals to find a relative date, and radioactive dating to find absolute dates." "I don't really know but I think that the carbon-14 dating can be used as absolute dating and a relative dating would have been an approximation of when a species like that lived. If you put the two together you can place it into an age bracket in the sedimentary rocks."
2 Group n % Ctl 17 24.6% Tx 28 36.4%	Response is very vague and missing important details. Inaccuracies and/or irrelevant ideas may be present, further detracting from the quality of the answer.	"Geologists age sedimentary rock through looking at the other layers around it to see what's going on. They look at fossils and any type of activity that was also happening."

Table 17 (continued)

1 Group n % Ctl 24 34.8% Tx 19 24.7%	Response contains only major inaccuracies or irrelevant ideas OR Student states they do not know.	"They combine the dating methods when dealing with angular conformities and disconformities. Geologists don't really know the 'actual' dates of any rocks, they just make them up. It's kind of disappointing." "I am not sure. Once they date the rocks, I know they can get information about the world's history and evolution. The data also helps predict the future."

*Total number of participants for control group = 69; treatment group = 77

For approximately one-quarter to one-third of the students in both groups, the responses either contained only inaccurate and/or irrelevant information or directly indicated that the student did not know the answer. Considering that the assessment was performed during the last month of the semester long class, it is surprising to note that this large of a portion of the class was unable to present more accurate information related to the question. The understanding of dating techniques is a key part of the class and was used in conjunction with a study of many facets of the Earth's development and history throughout the class. Because the length of time needed to describe the Earth's history is unfathomably longer than time units that human beings can encounter (a concept referred to as deep time), students' understanding of the timeline of events in Earth's history is often dependent on their understanding of dating techniques that can give the student some perspective about relative lengths of time. Philips (1991) reported the following common Earth science misconceptions among high-school through adult aged individuals: mountains and glaciers are formed rapidly, the Earth is between six and twenty thousand years old, and dinosaurs and humans coexisted on Earth. Findings from this study illustrate that many students do not accurately understand dating techniques. This lack of understanding could impede student's ability to fully understand concepts that rely on this type of information, such as those describe by Philips.

In addition, two specific ideas were commonly encountered in students' responses that present conflicts with the ways in which geologists actually work and that indicate misunderstandings of key ideas in geology. First, some students referred to the use of index minerals as a means of dating sedimentary rock. Apparently these students have taken two separate ideas (those of index fossils and index minerals) and altered or hybridized them as they fit the ideas into their own mental constructs. Index fossils refer to the fossilized remains of an organism that existed for a relatively short (geologically speaking), known span of time; index minerals are used to determine the heat and pressure conditions needed to form metamorphic rock. While index fossils can be used to determine relative dates, mineral deposits cannot be used as a time index for the Earth's crust because there is no specific time frame to which they can be isolated. If the minerals contain appropriate radioactive isotopes, then they can be dated via absolute dating techniques, but each time a particular mineral is encountered in a new setting it would need to be dated separately as it may have a different age than comparable mineral deposits found at other locations. A second erroneous idea common to student's responses was that carbon-14 dating could be used for rocks and minerals. Carbon-14 is only useful for dating organic matter since it is maintained at a stable level by living material and then begins to decline when the material dies. Minerals, as inorganic non-living material, do not maintain set levels of carbon-14 and thus there is no means of comparing current amounts of carbon-14 to some earlier amount. If geology instructors are aware of these common misconceptions, they can design instructional strategies that target these concepts and seek to promote more accurate understanding of the characteristics of index fossils and radio-isotopic dating.

Question GEOL-C: Dating a thick sedimentary layer to determine the age of the Earth. Question GEOL-C asked students to describe features that would be found in a layer of sedimentary rock and explain how these features could be used to determine the age of the Earth. The most informed views demonstrated an accurate understanding of multiple methods that can be used for dating sedimentary material. Table 18 provides an overview of the coding rubric.

Table 18: Summary of coding rubric for quiz question GEOL-C – Features used from sedimentary rock layer to determine the age of the Earth

Score & Frequencies*	Category Description	Example(s) from Students' Quiz Responses
4 Group n % Ctl 7 10.0% Tx 3 4.2%	Response provides at least two types of evidence (radio-isotopic dating of igneous material, use of index fossils, and unconformities, representing gaps in time) and/or a detailed description of relative dating methods to compare ages of various layers within the sediment.	"I would expect to see younger and different rocks on top, some intrusions, faults, and other things in the rock. If there are intrusions in the rock you can date them by half-life as well as other rocks in the column. If the half-life is accomplished for the bottom rock at a longer time than 10,000 years then you can infer that the bottom layer as well as the earth is older."
3 Group n % Ctl 35 50.0% Tx 34 47.9%	Response provides 1-2 types of evidence, but the response is missing important details such that the reader has to presume complete understanding of the concepts and terms included.	"You would see different types of rock and fossils that would help determine the age. These fossils could be fossils ... of plants or animals that were only alive at a certain time." "I would expect to see different types of rocks and various fossils. Scientists could use this to test the rock ages by drilling and using carbon-14 dating." "I would expect a smaller percentage to contain fossils of higher organisms, more volcanic and high heat/activity rocks."

Table 18 (continued)

2 Group n % Ctl 14 20.0% Tx 27 38.0%	Response is very vague and may only list items that could be found in the column of rock without description of how/why these items are useful or may make reference to the presence of numerous layers as the sole evidence for the age of the column of rock.	"I would expect to see many different types of rocks that would indicate different time periods. Maybe would also see deformation in the older rocks." "Different layers account for different periods of time."
1 Group n % Ctl 14 20.0% Tx 7 9.9%	Response contains only major inaccuracies or irrelevant ideas OR Student states they do not know.	"The rock would obviously get harder and softer from intense heat. I think the rock would get darker further down. These things would indicate how old each layer is and they could make a logical estimation how old the earth is."

*Total number of participants for control group = 70; treatment group = 71

As previously described, statistical analysis of the data did not reveal significant differences between the control and treatment groups. However, the description provided by the coding rubric can once again be used to provide a glimpse into student thinking and to reveal key areas that could benefit from additional instruction. For this question, in a manner similar to that described in the analysis of question GEOL-B, some students relied on a misunderstanding of radio-isotopic dating techniques to explain how dates of the material could be obtained. In particular, students tended to inaccurately describe that sedimentary material can be dated by radio-isotopic dating, that carbon-14 dating was useful for rocks, or that carbon-14 dating could provide an estimate of the age of the Earth. All of these ideas are problematic and contradict fundamental scientific principles used by geologists. Due to the ways in which sedimentary materials are formed from the recycling of other materials, it is not possible to use radio-isotopic dating to determine when sedimentary materials are laid down; only igneous materials can be dated by radio-isotopic dating. Carbon-14, as previously noted, is not useful for dating inorganic materials such as rocks, and the half-life of carbon-14 makes it useful for dating objects only up to about 70,000 years old. While this would be ample to date things as being older than 10,000 years (a commonly misconceived age of the Earth), carbon-14 would still be insufficient to date materials needed to approximate the actual age of the Earth.

Even more common was a generalized reference to dating the rocks that were found in the column, exemplified by the following student responses.

> You would expect to see older sedimentary rock as well as some intrusions of other rocks.
>
> The rocks would be deposited in layers. There may be more layers present than could have been laid down in 10,000 years.
>
> I would expect the column to have noticeable layers, showing different types of sediment that had been deposited and then turned into rock due to great pressure of more sediment on top. There may also be features such as fault lines and extinct volcanoes within the layers. These would show the old age of the Earth because it takes extremely long for them to form.
>
> There would be different types of deposited rock and they could use dating to prove that the Earth is older than 10,000 years.
>
> They could look at the different layers and date each of them to see how old the rocks are.

Based on these students' responses it appears that many of the students do not have a firm grasp of the methods that scientists use to date the materials of the Earth's crust. It is quite likely that without such an understanding they are more susceptible to misconceptions about the age of the Earth.

Question GEOL-D: Comparing ages of continental and oceanic rocks to support plate tectonics. Question GEOL-D asked students to explain why continental rocks are so much older than oceanic rocks and how this fact supports the theory of plate tectonics. The most informed views demonstrated an accurate understanding of how the ocean floor is formed at mid-oceanic ridges, slowly spreads outward toward the continents, and then is subducted under the continents to be recycled. Table 19 provides an overview of the coding rubric.

Table 19: Summary of coding rubric for quiz question GEOL-D – Comparison of continental and oceanic rock ages to support plate tectonics

Score & Frequencies*	**Category Description**	**Example(s) from Students' Quiz Responses**
4 Group n % Ctl 6 8.3% Tx 7 9.7%	Response at minimum refers to generation of new crust in the ocean, movement of ocean crust, and subduction of ocean crust under continental crust.	"Ocean floors are continual being reformed through subduction processes. The subduction zones explain the loss of old ocean floor, but mid-ocean ridges explain how new ocean floor is forming. At mid-ocean ridges, magma is being forced up through cracks in the crust causing the ridges to expand and add new ocean floor with fresh magma. This explains how plates can move because they are either being subducted or expanded at mid-ocean ridges."
3 Group n % Ctl 16 22.2% Tx 11 15.3%	While the explanation contains no significantly detracting inaccuracies, one of the following pieces is not included: generation of new crust in the ocean, movement of ocean crust, and subduction of ocean crust under continental crust.	"The difference in age occurs because of sea floor spreading. New ocean floor is being made, so the old floor is subducting underneath continental crust. This subduction helps to promote plate tectonics." "The ocean floor is slowly adding new crust. The plates pull apart, allowing molten material to fill the gap and the cycle continues."
2 Group n % Ctl 15 20.8% Tx 19 26.4%	Response is vague or missing important details, but contains few or no significant inaccuracies.	"The difference in age occurs by the ocean floor expanding and the younger rocks are at the bottom of the ocean." "This proves that the sea floor is spreading. If the ocean basin is younger than continental rock, then we know that the ocean basin is more newly formed from the mantle and magma."

Table 19 (continued)

1 Group n % Ctl 35 48.6% Tx 35 48.6%	Response contains only major inaccuracies or irrelevant ideas OR Student states they do not know.	"I don't know the answer but my best guess would be because land has been around for longer than the ocean and that earth was at one point a huge continent, oceans were somehow created and that would explain the difference in age."

*Total number of participants for control group = 72; treatment group = 72

Like the other geology questions discussed earlier, control and treatment group responses do not show significant differences, yet an examination of the coding rubric can still provide useful information about students' understanding of the geology concepts involved. Unfortunately for this question, almost half of the participants in both the control and treatment groups appear to have significant misunderstandings about why the oceanic and continental materials are of different age. When asked to describe why the age of the ocean floor is so much younger than the age of continental rocks, a number of students expressed the idea that the oceans were formed at a time considerably later than the continents. Between twelve and eighteen percent of students used descriptions such as the following:

> It means that the oceans were not uncovered until the plates that the continents are on moved over and created places for all of the water.
>
> The oceans weren't always where they are now. Plate tectonics occurred and moved continents causing different oceans. This is why the ocean rocks are younger, they weren't always there.

Since movement and recycling of ocean floor material is one of the key pieces of evidence scientists have supporting the theory of plate tectonics, it is discouraging to note that so many students fail to accurately describe this evidence and connect it to the ideas of plate tectonics. Two other types of misconceptions were also relatively common in students' responses. The first involved an idea that continental rocks used to be in the ocean, and the second involved an idea that rocks in the ocean get worn away more due to erosion and weathering from the movement of the water. Both were present in 5-7% of responses from the control and the treatment groups. Geology instructors can use this type of descriptive evidence to highlight areas that need further instruction to solidify students' understanding of key concepts.

The previous example not only highlights gaps in students' understanding, but it is also related to gaps in students' NOS understanding. Scientists often have to use indirect evidence to deduce new ideas about how nature acts. In this case, the indirect evidence is the differences of the ages of oceanic and continental crust materials, and it is instrumental in providing support for the idea that the crust consists of a number of moving and colliding plates. Scientists are not able to observe evidence of moving plates directly due to their enormous size and slow rate of movement. However, when put together with many other pieces of indirect evidence, a cohesive explanation of the construction of the Earth's surface can be deduced. If students are not familiar with examples of how this method of using indirect evidence is instrumental in the formation of foundational theories that allow us to explain the world around us (i.e., earthquakes, volcanic eruptions, formation or erosion of landforms over long periods of time, etc.), then they may be more likely to discount scientific proposals that seem to lack the backing of direct evidence – a serious misconception about the nature of scientific knowledge.

Homework Assignments

Description of Short Story Content

As students participated in the treatment by reading the short story assignments, they were required to respond to embedded questions as homework assignments. The first homework assignment (HW1) focused on the development of the ideas related to continental drift/plate tectonics using two short stories with four embedded homework questions in each story. The first story (SS1) presented the early development of ideas related to continental drift. The second story (SS2) presented the more recent development of a mechanism to explain how the movement of plates occurs. The second homework assignment (HW2) focused on the historical development of geologists' ideas about the age of the Earth, again using two short stories with four embedded homework questions in each story. One story (SS3) presented the early development of ideas related to the age of the Earth, particularly focusing on the differences between naturalists (who relied on interpretations of nature) and chronologists (who relied on written chronological descriptions of history, including Biblical accounts). The other story (SS4) presented examples of the specific methods used by naturalists between the 1850s and 1910s to estimate the age of the Earth. Tables 20-23 describe the geology and nature of science concepts that formed the key content of these short stories, demarcate which of these were topics addressed in embedded homework questions, and also indicate the relationship between these concepts and the quiz questions. The complete text of the short stories and their embedded questions is shown in Appendix C.

Table 20: Geology concepts addressed in short stories from HW1

Concept	Applicable to quiz question
Evidence for plate tectonics, including coastlines of Africa and South America w/ similarities in early geological features & fossil record	GEOL-A
Uniformitarianism –the same forces are at work today as in the past	GEOL-C (somewhat)
Isotasy – Oceanic crust is more dense than continental crust	GEOL-D
Pangaea – original super-continent that broke up as plates moved	GEOL-A
Topography of ocean floor – mountains and ridges	GEOL-D (somewhat)
Magnetic field data as evidence of continental drift	GEOL-D (weakly)
Relative ages of ocean floor compared to age of the Earth; sea-floor spreading used to explain	GEOL-D
Divergent and convergent boundaries of plates	GEOL-D
Further ideas related to plate tectonics: formation of volcano island chains as plates move; transform faults and earthquakes	

(Double line indicates break between SS1 & SS2)

Table 21: NOS concepts addressed in short stories from HW1

Concept	Addressed in embedded question	Applicable to assessment question
Cultural (particularly religious) influences on science	SS1, Q1	NOS-D
Much time is required to develop ideas in science	SS1, Q2	NOS-A (somewhat)
Data requires interpretation; need for creativity implied	SS1, Q3	NOS-A
Different scientists can interpret the same data differently		NOS-C
New theories should provide for improved explanation of data		NOS-C (weakly) NOS-E (somewhat)
Currently accepted ideas can suppress the acceptance of new alternative ideas		NOS-E
Cultural influences – Wegner's German heritage may have worked against him in a post WWI world		NOS-D
Science revolutions often start with someone who is not as heavily influenced by currently accepted ideas	SS1, Q4	NOS-E
Scientists must build consensus to get ideas accepted; they don't vote on whether to accept ideas	SS2, Q1	NOS-E
Scientists can't be completely objective – have to use some framework to view and interpret data; Different frameworks used by scientists can lead to different conclusions	SS1, Q2	NOS-C
Scientists often use analogies in their explanations – implied evidence of how scientists create explanations based on their prior experiences		NOS-A NOS-C NOS-D (all weakly)
Data doesn't show/tell scientists what to think; they must interpret the data	SS2, Q3	NOS-C
Good theories tend to unify a discipline; theories are explanatory while laws state relationships (laws and theories are different kinds of knowledge)		
Ideas in science have a tentative and durable nature – they may change at some time in the future, but they are very useful	SS2, Q4 (especially durability)	NOS-E (weakly)

(Double line indicates break between SS1 & SS2)

Table 22: Geology concepts addressed in short stories from HW2

Concept	Addressed in embedded question	Applicable to assessment question
Nicolas Steno observed layering of strata and linked this to the age of sedimentary material		GEOL-B&C
Catastrophism and uniformitarianism were two different early approaches used to explain and determine the age of the Earth		GEOL-C (somewhat)
Fossil record used as early evidence that Earth existed before humans		GEOL-C
Hutton used unconformities (i.e. detailed descriptions from Siccar Point) to conclude that cyclical processes have been at work in the Earth for a very long time by small incremental changes	SS3, Q3	
Stratigraphy – the study of the order of rock layering/strata		GEOL-B&C
Fossil record contained in strata		GEOL-B&C
Sedimentation rates	SS4, Q1	GEOL-B&C
Uniformitarianism		GEOL-C (somewhat)
Early attempts by naturalists to determine the age of the Earth: Phillips use of sedimentation rates, Kelvin's use of the Earth's cooling; Joly's use of salinity of oceans	SS4, Q2 & Q3	NOS-C (somewhat)
Radiation and radio-metric dating methods		GEOL-B&C
		GEOL-D
Divergent and convergent boundaries of plates		GEOL-D
Further ideas related to plate tectonics: formation of volcano island chains as plates move; transform faults and earthquakes		

(Double line indicates break between SS3 & SS4)

Table 23: NOS concepts addressed in short stories from HW2

Concept	Addressed in embedded question	Applicable to assessment question
Scientific work is influenced by the ideas and prevailing culture of the timeframe in which it is conducted	SS3, Q1 (weakly)	NOS-D
Natural (rather than super-natural) explanations are required in science		
Science as a social endeavor	SS3, Q2	NOS-E
Data requires interpretation by scientists and scientists must use some sort of theoretical framework to interpret data	SS3, Q3	NOS-C NOS-E (somewhat
Competing ideas can exist in science for extended periods of time		NOS-C
Science vs. religion is not an accurate description of the efforts to understand the age of the Earth	SS3, Q4	

Table 23 (continued)

Chronologists & naturalists were scientists of the time who used different approaches to determine the age of the Earth		NOS-C (somewhat)
Scientists’ backgrounds influence the ways that they approach scientific questions (methods they choose, how to interpret data, etc.)	SS4, Q2	NOS-C NOS-E (somewhat)
Scientists must be creative as they develop methods of study and as they interpret data	SS4, Q3	NOS-C NOS-E (somewhat)
Science ideas are inter-disciplinary and must cohere	SS4, Q4	NOS-E (somewhat)

(Double line indicates break between SS3 & SS4)

Coding and Analysis

Students’ responses to the homework questions were read and coded, using a continuum that ranged across five categories: 1) response demonstrates a sophisticated and accurate understanding of the concepts involved based on a comparison to contemporary accepted NOS views; 2) response appears to be accurate but is less detailed in nature than type (1); 3) response exemplifies a mixed view, demonstrating some accurate ideas and some misconceptions or response is too vague to be labeled as completely accurate; 4) response relies exclusively on misconceptions; and 5) response cannot be classified based on the degree and/or type of information provided by the student. This categorization of students’ responses to the homework questions was used to describe the types of NOS concepts for which treatment group students demonstrated a relatively strong understanding, and also the particular NOS misconceptions that appeared to interfere with students’ learning of the short story content. NOS misconceptions within students’ responses were examined and classified through an open coding process (Strauss & Corbin, 1998). All students’ responses were read and coded, even if the student did not participate in the end of semester assessment. The number of treatment group students responding to each of the homework questions is shown in Tables 24 and 25.

Table 24: Number of participants responding to embedded questions from Homework 1 – Continental Drift & Plate Tectonics

Question	SS1, Q1	SS1, Q2	SS1, Q3	SS1, Q4	SS2, Q1	SS2, Q2	SS2, Q3	SS2, Q4
Number of students responding	278	274	276	277	262	264	262	260
Type 1 responses (accurate & detailed)	8 (2.9%)	75 (27.4%)	43 (15.6%)	59 (21.3%)	26 (9.9%)	14 (5.3%)	91 (34.7%)	95 (36.5%)
Type 2 responses (accurate but less detailed)	38 (13.7%)	36 (13.1%)	52 (18.8%)	67 (24.2%)	105 (40.1%)	39 (14.8%)	64 (24.4%)	96 (36.9%)
Type 3 responses (mixed view or too vague)	55 (19.8%)	47 (17.2%)	132* (47.8%)	81 (29.2%)	92* (35.1%)	34 (12.9%)	45 (17.2%)	30 (11.5%)
Type 4 responses (relies only on misconceptions)	98 (35.3%)	92 (33.6%)	36 (13.0%)	61 (22.0%)	10 (3.8%)	121 (45.8%)	52 (19.8%)	16 (6.2%)
Type 5 responses (unclassifiable)	79 (28.4%)	24 (8.8%)	13 (4.7%)	9 (3.2%)	29 (11.1%	56 (21.2%)	10 (3.8%)	23 (8.8%)

*Most of these are type 3 due to insufficient detail provided in the response to be classified as type 2 rather than due to the presence of specific misconceptions.

Table 25: Number of participants responding to embedded questions from Homework 2 – Deep Time and the Age of the Earth

Question	SS3, Q1	SS3, Q2	SS3, Q3	SS3, Q4	SS4, Q1*	SS4, Q2	SS4, Q3	SS4, Q4
Number of students responding	274	272	272	272	280	266	275	279
Type 1 responses (accurate & detailed)	21 (7.7%)	14 (5.1%)	3 (4.7%)	5 (1.8%)	237 (84.6%)	24 (9.0%)	27 (9.8%)	24 (8.6%)
Type 2 responses (accurate but less detailed)	57 (20.8%)	47 (17.3%)	56 (20.3%)	42 (15.4%)		38 (14.3%)	131 (47.6%)	144 (51.6%)
Type 3 responses (mixed view or too vague)	60 (21.9%)	89 (32.7%)	55 (20.0%)	57 (21.0%)		99 (37.2%)	44 (16.0%)	74 (26.5%)

Type 4 responses (relies only on misconceptions)	106 (38.7%)	70 (29.0%)	100 (36.2%)	116 (42.6%)	43 (14.4%)	65 (24.4%)	19 (6.9%)	16 (5.7%)
Type 5 responses (unclassifiable)	30 (10.9%)	43 (15.8%)	52 (18.8%)	52 (19.2%)		40 (15.1%)	54 (19.6%)	21 (7.5%)

*Question 1 from short story 4 involved a calculation rather than a written response; students in type 1 performed the calculation appropriately, and students in type 4 did not.

Areas Where Students Exhibited Strong NOS Understanding

From this data, it is encouraging to note that five questions have a 50% or higher degree of accurate student responses (types 1 & 2 on the scoring rubric): questions 1, 3, and 4 on SS2, and questions 3 and 4 on SS4. These questions focus on the importance of consensus building in science, the need for interpretation of data, the durability of scientific knowledge (theories), the ways in which scientists must be creative, and the cohesiveness of scientific knowledge. In addition, question 3 from short story one, which also focused on the need for interpretation of data, includes well over 50% of students' responses in categories 1, 2, and 3, with almost all responses in category 3 being thus scored due to the absence of supporting examples rather than due to the presence of significant misconceptions. Most responses in category 3 for this question consist of an affirmative response, that data does need interpretation, but do not provide reasoning for why this is the case.

The NOS topics focused on in these questions coincide with the concepts addressed in assessment questions NOS-A, NOS-C, and NOS-E, as demonstrated in Tables 20 and 21. This alignment can be interpreted as evidence in support of the supposition that the use of the short story assignments contributed to the statistically significant differences in NOS understanding between the control and treatment groups for questions NOS-A and NOS-C. Although treatment group students were not statistically different from control group students on question NOS-E, they did exhibit an understanding of the durability of scientific knowledge in their responses to this quiz question. The homework questions which align with question NOS-E and on which students performed well emphasize the durability aspect of scientific knowledge more than its tentative nature. Again, there seems to be good alignment between the aggregate views of the treatment group on the homework and quiz questions.

NOS Misconceptions that Appear to Have Interfered with Learning

As documented in Tables 20-23, the short story homework assignments used during this study contained significant explicit illustrations of the nature of science and required students to consider how the history of science reflects NOS concepts such as the role of creativity in science, societal influences on science, the internal relationships of the scientific community, and the different interpretations of data that scientists can produce based on the theoretical framework used to view the data. While strong alignment between the short story content and the quiz questions quite likely contributed to the statistically significant differences between the control and treatment groups measured in this study, it must also be considered why statistically significant differences between the control and treatment groups were not produced for question NOS-E and why so many treatment group students still exhibited NOS misconceptions in their responses to questions NOS-A and NOS-C. Educational research indicates that one must always consider students' prior knowledge, including misconceptions, when implementing instruction designed to promote conceptual change (Posner et al., 1982). In this case, it appears that NOS misconceptions held by students before they engaged in the treatment interfered with learning as they interacted with the short stories. Students' responses to the homework questions provide significant insight into how these misconceptions affected students' learning, and comparisons can be made between the misconceptions demonstrated in homework and quiz responses.

Misconceptions about the tentative nature of science. For quiz question NOS-E, students were asked to explain how currently accepted scientific ideas affect individual scientists' work. Over 40% of students' responses in both the control and treatment group failed to acknowledge the relevance of the tentative nature of scientific knowledge with respect to this question. An examination of students' responses to homework questions can be used to highlight some specific misconceptions which may have contributed to students' failure to describe currently accepted scientific ideas as tentative.

In response to many of the homework questions, some students described science knowledge as proven or representing truth. These students' responses did not accurately reflect the tentative nature of scientific knowledge or the role that interpretation of data plays in the construction of knowledge. When responding to question two from SS1, students who relied on this type of misconception (32 of the 274 participants) described that ideas in textbooks are now known to be true with certainty due to extensive testing, whereas ideas from the past were often just thought up and had no data or observations to support them. The following student responses exemplify this position.

> Textbooks tend to use the more modern studies and also use true knowledge. Textbooks won't put assumptions or false information into the book.
>
> The idea[s] that some continents were created by volcanoes or were connected by land bridges are very believable ideas, but these theories do not have evidence to support that they are true. And unlike these ideas textbooks have ideas that are studied, tested, and true.

These students' attitudes about the currently accepted scientific ideas published in textbooks exemplify the fact that they do not recognize the tentative nature of currently accepted scientific knowledge. While they see former scientific explanations as flawed, current knowledge is viewed as truth. They fail to recognize that scientific ideas cannot be proven with certainty, but rather the ideas are used only as long as they work in the required contexts and no better, alternative explanations exist.

The idea that science ideas can be proven with certainty appeared to be a prevalent misconception in students' responses to several other homework questions as well, as demonstrated by the following students' responses.

> It shows science as social because they all talk to each other to bounce ideas off each other. If they were not social nothing would ever be proven because there would be no interaction to expand on ideas. (SS3, Q2)
>
> Data doesn't show or tell us anything. Data can't just "tell" you how to interpret it. When you observe something you illuminate your own ideas and make theories regarding them. Scientists tell what they have discovered, which is proven true, is then considered "fact" or "data." The data didn't tell them what to think though, or even show them what to think, that was up to the scientists on how they chose to interpret what they've found. (SS3, Q3)
>
> The science we learn about in school is the stuff that has already been researched and proven so it makes science seem more boring and not creative. (SS4, Q3)
>
> Absolute proof is assumed by concurrence of multiple scientists and an idea is not necessarily a set theory unless others come up with the same conclusion. (SS4, Q4)

Similarly, the use of the word *truth* was often interpreted as a misconception about the nature of science. Some students described that scientific knowledge represents truth or that it draws ever closer to an accurate representation of truth as more data is accumulated and more scientists come to consensus.

> With more support, one gets closer and closer to the truth. If many science disciplines agree on something, it is likely close to the truth because there are many views on the same issue coming to the same conclusion. (SS4, Q4)
>
> The more people they have to agree to this subject the better. It'll make it possible for the thing to become a true statement. (SS4, Q4)

> Science requires a lot of thought and research and by no means is a boring or dull process. It takes the right kind of personality to appreciate the scientific process and the methods one must use to research. Many people don't find that science is lacking any creativity it is just that they wish to not spend so much time researching something and maybe never coming up with a real truth. (SS4, Q3)
>
> Science is a social endeavor not only because scientist are influenced by their religion and culture, but also because scientists work together to come up with theories. They often elaborate on others' ideas or offer completely different alternatives to other's ideas. The work that one scientist does is never accepted as truth until other scientists review and agree with it. (SS3, Q2)

Students' usage of the words *prove/proven/proof* and *truth* throughout their responses commonly raised concern about students' conceptions of the nature of scientific knowledge. The examples listed above exemplify some of the varied ways in which students used these words. This researcher does recognize the potential for some ambiguity in interpreting what students actually think about whether or not science ideas are proven with 100% certainty. While some students' responses clearly indicate that this is the case, others less clearly express the degree of certainty that they believe is associated with a "proven" scientific idea. In the contexts of the short stories, which explicitly illustrated the tentative nature of scientific knowledge, and the homework and quiz questions, which asked students to reflect on NOS issues, however, these students' choices to use words such as "proof" and "truth" are interpreted as evidence that they have not adopted a view of currently accepted ideas as tentative.

NOS misconceptions about the discovery of knowledge. In a similar manner, an evaluation of students' responses to homework questions can be used to describe some potential causes for the 40% of the treatment group which still referenced scientific ideas as being produced exclusively through a process of discovery on quiz question NOS-A. Some students who referenced “discoveries” of scientific ideas in their homework responses explained that technology allows scientists to make discoveries.

> Technology has opened doors in discoveries. This may change a scientist’s view on a research project based on information by these new technologies. (SS2, Q2)
>
> In the science text books, normally some type of new technology is invented and then a new discovery happens. (SS1, Q2)

While technology is often a useful aid to scientists, calling the ideas that are developed from the use of technology “discoveries” is an over-simplification. Technology itself is built around a set of presuppositions which direct how it is used by scientists; new technologies typically are creative applications of formerly established scientific principles in new settings. Consequently, the data obtained from the use of technology has already been assigned meaning based on the design of the technology. However, textbooks may reinforce misconceptions through their simplified presentation of the work that goes into the construction of new scientific knowledge and their use of words like “discovery.” Another student also made links between textbook presentations and the concept of discovery, as demonstrated in the following homework response.

> Most of the time in text books it often just gives the date of when they discovered something out. From my previous years of being taught science I can’t remember seeing the problems that led up to a discovery. I can just remember being taught the discovery and it’s time when it was discovered. (SS1, Q2)

This response illustrates the student’s perception about how textbook representations of the development of scientific knowledge emphasize discovery and downplay the inventive nature of the process. If students have been exposed to this type of presentation repeatedly over their years of schooling, it is not surprising that so many students reference discovery as the mode by which science knowledge is produced in response to quiz question NOS-A.

Finally, the following two students' responses to homework questions demonstrate the ways in which students interpret the short story materials in light of their NOS misconceptions.

> Kelvin's ways of discovery with uniformitarianism and catastrophism are both very unique and interesting ways to determine scientific information. (SS4, Q3)
>
> Both the methods scientists use and the sense they make of data illustrate that science is a creative endeavor because scientific discoveries often involve thinking outside the box. Scientists most often need to follow the scientific method of observation-hypothesis-data-conclusion to create a theory for their discovery. (SS4, Q3)

In question three from SS4, students were asked to provide evidence from the short stories to describe how both the methods scientists use and the sense they make of data illustrate that science is a creative endeavor. In the first response, the student has misinterpreted information presented in the short story about the ways in which Kelvin creatively invented a new method to estimate the age of the Earth and a means to interpret the data he obtained. Instead of seeing Kelvin's work as an illustration of how scientific knowledge about the age of the Earth is produced through inventive processes, the student has applied the idea of discovery to the work, as if the knowledge already existed and was just waiting to be found. In the second example, the student has attempted to illustrate the creativity of scientists by applying a previously learned idea that all students follow a universal step-wise scientific method which allows them to discover knowledge. Rather than interpreting the short story as evidence that scientists do not all follow the same method, this student has interpreted the story in light of prior knowledge and has come to a conclusion that is different from the author's intent. These examples from students' homework responses provide insight into the ways in which students' prior ideas persist even when presented with evidence intended to initiate conceptual change. When students hold deep-rooted misconceptions about the nature of science it is likely that these ideas will be resistant to change – as evidenced by the 40% of the treatment group who still relied on descriptions of discovery as the mode of developing new scientific knowledge in quiz question NOS-A.

NOS misconceptions about objectivity. To consider potential causes for the significant number of treatment group students who failed to address the nature of scientific knowledge in response to quiz question NOS-C, it may be useful to examine students' responses to question two from SS2. This question reads: "Note the different interpretations depending on the framework and ideas one uses to make sense of the same data. People often think that good scientists are objective. What does this story imply about the possibility of scientists being objective?" It was considered desirable for students to indicate in their responses that scientists cannot be completely objective since they must use a theoretical framework and their prior knowledge to interpret data. However, 46% of students' responses were based on misconceptions about objectivity. The most common misconceptions involved misunderstandings about what it means to be objective (32% of all students) and stating that scientists are able to be and should be objective (33% of all students). To be completely objective, scientists would have to consider all possible interpretations and value them equally – a tactic that is both impossible and unfruitful in science. Scientists attempt to limit the sources of bias, but must use some criteria to screen and interpret their observations and ideas. In addition, although objectivity is commonly described as a key characteristic of scientists, Ryan and Aikenhead (1992) describe that values espoused by science often contradict the values practiced by individual scientists. "For instance, science publicly reveres objectivity, but individual scientists often rely on their subjective hunches in the privacy of their own labs" (p.567). No doubt, the public reverence for objectivity has influenced the ideas of students who indicate that scientists either do or should perform their work objectively. Some examples of these types of views can be seen in the following students' responses.

> Scientists should be somewhat objective in their research. They are dedicated to supplying factual theories to the public. Scientists need to use realistic data to explain the occurrences on our planet. They should not allow their emotions or personal expectations to interfere in their research.
>
> It's a good idea to be as objective as possible because objective ideas are the hardest to refute. Try to come up with ideas that have been tested and proven true.
>
> Well, I think the story implies that scientists can indeed be objective, and it really doesn't tell me any more than that.
>
> Scientists that are objective are good. They look strictly at the facts and let nothing else effect their decision. They know what their goal is and what they are shooting for, but also know how to achieve that goal.
>
> This story implies that as closer and closer you come to present day, scientists become overall more objective.

These students' responses provide examples of how students interpret the short story in light of their own ideas about objectivity and fail to acknowledge that scientists have expectations about their work based on the theoretical framework they use to design experiments, that scientists screen data and interpret its meaning through their prior knowledge, and that these factors are necessary and useful parts of the scientific process.

Quiz question NOS-C asked students to comment on why scientists, who have access to and make use of the same data set, can come to two completely different decisions about the meaning of the data. The context used for this question dealt with the dinosaur extinction. Within the treatment group 37.7% of students did not discuss the nature of scientific knowledge in their responses to NOS-C, but instead focused on evaluating the scientific evidence. If students assume that scientists are able to maintain pure objectivity in their work, as is indicated by the homework responses above, then they are unlikely to comment on factors which influence how a scientist interprets data in response to a question such as NOS-C.

It must also be taken into consideration that among the 46% of students who exhibited misconceptions about objectivity in their homework, many different possible meanings for the word objective can be interpreted from student responses. At least eight different meanings were referred to by three or more students. Table 26 shows a summary of these eight different meanings and the number of student responses that used each.

Table 26: Differing definitions of what it means to be objective, used by students in response SS2, Q2

Number of students*	How the students interpreted and used the word “objective”
22 (8.4%)	Being open to new/alternative interpretations or combining multiple viewpoints to make the best decision
12 (4.6%)	Holding to your own view-point and using it to judge/measure other ideas
4 (1.5%)	Relying on technology to eliminate bias
10 (3.9%)	Continually testing ideas in an attempt to disprove them OR Making sure you have enough evidence to support your views
17 (6.5%)	Using data, facts, and ideas that have been proven true, rather than opinions
8 (3.1%)	Avoiding any pre-conceived ideas when conducting experiments and making observations
6 (2.3%)	Examining all possible data, using all possible resources, considering all possible explanations
3 (1.1%)	Scientists have objectives (goals) so this makes them objective

*Total number of students responding to SS2, Q2 = 264

Interestingly, the most common meaning of objectivity described by these students was that it means being open to new interpretations of the data and/or to combining others’ viewpoints with their own to reach a better idea. The following student responses demonstrate this viewpoint.

> Scientists are objectivists because at any point in time they might have to change their point of view or ideas based on what other scientists have learned or discovered. Technology has opened doors in discoveries. This may change a scientist's view on a research project based on information by these new technologies.
>
> This story shows that scientists need to be objective because like in the story, sometimes there is a new piece of information that can be used to better explain their data. They need to have an open mind to accept things like this.

By contrast, another portion of the students interpreted being objective to mean using your own view-point to interpret data and selecting interpretations that coincide with your view-point. The following student quotes exemplify this position.

> This story implies that scientists are in fact objective when determining explanations for phenomena. Scientists make hypotheses and use data to support their thoughts. As some scientists maintained a "fixist" point-of-view of the earth and others maintained a "mobilist" point-of-view, when new explanations come along, scientists take the side that is accordant to the way they already think.
>
> Well, from what I read it seems that scientists are objective. They each tend to have their own opinions and to each of them what they've discovered is fact.

Still others interpreted being objective as meaning using only facts, data, or ideas that have been proven true when making decisions; these students often suggested that scientists should avoid using their own opinions.

> It's a good idea to be as objective as possible because objective ideas are the hardest to refute. Try to come up with ideas that have been tested and proven true.
>
> Objectivity comes from having data and facts to support your idea rather than opinion. A good scientist being objective would create an idea that is based on research and interpretation of observations, rather than past teachings and opinions.

Clearly, within the context of this question students used the word “objective” to mean many different things. Many of the meanings that students applied to the word involved misconceptions about what objectivity is and also about how scientists actually work. A sizable number of students have not been persuaded that scientists are not completely objective and that some degree of subjectivity must be seen as an inherent aspect of science rather than as a defect. Students who possess this type of misconception do not appear to understand the ways in which scientists must use a particular theoretical framework to design experiments, interpret data, draw conclusions, and make comparisons. Consequently, these types of misconceptions about objectivity could contribute to an understanding of why so many students did not discuss these NOS issues in response to quiz question NOS-C.

Other NOS misconceptions involving scientific language. As previously described in relation to the words "proven" and "truth," misunderstandings of the language commonly applied to science appeared to be prevalent among students' responses to many of the homework questions. It was particularly notable in the question described immediately above because students were asked to comment about objectivity in science, but in other questions misuse of similar words and ideas often became entangled with students' understandings of the nature of science as well. For example, in question three on short story one, when asked to comment on how scientists construct new ideas from data, 6.5% of student responses described the use of what has been called the scientific method. Nature of science experts have agreed that there is no universal, step-wise scientific method; instead, scientists tend to use whatever methods appear to work best (McComas, 2000). In addition, several students responding to this question indicated that allowing personal experiences or beliefs to influence ideas leads to faulty science – again showing a misunderstanding of the ways in which scientists actually work based on misconceptions about objectivity. It is likely that these types of misconceptions about the nature of science, which appear to have persisted within some students' conceptual frameworks even after engaging with the short story homework assignments, also affected students responses to the quiz questions and contributed to the number of responses which demonstrated relatively naïve NOS views.

Interpretation and Discussion of Results

When examined together, the qualitative findings and quantitative results from this study present a picture of the ideas possessed by students and the types of learning they achieved in a more meaningful way. Qualitative findings from this study provide insight into the NOS and science understanding of college-level introductory geology students. In many ways, the NOS understanding of these students resembles that of other groups who have been studied in the past (i.e., K-12 students and pre-service teachers), in that misconceptions about the nature of science appear to be prevalent.

This study can be viewed as further support for the body of evidence suggesting that students at virtually all levels of the educational system have a poor understanding of the nature of science. When viewed through the lens of researchers such as Lonsbury and Ellis (2002), who have described the ways in which NOS misconceptions adversely affect individuals' ability to make well-informed decisions on science related issues, the future for informed public decision-making regarding science appears dismal. However, the shifts in understanding that are demonstrated through this study provide a ray of hope that effective educational strategies can be developed to improve NOS understanding and pave a path toward more informed decision-making.

Quantitative results indicate that significant gains were made on students' understanding of 1) the variety of processes involved in the construction of scientific knowledge, 2) the subjective nature of data that allows it to be interpreted differently by different scientists, and 3) the roles that culture and society play in determining the way in which scientific work is conducted and scientific ideas are constructed. Qualitative descriptions, revealed through coding and interpreting students' responses, can be used to illuminate specific ways in which students' ideas related to these topics improved and also to highlight areas that would benefit from further instruction.

Processes Involved in the Construction of Scientific Knowledge

Ryan and Aikenhead (1992) have reported that most students believe that science knowledge accumulates through a process of discovery, implying that the knowledge pre-exists the discovery and is just waiting to be found, but that a more accurate description of the nature of science would indicate that scientists invent ideas to account for and explain data. This more accurate interpretation of the epistemology of science was illustrated through the homework readings based on HOS materials, and both quantitative and qualitative results indicate that students made improvements of their understanding of how science knowledge is produced. While only 3.6% of the control group articulately expressed the idea of how invention plays a significant role in building scientific ideas, 22.4% of the treatment group was able to do so. In addition, another 22.4% of the treatment group (compared to 5.5% of the control group) indicated in their written responses that invention plays some role in the construction of scientific knowledge, but either did so less articulately than the preceding group or relied on other types of NOS misconceptions in their rationales for how invention is involved. When compared to the control group, treatment group students were less likely to rely on rationales that indicated that science knowledge was always there waiting to be discovered and misunderstandings of what knowledge is (i.e.

equating knowledge with objects in nature such as plants or fossils or equating knowledge with technological advances such as scientific instruments).

These types of improvements are encouraging, yet they must also be considered in light of the fact that still 40.3% of treatment group students (compared to 63.6% of control group students) relied exclusively on descriptions of science knowledge as being discovered. In particular, the idea that extensive testing of science knowledge is a means of discovery was resistant to change. Homework responses also indicated that some treatment group students describe scientific knowledge as being discovered based on their beliefs about the use of technology and their ideas about knowledge which have stemmed from exposure to textbook presentations that emphasize discovery. These students likely have an ontological perspective strongly grounded in naïve realism and excessive rationalism, described as the beliefs that science ideas can be proven to be an accurate reflection of reality and that science brings us gradually closer to knowing truth (Ryan & Aikenhead, 1992). These types of views can be problematic, as exemplified by the tendency of some individuals to dismiss science knowledge as meaningless when they hear of changes in science ideas (McComas et al. 1998). Evidently, more work is needed to generate sufficient cognitive conflict for these students to adopt ideas that are more congruent with contemporary accepted views of the nature of science.

Multiple Interpretations of Data

Quantitative results also indicate that participants made statistically significant gains in their understanding of the ways in which scientists must interpret data, using a particular theoretical framework or perspective to do so, and consequently that it is not unusual for scientists to have some degree of disagreement about what conclusions should be drawn from the data. In the treatment group 40.3% of students expressed the idea that data is subject to different interpretations by different scientists, while in the control group only 20.7% of the students expressed these ideas. However, about three-quarters of these treatment group students did not provide a detailed rationale to indicate specific factors that cause different scientists to make different interpretations. For these students, the new mental constructs they have built may be relatively fragile and in need of reinforcement to prevent reverting to prior ideas.

From their homework responses, it was interpreted that students' ideas about objectivity often interfered with their ability to make strong links between unique attributes of individual scientists (i.e. their background, theoretical perspective, etc.) and the ways in which they design experiments, interpret data, and draw conclusions. From quiz question NOS-C, which was intended to elicit students' ideas about why scientists sometimes interpret data differently, 37.7% of treatment group students (compared to 46.2% in the control group) did not directly address the nature of scientific knowledge at all. It is possible that students' ideas about the objectivity of scientists interfered with their ability to see the relevance of NOS issues for this question. Further, 15.6 % of treatment group students (compared to 20.8% of control group) expressed views that data is subject to interpretation when there are flaws in the scientific processes used or in cases when direct observations cannot be made. Both views are problematic in that they imply that under appropriate circumstances completely unambiguous data could be attained, and that under these circumstances all scientists would agree on the meaning of the data. Again, they do not acknowledge the subjective nature of interpretation of data that requires scientists to view the data from particular theoretical perspectives. This aspect of the nature of science was well described by Lonsbury and Ellis (2002).

> While scientists assume a real world, their interpretations of sensory observations as well as the actual observations they seek are predetermined, guided by a preexisting paradigm or theoretical framework. As a result, any interpretation of that set of data, the scientific understanding itself, exists entirely within the paradigm that guided the observation collection. (The Nature of Science section, ¶ 4.)

In response to embedded questions within the short story homework assignments, 118 of the 276 students responding to question 3 in SS1 were able to express the idea that data needs interpretation but did not provide descriptions to indicate that they understood why this is the case. Also, in a question that asked students to compare textbook presentations of scientific ideas to the presentations of the short stories, 12% of students expressed the view that the ideas described in textbooks should be seen as truth or proven ideas. These students do not seem to understand and appreciate the implications stemming from the fact that scientific ideas are formed through human interpretation of data.

Students who express views such as those described above may still be under the impression that science demands right or wrong answers, described by Lederman et al. (2002) as a relatively naïve view of the nature of science. It is also possible that for these students, ideas about the nature of scientific knowledge are not at the forefront of their thinking when they consider scientific reports, particularly those in which conflicting conclusions are discussed. It can be concluded that these students need more practice at considering how ideas about the nature of science should impact the analysis of scientific reports.

The Tentative, yet Durable, Nature of Scientific Ideas

The gains that students made in their understanding of how data must be interpreted are likely related to an understanding of the tentative, yet durable, nature of scientific knowledge. These aspects of the nature of science were strongly illustrated through the short stories that treatment students read during this study. These students were required to consider the tentative, yet durable, nature of scientific knowledge in response to a homework question that asked them to explain why scientists hold onto a dominant theory (even if it doesn't work as well as desired) unless a very plausible alternative theory exists. In their responses to this question, 36.5% of students expressed views indicating that they understood the utility of current ideas in science even when they had notable imperfections. These students indicated that scientists needed to use these ideas to provide a framework from which to continue their work and/or that the ideas are built in a social context and can be improved or replaced through the interactive work of scientists. Another 36.9% of students expressed the idea that scientists have to continue to use the ideas as long as they work in some contexts until an improved idea can be identified. These students appear to recognize that science ideas are durable, in that they can be useful in numerous ways and contexts, even though they are tentative and may need to be improved or discarded in place of an alternative idea at a later time.

However, when asked to describe how currently accepted scientific ideas influence a scientists' work, 2.6% of the control group and 7.8% of the treatment group expressed views that currently accepted ideas can be equated to known truths and either cannot or should not be questioned by scientists. These students appear to have over-emphasized the durability aspect of scientific knowledge. This is surprising in light of the ways that the short stories portrayed individuals who questioned currently accepted ideas and consequently began revolutions in scientific thinking. A few of the students in this minority group emphasized scientific methods ("the scientific method") as an example of an idea that should not be questioned. Others may have interpreted the stories to indicate ways in which past ideas have changed, but failed to see connections to current scientific ideas. Solomon et al. (1992) reported a similar finding – that some students tend to dismiss the past as flawed but view current science as free from flaws, often due to technological advancements that they believe allow us to know with certainty that our ideas are correct. While it is encouraging to see such strong respect for scientific knowledge, too much respect can hinder scientific progress if scientists and the public fail to accept the possibility that some ideas may need to be rejected in the future. This can be particularly detrimental to public debate concerning funding of research and the goals that our society should hold for science.

Influences of Culture and Society on Science

Quantitative results also revealed improvements in students' understanding of the ways in which culture and society influence the work of individual scientists. In their responses to quiz question NOS-D 98.5% of treatment group students (compared to 73.7% of control group) described ways in which facets of culture and society act to guide and/or restrict the work of individual scientists. A diverse range of contemporary examples were presented, including societal attitudes toward global warming and stem-cell research, political influences on funding of research, various activist groups that oppose animal testing or other methods, cultural attitudes toward the human body, and the ways in which the individual beliefs of scientists are affected by the culture in which they situated. These findings are encouraging departures from the more naïve view seen in 27.3% of the control group – especially the 8.0% of the group that described that culture and society do not or should not influence a scientist's work at all, a view that was absent in the treatment group.

A related area of concern can be described from students' responses to one of the homework questions, however. In a question where students were asked to describe whether or not scientists could be objective, 33.3% of students indicated that scientists can be, should be, or are objective in their work. Numerous different possible definitions for the meaning of objectivity were implied in students' responses and it was apparent that considerable confusion existed about this idea. For example, some students used the idea of objectivity to indicate that scientists are open to new interpretations of data at a later point in time while other students used the idea of objectivity to indicate that scientists hold to their own particular viewpoint and use it to judge or measure the merits of ideas proposed by others. Still others indicated that objectivity meant avoiding any pre-conceived ideas or use of opinions when conducting experiments and making decisions. These students appear to be ignoring the ways in which scientists are influenced by cultural and societal thinking and consequently cannot fully separate themselves from this context. It may be the case that many students can see ways in which culture and society impact what scientists study, but have more difficulty seeing how these factors influence the ways in which scientists do their work and interpret data.

Influences of Currently Accepted Scientific Ideas on Science

Statistical analysis demonstrated that students in the treatment group did not make significant changes in their ideas about how currently accepted ideas affect the work of individual scientists. Although students in both the control and treatment groups described ways in which currently accepted scientific ideas can guide and/or restrict the work of scientists, a significant number of students (47.1% of the control group and 42.9% of the treatment group) did not address the tentative nature of current ideas when describing these types of effects. It appears that many students do not consider the nature of science as they think about the value of current ideas in science. This is not wholly surprising, given the ways in which most science instruction focuses significantly more on *what* science knows rather than on *how* science knows. Students are accustomed to focusing on the durability and utility of science knowledge, so descriptions of scientific knowledge as tentative is not at the forefront of their thinking. Students' responses to homework questions also demonstrated that students exhibited a stronger understanding of the durability of scientific knowledge than of its tentative nature. As has previously been described, this oversight can be problematic when scientific ideas are treated as concepts that are known with absolute certainty. Frequently, it is through the revision of, and sometimes through the rejection of, currently accepted ideas that scientific knowledge grows and changes.

Students did reflect a relatively accurate understanding of the importance of consensus building in science through their responses to one of the homework questions, indicating an understanding of the importance of collaboration among scientists to come to agreement about scientific ideas. This can be viewed as further demonstration of the ways in which students acknowledge the importance of currently accepted ideas as a means to judge new ideas. New ideas usually need to fit in with and complement currently accepted ideas; if they do not, then they should provide an alternative framework that allows for the reinterpretation of existing ideas – as occurred when the idea of continental drift was finally accepted by the scientific community. In a separate homework question, many students indicated that currently accepted ideas can be challenged – particularly by young scientists who may not be familiar with the current ideas. Although this type of view can be seen as acknowledgment of the tentative aspect of currently accepted scientific ideas, it is still problematic in that students focused primarily on youth and ignorance of science as factors that contribute to an individual's ability to propose alternative ideas. Students who based their response solely on the age of the scientist appear to miss the overarching idea that multiple different perspectives can be used to view and interpret data, depending on a wide range of factors that influence the scientist's background. For example, Wegner was not particularly young when he proposed continental drift but was new to the field of geology, and it appears that his background from other fields (including meteorology) caused him to view the information from a different perspective.

Misconceptions that Interfered with Students' Learning of NOS Concepts

Through an examination of students' responses to homework questions, it was determined that many treatment group students maintained significant misconceptions about the nature of science despite their use of the HOS curricular materials intended to promote more accurate NOS conceptions. In particular, misconceptions about whether scientific knowledge is proven or equivalent to truth, about the role that discovery plays in the construction of scientific knowledge, and about the degree to which scientists are able to maintain objectivity became entangled in students' attempts to reflect on the meaning of the short story content as demonstrated by their responses to homework and quiz questions.

Students who maintained a view that scientific knowledge can be proven through repeated testing or through the process of peer review leading to consensus building among the scientific community, did not represent accurate views about the tentative nature of scientific knowledge. To varying degrees, these students viewed currently accepted scientific ideas, such as those found in science textbooks, to be factual, known with absolute certainty, and useful for the construction of future knowledge but unable to be altered or rejected in the future. Many of them also maintained an ontological perspective that a separate reality exists and that scientists can determine the degree to which their ideas accurately reflect this reality, as evidenced by statements indicating that scientific knowledge is getting closer and closer to truth.

Students who relied on descriptions of scientific knowledge as being accumulated through a process of discovery often failed to acknowledge the ways in which scientists creatively design new methods for collecting data and invent ideas to account for data. These students did not represent accurate views about the ways in which scientists produce knowledge. For them, science ideas were often equated with data, objects found in nature, or instruments of technology designed by scientists. These students often failed to differentiate between the ideas and the tools scientists use to do their work. In support of these misconceptions, they relied on rationales that technology allows scientists to discover new information and that textbooks often focus on describing important scientific discoveries.

Students who expressed the opinion that scientists are, or should be, objective failed to acknowledge the host of subjective factors that are required in scientific work. These students did not express accurate NOS conceptions of the ways in which scientists use their theoretical frameworks to design experiments, interpret data, draw conclusions, and make comparisons. Their notions of what objectivity means were quite varied, and often conflicted with NOS concepts about the ways in which scientists work, individually and collaboratively, and the tentative status of scientific knowledge.

Students' Ideas about Plate Tectonics and Deep Time

Although quantitative results showed no significant differences between the control and treatment groups in terms of their understanding of plate tectonics and deep time, the qualitative findings from this study can still be used to illustrate particular strengths and weaknesses in students' thinking about these two concepts. The coding rubrics for geology questions demonstrate a hierarchy of various types of thinking commonly encountered among geology students about these concepts. This information could serve as useful tools for instructors and curriculum designers as they build classroom activities and readings to teach students about geology more effectively. In relation to continental drift and plate tectonics, the students showed better awareness of geologists' beliefs about the past movement of the continents rather than ideas about how and why the oceanic plates move. For example, almost half of the students in both the control and treatment groups were not able to accurately describe why the material of the oceanic crust is so much younger in age than the continental materials – an idea that relies on understandings of how new oceanic crust is created, moves, and is recycled through subduction under the less dense continental crust. Related to deep time and the age of the Earth, while students were generally aware of some of the features that geologists use to date materials in the Earth's crust, they lacked more specific knowledge of how these features were used. In particular, many students did not demonstrate a strong grasp of when and how radio-isotopic dating can be used and had relatively vague ideas about how geologists use relative and absolute dating techniques in conjunction with each other.

Some specific areas where students exhibited weaknesses can be described in more detail from the findings described in the coding rubrics. Some students' responses revealed confusion between index fossils and what students called “index minerals,” revealing a lack of understanding of the different processes involved in forming fossils and minerals. Because these students assumed that the presence of particular minerals could be used to date sedimentary material, it was interpreted that the students do not adequately understand how mineral deposits form and that the processes involved are not localized to specific eras of time in the same way that the conditions required to support specific life organisms have been.

Students’ responses to a question about continental drift can be used to illustrate the ways in which their thinking about this concept may be limited in its ability to consider multiple changes simultaneously. For example, students’ assumptions about climate demonstrated that students did not consider how the changes in the positions of the continents have affected the climates of these landforms.

Related to radio-isotopic dating, many students lacked understanding of what types of different radio-isotopes are used to date different kinds of materials. Students heavily relied on carbon-14 as the isotope of choice to date all kinds of materials: fossils, minerals, sedimentary rocks, etc. They lacked a clear understanding of what types of isotopes can be found in various materials, of what ages of materials can be dated using specific isotopes (based on half-lives), and of what types of materials cannot be assigned absolute dates through radio-isotopic dating. Other students did not reference the use of radio-isotopic dating at all, but instead relied solely on fossil evidence to describe how geologists provide ideas about the age of the Earth. These students may not have detailed ideas about the history of the Earth and the relatively recent development of life-forms compared to the origin of the Earth itself. Marques and Thompson (1997a) reported that some students have a misconception that life and the Earth originated at about the same time, and Trend (2001) also reported on widely varying conceptions that individuals have about the actual amount of time between major events in Earth's history. These types of misconceptions could be a cause for why some students in this study relied exclusively on the fossil record when asked about evidence that geologists use to determine the age of the Earth.

Finally, related to the comparatively different age of continental and oceanic rocks, students exhibited misunderstandings about how and when the continents and oceans were formed. Misconceptions expressed by students included an idea that the oceans were formed considerably after the continents, an idea that continental rocks are the old rocks that used to be in the ocean, and an idea that rocks in the ocean are young because the old rocks get worn away due to erosion and weathering from the movement of the water. Marques and Thompson (1997a) also reported some similar misconceptions that students have about the oceans and continents, including the ideas that the continents arose from the bottom of the ocean and that the same mechanisms cause the formation of continental and oceanic mountains.

While the quantitative results related to geology understanding encountered in this study initially may appear discouraging, it is important to note that although students' understanding did not improve, it also did not worsen. In fact, among the treatment group, students who spent substantial time working with the short story materials performed better on question GEOL-C (about evidence geologists use to determine the age of the Earth) than did students who spent less time working with the materials. This stands in contrast to the concerns expressed by some teachers who have avoided introducing NOS topics in their science courses because they deem it less worthy of classroom time than typical science content. By using short stories that simultaneously focus on geology and NOS concepts, students can engage in learning about the nature of science without losing valuable time for studying geology. The treatment group from this study performed no worse on the geology assessment questions than did the control group, and improved over the control group in NOS understanding.

It must be considered, however, that teachers may be reluctant to rely on short story assignments if they do not see direct evidence of how the short stories positively impact students' understanding of science content. In this study, although the original intent was to use the short story assignments in place of traditional homework assignments, the geology instructor ultimately chose to use them primarily in addition to her normal homework assignments and only replaced a portion of one homework assignment with the short stories. If teachers do not see the stories as a valuable way to teach science content, they are unlikely to use the stories or, when they do use them, to fully integrate the stories into their courses.

Reasons for Improvements in NOS Understanding

The statistical gains in NOS understanding demonstrated during this study provide evidence that history of science materials can be used effectively to address some common NOS misconceptions. Leite (2002) described that history of science materials are effective at illustrating the human activities in science, that science is a living, collective enterprise, and that science is influenced by our way of life. The materials used in this study were selected to specifically illustrate these types of NOS concepts.

The ways in which the short stories about the history of science were constructed likely provided important features that contributed to their success. Specifically, these stories were designed to provide a context for reflective, explicit, and highly contextualized consideration of key NOS concepts, as suggested by Clough (2006), Clough and Olson (2001), and Khishfe and Abd-El-Khalick (2002). The stories provided rich detail concerning the historical development of the concepts of plate tectonics and deep time, thus providing students with realistic views of who scientists are, how they work, how scientific knowledge is developed, cultural and societal influences on science, how the internal culture of science impacts the formation of new ideas, and the roles that creativity and interpretation of evidence play in science. In addition, prompts and questions were embedded within the short stories, explicitly attending students to and requiring students to actively reflect on the NOS concepts being illustrated.

Heilbron (2002) suggested that HOS materials should focus on key scientific principles while conveying useful scientific information beyond what the student would otherwise be exposed to, and Akerson et al. (2000) suggested that presenting this type of information in the context of science courses may provide the best grounds for improving NOS understanding. While many other studies at the college level have focused on improving NOS understanding in courses about philosophy or the methods of teaching, few studies have involved efforts that took place in the context of a college-level science course. This study attempted to fulfill both of these requirements by being implemented in an introductory, college-level geology course and focusing on two of the most fundamental principles used to unify the concepts taught in geology: plate tectonics and the age of the Earth.

Embedded questions within the stories were also designed to draw students' attention to some key misconceptions about the nature of science that would likely be present in their own prior thinking, and then to present cognitive conflict by pointing out the ways in which the stories illustrate ideas that conflict with these misconceptions. In so doing, students were asked to engage in an examination of their own ideas that is consistent with the conceptual change model proposed by Strike and Posner (1992). It was hoped that students would recognize ways in which the contemporary views of NOS more accurately align with the portrayals of how science works from the short stories, and in so doing would begin to change their thinking about the nature of science. Evidence of the treatment group's improved scores on several NOS questions provides a rationale for believing that this did take place.

Overall, the materials were carefully constructed to simultaneously illustrate key principles about the nature of science and geology, to be presented in a context where students would recognize the utility of the geology content and could appreciate the historical development of scientific ideas, and to cause students to engage in learning strategies designed to initiate conceptual change. It is believed that this combination of strategies contributed heavily to the improvements in NOS understandings described.

Suggestions for Future Uses of History of Science Materials

While several features of the design of the HOS materials have been described that likely contributed to their success, it is also believed that modifications to the construction and implementation of the HOS materials can also be made. Leite (2002) has described that HOS materials can be used to reveal students' science misconceptions, and this study provides illustration of some ways in which this can occur. However, attaining improvements in students' science conceptions is also desirable and several authors have suggested that this can occur (Driver, et al., 1996; Matthews, 1989; Solomon, et al., 1992). When considered in light of the types of strategies that promoted improvement in NOS understanding, two features that could be improved are evident. First, although the stories present key content about ideas of plate tectonics and deep time, students are not required to actively reflect on this content through the use of any embedded questions. Building in questions that require students to reflect on and apply the geology concepts could cause students to more actively engage with the geology materials presented. Second, although appropriate ideas about geology were presented in the short stories, attempts to address common misconceptions and specific strategies to initiate conceptual change about geology concepts were not included. The geology misconceptions illuminated by this study could be used to rework the short stories in ways that require students to actively reflect on these misconceptions and compare them to the more accurate views that geologists use in a manner that could promote conceptual change.

In addition, several former studies that used HOS materials to address students' NOS conceptions relied heavily on teachers who played active roles in mediating the learning that took place (Lin & Chen, 2002; Lonsbury & Ellis, 2002; Solomon, et al., 1992). While it is encouraging to note that, even without significant teacher-led implementation of the HOS materials, substantial improvements in NOS understanding were achieved in this study, it is likely that even more significant gains in NOS understanding could be made if geology instructors actively used the materials during class to lead discussions and engage students in considering the content of the stories. It is possible that the active use of the materials by geology instructors, informed by the descriptions of students' science misconceptions provided here, could also contribute to improvement in geology content understanding.

The work of Tao (2003) can be viewed as an illustration of the idea that students will interpret HOS materials such as the short stories through the filter of their own prior understanding. If they have deep-rooted, pre-existing misconceptions about the nature of science or geology, then they may interpret the short story material in ways that are different from those intended by the authors and use it to reinforce their misconceptions. In this study, these types of actions likely took place with respect to the usage of science-related terms such as objectivity, proof, and truth. Students' views of what these terms mean appeared to be quite widely varied. For example, at least eight different meanings for the word "objective" were inferred from students' responses. Clough and Olson (2004) have suggested that "words such as law, theory, prove, and true should be used carefully and students should be made aware of the importance of the words' meanings" when teaching about science and the nature of science (p. 29). The findings of this study seem to support this idea, providing another illustration of the ways in which an active role for the teacher could further support conceptual change when using HOS materials. Students' ideas about whether or not scientists are objective and whether or not scientific ideas are proven or true, for instance, often become entangled in their ideas about the tentative nature of scientific knowledge, the degree to which creativity plays a role in science, whether science ideas are invented or discovered, and whether or not society influences science. Because many students have deep-rooted misconceptions about the meanings' of these words, teachers will likely need to actively work to model appropriate usage of the words with multiple examples from science contexts throughout their teaching.

Potential Benefits from Improvements in NOS Understanding

While this study was not intended to measure changes in students attitudes about science or their ability to meaningfully engage in public debate on science related issues, the literature suggests that the types of improvements seen in students' NOS understanding would likely have these outcomes. It is hoped that illustrations of how creativity plays a role in science, how pure objectivity is not an accurate description of the processes used by scientists, and how social and cultural values impact science will help to humanize science and counter students' disinterest in science (Harding, 1991; Munro, 1993; Rossiter, 1982; Seymour & Hewitt, 1997; Tobias, 1990). Further, it is hoped that more accurate illustrations of the tentative, yet durable, nature of science and the critical role that interpretation (based on a particular theoretical framework) plays in determining the types of meaning that scientists make from data will help to counter the tendency that some less-informed individuals have to dismiss science as meaningless when they hear about changes in science knowledge (McComas et al., 1998). Finally, these types of improvements in NOS understanding could also play critical roles in preparing citizens who are better prepared to participate in public decision-making concerning science.

It must be acknowledged, however, that some significant misconceptions about the nature of science were still present in the treatment group and appear to be particularly resistant to change. Students' responses to homework and quiz questions illustrated that a cohesive view of the tentative aspect of scientific knowledge is difficult to attain, and is often entangled with students conceptions about objectivity, truth, and the ability to prove scientific ideas. For many students, while the views of past scientists can be seen as being flawed, there is little openness to the possibility that today's views may be similarly flawed. Again, a misunderstanding of the nature of scientific knowledge is implied. Many students appear to view today's knowledge as certain and proven, rather than as accepted and worthy of respect but still subject to change as new evidence is found or as reinterpretation of old evidence using a different perspective occurs.

While it is encouraging to see such strong respect for scientific knowledge, too much respect can hinder scientific progress if future scientists and the public fail to accept the possibility that some ideas may need to be rejected in the future. This can be particularly detrimental to public debate concerning funding of research and the goals that our society should hold for science. Overall, one is forced to wonder how these students use their views of what science is and how scientific knowledge is built when considering contemporary societal questions such as whether or not to fund basic research on stem cells, the pros and cons surrounding use of genetically modified organisms in farming, how to interpret data concerning the relationship between greenhouse gas emissions and global climate change, and the conflicting advice concerning dietary recommendations that is reported continually in the media. Continued efforts to address this aspect of the nature of science are needed.

CHAPTER 5: GENERAL CONCLUSIONS

This study provides evidence that inclusion of historically accurate NOS materials in science courses can lead to greater understanding of the epistemology and ontology of science, particularly related to the variety of processes involved in the construction of scientific knowledge; how data must be interpreted by scientists to reach conclusions; the tentative, yet durable, nature of science knowledge; and the effects that culture and society have on science, scientists, and the process of constructing scientific knowledge. The treatment group participants in this study used short stories designed to simultaneously teach about the nature of science and geology, and on an assessment of their understanding of these issues they showed statistically significant differences from a control group that did not use the short story assignments.

The short stories illustrated and explicitly drew students' attention to key NOS concepts in the history of geology and required students to reflect on the NOS and geology concepts involved through the use of embedded open-ended questions that referenced the short story material. It is believed that this design facilitated students' ability to understand and incorporate the short story content and as a result promoted improvements in students' understanding of NOS concepts – particularly the ways in which scientists often must invent explanations to account for data obtained through indirect means, the tentative and durable nature of scientific knowledge, and the ways in which culture and society interact with science to both guide and restrict what is done and how scientists think about and approach their work. Some evidence from this study can be interpreted to indicate that students better understood the durable rather than the tentative nature of science and also better understood the ways in which culture and society impact what scientist study rather than how they do their work.

The control and treatment groups did not exhibit statistically significant differences in their understanding of plate tectonics and deep time as it relates to the age of the Earth. While this result must be interpreted to mean that the short story assignments did not significantly improve students' understanding of geology, it should also be noted that the time students invested in completing the short story assignments did not detract from their understanding of geology. Geology instructors can interpret this to mean that HOS materials which simultaneously address NOS and geology concepts can be used in their classes without detracting from students' ability to master science content. In fact, some hope for improved learning does exist. Treatment group students who spent significant time (an hour or more) reading the short story assignment, reflecting on their meaning, and answering the embedded questions performed better on a question that required knowledge of the evidence geologists use to date layers of sedimentary material than did students who spent lesser amounts of time (half an hour or less). It appears that the short stories are capable of promoting science content understanding, and perhaps with modifications to their implementation statistically significant improvements in science content understanding will also be achieved.

In addition to promoting NOS understanding, the short story assignments can be used to provide an insight into students' thinking about NOS and geology concepts, thus providing instructors with information about the misconceptions that students possess. Effective instruction intended to promote conceptual change requires this type of insight (Posner et al., 1982). Coding and categorization of students' written responses to homework and quiz questions provided description of some specific geology and NOS misconceptions present in the population. These included students' ideas about the differences between oceanic and continental plates, students' understanding of the appropriate usage of radio-isotopic dating to determine the age of the Earth, and students' ideas about the scientific meaning and usage of words such as proof, objectivity, and discovery.

Implications

The ability to improve NOS understanding documented in this study has the potential to generate significant effects in science literacy. If measures such as these were used throughout undergraduate science courses, the goal of preparing a more scientifically literate citizenry that is motivated to participate in political discourse could be realized. McComas et al. (1998) have described that an accurate knowledge of the nature of science is needed for public decision making regarding science funding, formation and evaluation of public policies about science, and legal decisions based on science matters. Preparing students who are both versed in the content and context of science should be the goal of every science class. The use of NOS materials such as those studied here provides an opportunity to contextualize science content and promote greater understanding of science as it pertains to the public domain.

In addition, students who use these NOS materials may express greater interest in science as a potential career path. Leite (2002) reported that studies of the history of science have been recognized as a way to stimulate interest in and humanize the study of science since the early 1900's. In addition, as Clough and Olson (2004) have described, "integrating scientists' personal thoughts humanizes science and science education because it presents scientists as real people – with motives, prejudices, humor and doubts – a view not always shared by students." Perhaps the benefits of promoting this view can best be understood in the words of one of this study's participants, who offered the following response to a homework question that asked about the role of creativity in science.

> My personal opinion to why some students choose not to pursue science is because of the way science is taught in the years preceding college. Some educational institutions do not allow their students to explore the various methods that science can be applied. In high school science is taught in a memorization process without much effort to allow the students to use creative thinking and what they learned from science and apply to a relevant subject. In this particular historical episode, scientists have several ways to find answers to questions. For example, determining the age of the earth was a process in which many scientists utilized different properties of science to solve a question. Some chose to analyze sedimentation and primarily geology. Others thought using the changes of temperature and thermodynamic was the proper way to determine the age of the earth. Science must be thought of as a process of understanding through the use of several disciplines; these include geology, thermodynamics, and chemistry.

This student has taken to heart not only the lessons presented in the short story about the role of creativity in science, but also the more general ideas that can be appreciated when one reflects on the NOS content from history of science materials – that science is a unified, lively, and ever-changing field where humans attempt to interpret the actions and forces of nature in ways that impact our ability to understand and interact with the world around us.

Further Study

The work presented here also raises the potential for further study in several areas. Suggestions for future study include:

(1) Develop and test additional, introductory historical short stories which explicitly address the various types of *data* that scientists use, the ways in which both *objectivity and subjectivity* apply to scientific endeavors, the variety of types of *scientific methods* that scientists use, and the inherent conflict with NOS issues involved when scientific information is described as *proven* or known with certainty.

Students typically have deep-rooted misconceptions about these concepts, and explicitly addressing them could help students to adopt more informed views and better prepare them to consider NOS issues such as whether scientific knowledge is invented or discovered and why scientists can disagree about the meaning of data.

(2) Use short stories focused on contemporary science, in an attempt to illustrate that the same NOS ideas that are seen in the history of science also apply to the work of scientists today. This approach could be used to combat the view expressed by some students that the nature of science from the past is different from that of the present due to changes in culture, technology, or the knowledge base of science.

(3) Construct historical short stories that require students to reflect on and answer questions about science content as well as NOS issues. It is possible that this approach would better promote changes in students' science content understanding.

(4) Use the findings from this study to design curriculum (including historical short stories) that specifically targets students' geology misconceptions. If this can be accomplished in a way which promotes sufficient cognitive conflict for the students, it is possible that they may be convinced to adopt a scientific understanding which better aligns with accepted scientific ideas.

(5) Examine the effect of using historical short stories such as these with accompanying extensive teacher implementation of the materials, including incorporation of the concepts into the daily classroom dialog about science content, modeling of appropriate usage of science vocabulary to convey accurate messages about the nature of science, use of frequent teacher-led discussions to illustrate NOS concepts and to combat students' tendencies to interpret the short stories in light of their own

misconceptions about science, and emphasis of the importance and relevance of NOS understanding to the overall course content by integration of NOS questions into all primary forms of assessment, including unit exams. If statistically significant gains in NOS understanding can be achieved without extensive use of any of these strategies, as occurred in this study, even greater results could be expected from a study which incorporated a more active role for the science teacher.

Conclusion

Students' responses to the homework and quiz questions in this study exemplify the idea that students learn about the nature of science whether teachers and textbooks actively discuss these concepts or not. Students' rationales for their views often reflected interpretations of science that they have made based on the way it has been portrayed through textbooks and classroom environments which focus on mastery of content over understanding of processes. The implicit messages that students learn in this manner often conflict with the more accurate portrayals of science that can be achieved from an examination of how scientific knowledge has developed and changed over a period of time. Historical narratives provide an effective way of simultaneously teaching the nature of science and science content – a process which allows students to become well versed in multiple dimensions of scientific knowledge, thus contributing to the development of a citizenry that both understands and is interested in science.

REFERENCES

Abd-El-Khalick, F., Bell, R. & Lederman, N. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*, 417-436.

Abd-El-Khalick, F., & BouJaoude, S. (1997). An exploratory study of the knowledge base for science teaching. *Journal of Research in Science Teaching, 34*, 673-699.

Abd-El-Khalick, F., & Lederman, N. G. (2000). The influence of history of science courses on students' views of nature of science. *Journal of Research in Science Teaching, 37*(10), 1057-1095.

Aikenhead, G.S., & Ryan, A.G. (1992). The development of a new instrument: "Views on Science-Technology-Science" (VOSTS). *Science Education, 76*(5), 477-491.

Akerson, V. L., Abd-El-Khalick, F., & Lederman, N. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37*, 295-317.

Allchin, D. (1990). Teachers' views of prospects for the history and philosophy of science in science teaching. In D. E. Herget (Ed), *More history and philosophy of science in science teaching: Proceedings of the first international conference* (pp.165-171). Tallahassee, FL: Science Education and Department of Philosophy, Florida State University.

Alters, B. J. (1997). Whose nature of science? *Journal of Research in Science Teaching, 34*(1), 39-55.

American Association for the Advancement of Science. (1993). *Project 2061: Science for all Americans*. Washington, D.C.: Author

Appleton, K. (1997). Analysis and description of students' learning during science classes using a constructivist-based model. *Journal of Research in Science Teaching, 34*(3), 303-318.

Barrow, L., & Haskins, S. (1996). Earthquake knowledge and experiences of introductory geology students. *Journal of College Science Teaching, 26*(2), 143-146.

Bogdan, R. C., & Biklin, S. K. (2003) *Qualitative research for education: An introduction to theories and methods* (4th ed.). New York: Allyn & Bacon.

Brickhouse, N. W. (1990). Teachers' beliefs about the nature of science and their relationship to classroom practice. *Journal of Teacher Education, 41*(3), 53-62.

Brickhouse, N. & Bodner, G. (1992). The beginning science teacher: Classroom narratives of convictions and constraints. *Journal of Research in Science Teaching, 29*(5) 471-485.

Bruning, M. J. (2003). How young women come to know the engineering profession. *Dissertation Abstracts International, 64*(05), 1536A. (UMI No. 3090084)

Carey, R. L., & Stauss, N. G. (1968). An analysis of the understanding of the nature of science by prospective secondary science teachers. *Science Education, 52*(4), 358-363.

Clough, M. P. (2006). Learners' responses to the demands of conceptual change: Considerations for effective nature of science instruction. *Science Education, 15*, 463-494.

Clough, M. P. & Olson, J. K. (2001). *Effects of contextualized & decontextualized nature of science instruction on teachers' practices*. Paper presented at the National Association for Research in Science Teaching (NARST) Conference, St. Louis, MO, March 25-28.

Clough, M. P., & Olson, J. K. (2004). The nature of science: Always a part of the science story. *The Science Teacher, 71*(9), 28-31.

Clough, M. P., Olson, J. K., Stanley, M., Colbert, J. & Cervato, C. (2006). Project title: *Humanizing science to improve post-secondary science education: Pursuing the second tier*. Proposal (Number 0618446) submitted to the National Science Foundation Course Curriculum and Laboratory Improvement (CCLI) Phase II (Expansion) Program. Submitted for and funded at $293,718.

Conant, J. B. (1957). *Harvard case histories in experimental science*. Cambridge, MA: Harvard University Press.

Driver, R., Leach, J., Miller, A. & Scott, P. (1996). *Young people's images of science*. Bristol, PA: Open University Press.

Duschl, R. A. (1994). Research on the history and philosophy of science. In D. L. Gabel (Ed), *Handbook of research on science teaching and learning* (pp.443-465). New York: MacMillan Publishing Company.

Efflin, J. T., Glennan, S., & Reisch, G. (1999). The nature of science: A perspective from the philosophy of science. *Journal of Research in Science Teaching, 36*(1), 107-116.

George, D., & Mallery, P. (2001). *SPSS for windows: Step by step* (3rd ed.). Boston: Allyn and Bacon.

Glaser, B., & Strauss, A. (1967). *Discovery of grounded theory*. Chicago: Aldine.

Harding, S. (1991). *Whose science? Whose knowledge?: Thinking from women's lives*. Ithaca, NY: Cornell University Press.

Heilbron, J. L. (2002). History in science education, with cautionary tales about the agreement of measurement and theory. *Science and Education, 11*, 321-331.

Khishfe, R. & Abd-El-Khalick, F. (2002). Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39*(7), 551-578.

Kimball, M. E. (1968). Understanding the nature of science: A comparison of scientists and science teachers. *Journal of Research in Science Teaching, 2*(1), 3-6.

King, C. (2000). The Earth's mantle *is* solid: Teachers' misconceptions about the Earth and plate tectonics. *School Science Review, 82*(298), 57-64.

Klopfer, L. E. & Cooley, W. W. (1963). The history of science cases for high schools in the development of student understanding of science and scientists. *Journal of Research in Science Teaching, 1*, 33-47.

Krathwhol, D. R. (1998). *Methods of educational and social science research* (2nd ed.). Long Grove, IL: Waveland Press.

Kuhn, T. S. (1970). *The structure of scientific revolutions*, (3rd ed.). Chicago: University of Chicago Press.

Kurdziel, J. P., & Libarkin, J. C. (2002). Research methodologies in science education: Students' ideas about the nature of science. *Journal of Geoscience Education, 50*(3), 322-329.

Lederman, N. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29*, 331-359.

Lederman, N. G., Wade, P. D., & Bell, R. L. (1998). Assessing the nature of science: What is the nature of our assessments? Science and Education, 7(6), 595-615.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire: Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497-521.

Leite, L. (2002). History of science in science education: Development and validation of a checklist for analysing the historical content of science textbooks. *Science and Education, 11*, 333-359.

Libarkin, J. C., & Kurdziel, J. P. (2001). Research methodologies in science education: Assessing students' alternative conceptions. *Journal of Geoscience Education, 49*(4), 378-383.

Lin, H., & Chen, C. (2002). Promoting preservice chemistry teachers' understanding of the nature of science through history. *Journal of Research in Science Teaching, 39*(9), 773-792.

Lonsbury, J. G., & Ellis, J. D. (2002). Science history as a means to teach nature of science concepts: Using the development of understanding related to mechanisms of inheritance. *Electronic Journal of Science Education, 7*(2), Article 0002. Retrieved June 25, 2004, from http://unr.edu/homepage/crowther/ejse/lonsbury.pdf

Marques, L., & Thompson, D. (1997a). Misconceptions and conceptual changes concerning continental drift and plate tectonics among Portuguese students aged 16-17. *Research in Science and Technological Education, 15*(2), 195-222.

Marques, L., & Thompson, D. (1997b). Portuguese students' understanding at ages 10-11 and 14-15 of the origin and nature of the Earth and the development of life. *Research in Science and Technological Education, 15*(1), 29-51.

Martin, B. E., & Brouwer, W. (1991). The sharing of personal science and the narrative elements in science education. *Science Education, 75*, 707-722.

Matthews, M. R. (1989). A role for history and philosophy of science teaching. *Interchange, 20*(2), 3-15.

Matthews, M. R. (1994). *Science teaching: The role of history and philosophy of science*. New York: Routledge.

Matthews, M. R. (1998). In defense of modest goals when teaching about the nature of science. *Journal of Research in Science Teaching, 35*, 167-174.

McComas, W. F. (2000). The principle elements of the nature of science: Dispelling the myths. In M. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 53-70). Klewer Academic Publishers: The Netherlands.

McComas, W. F., Almazroa, H., & Clough, M. P. (1998). The nature of science in science education: An introduction. *Science and Education, 7*, 511-532.

McComas, W. F., Clough, M. P., & Almazroa, H. (2000). The role and character of the nature of science in science education. In M. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 3-39). Klewer Academic Publishers: The Netherlands.

McComas, W. F., & Olson, J. K. (2000). The nature of science in international science education standards documents. In M. McComas (Ed.), *The nature of science in science education: Rationales and strategies* (pp. 41-52). Klewer Academic Publishers: The Netherlands.

Munro, P. (1993). Multiculturalism redefined in science education research: Part two. In R. Good (Ed.), *Contributions from the history and philosphy of science to the question of multiculturalism in science education*. Symposium conducted at the annual meeting of the National Association for Research in Science Teaching, Atlanta, GA. (ERIC Document Reproduction Service No. ED364419.)

Murcia, K. & Schibeci, R. (1999). Primary student teachers' conceptions of the nature of science. *International Journal of Science Education, 21*, 1123-1140.

National Research Council. (1996). *National science education standards*. Washington, D.C.: National Academy Press.

National Science Teachers Association. (1962). The NSTA position on curriculum development in science. *The Science Teacher, 29*(9), 32-37.

National Science Teachers Association. (1990). *Science/Technology/Society: A New Effort for Providing Appropriate Science for All*. An NSTA Position Statement, Washington, D.C.: Author.

Palmquist, B. & Finley, F. (1997). Preservice teachers' views of the nature of science during a postbaccalaureate science teaching program. *Journal of Research in Science Teaching, 34*(6), 595-615.

Philips, W. C. (1991). Earth science misconceptions. *The Science Teacher, 58*(2), 21-23.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W.A. (1982). Accomodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Roach, L. .E., & Wandersee, J. H. (1995). Putting people back into science: Using historical vignettes. *School Science and Mathematics, 95*(7), 365-370.

Rossiter, M. (1982). *Women scientists in America*. Baltimore: Johns Hopkins University Press.

Rubba, P., & Anderson, H. (1978). Development of an instrument to assess secondary school student understanding of the nature of scientific knowledge. *Science Education, 62*, 449-458.

Rudolph, J. L. (2000). Reconsidering the ‘nature of science’ as a curriculum component. *Journal of Curriculum Studies, 32*(3), 403-419.

Ryan, A.G., & Aikenhead, G.S. (1992). Students’ preconceptions about the epistemology of science. *Science Education, 76*(6), 559-580.

Schwab, J. J. (1964). The teaching of science as enquiry. In J. J. Schwab & P. F. Brandwein (Eds.), *The Teaching of Science* (pp.31-102). Cambridge, MA: Harvard University Press.

Seymour, E., & Hewitt, N. M. (1997). *Talking about leaving: Why undergraduates leave the sciences*. Boulder, CO: Westview Press.

Shamos, M. (1995). *The myth of scientific literacy*. New Brunswick, NJ: Rutgers University Press.

Shapiro, B. L. (1996). A case study of change in elementary student teacher thinking during an independent investigation in science: Learning about the “Face of science that does not yet know.” *Science Education, 80*, 535-560.

Smith, M. U., Lederman, N. G., Bell, R. L., McComas, W. F. & Clough, M. P. (1997). How great is the disagreement about the nature of science? A response to Alters. *Journal of Research in Science Teaching, 34*(10), 1101-1103.

Solomon, J., Duveen, J., Scot, L., & McCarthy, S. (1992). Teaching about the nature of science through history: Action research in the classroom. *Journal of Research in Science Teaching, 29*(4), 409-421.

Songer, N., & Linn, M. (1991). How do students’ views of science influence knowledge integration? *Journal of Research in Science Teaching, 28*, 761-784.

Stinner, A., McMillan, B. A., Metz, D., Jilek, J. M., & Klassen, S. (2003). The renewal of case studies in science education. *Science and Education, 12*, 617-643.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research* (2nd ed.). Thousand Oaks, CA: Sage Publications, Inc.

Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. Duschl & R. Hamilton (Eds.), *Philosophy of science, cognitive psychology, and educational theory and practice* (pp. 147-176). Albany, NY: State University of New York Press.

Tao, P. (2003). Eliciting and developing junior secondary students' understanding of the nature of science through a peer collaboration instruction in science stories. *International Journal of Science Education, 25*(2), 147-171.

Tobias, S. (1990). *They're not dumb, they're different: Stalking the second tier*. Research Corporation, Tucson.

Trend, R. D. (2001). Deep time framework: A preliminary study of U. K. primary teachers' conceptions of geological time and perceptions of geoscience. *Journal of Research in Science Teaching, 38*(2), 191-221.

Wandersee, J. H. (1985). Can the history of science help science educators anticipate students' misconceptions? *Journal of Research in Science Teaching, 23*(7), 581-597.

Wandersee, J. H., & Roach, L. M. (1997). Interactive Historical Vignettes. In J. J. Mintzes, J. H. Wandersee, & J. D. Novak (Eds.), *Teaching science for understanding: A human constructivist view* (pp. 281-306). New York: Academic Press.

APPENDICES

Appendix A: NOS and Geology Assessment (Quiz) Questions

NOS-A: Consider that a gold miner discovers gold, but a musician creates a song. Some people think that science knowledge is discovered while others think that scientific knowledge is created.

(a) What do you think?
(b) Provide evidence using your knowledge of science.

NOS-C: Evidence can be used to support the idea that about 65 million years ago the dinosaurs became extinct. One group of scientists suggests that a huge meteorite hit the earth 65 million years ago and led to a series of events that caused the extinction. A second group of scientists suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these different conclusions possible if scientists in both groups have access to and use the same set of data to derive their conclusions?

NOS-D: In what ways, if at all, do the culture and society have an effect on an individual scientist's work? Include an example to explain your reasoning

NOS-E: In what ways, if at all, do currently accepted scientific ideas have an effect on an individual scientist's work? Include an example to explain your reasoning.

GEOL-A: Mineral deposits approximately 200 million years old have been discovered in Brazil. Geologists today want to predict where mineral deposits of a similar age might be found. Describe a likely prediction and a geologist's rationale for this prediction

GEOL-B: Provide an example of how geologists combine absolute and relative dating methods to bracket the age of sedimentary rocks.

GEOL-C: A five kilometer thick column of sedimentary rock can be used by scientists as evidence that the earth is far older than 10,000 years as they had previously thought. What features would you expect to see in this column and how could these features be used to support the later conclusion that the earth is very old?

GEOL-D: The oldest rocks of the continents are almost four billion years old, while the oldest rocks of the ocean basin are not even 200 million years old. Explain why this difference in age occurs and how it supports plate tectonics.

Appendix B: Coding Rubrics for NOS and Geology Assessment (Quiz) Questions

Coding rubric for NOS-A

Question: Consider that a gold miner discovers gold, but a musician creates a song.
Some people think that science knowledge is discovered while others think that scientific knowledge is created.
(a) What do you think?
(b) Provide evidence using your knowledge of science.

Category	F'2004	S'2007	Description	Student exemplars (Geology)
Type 1: (Color: light yellow)	n=0	n=4 (5.6%)	Respondents recognize how aspects of **both invention and discovery** contribute to scientific knowledge. They also provide supporting evidence, including one or more **specific exemplars** from science, in ways that are consistent with contemporary views on NOS.	"Scientists discover things about what they are studying but they have to use the new info and prior knowledge to create an explanation, such as when geologists discovered similar fossils on different continents and created the idea of a super-continent because it fit the evidence." (Sp'07)
Type 2: (Color: blue)	n= 2 (2.9%)	n=14 (19.4%)	Respondents recognize how aspects of **invention** contribute to scientific knowledge. They **may also recognize** aspects of **discovery.** Response is clearly articulated, but **does not refer to specific exemplars** from science. Response is **free from any inconsistencies** with contemporary views of NOS.	"Science knowledge is both discovered and created. It is created in the sense that questions we ask and the methods we go about looking for that answer (those) questions are created by the discipline of science. It is through the methods and techniques we have created using the nature of science that we answer these questions. It is discovered in that often what answers we find help us discover more questions to ask." (F04) "Scientific knowledge is created. Scientists must interpret the data they find; a discovery by itself means nothing unless a scientist 'creates' a meaning for it by interpreting the data." (S07) "I think that you create

				knowledge of science but you also must use tools that are found as data, such as fossils that support prehistoric animals can fly." (S07)
Type 3: (Color: green)	n= 3 (4.3%)	n= 13 (18.1%)	Respondents **recognize how aspects of invention** contribute to scientific knowledge. They may also recognize aspects of discovery. Responses may fall into this category if ideas are not as clearly articulated as Type 2. **OR** Supporting evidence contains at least one NOS idea that is inconsistent with contemporary views on NOS.	"Science knowledge is both (created and discovered). It's how the scientists think, what questions they bring up that matters. From the things I've learned in my science classes helped me to think 'outside the box' and try to figure out how things happen and why." (F04) "Scientific knowledge is not created, it is discovered mostly. The reason I believe this way is in discovering something, we didn't know about the world previously, such as finding an archeological artifact shows that uncovering is a main part of science; however, some measure of creativity is employed when interpreting that same archeological artifact." (F04) "I think that scientific knowledge is discovered but that hypotheses and methods of science are invented." (S07) "Both. New scientific things can be discovered but upon discovering them you use your opinion to judge what they are." (S07)
Type 4: (Color: yellow)	n=15 (21.4%)	n=10 (13.9%)	Respondents **state that invention occurs** and contributes to scientific knowledge. They may also recognize aspects of discovery. Supporting evidence is **largely inconsistent** with contemporary views on NOS.	"I think some science knowledge is discovered like finding dinosaur fossils. Those aren't created. But other science knowledge is created. The kind that must go through many experiments before finding an end scientific result." (F04). "It can be both discovered and created. (We) discover things

				like new planets, minerals, species, etc. (We) could maybe create new drugs, create in the way of cloning, etc." (F'04) "I think it is both because scientists/paleontologists/ archeologists, etc., go out to try to discover science and clues to our earth. However, once these people discover science, they must create hypothes(es) and theories to explain their findings. Therefore, scientific knowledge is both discovered and created." (F04) "I think that science knowledge is discovered, but the little links between them are created until proven. There has to be something found or seen to provide you with knowledge. You can't just make it up." (S'07)
Type 5: (Color: pink)	n=35 (50.0%)	n=27 (37.5%)	Respondent **emphasizes discovery** in the development of scientific knowledge. Supporting evidence may contain additional NOS ideas that are inconsistent with contemporary views.	"Science knowledge is discovered. Scientific facts and theories are discovered. New discoveries are found, it's not something you can go into a lab and make for the first time." (F04) "Science is definitely discovered. Once discovered it is then worked on or researched upon. Therefore, it is essential that knowledge is discovered and then researched. Though research can create new science, but only after it's discovered." (F04) "It is discovered because science is about making a hypothesis and testing different ideas over and over until you get a feasible answer." (S'07) "I think that science knowledge

				is discovered. People (scientists) discover new things every day (such as how Pluto was not a planet). They do not make information up." (S'07)
Type 6: (Color: purple)	n= 15 (21.4%)	n=4 (5.6%)	Non-classifiable and/or Does not provide supporting evidence	

Coding rubric for (NOS-B)
Question: "Evidence can be used to support the idea that about 65 million years ago the dinosaurs became extinct. One group of scientists suggests that a huge meteorite hit the earth 65 million years ago and led to a series of events that caused the extinction. A second group of scientists suggests that massive and violent volcanic eruptions were responsible for the extinction. How are these different conclusions possible if scientists in both groups have access to and use the same set of data to derive their conclusions?"

Category	F'2004	S'2007	Description	Student examples (Geology)
Type 1: (dark pink)	n = 2 (1.4%)	n = 0	Respondents **recognize and describe that multiple interpretations are possible.** They provide description which is consistent with contemporary NOS views conveying that science involves a human aspect **and** a degree of uncertainty.	"The evidence is interpreted differently between the two sets of scientists. The reasoning behind the different interpretations is that there is no concrete evidence or data to show or explain what caused the dinosaurs to become extinct. There obviously is evidence to show that both theories are practical and data shows some proof of each theory, but scientists haven't been able to disprove either theory. The human element is involved also. Scientists have their hypothesis and theories, and because of their bias, they will believe what they want to believe just like anyone else." (F04)
Type 2: (yellow)	n = 13 (9.4%)	n = 7 (9.0%)	Respondents **recognize and describe that multiple interpretations are possible**. They provide description which is consistent with contemporary NOS views	"Their conclusions may differ because of personal, nonscientific beliefs, or may differ because one scientist may interpret the data differently. Perhaps they are

			conveying that science involves a human aspect **and/or** a degree of uncertainty. Respondents' explanations are **less articulate than above**.	swayed in their decisions by a constituent placed in their study." (F04) "Each set of scientists believes that different things happened for different reasons, so although they are using the same set of data, it may be interpreted differently and that is how they may have come to different conclusions." (F04) "Both of these conclusions are possible by different scientists using the same set of data because different people/scientists interpret data differently. Data can be interpreted in several different ways based upon different levels of knowledge and different experiences." (S'07)
Type 3: (orange-red or orange w/ "+"	n = 12 (8.7%)	n = 24 (30.8%)	Respondents state that **different conclusions are possible because scientists interpret data differently or because data is open to interpretation**. No accurate description of the types of factors which cause scientists to interpret data differently are provided, but no NOS misconceptions are present either.	"Different scientists derive different information from data. Therefore, the same set of evidence brings different conclusions." (F04) "There may have been evidence to conclude both and each scientist had their own opinion." (F04) "Because the data can be interpreted different ways there is evidence that can support both theories." (S'07) "There is a lot of evidence of both of these causes and they both seem plausible. It depends on the individual scientist and how they analyze their own research." (S'07)
Type 4: (orange-red or orange)	n = 12 (8.7%)	n = 5 (6.4%)	Respondents state that **different conclusions are possible**. Respondents fall into this category if:	"Because no one really knows for sure. There is evidence, but not complete step by step information for what went on. So by just putting the pieces together,

			• their supporting reasons contain a **mixture of ideas, some that are and some that are not consistent with contemporary NOS views**	you can conclude different things, and these are just the two best possible conclusions they came up with." (F04) "Different scientists interpret the same results differently. Not everyone sees the same thing in the same way. Plus there is no defining evidence either way." (Sp'07)
Type 5: (green)	n = 20 (14.5%)	n = 7 (9.0%)	Respondents imply that if certain **insufficiencies in the scientific process** were eliminated, then we might be able to resolve this dilemma. Insufficiencies in the scientific process which the respondents might cite include: • Scientists make mistakes. • We need more data.	"These two different conclusions are possible because there isn't enough evidence supporting either conclusion. There really isn't a specific location that can be used as strong evidence that a meteor hit the Earth. However, there (is) a lot more reliable evidence to support volcanism." (F04) "As with anything, statistical data can be manipulated to prove or disprove the same idea. Scientists of the different theories may only be using portions of the data." (F04) "Because the data is inconclusive." (S'07)
Type 6: (purple)	n = 6 (4.3%)	n = 4 (5.1%)	The respondent contends that **we just can't know**. This claim is problematic because the respondent fails to grapple with the nature of scientific knowledge. Their response implies that if we were there, then we could know.	"Because nobody really knows what happened." (F04) "None of us were alive then so no one can possibly know exactly what happened." (F04) "There is no distinct evidence one way or another. It is hard to predict what caused the extinction." (S'07)
Type 7: (blue)	n = 61 (44.2%)	n = 28 (35.9%)	Respondents **do not speak to the nature of scientific knowledge**. Instead, they evaluate the scientific accuracy and/or plausibility	"Both events could kick up enough debris to block out sun and lower overall temperature enough to kill them off, or (it) could

			of the possible explanations using **geological explanations** to address the question. Responses in this category may be unclear as to whether they think multiple interpretations are possible.	have been both events together that led up to the die-off." (F04) "The huge meteorite that hit the earth could have caused plates to move which may have disrupted some sleeping volcanoes causing them to erupt in massive and violent explosions." (F04) "It is hard to determine why rock deformations have happened when rocks have metamorphosed. Metamorphism warped the rocks around fossils, leaving any evidence inconclusive." (F04) "Both events are catastrophic and would have similar effects on the rocks found from that time period." (S'07) "During the time that the dinosaurs became extinct, the world changed a lot. We know that just not one thing killed them off, but a combination of them." (S'07)
Type 8: (neon pink)	n = 4 (2.9%)	n = 0	Respondents rely on **significant NOS misconceptions,** such as claiming that evidence cannot be interpreted in multiple ways or claiming that theories have little worth (e.g., it's just a theory).	"I am not quite sure of how to answer this question. It is unknown to me how the same sets of evidence can lead to such varied results." (F04) "Because they are only theories - nothing has become a fact. They haven't been able to prove anything, so it's all speculation and theorizing." (F04)
Type 9: (neon orange)	n = 8 (5.8%)	n = 3 (3.8%)	Non-classifiable.	

F'04n=138 S'07 n=78

Coding rubric for NOS-D

Question: "In what ways, if at all, does the culture and society have an effect on an individual scientist's work? Include an example to explain your reasoning."

Category	Fall '06	Spring '07	Description	Student Exemplars
Type 1 (Color: neon pink)	n = 3 (1.7%)	n=9 (12.5%)	Response indicates that societal and cultural influences act both to **guide and restrict scientific endeavors** through cultural biases, actions of activism, restricted funding, political pressure, and/or religious teachings that value some endeavors and devalue other areas/types of scientific work. Response may also indicate that as society changes, the direction of science will likely change as well.	"Culture and society can affect a scientist's work both positively and negatively. Problems in society can drive scientists to find solutions – such as better building materials for people in areas at risk for natural disasters, or the creation of new kinds of medicine. On the other hand, negative public opinions about issues in science such as global warming or stem cell research might cause scientists to focus their work on areas that would be better received by the public, and therefore hinder scientific improvement." (F'06) "Early science was heavily influenced by the Bible and other cultural/religious works. Also, controversial science could be discouraged and might have trouble being accepted, however right it may be." (Sp'07)
Type 2 (Color: purple)	n = 67 (38.5%)	n=23 (31.9%)	Response indicates that societal beliefs and values tend to **limit or draw boundaries for scientific work** through the cultural biases, actions of activism, restricted funding, political pressure, and/or religious teachings that devalue certain areas/types of scientific work.	"I think culture and society affect a scientist's work in many ways. Most notably, the economics of research funding are controlled almost entirely by what society wants to research. Scientists use research funding to answer the questions that society is asking today. Rarely is money given to researchers to solve problems that do not relate to an issue in society, i.e. funding for biorenewable fuel research." (F'06) "Culture and society have a huge effect on scientist's work because if the public doesn't

				accept it they could try to stop the research from happening. They could try to stop it by sabotaging it or protesting. Some examples are releasing of animals that were used for testing or not giving money for stem cell research." (Sp'07) "Many old theories often become thought of as fact. When a new idea is produced to contest the old, some people do not accept it based on habit." (Sp'07)
Type 3 (Color: blue)	n = 31 (17.8%)	n=33 (45.8%)	Response indicates that society and culture **guide the work of scientists toward certain ways of thinking and explaining phenomena** – as the ideas of society change, new areas of science open up. This may have a positive or negative impact.	"Culture and society can affect a scientist by the way they think about an object. For example, some cultures may disagree with the fact that a scientist could dissect a dead body of a person because it maybe violates their belief or their religion." (F'06) "People tend to explore what they believe, which is greatly influenced by culture and society." (Sp'07)
Type 4 (Color: dark pink)	n= 10 (5.7%)	n=0	Response indicates that society and culture **guide the work of scientists toward areas of research where the greatest good can be accomplished** (i.e. medical research to cure a particular disease)	"I think that society and culture dictate what a scientist studies. They will study what is important to the average person so that their work will benefit all of society. If the work isn't for some greater benefit, then it's kind of a waste of time." (F'06)
Type 5 (Color: green)	n= 10 (5.7%)	n=0	Response indicates that the values of society and culture **allow for/promote the destruction of certain life forms and ecosystems**, thus limiting what is available for study.	"It depends on how society and culture have impacted the environment that the scientist is studying. Cultures that have abused the land will cause different studies from societies that have respected nature." (F'06)
Type 6 (Color: yellow)	n= 5 (2.9%)	n=1 (1.4%)	Response indicates that society and culture **question, critique, and demand proof from scientists** once scientific reports are made.	"If the culture doesn't accept what the scientist thinks is true it would make it hard to prove or disprove something. Like when people thought the world was flat or that the universe revolves

				around the earth." (F'06) "A scientist's ideas have to go along with the beliefs of the society in order to be generally accepted as true." (Sp'07)
Type 7 (Color: orange-red)	n= 11 (6.3%)	n=0	Response indicates that society and culture **do not or should not affect scientific work**.	"I don't think that culture and society should have an effect on a scientist's work because all the scientist is doing is researching or trying to discover/prove something. They should do their work without influence to give us the straight facts, although sometimes society does influence them. Scientists must now do things in an acceptable manner so as not to disturb the society or make society angry. I think this is dumb though, unless the scientists are doing something wrong/harmful, just let them do their work." (F'06)
Type 8 (Color: orange)	n=37 (21.3%)	n=6 (8.3%)	Non-classifiable	

F'06 n_{Total} = 154   S'07 n_{total}=72

Coding rubric for NOS-E

Question: "In what ways, if at all, do currently accepted scientific ideas have an effect on an individual scientist's work? Include an example to explain your reasoning."

Category	Fall '06	Spring '07	Description	Student Exemplars
Type 1 (Color: blue)	n = 2 (1.3%)	n = 1 (1.3%)	Respondents recognize both ways in which currently accepted ideas provide **helpful structure for or stimulation of scientific work and** ways in which currently accepted ideas can provide **limitations to or biases in the work of scientists**. Some degree of tentativeness of currently accepted ideas is also present.	"Current ideas can shape an individual's ideas in two ways: They can agree or disagree. For example, if a scientist doesn't believe in evolution, (he) will probably be looking for evidence to the contrary, and is therefore unlikely to ever agree. However, if a scientist agrees with current ideas, he will probably only consider evidence that is consistent with current theory, shaping his ideas."

			Response is free from any inconsistencies with contemporary views on NOS.	
Type 2 (Color: Neon orange)	n = 9 (5.8%)	n = 7 (9.1%)	Respondent strongly embraces and focuses on the idea that **currently accepted ideas are tentative and can change** in light of new ideas/evidence. Response is free from any inconsistencies with contemporary views on NOS. The response may also point out ways in which currently accepted ideas provide helpful structure for or stimulation of scientific work and ways in which currently accepted ideas can provide limitations to or biases in the work of scientists.	"It is kind of like scientific paradigms. A way of method and reasoning affects how research is interpreted and analyzed." "They give scientists a jumping off point for new ideas. Scientists have a choice to continue thinking along an old path or can use prior knowledge to branch out into something new."
Type 3 (Color: dark pink)	n=35 (22.7%)	n= 19 (24.7%)	Respondents recognize only ways in which currently accepted ideas provide **useful structure for and/or stimulation of scientific work.** Some degree of tentativeness of currently accepted ideas is also present. The structure and/or stimulation is described in either a positive or a neutral light. Responses in this category may contain one or more ideas that are inconsistent with contemporary views on NOS.	"This may have an effect because if a scientist doesn't want to believe something, they will try to prove it wrong and make their own law. Also if a scientist is working on supporting one law all their life and it changes right as they complete their research then it will have a major impact." "Well, I think that scientists work deals greatly upon the accepted scientific ideas. For instance what we just talked about in class on how the moon gravitational pull causes high and low tides in the ocean. If a scientist doesn't trust these accepted ideas then they better have good reasoning

				behind why they don't" "When scientists are working on new ideas they use accepted scientific ideas as well. If an accepted idea is incorrect, people have spent time researching for no reason."
Type 4 (Color: light pink)	n= 12 (7.8%)	n= 5 (6.5%)	Respondents recognize only ways in which currently accepted ideas provide **limitations to or biases in the work of scientists.** Some degree of tentativeness of currently accepted ideas is also present. Ideas of limitations and/or bias that are brought forward are often portrayed in a negative light. Responses in this category may contain one or more ideas that are inconsistent with contemporary views on NOS.	"Widely accepted ideas will often discourage individual scientists from proposing new theories. For example, the first hypotheses regarding continental drift were rejected because they opposed the currently accepted idea." "They don't always have an effect; if they always did no new ideas would be thought of."
Type 5 (Color: neon yellow-green)	n= 57 (37.0%)	n= 30 (39.0%)	Respondent indicates that scientists take currently accepted ideas into account to either guide or limit their work. Although no description of currently accepted ideas as having a tentative nature is included, a strong assertion that current ideas cannot change is also not made. Responses in this category may contain one or more ideas that are inconsistent with contemporary views on NOS.	"Currently accepted ideas are used as a starting point for other scientists to work off of." "If the idea is already accepted in the scientific community then a scientist might base new research off of what is already accepted." "As scientists grow up and learn through education and experiences, they will perceive the information they gather in a way as those that taught them. To expand knowledge in all areas of study, we must get away from that." "Scientists apply accepted theories to their work, I believe.

				For example, scientists use the theory of global warming and the idea on their new and current work on the idea."
Type 6 (Color: green)	n= 4 (2.6%)	n= 6 (7.8%)	Respondent indicates that **currently accepted ideas are viewed as unquestionable truth** by scientists or by the scientific community. The current work of scientists must fit together with currently accepted ideas. Although these responses generally refer to currently accepted ideas as providing a useful framework, the framework is seen as rigid and unchangeable.	"Scientific ideas that are currently accepted do effect individual scientists work. An example of this is the scientific method. This idea is currently accepted and effects scientists all the time when forming ideas and experiments. Without this method scientists would not have a effective way to figure out whether or not an idea will come out as planned and can help them to prove their ideas to others. If they didn't use this they would have most of their ideas/experiments believed to not be credible or proven." "Scientists conduct experiments differently based on what is accepted as scientific ideas. The scientific method for example. If a scientist does not abide by the rules of the scientific method, then people will not seriously consider the data." "I think that currently accepted ideas are seen pretty much as fact, so not very many people think outside the box to come up with new ideas. All ideas researched today are based on things that were proven before."
Type 7 (Color: yellow)	n= 2 (1.3%)	n= 2 (2.6%)	Respondent indicates that currently accepted ideas **do not have an effect on an individual scientist's work,** implying that scientists are able to maintain pure objectivity in their work.	"There is no effect from scientific ideas on individual scientific work because there is always something that can be altered or questioned making all existing data irrelevant." (F'06) "I don't think it has that much of an effect on the individual scientist. It only makes him look

				better and people respect and listen to his/her ideas more." (SP'07)
Type 8 (Color: orange)	n= 33 (21.4%)	n= 7 (9.1%)	Non-classifiable	

F'06 n_{Total} = 154 S'07 n_{Total} = 77

Coding rubric for GEOL-A

Question: "Mineral deposits approximately 200 million years old have been discovered in Brazil. Geologists today want to predict where mineral deposits of a similar age might be found. Describe a likely prediction and a geologist's rationale for this prediction."

Coding scheme for student responses:

Category	Fall'04	Spring'07	Description of category	Student examples
Type 1: (purple)	n = 23 (33.3%)	n = 18 (23.1%)	Student response describes the idea of a **super-continent (Pangaea)** which existed at the time in question and **refers to Africa as a likely location** to look since Brazil was connected to Africa.	"You would have to pick a place that was once connected to Brazil a long time ago. You would have to figure out what period the mineral deposits came from and find a spot where rocks/mineral deposits are shown from this same period. I would have to pick somewhere on the west coast of Africa that would have 'fit together' a long time ago when Pangeria was together." (Fall'04) "Along the western coast of Africa because it is thought that they were connected." (Fall'04) "A likely prediction would be Africa because the two continents were connected during the time that Earth had the large supercontinent Pangaea." (Spring'07)
Type 2: (pink)	n = 19 (27.5%)	n = 25 (32.1%)	Student response describes the idea of a **super-continent (Pangaea)** which existed at the time in question and suggests looking at areas that were connected to Brazil. **Student either**	"Nearby, or possibly same elevation in other places. Or check out Pangea and the areas that were once located near Brazil." (Fall'04) "Geologists might use the record of the locations of the Earth's continents to find where mineral

			does not refer to any specific areas to look or lists areas that would not have been connected to Brazil.	deposits of a similar age might be found. This would make sense because if the continents were once attached/ connected then they might find traces of similar mineral deposits.” (Spring’07) “They could look to any countries that were close or connected to Brazil during Pangea. They would have the same minerals as Brazil.” (Spring’07)
Type 3: (yellow)	n = 7 (10.1%)	n = 11 (14.1%)	Student response suggests looking for **areas that have similar specific geological characteristics** (i.e. topography, layering of deposits, volcanic activity, glacial movements during an Ice Age)**.** No rationale based on areas that may have been linked in a super-continent is presented**.** (The presence of similar geological characteristics alone does not necessarily ensure that any deposits formed are of the same age since similar events could have occurred at vastly different points in time.)	“They might look for a similar geologic location in other regions and countries, with similar topography, location, and characteristics. A geologist may argue that this would be the most rational thing to do, since what happened once in one area may be likely to happen again in a different location.” (Fall’04) “A geologist would probably predict that these minerals occurred in more than one place, therefore they would probably use evidence such as rock layers, depth, and the general environment around the site to identify other places alike. By using evidence found at the site, a geologist has an idea where else to look.” (Spring’07)
Type 4: (green)	n = 13 (18.8%)	n = 25 (32.1%)	Student response suggests **looking further in the same general location or nearby locations (focus is on geography rather than geology).** No rationale based on areas that may have been linked or had similar specific	“A likely prediction would be to keep searching related areas in Brazil. It makes sense that if some mineral deposits were found in areas of Brazil, then its likely that there would be more mineral deposits in related areas to where this discovery was made.” (Fall’04) “Mineral deposits of a similar age will probably be found in the same area, or an area with the same

			geological characteristics is presented**.** **OR** Students in this category suggested looking for **areas that have similar climates**. These students **confused mineral deposits with fossils** and relied on a rationale that similar climates would supports similar life forms and produce similar fossil records.	climate or similar things as Brazil. They would maybe predict they found this, because some type of weather or reaction uncovered these mineral deposits." (Spring'07) "An area next to Brazil because if it is attached chances are high that a place close to it will have similar rocks." (Spring'07)
Type 5: (blue)	n = 7 (10.1%)	n = 4 (5.1%)	Response contains **only major inaccuracies or irrelevant ideas**; no relevant and accurate information which addresses the question is included.	"Geologists would probably predict that minerals of a similar age might be found off the coast of Asia because the oceanic currents that brought these minerals to Brazil may have carried these same minerals through the Pacific Ocean and to Asia." (Fall'04) "The Midwest because it has a lot of the same features." (Spring'07)
Type 6:	n = 0	n = 1 (1.3%)	Unclassifiable.	

Coding rubric for GEOL-B
Question: "Provide an example of how geologists combine absolute and relative dating methods to bracket the age of sedimentary rocks."

Category	Fall'04	Spring '07	Description of category	Student examples
Type 1: (purple)	n = 2 (2.9%)	n = 0	Student response provides at least one relevant example of absolute dating and one relevant example of relative dating, each in sufficient detail to demonstrate that the student has a strong grasp of the concepts involved. An accurate description of how	"In this diagram (student drawn) we can use relative dating to know that the sedimentary rock is younger than igneous 1 but older than igneous 2 (relative dating). By determining the numerical ages of each igneous sample (using

			relative dating is used in conjunction with absolute dating is included. No significant inaccuracies are present.	radioactive decay) we can know that the sedimentary rock has an age between these two." (Fall'04)
Type 2: (pink)	n = 7 (10.1%)	n = 8 (10.4%)	Student response provides at least one relevant example of absolute dating and one relevant example of relative dating, with reference to how bracketing can be used to describe the age of sedimentary rock, but the degree of detail included and/or the presence of inaccuracies provides evidence that the student does not have a strong and/or flawless grasp of all of the concepts involved.	"Absolute will use definite aging methods (by) looking at isotopes and half lives. Relative dating is more common sense. If a dike is not layered it is younger because you tell that it formed over the sedimentary rock that was already there. By taking sample of dike, you could also date it with absolute dating." "With sedimentary rocks, we see layers of rock and we know that the oldest rocks are lowest layers and the higher layers are younger. Cross-cutting is also used to date rocks. These are examples of relative dating. Absolute dating would be dating using isotopes of carbon atoms (for example)."
Type 3: (yellow)	n = 19 (27.5%)	n = 22 (28.6%)	Student response 4) provides only an accurate example of relative dating, or 5) provides only an accurate example of absolute dating, or 6) fails to provide any description of how the two forms of dating are used to bracket the age of sedimentary rocks. An inaccuracy may be present, detracting from the quality of the answer.	"This rock layer's on top of that one therefore this one's older than that one." "They can use index minerals to find a relative date, and radioactive dating to fin absolute dates." "I don't really know but I think that the carbon-14 dating can be used as absolute dating and a relative dating would have been an approximation of when a species like that lived. If you put the two together you can place it into an age bracket in the sedimentary rocks."

				"By looking at the radiation of the rock as well as looking at what fossils it contains." "Some species that are preserved in rocks can be used to help date them if they are a widespread species and only lived for a certain, shorter period of time."
Type 4: (green)	n = 17 (24.6%)	n = 28 (36.4%)	Student response is very vague and missing important details. Although some appropriate ideas are included/stated, insufficient detail is included to determine if the student understands how these ideas are relevant to the question. Student responses may fall in this category if they do not include any examples of how dating occurs or if they include a picture only, with labels but no verbal description. Inaccuracies and/or irrelevant ideas may be present, further detracting from the quality of the answer.	"Geologists age sedimentary rock through looking at the other layers around it to see what's going on. They look at fossils and any type of activity that was also happening." "Based on what rocks are around them that they can put an absolute age on, they can then use relative age to determine whether the sedimentary rocks are older or younger than those." "They look at the rock layers and compare old layers to new ones. They have to use relativity to find absolute dating. They also use the changes of atoms stabilized in the rocks." "Geologists used fossils to distinguish ages of rocks while combining absolute and relative methods."
Type 5: (blue)	n = 20 (29.0%)	n = 15 (19.5%)	Response contains only major inaccuracies or irrelevant ideas; no relevant and accurate information is included.	"They combine the dating methods when dealing with angular conformities and disconformities. Geologists don't really know the 'actual' dates of any rocks, they just make them up. It's kind of disappointing."

				"Geologists combine absolute and relative dating methods to bracket the age of sedimentary rocks by a way of judging the rock type, where it comes from, and what it's made up of to decide exactly what age restrictions it should be qualified at. I'm not really sure how they combine the two processes, but the end results are the same." "Geologists combine absolute and relative dating methods to bracket the age of sedimentary rocks by the arrangement of rocks which will be different and will therefore provide a variation in information."
Type 6: (pale pink)	n = 4 (5.8%)	n = 4 (5.2%)	Student states that they do not know the answer or does not provide an answer.	"I am not sure. Once they date the rocks, I know they can get information about the world's history and evolution. The data also helps predict the future."

$n_{Fall'04}$ = 69 $n_{Spring'07}$ = 77

Coding rubric for GEOL-C
Question: "A five kilometer thick column of sedimentary rock can be used by scientists as evidence that the earth is far older than 10,000 years as they had previously thought. What features would you expect to see in this column and how could these features be used to support the later conclusion that the earth is very old?"

Category	Fall '04	Spring '07	Description of category	Student examples
Type 1: (purple)	n = 4 (5.7%)	n = 2 (2.8%)	Student response adheres to the accurate, detailed response shown above, providing **2-3 types of evidence and/or a detailed description of relative dating**	"I would expect to see younger and different rocks on top, some intrusions, faults, and other things in the rock. If there are intrusions in the rock you can date them

			methods to compare ages of various layers within the sediment. Descriptions contain sufficient detail to demonstrate that the student has a **strong grasp of the concepts involved**. **No significant inaccuracies** are present.	by half-life as well as other rocks in the column. If the half-life is accomplished for the bottom rock at a longer time than 10,000 years then you can infer that the bottom layer as well as the earth is older."
Type 2: (pink)	n = 3 (4.3%)	n = 1 (1.4%)	Student response adheres to the accurate, detailed response shown above, providing **2-3 types of evidence and/or a detailed description of relative dating methods to compare ages of various layers within the sediment**. The degree of detail included and/or the presence of inaccuracies, however, provides evidence that the **student does not have a strong and/or flawless grasp of all of the concepts involved**.	"The different layers would prove valuable in dating and showing a history. The column of rock might also contain fossils which when correlated with other data could prove helpful in dating as well. Also a tool that might prove to be useful is carbon-14 dating and other kinds of decay dating. Because of the constant rate of decay this too could help prove the conclusion."
Type 3: (yellow)	n = 15 (21.4%)	n = 14 (19.7%)	**Either two pieces of evidence with descriptions that contain insufficient detail** to demonstrate that the student has a strong grasp of the concepts, **or only one well-described piece of evidence** is included. Response **requires at least one description of how dating occurs (radio-isotopic dating or use of index fossils) with a rationale for how this data could be used to determine the age of the column of rock**. An inaccuracy from the table below may be present, detracting from the quality of the answer.	"I would expect to see fossils of species that lived long ago in the Jurassic, Triassic, and Cretaceous period. Underneath this layer of fossils would be another layer of fossils of creatures before the dinosaurs of amphibian and reptile types. Because we know that these creatures lived more than a million years ago by looking at how old their bones are we would know that the earth is older than 10,000 years." "I would expect to see different types of rocks and various fossils. Scientists could use this to test the rock ages by drilling and using carbon-14 dating." "You would see different

				types of rock and fossils that would help determine the age. These fossils could be fossils ... of plants or animals that were only alive at a certain time." "I think that they would possibly find some fossils of some sort. They may also find a dike that strikes through it. The fossils will be used to look at and date back to what time period they come from. The sedimentary layer is above the igneous rocks."
Type 4: (green)	n = 20 (28.6%)	n = 20 (28.2%)	**One or two of the key pieces of evidence are described, but the response is missing important details** such that the reader has to presume complete understanding of the concepts and terms included. A reference to a specific dating technique, if made, does not include a description of how this dating technique is useful to determine the age of the column of rock. Inaccuracies from the table below and/or irrelevant ideas may be present, further detracting from the quality of the answer.	"It should be below rocks that are 10,000 years old. It should be radiometric dating so it says it is much older than 10,000 years." "I would expect a smaller percentage to contain fossils of higher organisms, more volcanic and high heat/activity rocks." "There could be fossils or sediments that are very old. This shows that the earth is as old as the fossil or sediment." "The thickness and amount of layers and fossils could help them prove their point. It takes some time to form 5k of sedimentary rock."
Type 5: (orange-red)	n = 14 (20.0%)	n = 27 (38.0%)	Response is very **vague** and may **only list items** that could be found in the column of rock without description of how/why these items are useful **or** may make reference to the **presence of numerous layers as the sole evidence** for the age of the column of rock.	"I would expect to see many different types of rocks which would indicate different time periods. Maybe would also see deformation in the older rocks." "The sedimentary rock is older than 10,000 years

			Examples of vague: fossils, rocks, minerals older than 10,000 years old (student doesn't describe how the dating occurs); intrusions that describe the relative age (student doesn't describe how intrusions are useful or how relative dating occurs)	meaning all rock features that are below the sediment in the rock strata are far beyond 10,000 years of age when compared to the sedimentary rock, which supports the later conclusion that the earth is very old." "You would expect to see different layers and the layers would be different colors. You would also have different textures because of the different minerals in the layers. Different layers account for different periods of time." "You can tell by the rocks wear and tear, how deep it is in the earth, and possible fossils contained inside."
Type 6: (blue)	n = 12 (17.1%)	n = 5 (7.0%)	Response contains **only major inaccuracies or irrelevant ideas**; no relevant and accurate information is included. Students may state something to the effect of "old rocks would be found"	"The rock would obviously get harder and softer from intense heat. I think the rock would get darker further down. These things would indicate how old each layer is and they could make a logical estimation how old the earth is." "You could see many different cuts in the rock or it could be worn down by the ocean or land."
Type 7: (neon pink)	n = 2 (2.9%)	n = 2 (2.8%)	Student states that they **do not know the answer**.	"I don't know what to expect in this column."

$n_{F'04} = 70$ $n_{Sp'07} = 71$

Coding rubric for GEOL-D

Question: "The oldest rocks of the continents are almost four billion years old, while the oldest rocks of the ocean basin are not even 200 million years old. Explain why this difference in age occurs and how it supports plate tectonics."

Category	F'2004	S'2007	Description of category	Student examples
Type 1: (purple)	n = 2 (2.7%)	n=5 (6.9%)	Student response adheres to the accurate, detailed response shown above. Some details may not be explained thoroughly, but **response at minimum refers to generation of new crust in the ocean, movement of ocean crust, and subduction of ocean crust under continental crust**. In addition, specific **discussion of how this idea relates to plate tectonics is included** or a description of moving plates is used consistently throughout the explanation.	"Ocean floors are continual being reformed through subduction processes. The subduction zones explain the loss of old ocean floor, but mid-ocean ridges explain how new ocean floor is forming. At mid-ocean ridges, magma is being forced up through cracks in the crust causing the ridges to expand and add new ocean floor with fresh magma. This explains how plates can move because they are either being subducted or expanded at mid-ocean ridges." "Because of the ever expanding ocean floor, new rock is rising from the asthenosphere and the old rock is subducting. Plate tectonics predicted this would happen, particularly in subduction zones."
Type 2: (pink)	n = 4 (5.5%)	n=2 (2.8%)	Student response mostly adheres to the accurate, detailed response shown above. Some details are not explained thoroughly, but **response at minimum refers to generation of new crust in the ocean, movement of ocean crust, and subduction of ocean crust under continental crust. No discussion of how this idea relates to plate tectonics is included.**	"The ocean floor is younger because as the continental plates spread apart newer rock fills the void between them. When continental plates collide with the ocean plates, the oceanic plates are forced down back into the mantle. The oceanic plates are being forced outward from the middle, where the newer rock is being introduced to the sea floor." "Mid ocean rifts are continuously making new

				rock. Continental rocks are not being continuously made – so they're older. The new rock being formed on the bottom of the oceans pushes out and moves continents and the continents also move because of subduction."
Type 3: (yellow)	n = 16 (21.9%)	n=11 (15.3%)	While the explanation contains no significant inaccuracies, **one of the following pieces is not included: generation of new crust in the ocean, movement of ocean crust, and subduction of ocean crust under continental crust**. In addition, discussion of how this idea relates to plate tectonics may or may not be included. An inaccuracy from the table below may be present, but does not significantly detract from the quality of the answer.	"The difference in age occurs because of sea floor spreading. New ocean floor is being made, so the old floor is subducting underneath continental crust. This subduction helps to promote plate tectonics." "The ocean floor is slowly adding new crust. The plates pull apart, allowing molten material to fill the gap and the cycle continues." "Mid ocean ridges located at the bottom of the ocean are where new rock is formed as magma comes up from the mantle; the new rock forms on each side of the ridge and over time is pushed outward by more uprising magma. This means that rocks are older the farther they are from the ridge; because there are many mid-ocean ridges that are spreading at the same time, the rock mass must collide to form continents." "Subduction and ocean spreading gets rid of ocean rocks, but continental rocks are 'light' enough to 'float' on the surface." "Because of sea floor spreading. The floor of the ocean is continually renewing

				itself and in this process it moves the different plates also.”
Type 4: (green)	n = 15 (20.5%)	n=19 (26.4%)	**Response is vague or missing important details**, but contains few or no significant inaccuracies. No specific discussion of how the explanation relates to plate tectonics is included.	“This proves that the sea floor is spreading. If the ocean basin is younger than continental rock, then we know that the ocean basin is more newly formed from the mantle and magma.” “The difference in age occurs by the ocean floor expanding and the younger rocks are at the bottom of the ocean.” “Because of subduction zones make more land under the ocean.” “This is because older rocks are more dense than younger rocks. When the plates crash together, the young rocks will sink underneath the older one. The older one will form continents on top of the younger ones.”
Type 5: (blue)	n = 35 (47.9%)	n=35 (48.6%)	**Response contains only major inaccuracies or irrelevant ideas**; no relevant and accurate information is included. (See table of inaccurate student responses below.) OR Student states that they **do not know the answer** or understand the concept.	“When a continent and an ocean plate collide, the ocean goes on top of the continental plate. That is why the continental rocks are older than the oceanic rocks.” “I don’t know the answer but my best guess would be because land has been (around) for longer than the ocean and that earth was at one point a huge continent, oceans were somehow created and that would explain the difference in age.” “This occurs because the

				continents are part of the earth's original crust. It wasn't until later the oceans formed." "The continent rocks are older because they get less erosion. In the ocean there is more movement, therefore the rocks are worn away more. Plate tectonics are constantly moving causing this movement on land and rock under water."
Type 6: (pale pink)	n = 1 (1.4%)	n=0	Unclassifiable because student did not respond to the question.	

F'04 n = 73 S'07n=72

Appendix C: Homework Assignments (Short Stories)

Continents: A Jigsaw Puzzle With No Mechanism

Place your feet on the ground and describe the motion beneath you. While our senses give us the impression the Earth's surface is not moving, overwhelming evidence supports the idea that it is in constant motion. The Earth's surface is like a series of plates that move towards or away from each other producing earthquakes, volcanoes, and mountains. Over long periods of time the movement of these plates changes the position of entire continents. How did scientists develop this idea when common sense indicates the Earth's surface to be still? The following story will help you better understand how scientists came to this conclusion. It also provides an interesting glimpse into how science operates to create new knowledge.

Our story begins in the 15th and 16th centuries, as explorers' travels resulted in increasingly accurate maps of the world. Looking at these maps, some people noticed similarities in the edges of continents. For example, the Atlantic coast of Africa and the Pacific Coast of South America, although separated by thousands of miles, seem as though they could fit together. Francis Bacon suggested that some reason must exist to explain the way continents appear to fit together. In 1620 he noted, "The very configuration of the world itself in its greater parts presents conformable instances which are not to be neglected."

The accepted view at this time was that except for rare occurrences, the Earth's continents and oceans are 'fixed' in their positions and do not move. Reflecting this view, for the next several centuries the similarities in continents' borders were explained as the result of a sudden change in the Earth caused by catastrophic events. In 1596, Dutch mapmaker Abraham Ortelius suggested that the Americas were "torn away from Europe and Africa…by earthquakes and floods". In 1666, Father Francis Placet claimed that America did not exist before Noah's flood. He maintained that the American land mass was created "either by the conjugation of many floating islands…; or by the destruction of the island of Atlantis which after sinking down into the deep could have caused the uncovering of a new earth." While not referring to the flood of Noah, in 1801 Friedrich Humboldt argued that a giant current had dug out the landmass that connected Europe with America. He claimed "What we call the Atlantic Ocean is nothing else than a valley scooped out by the sea."

In 1858 Antonio Snider-Pellegrini was the first to note that similar fossils and rock formations are found on adjacent continents. He suggested that the continents we see today were created from an original single land mass. He thought that multiple catastrophes caused the separation of the single land mass. Those catastrophes included Noah's flood and outbursts of material from the Earth's interior along cracks in that original land mass.

1. **Note how several of these explanations use catastrophes appearing in religious texts to explain natural events. How does this illustrate the influence of the wider culture and prevailing ideas on people investigating the natural world?**

Destructive events such as earthquakes and volcanoes were known to occur regularly. However, some questioned whether such events, no matter how severe, could separate continents. In 1758 James Hutton proposed a Uniformitarian Principle. He claimed that the forces acting on Earth today are the same as they have always been. Thus, since we do not see extreme catastrophes today, they must not have occurred in the past. Hutton's "uniformitarianism" influenced the thinking of many 19th century scientists as they studied the Earth's history.

- **Uniformitarianism is the name given to an important geological idea that the natural processes acting today act in much the same way as they have in the distant past.**

For instance, in the late 1800s Edward Suess noted flows of lava from volcanoes and suggested that the Earth is cooling from a molten state. A cooling Earth would grow smaller and this would distort the Earth's surface much like the skin of a shrinking apple. This was thought to be how mountains and ocean basins were formed. Yet this 'contractionist' view could not account for the observation that mountains are formed only in certain locations, and that earthquakes and volcanoes tend to occur only in certain areas. Nor could it account for the observation that similar fossils and rock formations are found on different continents.

Suess also developed an explanation for the fossil evidence that did not rely on any catastrophic event. He suggested that land passageways once connected continents. These land "bridges" were thought to have permitted organisms to travel between continents. To explain why these land "bridges" are not seen today, he claimed they had sunk into the oceanic crust at some point in the past. While this would violate accepted knowledge that continental crust should float on more dense oceanic crust (this idea is know as the **law of isostasy**), many scientists supported this "landbridge" explanation.

2. **Note that each idea proposed thus far has some explanatory power, but also has significant problems. How does the time required to develop science ideas as described in this story compare to what is often conveyed in science textbooks.**

In the early 1900s several scientists proposed that the continents separated by having moved over the Earth's surface over a long span of time. This 'mobilist' view could provide an explanation for the fossil evidence, and much more. In 1910 Frank Taylor suggested that a "mighty creeping movement" of the crust formed mountains, and speculated that the tides moved the continents. However, he had no plausible explanation for a mechanism that could move continents. Thus, the scientific community paid little attention to his work.

Alfred Wegener in 1912 put forth a detailed explanation involving a slow "continental displacement" over vast periods of time. He proposed that around 200 million years ago one giant supercontintent, which he called **Pangea**, existed. Over time the continents had been pulled apart, and they were still moving. This idea was referred to as "drift", a term that critics of Wegener used when referring to the idea. Wegener's idea of continental displacement provided a plausible explanation for many geological phenomena, including:

- Why the contours of many continents seem to fit together so well,
- Why there were numerous geological similarities between Africa and South America, and between North America and Europe,
- Why many similar fossils exist in Africa and South America before the Paleozoic (when Pangea existed), and very few afterwards (when the continents would be separate).
- Why mountain regions are formed along coastlines, and are narrow and long (from the compression and folding of the leading edges of colliding continents, and

- Why there were glacial deposits in what are now warm regions

In explaining his theory to other scientists, Wegener noted his firm belief in the idea:

> Even though the theory in certain individual cases may still be uncertain, the totality of these points of correspondence constitutes an almost incontrovertible proof of the correctness of our belief that the Atlantic is to be regarded as an expanded rift. Of crucial importance here is the fact that although the blocks must be rejoined on the basis of other features—their outlines especially—the conjunction brings the continuation of each formation on the farther side into perfect contact with the end of the formation on the near side. It is just as if we were to refit the torn pieces of a newspaper by matching their edges and the check whether the lines of print run smoothly across. If they do, there is nothing left but to conclude that the pieces were in fact joined in this way.

3. **Note that Wegener and other scientists are creating ideas to *account for* what they observe. That is, nature and extracted data does NOT *tell* scientists what to think. Data doesn't speak—it must be noticed, valued, and interpreted. What does this imply about the way in which scientists construct new ideas?**

In a letter to a friend, Wegener argued that his theory provided a more plausible explanation for the fossil evidence than that provided by proponents of land bridges.

> You consider my primordial continent to be a figment of my imagination, but it is only a question of the interpretation of observations. I came to the idea on the grounds of the matching coastlines, but the proof must come from the geological observations. These compel us to infer, for example, a land connection between South America and Africa. This can be explained in two ways: the sinking of a connecting continent or separation. Previously, because of the unproved concept of permanence, people have considered only the former and have ignored the latter possibility. But the modern teaching of isostasy and more generally our current geophysical ideas oppose the sinking of a continent because it is lighter than the material on which it rests. Thus we are forced to consider the alternative interpretation. And if we now find many surprising simplifications and can begin at last to make real sense of an entire mass of geological data, why should we delay in throwing the old concept overboard?

In 1921 Wegener noted that he knew of no geophysicist who opposed his theory. However, his writings on this subject were not translated into other languages until 1922. Thus, his work was not well known outside of Germany. Beginning in 1922 most scientists, especially those in America, began criticizing Wegener's ideas. C.T. Chamberlin, a well-respected geologist, said during the1922 meeting of the Geological Society of America "If we are to believe Wegener's hypothesis we must forget everything which has been learned in the past 70 years and start all over again." In 1928, nearly all of the participants of the American Association of Petroleum Geologists were critical of Wegener's theory. They argued that Wegener was misinterpreting the data. They questioned the supposed jigsaw puzzle fit of the Atlantic continents, and denied that rock formations on opposite sides of the ocean are closely related.

- These scientists are looking at the same data as Wegener, but are interpreting it differently. That is, nature and extracted data are not *telling* scientists what to think. Wegener and other scientists are creating ideas to *account for* what they observe.

This intense opposition to Wegener's ideas by well-respected scientists affected other scientists. Years later, the geologist R.D. Oldham noted that scientists who accepted Wegener's theory would not say so publicly:

> But also I remember very well that in those days it was unsafe for anyone to advocate an idea of that sort…. Those ideas (solid earth and contraction) held the ground so strongly that it was more than any man who valued his reputation for scientific sanity ought to venture on to advocate anything like this theory that Wegener has nowadays been able to put forward…

Yet, while most scientists rejected Wegener's ideas, even critics found his idea intriguing:

> In examining the ideas so novel as those of Wegener it is not easy to avoid bias. A moving continent is as strange to us as moving earth was to our ancestors, and we may be as prejudiced as they were. On the other hand, if continents have moved many former difficulties disappear, and we may be tempted to forget the difficulties of the theory itself and the imperfection of the evidence. (Lake, 1923)

Wegener did not originally attempt to describe what kind of forces moved the continents. He knew his theory would be much stronger if he could propose a plausible physical mechanism for how the continents moved. He later proposed that the continents moved northward through the oceanic crust. He argued that the forces generated as the Earth rotated on its axis propelled the continents' movement. However, Harold Jeffreys, a highly respected English geophysicist, demonstrated that Wegener's proposed mechanism was "geophysically impossible." He argued that if the softer continental crust moved through the harder ocean floor the continents would break up. Additionally, Wegener had proposed that tidal forces moved the continents westward. Jeffreys noted that if the tidal force was this strong, it would halt the Earth's rotation in one year. Jeffereys demonstrated that Wegener's mechanism was implausible, but Wegener's confidence in the theory of continental drift remained steadfast:

> The Newton of drift theory has not yet appeared. His absence need cause no anxiety; the theory is still young and still often treated with suspicion. In the long run, one cannot blame a theoretician for hesitating to spend time and trouble explaining a law whose validity no unanimity prevails. It is probable, at any rate, that the complete solution to the problem of the driving forces will still be a long time coming, for it means the unraveling of a whole tangle of interdependent phenomena, where it is often hard to distinguish what is cause and what is effect.

Wegener was clearly aware that the history of science is filled with ideas that accurately account for phenomena, but with no underlying mechanism. For instance, Isaac Newton derived the universal law of gravity. However, even today no consensus exists on a theory that explains how bodies at a distance exert a force on one another.

- Note how this story illustrates that (1) scientific ideas develop over time, and (2) scientists do not vote on what the natural world is like. They do sometimes vote on what to call something or how to categorize it, but not how the natural world works. Much time (often decades) passes as scientific ideas emerge, develop and are eventually accepted or discarded.

The lack of a mechanism for continental drift may not have been the only reason scientists disputed Wegener's idea. World War I had ended just a few years earlier, and negative sentiment toward his German heritage widely existed. Moreover, Wegener was a meteorologist by training, spent most of his time studying meteorology, and was professionally employed in this field. Thus he may have been seen as an outsider who did not have the specific training in the earth sciences needed to work in this field of science. However, this may have been beneficial as Wegener could tie interdisciplinary knowledge together because has no stake in preserving the status quo in any one field. Louis Frank (1990, p. 13) wrote of two deadly sins in science: advocating an idea that (1) is at odds with what everyone else is thinking and doing while (2) not affecting their own field of study.

4. Currently accepted scientific knowledge influences scientists' interpretation of data. Oftentimes someone who is young in age or new to a field of study begins revolutions in scientific thinking. Why might this be the case?

Data Doesn't Speak
The Development of a Mechanism for Continental Drift

While many scientists criticized Wegener's theory, a few respected geologists supported it. In 1929, Arthur Holmes suggested a more plausible mechanism for how continents could move. He proposed that convection currents in a fluid layer beneath the crust, caused by heat released from radioactivity within the earth, allowed the continents to move. In 1937, Alexander Du Toit proposed that Pangea had originally broken into a northern supercontinent, which he called Laurasia, and a southern supercontinent called Gondwanaland. These ideas were based on his work in Africa and much evidence from South America and South Africa. Many European and American geologists were unaware of this work.

However, despite the plausibility of these new ideas and the support of some well-known geologists, Wegener's theory languished. Bailey Willis stated in 1943:

> I confess that my reason refuses to consider 'continental drift' possible. This position is not assumed on impulse. It is one established by 20 years of study of the problem of former continental connections as presented by Wegener, Taylor, Schuchert, du Toit, and others with a definite purpose of giving due consideration to every hypothesis which may explain the proven facts. But when conclusive negative evidence regarding any hypothesis is available, that hypothesis should, in my judgement, be placed in the discard, since further discussion of it merely incumbers the literature and befogs the mind of fellow students.

1. **The scientist's perspective above raises one of the most interesting aspects of doing science. Note that while some scientists have discarded Wegener's theory, others support the idea or some variation of it. Decisions regarding the acceptance or rejection of scientific ideas are a very complex process. How does this example illustrate the importance of consensus building in the scientific community versus the views of individual scientists?**

Because so little was known about the ocean floor, determining if and how continents move was very difficult. One scientist noted that trying to understand the Earth without knowing about the ocean floors "was like trying to describe a football after being given a look at a piece of the lacing." For centuries, most people thought that the ocean floor was flat and featureless. However, beginning in the 1600s, deep-sea line readings by naval explorers provided evidence that the ocean floor was not flat. By the 1850s, evidence supported the existence of underwater mountains in the middle of the Atlantic Ocean. Survey ships laying the trans-Atlantic telegraph cable in the early 1900s confirmed these ideas.

Technological development over several centuries had helped scientists better understand what the ocean floor looked like. During the 1940s and 1950s, technologies initially developed for the military were adapted by geologists and used to provide a much better idea of the ocean bottom. For example, sonar devices that had been developed to track warships on and under the ocean surface provided confirming evidence of ocean floor ridges and trenches. By the 1950s, sonar data supported the idea that a global mid-ocean ridge existed.

A very important piece of data was collected using magnetometers. These devices, adapted from airborne equipment used to detect submarines, indicated variation in the magnetic field of the rocks that make up the ocean floor. This variation consisted of areas with normal polarity (a compass points in the direction we know as the North Pole) and reversed polarity (imagine a compass pointing in the direction we know as the South Pole). An interesting feature was that this variation was not random, but rather was found in alternating stripes (Your teacher or textbook will have an illustration of this). Developing an explanation for this occurrence would play a crucial role in explaining how the continents move.

To understand these phenomena, scientists needed an accurate age of the rocks found in the ocean. They were able to do this using techniques developed by nuclear scientists during the development of the atomic bomb. By using the ages of rock samples from around the globe, scientists determined when the magnetic reversals had occurred. Once again, the development of technology played a key role. The idea of dating rocks based on the amount of radioactive material in them had been around since early in the century. However the technology to accomplish this was not available until after World War II.

The data collected from the magnetic study of rocks and the radioactive dating were interpreted to mean that the geomagnetic pole had moved – a phenomenon called **polar wandering**. S.K. Runcorn studied ancient rocks from Europe and interpreted the data as indicating that the "North" pole had moved from a location near Hawaii about 600 million years ago to its present position. Two possible explanations existed for how this could have occurred. Scientists who maintained a "fixist" view of the Earth thought the pole was what had moved. Scientists who maintained a "mobilist" view of the Earth maintained that the continents had moved in their relation to the pole.

2. **Note the different interpretations depending on the framework and ideas one uses to make sense of the same data. People often think that good scientists are objective. What does this story imply about the possibility of scientists being objectivity?**

To resolve this problem, Runcorn studied rocks in North America. The data he collected could be interpreted to mean that the pole had moved. However, the path of the pole based on rocks from North America was different than the path derived from rocks in Europe. The 'mobilist' view that the continents had moved and not the pole made sense of both North American and European rocks without contradiction. The apparently different paths of pole could be explained as the pole remaining still and the continents moving in different directions in relation to the pole. Runcorn, who had been a critic of continental drift, became a supporter based on this new evidence.

Moreover, the sediment layer on the ocean bottom was much thinner than would be expected if the oceans had existed since the formation of the Earth approximately 4 billion years ago. The oldest portions of the ocean floor appeared to be less than 200 million years old. According to the 'fixists' view, the ocean floor would have a very thick layer of sediment consistent with at least a 3.8 billion year old Earth. The "fixist" view of continents could not account for the relatively young age of the ocean bottom sediment layer compared to the age of the Earth.

Another piece in the puzzle came from scientists who recognized a pattern to the location of earthquakes and volcanoes around the Earth. Using seismographs, scientists determined that earthquakes tend to occur near the ridges and trenches around the earth. It was also determined that the majority of the volcanoes on Earth tend to occur near the ridges.

An explanation accounting for these observations was proposed by Harry Hess in 1960. Hess studied oceanic ridges and was a critic of continental drift in the 1940s and 1950s. However, he was open to examining many ideas when attempting to solve the mysteries of nature and favored the use of what has been described as "multiple working hypotheses". He argued that, "Without hypotheses to test or disprove, exploration tends to be haphazard and ill-directed. Even completely incorrect hypotheses may be very useful in directing investigation toward critical details".

Hess proposed a mechanism for continental drift that accounted for much of the new evidence available to scientists. He argued that new seafloor was created at the mid-ocean ridges and then spread out toward the trenches where it descends into the mantle. Another scientist, R.S. Dietz, independently developed the same idea in 1961 and coined the term "**sea-floor spreading**" to describe it. The following are Hess's words describing sea floor spreading:

> A continent's leading edges are strongly deformed when they impinge upon the downward moving limbs of convecting mantle… Rising limbs coming up under continental areas move the fragmented parts away from one another at a uniform rate so a truly median ridge forms as in the Atlantic Ocean… The cover of oceanic sediments and the volcanic sea mounts also ride down into the jaw crusher of the descending limb, are metamorphosed, and eventually probably are welded on to the continents.

- **Wegener had used the analogy of the torn newspaper. Here Hess speaks of rising limbs and jaws. Scientists use analogies, even when speaking to other scientists, because new thinking is always connected in some way to prior thinking, and making reference to well understood ideas helps others understand new thinking.**

Hess's idea explained how continents drift around the Earth. Two types of boundaries existed between the plates; **divergent boundaries**, such as the Mid-Atlantic Ridge, where new crust is formed; and **convergent boundaries**, where two plates collide and the crust would be 'recycled' into the mantle. Thus as the plates grew from the creation of new seafloor, the continents would move with the plate. Yet he noted that there was a difference between Wegener's theory and his idea:

> This [my view] is not exactly the same as continental drift. The continents do not plow through oceanic crust impelled by some unknown forces, rather they ride passively in mantle material as it comes to the surface at the crest of the ridge and then moves laterally away from it.

Hess's mechanism provided explanations for why:

- the oceanic ridges are found in the middle of the oceans and have a high temperature;
- fracture zones widen;
- volcanoes tend to occur near the oceanic ridges; and
- ocean floor is older than 180 million years and predicted to never exceed 200 million years.

Hess's mechanism explained many things about the ocean floor, but scientists who held to a 'fixist' and 'contractionist' view of the Earth still largely rejected it. However, over the next few years several groups of scientists provided additional evidence that convinced most scientists to accept the 'mobilist' view of plate tectonics.

- **Again, notice that scientists do not vote on what nature is like. Often, long periods of time and much evidence from many sources are required to persuade scientists, and some are never convinced.**

While magnetic reversals had already been described, Fred Vine and Drummond Matthews suggested that, if seafloor spreading occurs, then strips of seafloor material having reversed polarity spreading out symmetrically and parallel to the ridges should exist. Having no data to determine the rate at which the sea floor spread each year, they assumed the rate to be several centimeters per year. This correlated strongly with the known pattern and age of magnetic reversals. Yet as Vine noted, 'it created more problems than it solved,' because the idea of sea floor spreading was still not widely accepted. Whether magnetic reversals had occurred was still being debated, and no empirical data supported the prediction of symmetrical and parallel ridges. In fact, some scientists interpreted the initial data as inconsistent with predicted results. The disagreements in making sense of data are illustrated in the following passage:

> I remember in 1966 Bill Menard came up here and spent the whole day looking at profiles-he never said a word. Joe Worzel, who was one of the chief opponents … came up and said, "Bill, what do you think? Do you see this silly correlation; this lousy correlation [between magnetic profiles]? Menard looked up and said, "[#@*#@*!, how good do you want them to be?"

Yet, by 1966 some key magnetic profiles, especially one known as Elantin-19, provided evidence to support Vine and Matthews' hypothesis. Walter Pitman, who put together this profile, noted its importance:

> It hit me like a hammer…. In retrospect, we were lucky to strike a place where there are no hindrances to sea-floor spreading. We don't get profiles quite that perfect from any other place. There were no irregularities to distract or deceive us. That was good, because by then people had shot down an awful lot of sea-floor spreading. I had thought Vine and Matthews was a fairly dubious hypothesis at the time, and Fred Vine had told me he was not wholly convinced of his own theory until he saw Elantin-19. It does grab you. It looks very much like the way a profile ought to look and never does.

Following the publication of the Elantin-19 profile, other data that had initially been interpreted as inconsistent with sea floor spreading were reinterpreted as supporting Vine and Matthews' hypothesis.

3. **Given that data must be interpreted, how do statements like "The data shows . . ." inaccurately convey how scientific ideas are developed?**

Interestingly, another scientist, Lawrence Morley independently developed this idea at the same time; however, his paper presenting this was rejected by the prestigious scientific journal *Nature* in February of 1963 – the same journal which then published Vine and Matthews' idea in September of 1963. Morley's paper was also rejected by the J*ournal of Geophysical Research* with the comment, "This is the sort of thing you would talk about at a cocktail party, but you would not write a letter on it." Morley did not make further effort to publish his idea and never worked in this field again.

J. Tuzo Wilson provided two other pieces of evidence to support sea floor spreading and plate tectonics. In 1963, he proposed that volcanic island chains, such as Hawaii, which are not located near an oceanic ridge, are actually formed due to the movement of a plate over a stationary 'hotspot' in the mantle. This explained an apparent contradiction in the plate tectonic theory that some volcanoes occur thousands of miles from a plate boundary. This idea was not accepted at first and Hess's paper presenting it was rejected by all of the major scientific journals. It was eventually published in the *Canadian Journal of Physics,* a relatively obscure journal.

Then in 1965, based on the observation that oceanic ridges and trenches can end abruptly, Hess proposed that if the continents are drifting, there must be a third type of fault to connect two ridges or trenches and 'transform' the movement of the plates horizontally resulting in shallow earthquakes. Wilson, who had written papers on supporting a 'contractionist' view of the Earth in the 1950s, noted that transform faults cannot exist unless the continents are indeed moving:

> Transform faults cannot exist unless there is crustal displacement and their existence would be provide a powerful argument in favor of continental drift and a guide to the nature of the displacement involved.

Based on the work of Vine, Matthews and Wilson and other supporting evidence, the majority of scientists who had been critics of continental drift and plate tectonics, quickly became supporters of this 'mobilist' view of the Earth. The following passages illustrates this:

Sir Edwards Bullard's comment about a conference he attended in America in 1966 where much new data was presented supporting sea-floor spreading and drift:

> The effect was striking. As we assembled on the first day, Maurice Ewing came up to me and said, I thought with some anxiety, 'You don't believe all this rubbish do you, Teddy?' At the end of the meeting I was to sum up in favor of continental movement and Gordon Macdonald against; on the last day Macdonald was unable to attend and no one else volunteered to take his place.

The following passage illustrates how scientists accepted sea-floor spreading once they could see the relevance it held to their own research:

> Reidel came up to me at some time in 1967 or so and said, "Look, my data can't be compatible with sea floor spreading." He collects cores and dates radiolaria [microfossils] and he knew the stratigraphy of the sea floor before JOIDES [ocean drilling] stuff. He said that his data don't agree with this, but he didn't know how to run a decent test. Since he knew I had the magnetics data that existed, he asked if we could work together and I would tell him how old the sea floor is from the magnetics and he would tell me how old it really was… I got out the maps and did the best I could to give him the ages, and he plotted this with his samples. He didn't destroy the idea; they were in perfect agreement. So he says "Ye Gods!" and writes a paper about the confirmation of sea floor spreading.

And like all good scientific theories, plate tectonics helped *make sense of phenomena* and *made accurate predictions* regarding natural phenomena:

> I found that…I could read a lot of papers in geological journals and start to see something important and significant in them. Before I just read the ones in my specialty, I didn't even understand what the others were about. But suddenly—really almost overnight—I could see significance in these things that I had never paid any attention to before. (Oliver)

> Sea floor spreading was a wonderful concept because it could explain so much of what we knew, but plate tectonics really set us free and flying. It gave us some firm rules so that we could predict what we should find in unknown places. (Atwater)

The following quotation illustrates how good theories also *unify a scientific discipline* bringing together what at the surface appear to be disparate fields.

> Earth science is no longer a compartmentalized science, it is a unified science that is glued together by the theory of plate tectonics. This is most vividly displayed on the deepsea drillship Glomar Challenger where paleontologists, geochemists, sedimentologists, petrologists, and geophysicists all work together on sediments and rocks recovered from beneath the deep sea floor. Without the theory of plate tectonics as a background framework, this interaction would be almost impossible. (Larson)

- **The general public often dismisses theories as being mere speculations. However, theories are often so well supported by evidence that scientists accept them as accurately accounting for how nature works. The theory of plate tectonics illustrates the central role that theories play in science. Scientific theories explain why scientific laws work, bring coherence to a field of study, and they suggest research questions worth pursuing, how to go about answering those questions, and how to interpret data derived from research.**

While plate tectonics provides a robust explanation for the major geological processes on Earth, the following passages demonstrate the caution that scientists profess until theories have withstood the test of time:

> I think that we should work the theory of the new global tectonics for all that it is worth—just as we should do with any theory or model, for it is through such intensive studies that we obtain large quantities of valuable information. We should reexamine the geologic data within this new conceptual framework, but we must not assume that we have arrived at the final solution—because geology just is not that simple. (Wylie, 1974)

> If the plate tectonics model is false, it will nevertheless be difficult to refute or replace, for the plate model is so widely believed to be correct that it is difficult to publish alternative interpretations. Lacking well-known alternatives, a dominant model will not be rejected… (Saull, 1986)

4. **The first rule of wing walking (walking on the wing of a biplane) is that you never let go of one wing wire until have hold of another. Using this analogy, why do scientists hold onto a dominant theory (even if it doesn't work as well as desired) unless a very plausible alternative theory exists?**

Early Efforts to Understand the Earth's Age: Naturalists and Chronologists

Advances in science are to often wrongly portrayed as the work of one person or a few individuals battling in the name of modern science against the darkness of ignorance and narrow-minded religion. How scientific understanding changes, as illustrated in early attempts to understand the earth's age, debunks the commonplace "science versus religion" perception. This historical episode also illustrates that many individuals, over long periods of time and in strange ways, contributed to our current knowledge of the earth's age. Examining the evidence and arguments put forward for the earth's age will help you better understand how science works and the important science idea that the earth is very old.

In the Western world, the earliest known efforts to determine the earth's age came from people who, by modern standards, would not be considered 'geologists'. Around 350 BC, the Greek philosopher Aristotle suggested that the earth and the universe were eternal—they had always existed and would forever exist. Jewish and Christian philosophy, on the other hand, argued that the earth was created, and this view became widely held in the Western world. Many scholars were unconcerned with these speculations, and were simply content to say the earth was old—on the scale of a few thousand years. Given that at that time in history few people lived beyond fifty years, several thousand years seemed like a very long time. The disinterest in pursuing serious study of the earth's age was illustrated by the lack of activity in this area among theologians or those we today would call "scientists".

Beginning about 1650, interest in the age of the earth was rekindled, but for different reasons. This was the time of the Renaissance and the Reformation throughout Europe. Theologians and other scholars increasingly retranslated Biblical, Greek, and other texts. In addition to correcting bad translations, some scholars began to raise questions about some Biblical stories such as the Genesis account of creation, and Noah's Flood. At this same time, people of all faiths and nationalities traveled—mostly across Europe—to better understand the world beneath their feet. Trading ships also returned from the Americas and Asia bringing exotic news reports. As humans scrutinized texts and explored the earth in new ways, some interpreted the evidence as supporting a young earth, while others put forth evidence suggesting the earth was undeniably old.

One approach to understanding the earth's age was to analyze chronologies found in texts that included, but was not limited to, Biblical scripture. This approach entailed estimating the lifetimes of historical figures and then placing them in order according to ancestry. Using this approach with the Bible had its limitations as much of it is simply a genealogical list of who begat whom. So chronologists turned to other records of mankind's existence, such as secular books and royal lineages. Reports from those having traveled to many parts of the world posed problems to the chronologies. The Chinese and Egyptians seemed to have much richer, longer histories than those of the Europeans. Lack of reliable records frustrated chronologists. Like all researchers, they had to make a judgment regarding the veracity of old and new information. They decided that this conflicting new evidence was unreliable and dismissed it, trusting their own written records instead.

Overall, chronology is a good example illustrating how inquiry of the natural world must be considered within the timeframe it occurred and the prevailing culture. In the late 1600s, chronology drew respect for its rigorous collection of data and precise conclusions. In this sense, it possessed characteristics that 'modern' science values. Today, chronologists' efforts to understand the age of the earth are often unfairly ridiculed. This is because some modern Creationists, in declaring James Ussher's date of October 23, 4004 BC to be the exact day of creation, have distorted the historical context in which those chronologists worked. That the chronologists did not force the earth to be young is important for understanding the context of early work regarding the age of the earth. The dominant culture already told chronologists that the earth was young. They simply found a method to defend their culture's viewpoint.

A second approach to understanding the earth's age, which came to be known as naturalism, reflected a new way of thinking about and investigating the natural world. This new way of thinking emerged over a long period of time and was influenced by many individuals. Because of the significance this emerging new way of thinking would have for science and all of society, this period of time (circa 1550 to 1730) is often called the Scientific Revolution. Astronomers like Copernicus argued that the sun should be at the center of the solar system; doctors like William Harvey argued for the circulation of blood in the human body; and physicists like Isaac Newton argued that the world should be understood through the interaction of forces and matter. The whole Newtonian system put forth two very important considerations for geologists: (1) the world should be explained in terms of natural events and not through supernatural intervention; and (2) the history of the earth might not coincide with the history of humans. The idea that the earth may have existed prior to humans populating its surface was very unsettling to seventeenth century scholars.

This complex and changing cultural backdrop is the context that the first 'true' geologists (using today's standards) worked within. While skepticism regarding using chronology to date the earth had always existed, those who opposed that approach now looked to evidence the chronologists had dismissed — the natural world. Calling this approach learning from "the Book of Nature," a new class of 'naturalists' argued that investigating the rocks and oceans were the best way to understand the earth's history. But both the former and emerging new ways of thinking influenced their approaches to understanding the age of the earth, and the judgments they made regarding evidence.

These naturalists were gentlemen of 'proper' society, spending their leisure time enthusiastically inspecting the nooks and crannies of the earth. Erasmus Darwin, Charles Darwin's grandfather, was known for climbing into the gullies and cracks of the English countryside in Derbyshire wearing his powdered wig, breeches, and topcoat. In 1787 the Frenchman Horace-Bénédict de Saussure led a team of men to the top of Mount Blanc, the highest point in the Alps, carrying mercury barometers and other equipment to test the air. Perhaps most important to understanding the age of the earth, naturalists like Nicolas Steno studied strata and put forward the idea that the layers had been laid in order of the oldest at the bottom and most recent on the top. Embedded in these layers, Steno and others noticed, were preserved shapes of animal bones that nobody had ever seen before—fossils. This discovery would drive a whole new generation of naturalists to study the earth's age to explain how the fossils got there.

1. **Those who are investigating the natural world at this time have either the personal financial resources or the financial support from others to conduct their work. The word "scholar" comes from the Latin word "scholee" which means "leisure time". Today we hardly think of conducting scholarly work as "leisure". Why do you suppose that in the past, leisure time was associated with doing science and other forms of scholarship?**

Determining the age of the earth was also necessarily tied to developing an explanation that would account for how physical processes work to shape the earth over time. Two approaches existed for developing a 'theory' of the earth. One was to use Biblical events to explain a short timescale, and the other was to use natural events to predict a long time scale. In some cases the short timescale is associated with **catastrophism**, the idea that massive earthquakes, floods, and other events unlike those experienced today shaped the earth. The longer timescale is associated with **uniformitarianism**. This explanation of the earth claimed that forces presently acting on the earth are the same as those that have acted in the past. Both approaches had their proponents within the scientific community, and both made reference to evidence of the natural world to support their thinking. The work of Jean-André de Luc and James Hutton illustrates these two approaches, but they are only two of the many individuals in both camps.

Jean-André de Luc was born in Geneva, Switzerland, and would later move to England and travel most of Europe. He was the first to use the word 'geology.' He was adept with tools and made the portable barometer used by Saussure in the Alps. While not adhering to a literal interpretation of the Bible, he wanted to explain the world in accordance with Scripture. Pointing to a set of marine fossils he found in the Swiss highlands, he called this the "apple of discord between [scientific scholars]." How could aquatic life be fossilized 7,000 feet above sea level in a landlocked region? Around 1780, the best explanation, he thought, was that at one point, the earth had been entirely flooded. Very gradually, the water levels lessened and at the same time, the current continents on which naturalists now walked had risen from the bottom of the ocean. After a couple thousand years, the world would look like it does now and humans would populate its surface. De Luc didn't think Noah fit all of the world's creatures into the ark, but he certainly thought a very recent catastrophic flood shaped the world's landmass.

De Luc was just one of many scientists who tried to link scientific laws to biblical history. Almost 100 years earlier, Thomas Burnet had written *The Sacred Theory of the Earth* using Scriptures as the starting point and trying to weave Newton's laws into his theory of the earth's evolution. As Burnet's friend and colleague, Isaac Newton had assisted with and endorsed Burnet's book.

- Note that De Luc and other scientists are straddling two worlds – one trying to understand the natural world in terms of naturalism, the other trying to understand the natural world in terms of biblical literalism.

De Luc wasn't alone in his arguments, but he was original in his methods. Unlike other scholars, he wanted his work to be understood by regular people unfamiliar with geology. He presented arguments for and against the Biblical account of Genesis, remarking that his new 'geological' method illuminated the full meaning of Scripture without contradicting it. However, he shied away from explaining the origin of the earth. Noting the oldest rocks, or the "Primary" rocks, had no fossils, he turned to the "Secondary" rocks of more recent origin. He interpreted this to mean that at one time animals and vegetation unlike those seen in modern times populated the earth. In the late 1700s, though, geologists had yet to find human fossils. De Luc and other naturalists interpreted this evidence to mean that the earth existed *before* humans walked its surface. If so, then the age of humans was very recent.

About the same time, across the English Channel in Britain, James Hutton also traveled the countryside looking at exposed strata. Hutton is often called the 'father of geology,' but that does a gross injustice to the many other individuals working to understand the earth. At the same time Hutton traversed Britain, countless other naturalists traveled the world. In many cases, they were like Erasmus Darwin, hunting minerals to be used for industry. In other cases they were like de Luc, trying to explain the earth. In some recent histories, Hutton is portrayed as the noble scientist who fought the tyrannical grasp of religion. This is far from the truth.

Hutton was most well known for his 1795 book, *Theory of the Earth*, which argued for a near eternal world that had "no vestige of a beginning, no prospect of an end." As a background to this scientific proposition, Hutton should be seen as a man of his time. Trained as a doctor and familiar with the new ways of thinking about the natural world, he accepted the Newtonian explanations of gravity, light, and heat. He agreed that these were the forces that conducted nature and caused the seasons and other natural phenomena. He was also a deist, a new religious expression at the time, which meant that he believed God created and designed the world in a nearly mechanical way, such that after creation God never needed to intervene. The Newtonian laws, then, commanded over a land with was set up for human life, or as Hutton said, "We are thus bountifully provided with the necessities of life; we are supplied with things conducive to the growth and preservation of our animal nature, and with fit subjects to employ and nourish our intellectual powers."

Hutton's friends included fellow scholars and members of the Scottish Enlightenment who provided an environment that nurtured progressive ideas. Among the influential figures in the Scottish Enlightenment were intellectual icons such as David Hume (philosopher), Adam Smith (*The Wealth of Nations),* Joseph Black (discoverer of carbon dioxide), and

James Watt (inventor of the steam engine). Hutton counted all of these men among his friends, but Joseph Black, with whom he shared a love of chemistry, was his closest friend. Hutton and Black brought their formidable grasp of chemistry to bear on the geological problems that Hutton was considering.

2. **Consider how scientist's many associations likely influence and nurture their thinking. Many people dislike the thought of a science career, seeing it as a solitary undertaking. How does this story illustrate that science is a social endeavor?**

Hutton traveled extensively, observing exposed rocks and strata found in quarries and cliffs. After a trip in 1786 to southwestern Scotland to Galloway, he wrote, "…here we found the granite interjected among the strata, in descending among them like a mineral vein, and terminating in a thread where it could penetrate no farther…[this] will convince the most skeptical with regard to this doctrine of the transfusion of granite."

The most popular story of Hutton is his trip in 1788 to Siccar Point on the east coast of Scotland. As he looked up at the cliff face, he saw an 'unconformity' in the rocks. At the bottom of the cliff was gray micaceous greywacke. However, instead of lying horizontal, as they were accustomed to seeing in quarry walls, the beds were standing straight up. Above this layer was a nondescript jumble of large fragments of the greywacke, in a layer perhaps two feet high. Above that was another large exposure of layered rocks, this time lying horizontally and red in color.

Hutton explained what they were looking at to his companions. This unconformity, he said, demonstrated the cyclical process of nature. The greywacke that was standing vertically at the bottom of the cliff face had originally been laid down as horizontal deposits, which, he explained, was the only way sediments formed. After an enormous amount of time and the application of subterranean heat, they were transformed into rock. Then, the intensity of the heat was such that it caused the horizontal strata to buckle and fold and rise above sea level, resulting in the vertical formation that they were seeing. The tops of the buckled rocks immediately began eroding and after a time, the land was once again submerged under water. The jumble of fragmented greywacke that overlay the top of the buckled rocks was formed in the early stages of submersion, when waves crashed onto the shore. After the buckled rocks were once again submerged deeply under water, new sediments started piling on top of them. This time, the strata were formed from red-colored grains from different rocks on the earth's surface. Subterranean heat and pressure once again acted to form the sediment into rocks and raised it above sea level again, but this time with less force, since the strata didn't buckle, but remained horizontal. He knew this idea to be similar to volcanoes, which he saw to be a sort of natural 'safety-valve' for the earth. When pressure got too high, volcanoes released magma, moving interior matter to the earth's surface.

Through these cycles, Hutton, a deist looking for a natural explanation, reasoned how the earth regulated and preserved itself over time. Knowing that human history failed to record any drastic erosion, he argued that the processes must take place over a very long time, indescribable to humans. This indefinite timescale, practically an eternity, drew cheers and criticism, but so did every other theory of the earth. Hutton's main contribution to the history of geology at Siccar Point was to propose that very small changes happened over a very long time, which would become the backbone of the uniformitarian argument. Much later, Hutton's associate John Playfair would remark of their trip to the Scottish coast:

> We felt ourselves necessarily carried back to the time when the [sedimentary rock] on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited in the shape of sand or mud, from the waters of a superincumbent ocean. An epoch still more remote presented itself, when even the most ancient of the rocks instead of standing upright in vertical beds, lay in horizontal planes at the bottom of the sea, and was not yet disturbed by that immeasurable force which has burst asunder the solid pavement of the globe. Revolutions still more remote appeared in the distance of this extraordinary perspective. The mind seemed to grow giddy by looking so far into the abyss of time.

3. **Many textbooks and teachers will talk about what data *shows* or what data *tells us*. How does Hutton's and other scientists' need to convince others of the meaning of observations illustrate that data doesn't *show* or *tell* scientists what to think?**

The early theories of the earth's age depended on many individuals of many beliefs from many countries. Of these early geologists, Hutton is today often seen as the 'winner'. However, during his career he often faired little better than other naturalists in defending his ideas of the earth. While he made significant contributions to our understanding of the earth, science textbooks typically give him excessive credit for today's accepted theory of the earth. This episode in the history of science should be remembered as a time when very different kinds of science battled for acceptance. Each group gathered evidence and argued, using their own methods, for their particular conclusions. Understanding the earth's age, like the development of all scientific ideas, was influenced by social factors and clearly required the talents and efforts of more than one person.

4. **How does this story illustrate that science versus religion is not an accurate description of efforts to understand the age of the earth?**

A Very Deep Question: Just How Old is the Earth?

Early efforts to understand the earth's age cannot be fairly categorized as a battle between science and religion. Rather, those early efforts reflected two different empirical approaches to collecting and interpreting evidence. The chronologists' approach was to carefully analyze historical texts of all sorts, including the Bible, to estimate the lifetimes of historical figures and then determine the earth's age by placing them in order according to ancestry. The naturalists' approach was to carefully study the natural world, referring to it as "the Book of Nature", to understand the earth's history. People of faith were found in both of these camps.

The naturalists argued that the earth was old, but how old remained a mystery. Many naturalists, including James Hutton, showed no interest in plotting a chronology of geological history, and even explicitly rejected that task. Chronologists, on the other hand, sought to determine *temporal sequence* arguing that 'what happened when' mattered. Even if determining precise dates was not possible, getting events in the right order was important to them. Most scholars became convinced throughout the nineteenth century that the naturalists were correct in their assertion that the earth had a deep history. Many of them began to wonder if the earth's age and other geological events could ever be determined with precision.

The first generation of geologists included men like James Hutton who were independently wealthy and spent their free time practicing geology. The following generations of geologists made their living doing geological research in the field, reporting it to their colleagues, and teaching it in universities. Professional societies increased greatly in the nineteenth century, and they provided a place for scholars to share ideas with other intellectuals. In 1807, the Geological Society of London began as a dinner club at a pricey tavern in order to keep away men from lower society. In 1825, it opened its doors somewhat, and admitted any man with an interest in geology. Reflecting the wider gender role norms in society that existed at that time, women were forbidden. The geological society aimed to understand the earth and concentrate solely on geological matters. However, this focus did not last long. Politicians sought geological evidence to help locate valuable coal, and Charles Darwin's mechanism for biological evolution — natural selection — was in need of geological evidence supporting an earth that was at least hundreds of millions years old. Motivated by an interest in the earth itself, but also by the importance of geology in many fields of study, geologists sought to understand the earth's structure, its features, and the very difficult problem of its timescale.

In the 1850s many methods were being used to determine the timing of geological events. Three were particularly popular—stratigraphy, fossils, and sedimentation. At the time, none of these methods could be used to establish exact ages of the earth, but they were used to determine the order that geological events had occurred. **Stratigraphy** studies the order of rock layering, or strata, and it remains a staple of modern geology. As geologists studied these rocks, they found remnants of what appeared to be plants and animals embedded in the strata. Throughout human history, these remnants had been used in religious and cultural ceremonies and collected like memorabilia, but not until the late 1700s did anybody seriously think they were fossils of long-dead, and possibly extinct, animals. In the 1850s some thought that the placement of these fossils within the strata could be used to determine the earth's age.

Others thought that the process of **sedimentation** would provide the only reliable estimate of geological events. As rocks wore away, or 'denuded,' from rain, wind and floods, particulate matter (ranging from large grains to silt) and dissolved ions would be sent to settle in lower lying areas such as valleys, rivers, and oceans. Some geologists believed they could measure this flow of sediment and calculate how long it would take to make some of the enormous rock formations. For instance, if the thickness of a modern sedimentary deposit is measured, and the rate that sediment is added to it over a period of a year is known, then the length of time that the sedimentary deposit has been forming can be easily calculated.

1. **John Phillips, in 1860, used the idea of sedimentation to estimate the earth's age. Based on the rate of sedimentation he observed occurring today, he assumed that approximately one foot of land eroded into the ocean every 1,330 years. He speculated that geologic columns would have a maximum height of 72,000 feet. Using his approach and numbers, calculate the approximate age of the earth he came to.**

This approach relied upon **uniformitarianism**, the idea held by many geologists that forces presently acting on the earth are the same as those that have acted in the past. Thus, the uniformitarian view holds that the rates of sedimentation processes occurring today have occurred at the same rate in the past. Shortly after 1860, a variety of approaches relying on sedimentation had been used to provide an approximate age of the earth, and values ranged from 38 – 300 million years.

- **While this age range is enormous, geologists are all in agreement that the earth is very old.**

William Thomson (better known as Lord Kelvin, the namesake of the Kelvin temperature scale), argued that he could approximate the earth's age by estimating the amount of heat it lost over time. A schooled physicist, Kelvin had no formal training in geology. He made his name in the 1850s as a technical advisor on the transatlantic cable, and he made several contributions to our scientific understanding of heat. His work in this area contributed to the foundations of the second law of thermodynamics, known as 'entropy.' To him, entropy was the measure of heat lost when two bodies of different temperatures interacted and came to equilibrium of temperature. For example, when ice cubes are placed into a glass of water, energy in the form of heat moves from the water to the ice. The water loses heat and cools; the ice gains the heat and melts. This meant that the total amount of energy could not be lost (or created), but just reallocated to the air, the glass, the table, or something else. He thought this reallocation of energy applied to the sun and the earth, and could be used to estimate the earth's age.

Kelvin's approach was in opposition to the sedimentary technique used by geologists. The basis of his argument was that in every interaction, energy must be transferred. This would be the case for the earth and sun as well. Thus, since their respective beginnings, both have been losing heat. He first turned his approach on the sun. Because the sun gave off enormous heat over a long time, it must be fueled by something. Many scientists thought the sun's heat was a product of chemical reactions, but nobody understood how chemicals could react to produce such enormous energy. Kelvin suggested that meteors crashing into the sun powered the reactions, analogous to meteors that were known to strike the earth. He thought that the sun's enormous gravity pulled in these unseen meteors. That interaction, he speculated, would provide enough reallocated energy to keep the sun burning for a long time.

In 1850, however, scientists had no evidence that anything similar had been going on with the earth, so Kelvin took this to mean the earth had been losing energy since its birth. He then collected data on temperatures inside caves and volcanoes to determine the earth's interior heat and compared it to the surface temperature and estimated how long it would take the earth to cool to its current temperature. At first he calculated about 100 million years, but this calculated number fell as he considered other variables and additional information. By 1900 Kelvin placed the earth's age at 24 million years old. Despite the many uncertainties in his calculations, Kelvin maintained that his approach clearly refuted theories that had put forth an earth that is hundreds of millions of years old.

Kelvin's conclusion raised concerns about the viability of uniformitarianism because his calculated time frame was far shorter than uniformitariansim would require. However, the earth's age was not as important to Kelvin as emphasizing that geological theory must be consistent with well-established physical principles. In 'On the Secular Cooling of the Earth,' Kelvin argued that geologists, particularly those advocating uniformitarianism, had neglected the principles of thermodynamics in their speculations. Kelvin also denied **catastrophism**, maintaining that geological speculation must be physically and philosophically sound. Kelvin thought that scientific laws reflected regularity in nature, which in turn he believed was the working of a providential intelligence. However, the universe for Kelvin was mechanical and worked on physical relationships.

But geologists were not arguing against a mechanical universe that worked on physical relationships. John Joly's work provides, perhaps, the best example of the geologists' adherence to these two assertions. He and other geologists were using different data, and their calculations based on it gave a much older earth. Joly applied the technique of sediment analysis to the salinity, or salt content, of the oceans. He assumed the oceans began as entirely fresh water, and that through erosion of rocks had slowly acquired its current salinity. This argument hinged on the realization that sodium appears in the ocean paired with chlorine, magnesium, and potassium. He had to measure the respective amounts of each salt present in the ocean and then factor the chemical weight of sodium. He concluded that there was 14.151×10^{12} tons of salt in the ocean, and then divided this by what was accepted at that time as a good estimate of the annual flow of sodium into the ocean. The result of this calculation was that 90 million years would have to pass to reach the ocean's current salinity level. Announcing this result in 1899, he and many other geologists had reached a similar conclusion that the earth was approximately 100 million years old.

At the turn of the century, then, two quantitative, 'scientific' estimates of the earth's age had two very different results. Kelvin measured the loss of heat by the earth and arrived at 24 million years, while the geologists had measured the accumulation of sediment and concluded that the earth was 100 million years old. Each of these methods made sense, and few scientists were willing to change their minds.

2. **Note that how scientific research is conducted (the *processes* of science) is intertwined with prevailing ideas about natural phenomena. This, in turn, affects new thinking about the natural world. Use information from this short story to explain how scientific knowledge and scientific process are intertwined.**

3. **Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process. Using this historical episode, explain how *both* the methods scientists use and the sense they make of data illustrate that science is a creative endeavor.**

The next method for determining the earth's age would come from investigations that began at the turn of the 20th century into newly observed phenomena. In 1896, Henri Becquerel serendipitously noticed that wrapped photographic plates in a drawer with a mineral called "pitchblende" become exposed. He interpreted this to mean that the mineral was emitting something that caused the photographic plate exposure. After subjecting the mineral to extreme heat, acids, and bases, the pitchblende sometimes chemically reacted, but the emanation exposing photographic plates continued. This was interpreted as meaning that the emanation was not the result of a chemical reaction, but rather was coming from deep within atoms in the pitchblende. Moreover, the emanation had similar penetrating properties to X-rays, the name given to a phenomena investigated by Wilhelm Röntgen just one year earlier.

A new element, uranium, was isolated from the pitchblende and it was determined to be responsible for the penetrating rays. In 1898, Pierre and Marie Curie announced they had isolated two new elements—radium and polonium—and called the energy they gave off "radioactivity." A few years later, Ernest Rutherford determined that X-rays and radioactivity were actually two different events. Whereas X-rays were high energy electromagnetic radiation (the same kind of energy that made up visible light), radioactivity was the process by which elements *changed* into other elements. Put simply, unstable *parent* elements gave off protons and neutrons and form a *daughter* element. At the time, Rutherford's claim that one element could change into another sounded like oldfashioned and now rejected alchemy. Nonetheless, research progressed quickly and just after the turn of the century, researchers had determined that three kinds of radiation existed. Weak and easily absorbed radiation that could be deflected by a magnetic field was called *alpha* radiation. Somewhat penetrating radiation that was deflected by a magnetic field in the opposite direction of alpha radiation was called *beta* radiation. And highly penetrating radiation that was not deflected by a magnetic field was called gamma radiation.

This newly understood phenomena, radiation, would soon play the key role in the fifty-year struggle to determine the earth's age. In 1903, Pierre Curie and his student announced that as radium gave off energy, it also gave off heat; enough that one gram of radium could melt a gram of ice over the course of a day. Then Rutherford and his student realized that if radium gave off heat in the lab, it must also do this in its natural habitat—the earth. They calculated that as little as five parts in ten billion of radium would heat the earth enough to keep it sustainable far longer than Kelvin's estimate of 24 million years.

- **School science is divided into subjects, but that is not how science truly works. Note how geology, chemistry and physics are all tied together in understanding the earth's age. Moreover, the work in these areas had significant implications for work in biology. Charles Darwin understood that natural selection, his proposed mechanism for biological evolution, would only work if life had existed on earth for at least hundreds of millions of years. Thus, work regarding the earth's age transcended scientific disciplines.**

Kelvin refused to accept that radiation actually gave off energy as had been reported—for him, all energy was the result of gravitational interactions. Kelvin remained firm in his view that the earth was 24 million years old, and this produced some awkward situations. At one conference, Rutherford was set to give a lecture that would essentially discredit Kelvin's theory. As Rutherford took the stage, he saw Kelvin sleeping in the back. Momentarily relieved that the famous physicist may not hear his speech, Rutherford began. To his horror, Kelvin awoke as he began talking on radiation. Rutherford would later recall that, "I saw the old bird sit up, open an eye and cock a baleful glance at me!" Rutherford's point was not to mock Kelvin, but to say that he had found a new way of estimating the age of the earth.

Most physicists and geologists soon recognized that this newly understood natural phenomenon was a likely solution to the previously irreconcilable difference between the physical and geological estimates of the earth's age. Using Rutherford's ideas, Bertram Boltwood pioneered a method of radiometric dating in 1907. If one knew the time it took for a parent element to decay into a daughter element, then measuring the ratios of each element in a sample and calculating how long it would take to get the observed ratios was a simple matter. This method sent estimates of the earth's age skyrocketing as high as two billion years. But many samples also came back with a date of 400 million years.

This wide range of values could not be explained until 1913 when scientists began to understand that while any one kind of element had the same number of protons, it could contain different numbers of neutrons. These different forms of the same element are called **isotopes**. Carbon, for example, has three isotopes. Most all carbon on earth is in the form of carbon-12, which has six protons and six neutrons. However, minute amounts of carbon-13 and carbon-14 exist, with seven and eight neutrons respectively. While the chemical properties of a radioactive element's isotopes are the same (i.e. Carbon 12, 13, and 14 chemically behave the same), its nuclear properties can vary drastically. In the case of Boltwood, he tried to measure the decay rate from uranium to lead. Measured in a 'half-life,' or the time it takes half the parent element to decay, the more abundant uranium-238 decays to lead-206 with a half-life of 4.5 billion years. Meanwhile, the rare uranium-235 decays to lead-207 with a half-life of 700 million years. Until the development of mass spectrometers in the 1930s, it was very difficult for scientists to determine which isotope they were using. Once understood, however, this radiometric dating would play a key role in our current understanding of the earth's age.

As radioactivity and its implications for geological dating became better understood, scientists acted in new ways to determine the earth's age. Rutherford and Joly teamed up in 1913, studying a particular kind of mark left by radioactive decay in rocks. Interestingly, while Joly argued that sedimentation was a uniform process throughout history, he never accepted that radioactive decay was uniform. He tried unsuccessfully to reconcile the 100 million year estimate of the earth's age calculated using his salinity dating process, with results that came from calculations using radioactive decay. Meanwhile Arthur Holmes, perhaps the first geologist to fully grasp the implications of modern physics, was willing to try all the new methods to get the two fields working with each other. A lifelong geologist who had traveled the world working for mining and oil companies, Holmes would settle into a professorship and act as a diplomat between scientists. His work produced an age of the earth that was approximately 2 billion years old.

4. **Scientists are rarely pleased with ideas that do not cohere. Why do you think that scientists want their ideas to fit together, even if those ideas come from different science disciplines?**

Over a century's worth of work was needed to convince most scientists by the 1850s that the earth was very old. Another century of work, and hard-earned new knowledge from various scientific disciplines, was required to provide convincing evidence that our earth is several billion years old. Today, the phrase 'deep time' is often used when referring to the staggering and difficult to grasp age of the earth. The modern estimate of the earth's age, determined by uranium-lead radioactive dating of earth materials and meteorites from the asteroid belt (thought to have formed at approximately the same time as earth), is about 4.5 billion years. Science textbooks often cite that number, but hide the extensive debate that took place regarding how knowledge of the earth should be sought, how data should be interpreted, and how knowledge from various scientific disciplines is expected to cohere. In doing so, they distort how science works, and make science careers appear far less than the creative and interesting profession than it is.