Chapter 18
Teaching Controversies in Earth Science: The Role of History and Philosophy of Science

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18.1 Teaching Controversies in Earth Science: The Role of History and Philosophy of Science

"Battle heats up over Alaskan petroleum reserve" (National Public Radio News, July 17, 2011), "Group ends call for hydro-fracking moratorium" (CBC News, 7 July 2011), "Greenpeace report links western firms to Chinese river polluters" (Guardian, 13 July 2011), "Climate change and extreme weather link cannot be ignored" (Dominion Post, 14 July 2011), and "'Jury Is Out' on Implementation of Landmark Great Lakes Compact" (New York Times, 14 July 2011)—headlines such as these are an everyday occurrence. The articles themselves not only inform us about the issues concerning the planet on which we live but also indicate the economic, political, and social influences/implications inexorably tied to them. It is reasonable to assume that a certain "working knowledge" of the systems of earth is necessary for one to be able to understand the issues as they are and even more so if one would want to make informed decisions (personal, political, social, or economic) related to such issues. This especially holds true for the current generation of K–12 students. They are the citizens of the future and should be

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prepared with the education needed to intelligently evaluate circumstances with potential adverse environmental impact. Hoffman and Barstow emphasized this in their call to action:

> Understanding Earth's interconnected systems is vital to the future of our nation and the world. Ocean and atmospheric interactions effect our daily lives in multiple, significant ways. Long-term changes in ocean and atmospheric processes impact national economies, agricultural production patterns, severe weather events, biodiversity patterns, and human geography. Global warming and its effects on glacial mass balance, sea level, ocean circulation, regional and global weather and climate, and coral bleaching, to name only a few potential impacts, are important global issues that demand immediate attention. (Hoffman and Barstow 2007, p. 9)

This general philosophy is borne out in the National Science Education Standards (NSES) (NRC 1996, 2012). The NSES have placed an equal emphasis on the teaching of Earth and Space Science (ESS) as has been given physics, chemistry, and biology. We direct the reader's attention to very recent works, such as the Next Generation Science Standards (NGSS) (Achieve, Inc. 2012) and the Earth Science Literacy Principles[1] (Earth Science Literacy Initiative 2010). The NGSS give an example of the emphasis placed on geoscience education by way of both the disciplinary core ideas and the crosscutting relationships, while the Earth Science Literacy Principles delineate nine big ideas in the geosciences as a framework of what a literate citizen of the USA should know within the domain of earth science. However, in the past several decades, ESS teaching has been struggling to keep pace with teaching in the other sciences. Currently, only about 7 % of US high school students have taken a course in ESS, and there are just over 10,000 earth science teachers at the secondary level in the USA, compared to about 52,000 for biology (Lewis and Baker 2010). In her review of the education research literature focused on earth science conceptions, Cheek (2010) found only 79 empirical investigations published between 1982 and 2009. Our search for investigations focused on the use of history and philosophy of science (HPS) in teaching earth science yielded fewer than 20. In this book alone there is only one earth science chapter compared to the six for physics and three each for biology and chemistry. With these statistics in mind, it is obvious that there is a need to (1) increase the number of students taking ESS classes at all levels of schooling, (2) increase the number of earth science majors graduating from universities, (3) increase the number of highly qualified earth science teachers, and (4) enhance the quantity and quality of earth science education research (and especially in the field of HPS use in teaching earth science). We hope this chapter will be a small stepping-stone toward this goal.

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[1] The nine ESLP big ideas are as follows: 1-earth scientists use repeatable observations and testable ideas to understand and explain our planet; 2-the earth is 4.6 billion years old; 3-the earth is a complex system of interacting rock, water, air and life; 4-earth is continuously changing; 5-earth is the water planet; 6-life evolves on a dynamic earth and continuously modifies earth; 7-humans depend on earth for resources; 8-natural hazards pose risks to humans; and 9-humans significantly alter the earth.

Cheek (2010) pointed out that in general, students' understandings of geoscience concepts have not improved over the past several decades. She did assert that we know more about students' geoscience conceptions than we did 27 years ago and now we need to utilize that information to enhance instruction. Efforts to do just that have included utilizing an earth systems approach where the main focus of instruction is to develop students' understanding of the four different *spheres* (geo-, bio-, hydro-, and atmo-) and how they influence and are influenced by each other (Rankey and Ruzek 2006). Earth science by design (ESbD) (Penuel et al. 2009), an extension of Wiggins and McTighe's (2005) work, is an approach whose goal is to achieve enduring understanding through teaching about earth via a few *big ideas*.

Another seemingly fertile approach, though underutilized, has been the incorporation of HPS within instruction, with emphasis on the many controversies experienced throughout the history of the earth sciences (Bickmore et al. 2009b; Montgomery 2009). By HPS, we are referring to the many factors that influence the progression of scientific understanding. This may include economic, political, or social factors. It also encompasses philosophical considerations which oftentimes are responsible for directing investigations and discerning observational data from the "noise." These philosophical differences may form the basis of controversy as well. For our purposes we will use Venturini's definition of controversy:

> Controversies are situations where actors disagree (or better, agree on their disagreement). The notion of disagreement is to be taken in the widest sense: controversies begin when actors discover that they cannot ignore each other and controversies end when actors manage to work out a solid compromise to live together. Anything between these two extremes can be called a controversy. (Venturini 2010, p. 261)

The history of the geosciences is rife with controversial issues such as how marine fossils could be found at mountain tops (Cutler 2003), plutonism versus neptunism (Repcheck 2003), "uniformitarianism" versus "catastrophism" (Şengör 2001), deep time and the age of earth (Repcheck 2003), hollow earth theory, contracting earth theory (Oreskes 1999), the use of fossils to date rocks (Rudwick 1985), expanding earth theory (Adams 2005), continental drift versus land bridges (Oreskes 1999), the theory of plate tectonics (Oreskes and LeGrand 2001), dinosaur extinction (Alvarez and Chapman 1997; Glen 2002), the "current and heated" controversy concerning plume theory (Anderson and Natland 2005; Anderson 2006; Glen 2005), as well as the ever-present conflict between science and religion (Bickmore et al. 2009a). Instructors have found that "teaching the scientific controversy" has been effective at garnering interest from students, enhancing their critical thinking skills, not just in the geosciences[2] but also physics (De Hosson and Kaminski 2007), chemistry (Justi 2000), and biology (Seethaler 2005).

Researchers have also found that incorporating HPS within instruction helps to augment students' understandings of the nature of science (NOS) as emphasized in the NSES (NRC 1996, 2012). The use of HPS as an instructional tool was written

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[2] For examples, see Dolphin (2009), Duschl (1987), Montgomery (2009), and Pound (2007).

about as early as the mid-twentieth century (Conant 1947). Conant emphasized the importance of students understanding the "tactics and strategy" of science. The other efforts of infusing HPS into instruction, such as Harvard Project Physics and the BSCS Biology, also deserve accolades (Matthews 1994/2014). Matthews also stated that teaching with HPS is important because it promotes better comprehension, is intrinsically interesting, counteracts scientism and dogmatism, humanizes the process of science, and connects with disciplines within science as well as outside of science, and historical "learning" reflects individual learning about concepts. Many others have written in favor of the use of HPS within science instruction.[3]

In this chapter, we will situate the geosciences philosophically and methodologically with respect to biology, chemistry, and physics. We will highlight four different geoscience concepts and their related controversies, including what we know about the use of HPS for teaching these concepts, what has been done, and what, in our minds, is still in need of being done. We will offer pedagogical, cognitive, and historical rationales for the use of controversy in teaching earth science concepts, and we will organize our discussion of controversies within the context of the four spheres of the earth—geosphere, biosphere, hydrosphere, and atmosphere. Though highlighting a particular domain within the geosciences, each phenomena surrounded by a historical and philosophical controversy will also exemplify its global nature in terms of its influence. The controversies described below are those surrounding the acceptance of plate tectonics as the grand unifying theory of earth (geosphere controversy); the meteorite impact theory explaining the Cretaceous–Paleogene (or K–Pg) mass extinction (no, it was not just dinosaurs that went extinct) (biosphere controversy); the connection of rhythmic long-term weather variations in various parts of the world to oceanic temperature in the tropical Pacific Ocean, also known as ENSO (hydrosphere controversy); and finally, the current controversies surrounding the acceptance of anthropogenic global climate change (**ACC**) (atmosphere controversy).

18.2 Nature of the Earth Sciences

What is the nature of the earth sciences? How are they, as disciplines, distinguished from other sciences? Some might be surprised that these questions are even being posed, as they seem so basic. However, we believe that these questions need answers for several reasons. Unfortunately, for much of the last century, the earth sciences have been portrayed as derivative disciplines whose logic and methodology were furnished by the physical sciences. Indeed, the history of the earth sciences is annotated by episodes where not only physicists but even (surprisingly) some geologists tried to reconstitute the earth sciences as a tributary of physics (Dodick and Orion 2003).

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[3] See, for instance, Allchin (1997), Bickmore et al. (2009b), Justi (2000), Matthews (1994/2014, 2012), and Rudolph (2000).

This trend has continued into recent times such that Gould (1986, 1989) noted that some scientists do not accept the methodological diversity of the sciences and specifically disparage the earth sciences as being less scientific than the physical sciences.

Unfortunately, this message that the earth sciences are derivative has been reinforced by work in the history and philosophy of science (HPS). For much of the twentieth century, the classic works of HPS emanated from scholars (Popper, Kuhn, Lakatos) who largely relied on examples from physics to illustrate their discussions, a critique which has been mentioned by others.[4] In fact, even in the small number of philosophical works that have examined their nature, the earth sciences have been declared as either derivative or at least as not unique sciences.[5] It is only in the last 30 years or so that this lack has been redressed, as witnessed by the increased number of tomes connected to HPS works dedicated to the earth sciences, as well as the publication of *Earth Sciences History*, the only academic journal exclusively devoted to the history of these disciplines.

Unfortunately, such work has not penetrated into the world of education, such that some science educators are often left with the impression that the earth sciences are less rigorous than the physical sciences and thus less worthy of being taught as part of the standard science curriculum (Dodick and Orion 2003). Such thinking is mistaken because it does not consider the special nature of the earth sciences as one of the historical and interpretive (or hermeneutic) sciences (Frodeman 1995; Orion and Ault 2007) which classically attempt to reconstruct past phenomena and processes by collecting their natural signs during fieldwork. This nature is shared to a large degree with other historical fields such as evolutionary biology and astronomy (Cleland 2001, 2002). Concurrently, it contrasts with experimental sciences such as physics or molecular genetics in which natural phenomena are manipulated within the controlled environs of a laboratory in order to test a hypothesis. Indeed, the differences between these two groups of science are derived from the fact that the historical sciences, such as the earth sciences and evolutionary biology, developed specific methodologies to cope with problems that could rarely be tested under controlled laboratory conditions.[6]

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[4] See, for instance, Baker (1996), Frodeman (1995), Greene (1985), and Mayr (1997).

[5] See, for instance, Bucher (1941), Goodman (1967), Schumm (1991), and Watson (1969).

[6] We do not mean to imply that the earth sciences are devoid of experimentation. Indeed, whole fields within the earth sciences including geophysics, geochemistry, and climate science have tested some of their claims using cutting-edge experimental methods which produce important research results. Philosophical classifications sometimes simplify, ignoring the overlap that occurs between categories, and this is the case in the historical–experimental dichotomy we use in this chapter. We still believe that it is a fruitful classification as many philosophers and historians of science have used it in their definition of different sciences (See Dodick et al. 2009 for a review of the development of the term *historical sciences*). Moreover, one of us (Argamon et al. 2008; Dodick et al. 2009) has tested this dichotomy empirically and has indeed found that the earth sciences (representing diverse fields including geology, geochemistry, and paleontology) do fall more regularly into the historical science category.

Table 18.1 Methodological contrasts between the experimental and historical sciences

Dimension	Experimental	Historical
Research goal	General laws and behaviors	Explanations for ultimate and contingent causes
Evidence gathered by	Controlled manipulation of nature	Observing/analyzing preexisting entities and phenomena
Hypotheses are tested for	Predictive accuracy	Explanatory accuracy
Objects of study	Uniform and interchangeable entities	Complex and unique entities

Recently, a growing number of scientists, philosophers, and educators have critiqued the idea of there being a universal scientific method largely emanating from the experimental-based, physical sciences[7] and instead promoted the view that different combinations of logic and methods can and should play different roles in different disciplines. Indeed, one of us has empirically tested such claims by analyzing the pattern of language use in the historical and experimental sciences, respectively; the results of this work show (statistically) significant variation in language use between the two groups of sciences that are derived from the specific methodologies employed by these two groups of sciences (Argamon et al. 2008; Dodick and Argamon 2006; Dodick et al. 2009).[8]

This following discussion will review this empirical work to provide the reader with a better understanding of the methodological differences between the historical and experimental sciences. By doing this, we also create a philosophical framework for analyzing the historical controversies that we present later in this chapter. Table 18.1 presents four methodological contrasts between historical and experimental sciences which will be used in this discussion.[9]

The ultimate *research goal* of the experimental sciences is a general statement or causal law that is applicable to a wide variety of phenomena in many contexts (Kleinhans et al. 2005). To achieve this goal, *evidence is gathered* via controlled experimentation within laboratories in which the natural phenomena are manipulated to test a facet of a theory or hypothesis (Case and Diamond 1986). The quality of such a *hypothesis is tested* by the consistency of its predictions with the results of its experiments. Finally, the form of such experimental research is dictated largely by the fact that it is conducted on uniform and interchangeable *objects of study*, such as atoms; the fact that such entities are uniform, or nearly so, makes the formulation

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[7] See, for instance, Cartwright (1999), Cleland (2001, 2002), Cooper (2002, 2004), Diamond (2002), Dodick et al. (2009), Frodeman (1995), Gould (1986), Kleinhans et al. (2005, 2010), Mayr (1985), and Rudolph and Stewart (1998).

[8] These studies encompassed a series of experimental fields including physical chemistry, organic chemistry, and experimental physics; historical fields included paleontology, geology, and evolution.

[9] This section is arranged to correspond with the ordering of Table 18.1. The dimension under consideration is delineated in italics.

of general laws possible in principle and experimental reproducibility a reasonable requirement in practice (Diamond 2002). This desire for reproducibility means of course that results of a given experiment should be uniformly reproduced, given the same conditions, in any laboratory in the world; this result fulfills one of the basic principles of science, the principle of uniformity of law (Gould 1965, 1987).

In contrast, the *research goal* of historical sciences, such as the earth sciences, is to uncover ultimate and contingent causes buried in the past whose effects are interpreted only after very complex causal chains of intervening events (Cleland 2001, 2002). Accordingly, *evidence is gathered* by observation of naturally occurring signs exposed during fieldwork, since controlled experimental manipulation is usually impossible due to the fact that the historical sciences are interpreting cause and effect in past events that cannot be repeated or replicated; in fact, even if this were possible, the enormous amount of time, space, and the complex relationship of variables needed to affect the result would inhibit such scientific research from happening.

Such observation is not a passive act of simply looking, or searching for evidence, as the word "observe" might imply to those unfamiliar with the earth sciences. This is due to the fact that such evidence is often hidden in time and space from an earth scientist. Instead, such observations are guided by deep inferences and intuitions about earth processes that are developed by earth scientists through long periods of exposure to field materials.[10]

When possible, rather than making observations on a single entity (such as an outcrop), historical science relies on natural experiments (Case and Diamond 1986; Diamond 2002).[11] Natural experiments are based on analyzing the effects of natural (i.e., not manipulated by the experimenter) perturbations in the field. In implementing such studies, the researcher must also choose at least one "control" site, which is similar to the experimental site, but that lacks the same natural perturbations. Unlike laboratory experiments, natural experiments do not control their independent variables due to the confounding complexity of field conditions.

This focus on past causation in historical sciences implies that the ultimate *test of* (the quality of their) *hypotheses* is explanatory adequacy via retrodiction of specific past events rather than prediction as in experimental sciences[12]; this is due

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[10] In the past earth scientists were restricted to physically uncovering hidden field materials; this of course restricted their research to areas to which they had access. However, technology has revolutionized this search, for example, tools, such as remote sensing via satellite makes the invisible visible, both here on earth, as well as on other planetary bodies.

[11] Diamond and Robinson (2010) have also documented how natural experiments are also applied within the humanities and social sciences where controlled experimentation is impossible.

[12] As Schumm (1991, p. 7) notes, the term prediction in science is used in two ways: "The first is the standard definition to foretell the future. The second is to develop a hypothesis that explains a phenomenon." Based on the second definition, such predictions have the typical form of: "if a given hypothesis is correct then we predict that the following process or phenomenon will occur." In the case of experimental sciences, both definitions are methodologically applicable. Schumm (1991) argues that in some fields of earth science (e.g., geomorphology), prediction to the future (i.e., the first definition), based on extrapolation, is also part of their current methodology.

to the fact that the *objects of study* in historical sciences such as the earth sciences are complex, unique, and contingent, with very low chances of repeating exactly (Kleinhans et al. 2010). This methodological need places great stress upon earth scientists' powers of "retrospective thinking," in which they apply knowledge of present-day processes in order to draw conclusions about processes and phenomena that developed millions of years ago (Orion and Ault 2007), a methodology that the historical sciences terms actualism.[13]

The methodology of such explanatory reasoning derives from what Cleland (2001, 2002) calls the "asymmetry of causation," in that effects of a unique event in the past tend to diffuse over time, with many effects being lost and others confused by intervening factors. Making sense of such complexity requires, therefore, synthetic thinking (Baker 1996), in which one fits together complex combinations of evidence to form arguments for and against multiple working hypotheses (MWH) which often compete with each other.

In addition to sifting through the complexity of processes, earth scientists must also deal with the complexity of the physical entities they study. Unlike subatomic particles, for example, which are all uniform, the individuals studied by earth scientists—fossils, strata, igneous intrusions—are all unique (though often similar) individuals, whose precise form and function cannot always be reconstructed. This usually removes the chance of formulating universal laws and allowing only statistical explanations of relative likelihoods at best, so that arguments for and against multiple hypotheses must be made on the preponderance of the best evidence.

Even so, we argue that such predictions are far less common and accurate in historical sciences, than they are in experimental sciences, in large part due to the complexity of the phenomena studied in such disciplines; instead, historical science focuses on reconstructive explanations, via the method of retrodiction, which might be defined as a specification of what did happen (Engelhardt and Zimmermann 1988; Kitts 1978). As Ben-Ari (2005, p. 15) notes "retrodiction is essential if theories are to be developed for the historical sciences." Indeed, Schumm (1991) admits that it is only when the present conditions are understood and when the history of the situation has been established that predictions to the future (i.e., the first definition) can be made with some degree of confidence in earth science. In other words, in historical-based sciences, such as the earth sciences, reconstructing past conditions takes precedence and as a method has greater validity than predicting the future.

[13] In defining actualism, some philosophers and geologists separate between two definitions of the earth sciences most important, but most misunderstood concept, uniformitarianism (Hooykaas 1959; Gould 1965, 1987; Rudwick 1971).

Substantive uniformitarianism or sometimes uniformitarianism claims that geo-historical uniformity exists between present and past geological phenomena, such that the force, rates, and types of phenomena do not change over the course of geological time.

Methodological uniformitarianism or simply actualism is a method permitting an earth scientist, via analogical reasoning, to explain the geological past based on geological events observed in the present. On the basis of these observations, geologists make inferences about the types of causes and their force in the past.

These two types of uniformitarianism were conflated together by Lyell (Gould 1984, 1987) which has led to some of the modern-day confusion of the term uniformitarianism. We will discuss the impact of Lyell's conflation when we discuss the case study concerning the Cretaceous–Paleogene extinctions.

Thus, reasoning about the relative likelihood of different assertions is endemic to the synthetic thinking patterns of historical science.

As can be seen, inquiry within the earth sciences cannot guarantee reproducible results over space and time like the experimental sciences. Indeed, the very purpose of the earth sciences is to explain the unique, contingent, and complex systems acting over the entire earth and its interacting "spheres" (geosphere, hydrosphere, atmosphere, and biosphere) as well as analyzing their subsystems on more local scales (Orion and Ault 2007).

This concern for global complexity can and should be used as a tool of science education because it prevents the earth sciences from being portrayed as what Allchin (2003) terms a science of *myth-conception*. By myth-conception, Allchin (2003) is referring to a narrative device which embodies a "world view that provides formulae or archetypes for appropriate or sanctioned behaviour." For example, the history of science has sometimes portrayed discoveries as the efforts of a single, idealized scientist. Even the names used to describe these discoveries support these impressions: "Mendelian genetics," "Darwinian evolution," and the "Copernican revolution."

Such idealized portrayals of science sometimes occur because its narrative is shaped by "sharpening" what is considered the central message, while "leveling" the details thought to be less central (Allchin 2003). Moreover, science is often considered as a problem-solving endeavor in which the goal is to get the single, right answer; this has sometimes infected its philosophy, such that the questions that have been asked ("What is the method of science?" or "How does science advance?") focus on a single process (Oreskes 2004) As Oreskes (2004) argued, many academic fields, including history, art, and literature, embrace multiple perspectives as they analyze a problem and so in fact do the sciences. Nowhere is this more evident than in the earth science paradigm of plate tectonics, which embraces multiple conceptual tools including experimentation, mathematical models, novel instruments, analogical reasoning, and visualization. Equally important, plate tectonic theory synthesized huge amounts of data that were collected by many scientists, working on independent problems, and scattered over the entire earth. Indeed, without such global efforts the theory would have never been accepted. Concurrently, this global effort has meant that plate tectonics have not acquired the attached name of one archetypical scientist. Thus, it is the perfect scientific theory for demonstrating the nature of science to students. As we will show, plate tectonics is not unique, and all of the controversies that we will be exploring in this chapter also demonstrate this global nature of the earth sciences.

18.3 Why Controversies?

We believe that framing the learning of the earth sciences in historical controversies is justified from the perspectives of the learning sciences, as well as the history and philosophy of science.

From the perspective of the learning sciences, it is well known that students (up to and including their university years) are often epistemological dualists, viewing academic issues in terms of true or false, right or wrong, credit or no credit (Alters and Nelson 2002). At first glance this poses some dangers to the deeper critical thinking skills that we want students to develop. This assertion is also sometimes reinforced, ironically, by popular misinterpretations of the conceptual change movement which often sees "mis"conceptions as entities to be uprooted and so to be replaced by the final "correct" conception. However, the progenitors of the conceptual change movement themselves, Posner and his colleagues (1982), noted in their original article that conceptions, for the good and the bad, are important scaffolds that lead to further conceptual development. Moreover, diSessa and his colleagues (diSessa 1988; diSessa 1993; Smith et al. 1993) in their works on "learning in pieces" emphasized that ideas perceived as misconceptions have a heuristic potential that allow them to do important conceptual work; the key is for the student and scientist to know the limits of validity connected to such conceptions.

More recently, Marton et al. (2004) have outlined a theory of learning that connects perfectly with the comparative nature of controversies. The key facets of this theory are the "object of learning," "variation" between objects of learning, and "the space of learning." The object of learning is the concept that is to be learnt in a given lesson. From the teacher's perspective, the goal of the lesson is to present an intended object of learning, which through the discourse of the lesson becomes the enacted object of learning or what is possible to learn in the lesson. Finally, from the learner's point of view, what is actually learnt is termed the lived object of learning. The key way in which the object of learning becomes enacted is through the teacher's use of variation. In other words, according to Marton and his colleagues, learners can only learn an object when it is presented in comparison to something with which it differs. For example, if the objects of learning are the colors green and red, learners who are color-blind will not be able to see the difference between these and, therefore, opportunities for them to learn will not be available. These variations create a space of learning which refers to what is possible to learn in that particular situation. This space is largely created through language.

Finally, the idea of controversy connects perfectly with the recent movement toward using argumentation as an important component of classroom discourse. Veerman (2003, p. 118) succinctly summarized the value of classroom argumentation when he noted that, "in argumentation…knowledge and opinions can be (re)-constructed and co-constructed and expand students understanding of specific concepts or problems." Moreover, argumentation dovetails perfectly with *inquiry*-based learning in which students replicate what scientists do when they are pursuing an authentic scientific problem, as research programs can be viewed as large-scale arguments supporting and falsifying different theoretical frameworks.

Controversies also align with the history and philosophy of science, both on a general level and a specific level. On the general level, we reference the educational philosopher Joseph Schwab (1964) who argued that all too often, students merely learn the facts and final outcomes of scientific research, what he called the "rhetoric of conclusions." This is certainly the case in many textbooks where one scientist's conception is simply shown to replace a previous scientist's conception, without a deeper reference to the many factors that influenced this development. Gould (1987) labeled this as "cardboard" history because of its two-dimensional nature. In response, Schwab (1958, 1962, 1963, 1966, 2000) promoted the *science as inquiry* model. Recognizing that students should come to understand how scientists interpret information and form ideas, Schwab stressed the idea that proper science education should show how these products were derived by scientists—how a body of knowledge grows and how new conceptions come about. To achieve this goal, Schwab emphasized the use of history of science including the reading of original papers and historical narratives exposing the developmental path of scientific concepts (Schwab 1963). The use of historical controversies connects perfectly with Schwab's philosophy, because properly constructed, such controversies can also teach about the complex pathways in the development of scientific concepts.

On a specific level, the idea of controversies strongly aligns with one of the key methods in geology, "multiple working hypotheses" (MWH), which were most prominently elucidated by Gilbert (1886), Chamberlin (1890/1965, 1897), and Johnson (1933).[14] Although mentioned in a previous section of this chapter, we will expand this discussion as MWH has importance both for the general structure of the earth sciences, as well for its connections to controversies.

Chamberlin (1965, p. 755–756) recognized three phases in the history of intellectual methods. The first phase was based on the *method of the ruling theory* where a "premature explanation passes into a tentative theory, then into a theory, and then into a ruling theory." This linear process, in Chamberlin's opinion, was "infantile" for the reason that only if the tentative hypothesis was by chance correct does research lead to any meaningful contribution to knowledge. Less problematic, in his view was the second phase based on a *working hypothesis*, which is a hypothesis to be tested, not in order to prove it but rather as a stimulus for study and fact finding ("ultimate induction"). Nonetheless, a single working hypothesis can unfortunately be transformed into a ruling theory, and the need to support the working hypothesis, despite evidence to the contrary, can become as strong as the need to support a ruling theory. Chamberlin therefore suggested his third phase, based on *MWH*, which was thought to mitigate the danger of controlling ideas. It did so because the investigators develop many hypotheses that might explain the phenomena under study. This was done prior to the actual research and hypotheses were oftentimes in conflict with each other.

Both Blewett (1993) and Johnson (1990) have criticized MWH based on its logic and practicality, respectively. However, as Baker (1996, p. 207) has argued, such criticism occurs "within the context of our times." Thus, for example, Blewett's critique was largely based on a "physics-based philosophy of science." Baker, however, suggested that we look at what MWH meant when it was first formulated. First, it was intended as a method for "naturalists" (whose work was conducted in the field) and not mathematical physicists (who were lab-based experimentalists).

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[14] Additional work was provided by Gilbert (1896), Chamberlin (1904), and Davis (1911).

Second, the purpose of MWH was, in Chamberlin's view, to facilitate certain "habits of mind" which were of special concern to naturalists generally and geologists specifically. This second purpose certainly integrates with the goals of science education in which we try to open students' scientific worldview to alternatives, as they often stubbornly (as epistemological dualists) adhere to a single conceptual framework.

This of course does not mean that the experimental sciences do not avail themselves of MWH. Indeed, Platt (1964) reported on the use of such a method in both molecular biology and high-energy physics, both of which are definitely experimental in nature. Moreover, he advocated its use, which is part of a larger method he termed "strong inference" in other sciences, for its ability to bring rapid research advances. However, this does not necessarily mean that such experimental fields need to avail themselves of MWH. A more linear process of testing single hypotheses is possible and is still followed in many laboratories.

In the case of the earth sciences, MWH has a practical value even today for its practitioners. As earth science is often conducted in the field (or with materials that must be collected from the field), it focuses on complex natural systems, which are often the result of several irreducible causes, and the application of MWH makes it more likely that a scientist will see the interaction of the several causes. Moreover, from a practical perspective MWH has value because earth scientists conduct periodic stints of fieldwork (unlike laboratory scientists who have full-time access to their lab-based experiments). This means that it is critical to test multiple hypotheses when they have direct access to their primary data (Blewett 1993).

18.4 Highlighting the Four Controversies

We will turn our attention, now, to the four case studies of scientific controversy that we wish to highlight in this chapter. Those controversies are those surrounding the development of the theory of plate tectonics, the impact theory of mass extinction at the end of the Cretaceous, the El Niño Southern Oscillation (ENSO) theory of control over long-term weather, and the current controversy surrounding anthropogenic climate change (ACC). We discuss these four cases for a number of different reasons.

First, the concept at the center of each case study is popular, in that each have been in the popular media fairly recently and both scientists and the general public should have some familiarity with them. Second, each phenomenon has, or has had an impact that reaches a global level, influencing all systems of the earth. Plate tectonics, for instance, is considered the grand unifying theory of the earth. We have designated it as a phenomenon that occurs within the geosphere. However, its impacts reach into oceanic composition and circulation, planetary wind patterns, and selective evolutionary pressures. Third, each of the case studies highlights nicely the history and philosophy of the geosciences. That is, they utilize methods that emphasize earth science's historic and interpretive nature as discussed earlier in this chapter.

In each case, scientists observed an entity or phenomenon's "end product," such as a mass extinction, a mountain range, or anomalous weather conditions. They had to discriminate among a multitude of possible and complexly related variables to determine causation. In the quest for contingent causes, they built models and then looked back in history for explanatory accuracy. This is not to say that each of these episodes played out in the same way as any of the others. It is through our framing of the controversies that we draw out similarities.

18.5 Geosphere: The Acceptance of Plate Tectonics as the Grand Unifying Theory of the Earth

The history of thoughts concerning the origins of continents and ocean basins is a long one, starting before biblical time right up through the present. A comprehensive treatment of this topic is out of the scope of this chapter but can be found in Şengör (2003) for those who are interested. This section demonstrates the general structure of geology as it pertains to the development of the theory of plate tectonics. As with the other controversies discussed in this chapter, this section displays the global nature of the phenomenon under investigation. Although there is a long history on this topic, we begin the story of the development of the theory of plate tectonics with the introduction of the theory of continental drift in 1912 by Alfred Wegener (Wegener and Skerl 1924). At this time, there were multiple varied (and contradictory) working hypotheses to explain the dynamics of the earth. As described by Alexander Du Toit, geologists considered that

> geosynclines and rift valleys are ascribed alternatively to tension or compression; fold-ranges to shrinkage of the earth, to isostatic adjustment or to plutonic intrusion; some regard the crust as weak, others as having surprising strength; some picture the subcrust as fluid, others as plastic or solid; some view the land masses as relatively fixed, others admit appreciable intra- and intercontinental movement; some postulate wide land-bridges, others narrow ones, and so on. Indeed on every vital problem in geophysics there are…fundamental differences of viewpoint. (Du Toit 1937, p. 2)

Specifically, by the end of the nineteenth century, there were two different models for earth dynamics relying on the thermal contraction of the earth. Edward Seuss hypothesized that the crust of the earth was homogeneous and allowed for continents and ocean basins to be interchangeable. Basins were places where contraction left room for the collapse of large areas of crust. James Dana, on the other hand, saw a difference in the composition between ocean crust and continental crust where ocean crust was denser and therefore sank further into the earth. The implication of Dana's contraction theory is that continents and oceans are permanent, or "fixed," entities on the earth's surface. Ironically, though Wegener's theory reconciled many of the controversies noted by Du Toit, it was for that very reason, and some others as well, that it faced an uphill battle for acceptance, especially for North American scientists (Oreskes 1999).

A meteorologist and cartographer, Wegener became interested in the problem of the origin of continents and ocean basins upon noticing the similarities between coastlines of western Africa and eastern South America. Although he was not the first to notice these similarities (Hallam 1973; LeGrand 1988; Oreskes 1999), he was the first to rigorously explore lateral displacement of the continents as a causal explanation for these observations. Besides the "jigsaw" fit of the continents, Wegener "drew on several elegant lines of empirical evidence" (Glen 2002, p. 102), including such complex entities as paleontological, paleoclimatic, and geographical and geophysical effects[15] to support his argument that a supercontinent he referred to as Pangaea existed up to about 205 million years ago and began rifting apart until assuming the current continental positions.

Wegener's hypothesis received some acceptance in Europe, South Africa, and Australia. This was not the case in North America, where the idea of drifting continents and its implications did not set well with many geologists for both empirical and philosophical reasons (Oreskes 1999). Rollin Chamberlin (1928) delineated 18 arguments against the drift hypothesis. Generalizing from this list shows what the major objections were. First, Wegener provided no reasonable mechanism or force for moving continents through softer, but solid ocean crust without showing some kind of deformation. Second, geologists found Wegener's ideas to be "superficial" because he generalized his conclusion from the generalizations of others' works in paleontology, paleoclimate, and geophysics. Third and considered more important (Oreskes 1999) was that that Wegener's ideas did not seem to appeal to the philosophy of uniformitarianism, held in great esteem by geologists at the time. Part of the ability to interpret past events was to consider the natural processes to be uniform through time. Wegener's hypothesis did not show the cyclicity that had been observed in other interpretations of the past. Indeed, Chamberlin (1928) considered Wegener's hypothesis to be "a 'footloose type'"—one that "takes considerable liberties with our globe and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories" (p. 87). In the same publication Schuchert (1928, p. 140) critiqued drift stating, "We are on safe ground only so long as we follow the teachings of the law of uniformity in the operation of nature's laws."

During this time, thermal contraction and its corollary, land bridges, were not nearly as comprehensive as drift in putting observations into the context of a global phenomenon, plus contraction and land bridges had major geophysical difficulties as explanatory models. It would take about 40 more years to amass the right data to be analyzed at the right time by the right people for the idea of lateral motion of continents to gain widespread acceptance. These data would eventually come from the emerging and global studies in radiometric dating, paleomagnetism, physical oceanography, and seismology. It was not that anyone in these fields was working specifically on this question of the origin of continents and oceans. The emergent data began to converge and the lateral drift interpretation of earth's past could no

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[15] See Hallam (1973, pp. 9–21) for a detailed description of Wegner's various lines of evidence.

longer be ignored. This idea of convergence of data will be important in the controversies that follow as well.

There were two lines of investigation in paleomagnetism. One was concerned with explaining an apparent "wandering" of the magnetic poles of the earth and the other with a reversal of polarity of the magnetic field over time. Pierre Curie, in 1895, determined that as hot, iron-bearing rock cooled to below the Curie temperature (approximately 260° C), it would assume the earth's magnetic signal at that time. When measuring magnetic signals within continental basalts of different ages and from different parts of the world, geologists found that the magnetic north pole of the earth appeared to have moved through time. The only explanations for this were that either the pole had indeed "wandered" through time or the continents did or both. In the mid-1950s, Runcorn assembled "polar wandering paths" for North America, Europe, Australia, and India and compared them to each other. The paths were not parallel. This suggested, then, that the continents and not the pole did move over time (Morley 2001).

The second line of investigation looked at another phenomenon which was that the magnetic polarity observed in the rocks every once in a while showed a 180° reversal in polarity compared to the earth's current polarity. At first such an observation was ignored as being a phenomenon of the extraction process or some sort of chemical reaction within rocks of certain composition. However, as data became more global, it became obvious that rocks of the same age maintained the same polarity, whether that polarity was normal or reversed. This led researchers like Cox, Doell, and Dalrymple to consider the changing of the earth magnetic polarity to be a global phenomenon that was recorded in the rocks as it happened. Utilizing the advancements in radiometric dating, they set about constructing a timeline of magnetic reversals. Glen (1982) showed the evolution and refinement of this timeline starting in the late 1950s to 1966.

Though there was no other way to interpret the polar wandering evidence than by the drift of the continents, geomagnetism was a new field and most geologists, not really understanding it, were skeptical of the implications (Oreskes 1999). That having been said, Cox, Doell, and Dalrymple's evolving magnetic reversal scale, published through 1966, would eventually be the key to unlock the secret to earth dynamics (Glen 1982).

Meanwhile, due to world events such as WWII and the beginning of the Cold War era, the ocean basins became very important objects of investigation. Teams of researchers out of Columbia University's Lamont-Dougherty Geological Observatory (now Lamont-Dougherty Earth Observatory, or LDEO), under the guidance of Maurice Ewing, a staunch "fixist," began making observations and taking ocean crust and sediment cores from the seafloor. Results from this data collection extravaganza included Marie Tharp's and Bruce Heezen's discovery of an enormous though narrow chain of mountains running the length of the Atlantic Ocean (Heezen et al. 1959). They also observed a large rift running lengthwise down the center of this mountain chain. Other pertinent observations were a general rise in elevation of these so-called ocean ridges, high heat flow within the rifts, lower sediment thickness, and increasing age symmetrically about and away from the ridge.

In response to these findings, Hess (1962), originally a fixist, posed a contingent cause in what he referred to as "an essay in geopoetry." Hess proposed a theory that had the mid-ocean ridges as places where hot mantle rose and pushed the ocean crust away laterally from a rift. This crust would move like a "conveyor belt" and eventually cool and be consumed as it sank and reentered the earth. His theory would later become known as the theory of seafloor spreading (Dietz 1961). At approximately this same time, former drift proponent, S. Warren Carey, proposed another interpretation, or model, to explain these global observations. His idea was that the earth, at the end of the Paleozoic era, began to grow and the solid crust of the earth began to fragment and spread apart as the earth grew to its current position today. Carey (1976) claimed his ideas were eclipsed by the idea of subducting crust which "has enjoyed meteoric rise to almost universal acclaim, and every aspiring author must jump on the bandwaggon [sic] to gild another anther of this fashionable lily" (p. 14).

Another team of geologists from Scripps Oceanographic Institute were conducting their own studies of the seafloor and discovered an unexplainable pattern of magnetic anomalies. The pattern was that of alternating parallel stripes of reversed and normal magnetism in the basalts near and parallel to the ocean ridges (Mason and Raff 1961; Raff and Mason 1961). It took Fred Vine, a physicist, trained in geomagnetism himself and sympathetic to the drift hypothesis, to combine Cox, Doell, and Dalrymple's magnetic reversals timeline with Hess' verses of geopoetry to answer the question of the "zebra stripe pattern" on the seafloor (Vine and Matthews 1963). Coincidentally, and independently, Canadian geologist Lawrence Morley, also trained in magnetism, saw the Raff and Mason paper and a paper about seafloor spreading (Dietz 1961) and had a similar "eureka" moment (Morley 2001). Despite two attempts to get his interpretation of displacement published, he was unsuccessful. Vine and his advisor at Cambridge, Drummond Matthews, published the idea in *Nature* in 1963. Despite this, many still referred to it as the Vine–Matthews–Morley hypothesis.

Their model only gained a warm reception. As data mounted, however, the explanatory/interpretive power of plate tectonics could no longer be discounted. These new data came from the development of the World Wide Synchronized Seismic Network (WWSSN) (Oliver 2001). Implemented in the 1950s as an attempt to discover the testing of nuclear bombs, the WWSSN gave unprecedented seismic data in terms of both quantity and quality. With an accurate delineation of the patterns of earthquake occurrence, the pattern began to emerge suggesting the outlines of tectonic plates. An understanding of the general physics of earthquakes, starting in the early 1900s (Reid 1910), advanced the field of seismology to the point where seismologists were not only able to accurately pinpoint earthquake locations and estimate their depths but also use the record of first movement of a seismic wave to tell the direction of slip along a fault plane. It was this last form of interpretation that verified J. Tuzo Wilson's (1965) prediction of a new kind of fault found along the mid-ocean ridges—the transform fault—using seismic data (Sykes 1967).

It was this explanatory accuracy, problem-solving capability (Frankel 1987), and retrodictive power that helped lead to final acceptance of the idea of horizontal displacement of the continents (plates) by the vast majority of geologists, fully 60 years after Wegener first proposed it.

The controversy of what actually causes plate motion has not ended, however. There are those, however few, who continue to advocate for an expanding earth (Maxlow 2006; Wilson 2008). The mechanism for the driving of the plates came about once Wilson (1963) proposed shallow stationary "hot spot" plumes to explain the Hawaiian Islands chain. Then it was Morgan (1972) who took Arthur Holmes' (1928) shallow mantle convection model and combined it with Wilson's "hot spot" plume model and then extended them by proposing deep mantle material rising as narrow plumes and then sinking as broad tongues of cooler, denser material in the style of convection cells. Despite some limitations in this theory, it was simple enough (elegant) to garner the attention of many geologists as the explanation for plate motion, eclipsing other multiple working hypotheses (Glen 2005). Although there is consensus that some form of mantle convection is responsible for the lateral motion of the plates, the details of the nature of that convection and the role plates play in the surface expression of earth dynamics are still under much debate (Anderson and Natland 2005; Glen 2005).

It has been the controversies surrounding the development of this grand unifying theory of the earth that have been used by teachers teaching plate tectonics. Sawyer (2010) has used the seafloor data to engage his students in discovering plate boundaries. Paixão et al. (2004) used the controversy between drift and land bridges to engage her participants in discussion and argumentation. Duschl (1987) utilized different explanations for earthquakes to have students compare and contrast them and finally develop arguments for the most appropriate one. Pound (2007) utilized the theory of the hollow earth to engage her students in an activity of critical thinking. Dolphin (2009) utilized many different controversies and alternative models of earth dynamics to facilitate students' understanding of both earth dynamics and the critical evaluation of models. Though the use of these strategies is laudable, none of the experiences were approached in a manner to garner empirical data for gaining understanding of the efficacy of their use.

Another limitation of all of these examples is that though historical models were utilized in the class, it was usually done with the "right answer" in mind. There was no opportunity for the students to create a "wrong" model. In this way, students rationalize their reasoning to fit the conclusion rather than rationalizing data to create their own conclusion (Allchin 2002). A stronger approach in any of these strategies would be to allow students to explore the alternative models *prior to* knowing which model is the best fit. In this way, students utilize multiple working hypotheses, develop critical tests, and must determine the reliability of data as opposed to taking the "right answer" for granted and seeing how the data supports it and missing the scientific process altogether. Later in this chapter, we give an example of a possible approach to instruction using this controversy.

18.6 Biosphere: The Meteorite Impact Theory Explaining the Cretaceous–Paleogene Mass Extinction

On March 4, 2010, the following byline appeared in the popular science Internet site Science Daily:

> The Cretaceous-Tertiary mass extinction, which wiped out the dinosaurs and more than half of species on Earth, was caused by an asteroid colliding with Earth and not massive volcanic activity, according to a comprehensive review of all the available evidence, published in the journal Science. A panel of 41 international experts […] reviewed 20 years' worth of research to determine the cause of the Cretaceous-Tertiary extinction, which happened around 65 million years ago. (http://www.sciencedaily.com/releases/2010/03/100304142242.htm)

This pronouncement was based on an article published by Schulte and colleagues (2010) in one of the most important professional science journals in the world—*Science*. Similar bylines were carried by a broad number of newspapers, websites, and television news agencies around the world. It would seem that, at least to the popular media, the well-known controversy concerning the Cretaceous mass extinction was settled. However, is this true?

To understand this issue better, we briefly return to the 1980 article written by the Berkeley-based team of physicist (and Nobel laureate) L. Alvarez, his son and geologist W. Alvarez, and nuclear chemists F. Asaro and H. Michel (Alvarez et al. 1980) igniting the controversy. Their mass extinction proposal was motivated by their analysis of *unearthly* concentrations of the element iridium, within pencil thick clay layers at three separate locations around the world: (Gubbio) Italy, (Stevns Klint) Denmark, and (Woodside Creek) New Zealand. These layers were formed 65.5 Ma, at the time of the dinosaur extinction at the boundary between the Cretaceous and Paleogene periods (now designated K–Pg, but in the past as K–T). In the earth's crust, iridium is exceedingly rare (measured in parts per billion); however, these exposures showed iridium concentrations of about 30 (Italy), 160 (Denmark), and 20 times (New Zealand), respectively, above the background level at the time of the Cretaceous extinctions.

Based on this evidence the Alvarez group proposed that these anomalous layers were the remnants of a 10-km iridium-rich meteorite that impacted the earth at the end of the Cretaceous. This impact created a global dust cloud that blocked the sun (atmosphere effect) while chilling the planet so that photosynthesis was suppressed causing a collapse in the food chain (biosphere effect). The result was a mass extinction of 75 % of all oceanic animal species and all land animals greater than 20 kg in mass, including all of the (non-avian) dinosaurs.

In the first 14 years of research following this paper, some 2,500 articles and books were published concerning this extinction (Glen 1994a), and this number has easily doubled since then. Like most large-scale, earth science studies, this research brought into play a multidisciplinary and worldwide collaboration of scientists including paleontologists, sedimentologists, (geo)physicists, and (geo)chemists while prompting the development of ingenious experiments, field studies, and new instruments (such as the coincidence spectrometer) to test the varied lines of evidence undergirding this theory. Moreover, although the primary evidence collected to test this theory emanates from the geosphere and biosphere, it has grown exponentially to encompass all of the "spheres" composing the earth. It is truly a global research effort in more ways than one.

In this section we briefly review the evidence underlying this theory while contrasting it with rival mechanisms that have also been suggested for the extinction. This is a perfect HPS controversy that demonstrates the unique features of the earth sciences as a historical and interpretive discipline whose major goal is to reconstruct past phenomena.

From the beginning, the challenge was to locate the estimated 200 km (in diameter) crater, at the K–Pg boundary that was retrodicted by the Alvarez group. As Glen (1994a, p. 12) notes "such a crater, of course would be the smoking gun." An early candidate included the Manson structure in Iowa (Hartung and Anderson 1988), but its geologic composition, size, and radiometric age eventually ruled it out (Hartung and Anderson 1988; Officer and Drake 1989). Thus, the search turned to the Caribbean Basin due to the proposition raised by Bourgeois and colleagues (1988) that at sites near the Brazos River (Texas), an iridium anomaly and the K–Pg boundary usually overlie a sequence of layers that they suggested were deposited by a tsunami that was generated by an impact into the sea. Thus, in the late 1990s, the Chicxulub crater site at the tip of the Yucatan Peninsula in Mexico was suggested as the site of impact (Hildebrand and Penfield 1990; Kring and Boyton 1992); in fact, its discovery was rather serendipitous, dating back to an oil search in 1981, which even at that time, Penfield and Camargo (1981, as cited in Glen (1994a)) suggested as being the remnant of an impact crater.

In the following years, evidence mounted that it indeed was the impact site associated with the extinction. Cores drilled by two separate teams arrived at the same radiometric date of 65.5 Ma (Sharpton et al. 1992; Swisher et al. 1992); moreover, one of the team's (Sharpton) cores indicated an iridium anomaly. Finally, its location has been correlated with the worldwide *ejecta* distribution pattern, related to distance from the Chicxulub crater (Claeys et al. 2002; Smit 1999). Ejecta are materials emitted by the impact including spherules (formed by the rapid cooling of molten material thrown by the impact into the atmosphere), shocked quartz (which are indicative of extremely high impact pressures), and Ni-rich spinels (which are markers for cosmic bodies such as meteorites or asteroids) (Bohor 1990; Montanari et al. 1983).

From a philosophical perspective, the successful uncovering of such physical evidence fits perfectly within our previous discussion of the nature of the earth sciences. This evidence was not manipulated in a set of controlled experiments but was rather gathered by many insightful observations on a set of interrelated signs, exposed during a globally based fieldwork effort. Moreover, such evidence fulfills the all-important scientific function of providing testable, interpretable evidence that could be used to reconstruct a complex and contingent historical event of the past. Many of the previous purely biological hypotheses (such as disease or over-competition) did not leave behind such testable evidence. Moreover, such biological explanations cannot explain the global extinction patterns; consequently, they have been found wanting (Dingus and Rowe 1998). For this reason, many scientists have focused on physical mechanisms including tectonics, sea level, and climatic changes which also favor a gradual extinction pattern.

Especially with the advent of the stratigraphic evidence for impact, some of those opposed to impact coalesced around the hypothesis that massive volcanic eruptions, which occurred between 60 and 68 Ma centered on the Deccan Plateau in west-central India, caused the environmental collapse responsible for the Cretaceous extinctions (Glen 1994a). To satisfy its critics, volcanism must account for the K–Pg boundary evidence that was supposedly left by an impact (Glen 1994a), most notably the anomalous iridium deposits and shocked minerals. In the former case, using actualistic logic, a hallmark of the historical sciences, proponents were able to show that (at least some) modern volcanoes could draw up iridium from the earth's interior at concentration levels matching those found by the Alvarez group (Felitsyn and Vaganov 1988; Koeberl 1989). The latter case, involving shocked quartz, was more difficult to support because although this mineral associated with some volcanic deposits (Officer et al. 1987), its fracture patterns do not match those found associated with the K–Pg boundary (which were the result of high-energy impact). Thus, actualistic reasoning does not seem to support the volcanists' cause. It might be added that the Deccan traps were a nonexplosive type of volcano and so could not be the source of the shocked quartz. So, the volcanists would need to find alternative sites of volcanism to support their arguments, which would concurrently challenge the theory of impact.

As important as the physical geological features are, they are only evidence of impact; ultimately, this is a theory of extinction, which means that the fossil evidence must validate the fact that the impact is the source of the extinction; for even though many scientists accept both the evidence of impact and its timing, there was (and still is) disagreement about the impact as *the only* cause of the extinction. Thus, in analyzing the pattern, we need to divide the discussion into a set of multiple working hypotheses about extinction at the K–Pg boundary to include a gradual pattern (due to a possible combination of physical and biological factors), an "instantaneous" pattern[16] (caused by an impact or volcanism), and a stepwise pattern (possibly caused by multiple impacts). Concurrently, what is also fascinating about this debate is that it divides its supporters along disciplinary lines.

At least at the beginning of the debate, many earth scientists in general objected to impact. Most notable in their opposition were the paleontologists (*the* scientists who are professionally trained to reconstruct fossil life); they specifically objected to impact because the K–Pg boundary was not marked by an abrupt extinction event at the end of the Cretaceous; in other words if impact was the sole cause of extinction, there should have been no major change in the diversity of a group of organisms—such as the dinosaurs—during the Late Cretaceous (Glen 1994c; Ryan et al. 2001; Macleod et al. 1997). Instead, in their view, the fossil record favored a pattern of gradual extinction during the Late Cretaceous.

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[16] Instantaneous in terms of the massive span of geological time.

Such objections to an instantaneous, abrupt pattern are still strong among the paleontological community. In a letter sent to *Science* in response to Schulte and his associates (2010), a team of 23 scientists led by Archibald and his colleagues (2010, p. 973) argued that the review of Schulte et al. (2010) "has not stood up to the countless studies of how vertebrates and other terrestrial and marine organisms fared at the end of the Cretaceous. Patterns of extinction and survival were varied – pointing to multiple causes at this time."

Concurrently, Glen (1994b), drawing upon Pantin (1968), suggested that paleontologists objected to having what is in essence a biological phenomena—extinction—imposed upon them by magisterial authority of the "restricted sciences," i.e., sciences that emphasize the use of a small number of powerful laws in matters of great theoretical significance (such as physics). Such objections were reinforced by L. Alvarez's scathing opinion of paleontologists when he remarked in the *New York Times* (1.19.88) "they're really not very good scientists. They're more like stamp collectors."[17]

Indeed, this was not the first time that such disciplinary conflicts have occurred between physics and earth science. Physicist Lord Kelvin tried to impose a limited geological time scale on Darwinian evolution, and Sir Harold Jeffreys attacked the nascent understanding of continental drift, based on pure physical models, without ever considering the validity of the geological evidence (Dodick and Orion 2003). In these historical cases the magisters of physics ignored the methodological uniqueness of historical sciences; so too the paleontologists argued that L. Alvarez was also wrong in his interpretation. Partly trained in biology, paleontologists understand that like other historical events extinction is a complex, contingent phenomenon that cannot always be reduced to a single cause as Archibald and his colleagues (2010) intimated in their recent reply to Schulte his associates (2010).

Such disciplinary battles have even extended within the earth sciences. Geochemistry, planetary geology, and other more physically oriented branches of the earth sciences were more inclined at the beginning of this debate toward accepting impact (Glen 1994b). Even today, such divisions exist as Archibald and colleagues (2010, p. 973) criticized Schulte's (mostly) physical geological team because it did not include researchers "in the field of terrestrial vertebrates…as well as freshwater vertebrates and invertebrates." It might be added, however, that today most paleontologists accept the idea of impact as one of the extinction factors (along with marine regression, volcanic activity, and changes in climatic patterns), so the physical geologists and paleontologists have drawn somewhat closer together.

In the last half of the 1980s, as more scientists look at the K–Pg boundary layer, a third extinction pattern was suggested—stepwise mass extinction—in which

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[17] This critique of paleontology has antecedents in Ernst Rutherford's famous quote about science in general: "All science is either physics or stamp collecting." In his book, *Wonderful Life*, Gould (1989) makes a strong argument for the special nature of the historical sciences, such as paleontology, and their methods, as well the general value of epistemological diversity in the sciences. This argument eloquently recapitulates many of the points raised in our chapter in the section dealing with the nature of the earth sciences.

different kinds of organisms disappear within different layers before the end of the Cretaceous and the layer containing the iridium (Mount et al. 1986; Keller 1989). Correlated with this finding is the fact that in some localities, iridium is not restricted to the K–Pg boundary clay but appears to diminish gradually in concentration as one moves up or down from this layer (also termed "smeared anomalies"). Such evidence points to the possibility that multiple impacts were responsible for the extinction (Dingus and Rowe 1998). At the same time some of the volcanists have seized upon such stepwise patterns as supporting their claim, as it fits the major pulses of volcanic activity and associated environmental havoc resulting from periodic eruptions, which they claim happened in the Late Cretaceous.

Surprisingly, the earth science community also objected to impact because according to historian of science Glen (1994a) and paleontologist Gould (Glen 1994c), instantaneous global effects violate the understanding of one of geology's most important principles—uniformitarianism. Uniformitarianism has had many different interpretations over its history (Oldroyd 1996), but it would appear that the definition that many earth scientists adopted was the restrictive definition of Lyell (1880–1883), which assumed that in geology "no causes whatever have . . . ever acted but those now acting, and that they never acted with different degrees of energy from which they now exert" (Lyell 1881, vol. 2, p. 234). In other words actual causes were wholly adequate to explain the geological past not only in kind but also in degree (Rudwick 1998). Lyell based his uniformitarianism definition on Newton's use of the philosophical principle of vera causa in which only those processes operating today would be accepted as geological causes (Laudan 1987).

Lyell's adoption of Newton's vera causa was his philosophical response to geologists who invoked catastrophes as earth shaping forces. Lyell disapproved of catastrophes because they implied that geology relied upon unknown causes, which violated the principle of simplicity (i.e., the best scientific explanations are those that consist of the fewest assumptions). Lyell believed that the a priori application of uniformity (based on vera causa) was necessary, if geology, like physics, was to be considered a valid, logically based science (Baker 1998, 2000). However, the adoption of such restrictive principles is short sighted because it does not consider geology's unique defining characteristics, its historical interpretive nature, and indeed, during Lyell's time his definition of uniformitarianism was largely rejected, yet in the twentieth century, it influenced the thinking of many earth scientists (Dodick and Orion 2003). In simple terms, such scientists were trying to be more like physicists than the physicists in their application of this defining principle.

Today, the situation has changed. With mounting evidence, most earth scientists do accept the reality of an impact 65.5 Ma. However, the debate continues about whether it is the sole cause of the mass extinction or just one of its contributing factors. Thus, paleontologists continue their examination of the K–Pg boundary to more accurately delineate the extinction patterns on the biosphere. Similarly, sedimentologists, (geo)chemists, and (geo)physicists continue their mapping of the K–Pg layer to better understand its geology and the devastation an impact would have imparted upon the Cretaceous geosphere, hydrosphere, and atmosphere.

For those interested in earth science education, the debate surrounding the K–Pg extinctions is a perfect historical controversy that summarizes many of the most important features of the nature of the earth sciences as a unique branch of science. Concurrently, it shows how the human factor of philosophical and disciplinary prejudices shapes the actors in a debate, sometimes in spite of what the "objective" evidence says. Thus, this controversy deserves a place in any well-designed earth science curriculum.

18.7 Hydrosphere: Ocean and Atmosphere Coupling

The section that follows will discuss aspects of a coupled ocean/atmosphere phenomenon in the Pacific Ocean with dramatic effects on long-term weather all over the world. At first glance, it seems that when talking about El Niño and the Southern Oscillation (ENSO), one might not think of it as a controversial issue at all, but even in the late 1990s, many scientists in the fields of weather, climate, and oceanography still considered ENSO researchers as "renegades" (Cox 2002) when Ants Leetmaa successfully predicted and publically announced a major El Niño event to occur that year, along with predictions of severe long-term weather. The fact is there were many controversial issues needing resolution before ENSO could gain consensus as an explanation for aberrant, long-term global weather. It took almost 100 years of investigation to gain full consensus, including with the general population, from scientists' first awareness of a possible connection between a warm current off the west coast of South America and unusually mild or wet winters in parts of North America and Europe and drought conditions in Africa, India, and Australia.

As we have tried to demonstrate with each of the controversies highlighted within this chapter, the phenomenon of ENSO is one of global scale and has influence on all of the earth systems. Though El Niño is the name Peruvian and Ecuadorian natives gave to the occurrence of a warmer than normal current along the eastern margin of the Pacific Ocean basin, ENSO identifies a phenomenon that actually results from the *interaction* of the ocean and the atmosphere to create conditions that have a profound impact on the long-term weather and biota around the globe. To give an example of the scope of impact, Glantz (1996) listed these effects of the 1982–1983 El Niño event. There were droughts in Africa, India, and Central and parts of South America, to which 400 deaths and almost $7 billion (USD) in damages were attributed. At the same time, flooding in parts of Western Europe, South America, the USA, and Cuba were responsible for about 300 deaths, 600,000 people being displaced, and $5.5 billion in damages accumulating. Severe storms and tropical cyclones battered many of the islands in the Pacific from Hawaii to Polynesia, as well as large portions of the USA. Effects were also detrimental to the East Pacific fishing industry and to the nesting sites for 10s of millions of birds on Eastern Pacific Islands and the west coast of South America. Likewise, Philander (2004) noted that over 20,000 deaths; over 100,000,000 physically affected, including 5,000,000 displaced; and $33 billion in damages resulted from the 1997–1998 El Niño event. The phenomenon identified as ENSO is global; its impact, significant.

The story of ENSO is also one demonstrating the convergence of studies. In this case, studies focused on ocean circulation and on atmospheric circulation (i.e., it takes into account the hydro- and atmospheres). It was this dichotomy, atmospheric science versus oceanography, which played a role in the controversy, as our understanding of how the air and ocean interact to influence long-term global weather patterns. This included the theoretical pitting of the meteorologists (mainly American), who, as empiricists, utilized patterns observed in synoptic weather maps to form short-term weather predictions, against the forecasters (mainly from the European Bergen School of Meteorology) who utilized the physics of the atmosphere and computed weather forecasts, by hand at first but then by computer (Cox 2002). There were the philosophical differences in looking at the phenomenon. It made a difference whether one saw El Niño as a departure from the normal conditions or whether they saw it as a uniform cycle perturbed by outside, random conditions (Philander 2004). There was also the clash of personalities (Cushman 2004a). Jerome Namias looked to the north at the polar front and an atmospheric oscillation known as the Rossby wave to be the control of long-term weather around the world, while Jacob Bjerknes looked to the tropical pacific and the Southern Oscillation, first discovered by Gilbert Walker, as the main impetus for long-term weather variations.

A severe drought in India from 1877 to 1899 and ensuing famine caused the British government to send Gilbert Walker to India, in 1904, to become the head meteorologist and attempt to better forecast the monsoons than then current meteorologist, Sir John Eliot. Eliot's forecasts were descriptions upwards to 40 pages long … and mostly incorrect. Walker was an unlikely candidate for this position as he was trained as a statistician. However, he set to work recording weather conditions around the world. He noted some correlations among distant locations on earth. One of these was a "swaying" of the atmosphere in the tropics of the Pacific Ocean. When there was high pressure in the west, there was low pressure in the east. When it was high in the east, it was low in the west. He called this swaying the *Southern Oscillation*. He also found that observations of the weather in distant parts of the world correlated highly with this oscillating air over the Pacific Ocean. However, his findings did not impress many of the meteorologists of the time because they were strictly mathematical and therefore only descriptive. In other words, because Walker postulated only correlations and no explanation for the correlations, it made other meteorologists very skeptical of the findings. From the point of view of the meteorologists, Walker was not doing science in the conventional "make a hypothesis and then test it" way (Cox 2002). In essence, however, Walker *was* doing science, in an historic and interpretive sense. Paralleling what we described above, he looked at complex and preexisting entities to discern patterns and interpret them.

At approximately the same time, on the west coast of South America, a peculiar periodic warm current, years earlier named El Niño by Peruvian fishermen, became the focus of scientific inquiry (Cushman 2004b). *El Niño*, translated into English, means *little boy*, but when capitalized, it intimates *the Christ child*, or *Jesus Christ*. They gave this name because of the phenomenon's repeated occurrence around Christmastime. They identified this phenomenon because it brought with it disruptions in normal rainfall patterns as well as behavioral (including nesting and reproductive) patterns in fish and birds along the west coast of South America. Most considered El Niño to be a local phenomenon affecting only portions of South America and therefore did not warrant much attention. The phenomenon became very important to the USA after a strong El Niño event during 1925–1926 caused major disruptions in the US fishing industry in the Pacific. As Cushman (2004b) described in his book, the importance of business, colonialism, and national security has motivated intense study to modern times, into the connection between the ocean and the weather.

Robert Murphy, an ornithologist from the USA, noted the effects on the bird populations he was studying and proposed a connection between Walker's Southern Oscillation and the El Niño event he was experiencing. However, there was a great deal of doubt concerning the reliability of the data Murphy was using, as well as concerns about the connection between oceanic and atmospheric phenomena (Cushman 2004b). Then, through the 1930s and 1940s, interest in El Niño waned. Up until that time, US agricultural interests were wrapped up in Peru because the Peruvians were the world's largest producers of bird guano, much of which was exported to the USA as fertilizer for the growing agricultural industry. Bird nesting habits and therefore guano production were very much influenced by El Niño, but that became a nonissue with the development of man-made fertilizers (Glantz 1996). As the economic importance of guano production waned, so did the interest in studying El Niño.

It was not until post-WWII and the Cold War era that physical properties of the ocean again became of national interest and new studies began. The International Geophysical Year, 1957–1958, coincided with this renewed interest. Many countries began recording data with better equipment and with greater rigor than previously. National security and national self-interest through the US fishing industry precipitated a renewed interest in ocean and atmosphere dynamics. Jacob Bjerknes, son of famous meteorologist, Vilhelm Bjerknes, and creator of the cyclone model of mid-latitude weather, turned his attention to El Niño. He discerned a connection between the Southern Oscillation, what he identified as *Walker Circulation*, and the periodic warming of the tropical Pacific Ocean, known as El Niño. Bjerknes and others such as Jerome Namias, who earlier had helped model upper atmosphere oscillations known as the Rossby wave, echoed claims already made of the connection between the atmosphere and ocean and their affect on weather in distant parts of the world. Such cross-disciplinary studies—oceanography and meteorology—were conceptually new and as yet quite suspect from other scientists. Where Bjerknes looked to the Walker circulation in the tropical Pacific for an explanation of global, long-term weather, Namais looked instead to the mid-latitude polar front as the engine driving such phenomena (Cushman 2004b). The military became interested in developing new buoy technologies motivated by its need for defense against Russian nuclear submarines. As a side note, it was this same fervent interest in the ocean by the military that generated the JOIDES (Joint Institutions for Deep Earth Sampling) expeditions that were so instrumental in collecting the seafloor data later used in support of the theory of plate tectonics. With the international efforts to collect data, Bjerknes had the resources to connect El Niño with the Walker circulation (Southern Oscillation). The study of ENSO began at that point.

The mechanism discerned by Bjerknes to explain his observations was that in the Pacific, along the equatorial region, winds generally blow from the east across the basin to the west. This pushed the warm water to the west and allowed a rise of the thermocline, the thin layer of water separating warm, well-mixed upper-level water from the colder, less-mixed water below. This brought the cold water to the surface making the west coast of South America cool and dry. An El Niño event was identified when the easterlies were not so strong and warm water resided in the eastern parts of the Pacific Ocean basin. This warm water interrupted fish migrations. It was also responsible for warmer, moister regional weather which interrupted bird nesting behaviors. It also caused more rain along the western coasts of North and South America and affected long-term weather all through Africa, North America, and Europe, as noted above. Here again, as we have recounted in each of these sections, this phenomenon spans its impact into many realms of study from the physics of energy exchange between the air and the sea to the effects on life on earth. In essence, rather than being a derivative science, the geosciences are more a place for the practical application of understandings from the other disciplines.

The scientific community was still divided, however. There was skepticism in being able to mathematically model the weather. There was skepticism in the utility of cross-disciplinary investigation. They saw El Niño scientists as renegades (Cox 2002). There was skepticism that a local fluctuation in ocean surface temperature could explain worldwide weather. The idea gained traction, as the number of published articles related to El Niño doubled every five years from 1980 to 2005 (Philander 2004). What the public heard of El Niño and its effects through the 1980s and 1990s resulted in its conflation with other atmospheric hazards making the news at that time, namely, the hole in the ozone layer over Antarctica and threats of global warming. Many considered reports of El Niño as just another liberal, big government orchestration (Cox 2002), very much like that continuing to surround the issue of global climate change today.

It was not until 1997, when Ants Leetmaa, then director of the National Climate Prediction Center, declared on national news that he expected a very significant El Niño event. For the previous decade or so, the National Climate Prediction Center had been participating in and receiving data from the Tropical Ocean Global Atmosphere (TOGA) program. Leetmaa and others receiving these data noted a warming of the waters at a far faster pace than had been observed before. Guided by computer simulations, Leetmaa laid out a number of predictions of anomalous long-term weather conditions contingent on this warming, including heavy rains in Southern California and the rest of the Southern USA and a warmer than usual winter in the northeast of the country. He also talked of a more quiescent than normal hurricane season. Reception of Leetmaa's warnings was cool. Many thought that Leetmaa had overstepped the types of predictions ENSO scientists were able to make. El Niño became somewhat of a household name the following spring when these predictions came to pass.

In this sense, the concept of ENSO had an advantage in its explanatory power as well as its relatively short-term predictive capabilities over the other controversies noted in this chapter. Various computer models, an example of multiple working hypotheses, used initial conditions and projected outcomes into the future: an interpretation of how nature *will be* as opposed to the plate tectonics controversy or the dinosaur extinction controversy where events had already taken place and scientists were left to interpret the results of *past actions*. Similarly, there are many investigations looking into how to utilize effects of El Niño to interpret the extent of past El Niño events.[18] Leetmaa reported his predictions and everyone could be around to witness whether they came to pass or not. It was not an experiment in the sense that variables were controlled, but it had the feeling of an experiment because predictions were made and it was just a matter of waiting them out. This type of "natural experiment" is very characteristic of the historic sciences, like the earth sciences. In this case, the ENSO phenomenon happens on a scale of time that makes it possible to make predictions and see them borne out over several months. And the fact that the predictions were fulfilled gave strength to the models and gave rise to a general consensus within the scientific community as well as the general public concerning the validity of ENSO—the interaction between ocean and atmosphere—as a world weather controller. It also provided evidence supporting the use of computers to predict long-term weather.

18.8 Global Warming: A True Controversy?

Depending on the background of the reader, the title of this section should give pause. If we were to survey climate scientists, then the vast majority would agree with the primary conclusions of the Intergovernmental Panel on Climate Change (IPCC)[19] (IPCC 2007) which states that anthropogenic greenhouse gases have been responsible for most of the "unequivocal" warming of the earth's average global temperature over the second half of the twentieth century. In fact, in their extensive study of (1,372) climate researchers and their publications, Anderegg, Prall, Harold, and Schneider have shown that

> (i) 97–98 % of all of the climate researchers most actively publishing in the field [surveyed in their research] support the conclusions of the IPCC and (ii) the relative climate expertise and scientific prominence of the researchers unconvinced by anthropogenic climate change (**ACC**) are substantially below that of the convinced researchers. (Anderegg et al. 2010, p. 1207)

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[18] See, for instance, Galbraith et al. (2011), Khider et al. (2011), Nippert et al. (2010), and Romans (2008).

[19] Created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, IPCC's purpose is to evaluate the state of climate science as a basis for informed policy action, primarily on the basis of peer-reviewed and published scientific literature (Oreskes 2004).

Similar results were obtained by Doran and Zimmerman (2009) in their web survey of over 3,000 earth scientists, as well Oreskes's (2004) analysis of (928) abstracts dealing with climate change, published in refereed journals from 1993 to 2003. Finally, Powell (2011) on the *Skeptical Science* Internet site surveyed 118 of the best-known ACC skeptics. He found that 70 % of them have no (peer-reviewed) scientific publications that deny or cast substantial doubt on ACC. Moreover, none of their papers offers a "killer argument" falsifying human-caused global warming. The best they can do is claim that the measurement sensitivity of ACC is low, which they have been unable to substantiate and which much evidence contradicts (http://www.skepticalscience.com/Powell-projectPart2.html). So it would seem that at least among the majority of professional scientists who are most active in climate research, ACC is accepted as a (worrisome) trend that requires immediate response from nations around the world to ameliorate.

However, among the US public, the story is very different. In a recent Gallup poll, 51 % of its citizens expressed concern over ACC in 2011, compared to 65 % in 2007. Moreover, 52 % of the 2011 survey believed that the increase in the earth's temperature was due to pollution from human activities as opposed to 43 % who believed that it was due to natural changes in the environment. Just four years previously these figures stood at 61 % and 35 %, respectively (http://www.gallup.com/poll/146606/concerns-global-warming-stable-lower-levels). Clearly, much of the US public does not agree with the implications of much of the peer-reviewed research. Although not as severe, skepticism about ACC has also increased in the European Union, Canada, Australia, and New Zealand, based on surveys conducted in the last three years (Ratter et al. 2012). Thus, in the case of ACC, the public controversy is at odds with the much higher acceptance that this phenomenon has received among the majority of climate scientists, as well as their scientific colleagues within the wider earth science community.

One result of this controversy is that it impacts how students understand the workings of the atmosphere. In fact, ACC is a special subject because students face two challenges to their learning about it. First, like all other earth science topics discussed in this chapter, ACC is a complex scientific problem that is studied by a multidisciplinary, global team of climate scientists, oceanographers, atmospheric chemists, and geologists. Even in their early years at university, students do not usually have the broad background to understand this problem; adding to this problem is that they also hold large numbers of misconceptions about this and other atmospheric issues.[20]

Second, in order to understand ACC, students (like the general public) must overcome misinformation perpetuated by a smaller number of vocal, skeptical politicians and experts that are the source of the controversy (Theisen 2011). Relative to the much larger community of experts who have gathered strong evidence for ACC, the skeptics have a broad platform in the public media; this is due to the balance that

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[20] See, for instance, Gautier et al. (2006), Jeffries et al. (2001), Shepardson et al. (2011), and Theisen (2011).

the media gives to this issue—a balance which in fact diverges from the much greater acceptance this issue receives from professional scientists (Boykoff and Boykoff 2004). Indeed, in her study of students at the University of Vermont, Dupigny-Giroux (2010) found that most undergraduates cited some form of media as their primary information about climate, which in turn reinforces their misconception that a (balanced) controversy exists.

In this regard, ACC which is played out in the public eye differs from the other three controversies, presented in this chapter, which are largely debated among scientists and have had much less impact on the public. This controversy is less politically contrived than the false "controversy" that religious forces have presented in order to falsify evolution. However, as we will see, the roots of the ACC controversy also have political overtones, which are partly derived from the scientific background and motivations of some of its opponents, as well as the general economic situation which influences the publics' attitudes.

Thus, the question that we need to ask is as follows: If much of the scientific establishment supports ACC, how does such skepticism thrive? To answer this question we will (briefly) examine the history of the ACC idea. Concurrently, we will show that the ACC problem encompasses many of the unique features of the earth sciences. We believe that it is important for students to understand these historical and philosophical features of the ACC idea because it helps to explain the background behind the scientific and even political opposition.

The earth maintains a habitable temperature because of the natural greenhouse effect occurring in its atmosphere. Various atmospheric gases contribute to the greenhouse effect, whose impact in clear skies is 60 % from water vapor, 25 % from carbon dioxide, 8 % from ozone, and the rest from trace gases including methane and nitrous oxide (Karl and Trenberth 2003). Clouds also add to this greenhouse effect. On average, the energy from the sun received at the top of the earth's atmosphere amounts to 175 petawatts (PW = a quadrillion watts), of which 31 % is reflected by clouds and from the surface. The rest (120 PW) is absorbed by the atmosphere, land, or ocean and ultimately emitted back to space as infrared radiation (Karl and Trenberth 2003).

Since the early twentieth century, the average temperature of the earth's surface has increased about 0.8 °C, with about two-thirds of that increase occurring since 1980 (NRC 2011). Such global warming is caused by increasing concentrations of greenhouse gases produced by human activities such as deforestation and the burning of fossil fuels (NRC 2011). As such concentrations rise, they act to increase the opacity of the atmosphere to infrared radiation, trapping it in the atmosphere and raising the temperature of the planet.

The idea of ACC is not recent; indeed, the idea that changes in atmospheric greenhouse gas concentrations can and do cause significant climate changes was proposed qualitatively in 1864 by renowned physicist John Tyndall, when he discovered carbon dioxide's opacity to IR radiation (Sherwood 2011). In 1896 the future Nobel chemistry laureate Svante Arrhenius quantitatively predicted that such warming would be caused by coal burning; the prediction was tested and promoted by steam engineer Guy Callendar in the late 1930s (Sherwood 2011).

In the 1950s, the scientific debate focused on whether or not greenhouse gases were accumulating in the atmosphere and, if so, what affect this was having on global temperatures. Against the background of this debate, chemist David Keeling, from the Scripps Institute of Oceanography, sought to find out; in 1957, he set up an array of newly developed gas analyzers on Hawaii's Mauna Loa volcano to measure atmospheric levels of carbon dioxide. Keeling discovered two trends: first, he measured the average monthly value at 315 p.p.m (p.p.m. = parts per million). Keeling saw the values drop from May to September and then rise again into the next year. This cycle continued with decreases in the summer when plants soak up carbon dioxide and grow and increases in autumn and winter when plants are less biologically active (Smol 2012).

The second trend found by Keeling was that global carbon dioxide levels were rising annually from various human activities, creating a rising trend on the graph he constructed. Measurements that continue until the present demonstrate that atmospheric carbon dioxide concentration had risen to 394 p.p.m by June 2011. Moreover, the current carbon dioxide level far exceeds its natural fluctuation (180–300 p.p.m.) over the past 800,000 years. Scientists reconstructed this historical range by studying the planet's natural archives, represented by natural traces found in tree rings, the sediments of lakes and oceans, and ice cores (Smol 2012). Such proxy records combined with measurements of global temperatures today have shown that the world has warmed throughout the twentieth century. Models of such warming into the future suggest and predict that the earth will continue to warm into the future.

Climate scientist Steven Sherwood (2011) framed the historical development of the ACC idea by comparing it to some of the major paradigmatic shifts affecting physics. For example, Copernicus' published his model of the heliocentric universe in 1543. However, it was not until Kepler's calculations of 1609 (Gingerich 2011) and Galileo's observations in 1610 that provided the critical evidence to convert the top astronomers to the Copernican view. Nonetheless, acceptance among most scientists did not occur until the late seventeenth century, while the public at large remained opposed until the eighteenth century (Kuhn 1957). A similar pattern was seen in the fight for acceptance of Einstein's theory of general relativity (Sherwood 2011).

In the case of the heliocentric universe, a large source of public criticism was religion. As Gould (1987) and Freud before him noted, the invention of a heliocentric universe is one of seminal scientific discoveries as it displaced humans from the center of the universe, breaking their cosmological closeness to God. Such a view threatened the political power base of the Church which saw itself as the guardian of the human connection to God, and it is well recorded about the pressures that the Church brought to bear on scientists who supported Copernicus. In the case of Einstein, religious and political factors also affected the public debate against him and his theories, as anti-Semitic jibes and accusations of being a communist were thrown in his direction (Sherwood 2011).

In the case of global warming, politics is also a strong motivator of public skepticism. Gauchat (2012) has analyzed trends in public science in the USA from 1974 to 2010. He found that conservatives began this period with the highest trust in science, relative to liberals and moderates, and ended the period with the lowest; with regards to ACC, specifically, a decreasing number of conservatives doubt that it is occurring. Complicating the political situation are economic factors. In evaluating public opinion data from the USA, Scruggs and Bengali (2012) suggested that the decrease in belief about global climate change is likely driven by economic insecurity connected to the recent recession. A similar analysis of opinions from the European Union supports an economic explanation for changing public opinion.

However, such public skepticism does not explain the scientific skepticism for global warming. We have already seen that the peer-reviewed data overwhelmingly supports ACC and that the scientific skeptics largely do not come from the forefront of climate research. Therefore, we ask: why does such scientific skepticism survive and even thrive?

Sherwood (2011, p. 42) has argued that it is the very nature of global warming, as a scientific problem, that has created the skepticism among some scientists. He suggests that the heliocentric universe, general relativity, and global warming have all been scientifically opposed because of the "absence of a smoking gun or a bench top experiment that could prove any of them unambiguously." Moreover, he notes that what global warming shares with the other theories is: "its origins in the worked-out consequences of evident physical principles rather than direct observation." Such "bottom-up deduction is valued by physics perhaps more than by any other science," and many of the leading climate scientists were trained as physicists. Finally, he adds that global warming is based on "physical reasoning… rather than on extrapolating observed patterns of past behavior."

We agree with Sherwood's (2011) assessment that it is the misunderstanding of the scientific nature of the global warming problem that is one of the sources of its opposition. However, we do not think that this is connected to it being a strictly physics-based problem. In fact, the characteristics that Sherwood uses to define this problem also fit well within the structure of historical sciences (such as the earth sciences) that we mentioned earlier in this chapter. Most of the problems that the earth sciences tackle do not lend themselves to benchtop, controlled experiments nor direct observations, due to these sciences' massive scales, both in terms of space and time, as well as the large number of interacting variables that are impossible to replicate and control in the laboratory. Moreover, although some climate scientists certainly create multiple mathematical models, what we consider to be multiple working hypotheses, in order to predict the magnitude of future trends in global warming, others are using, as we have seen, evidence from the past such as ice cores and tree rings to reconstruct the past atmosphere. So there is a strong element of "history" in this research as well.

These arguments, concerning the nature of different sciences, are inadvertently supported by Oreskes and Conway (2010), in their book *Merchants of Doubt*. A main theme of this book is that a handful of politically conservative physicists in the USA, with strong ties to both industry and conservative think tanks (such as the George C. Marshall Institute), have challenged the scientific consensus on issues such as the dangers of smoking, the effects of acid rain, and the existence of ACC.

The authors charge that this has resulted in deliberate obfuscation of these issues which in turn has influenced public opinion and governmental policy.

Oreskes and Conway's (2010) main argument is about the deleterious effects of politically connected, powerful scientists on the government's environmental and health policy. However, it is interesting to note that they specifically identify Bill Nierenberg, Fred Seitz, and Fred Singer as the three physicists who were most prominent in leading the battle against ACC; Nierenberg and Seitz were part of the Manhattan (atomic bomb) project, whereas Singer developed earth observation satellites. In simple terms all three scientists came from branches of physics that more closely rely upon experimental, reductionist methods. Possibly, it is their scientific background which creates prejudice against the multidisciplinary, historical, and interpretive methods of global climate research. This, combined with their political histories as past cold warriors, who also represent conservative business and political interests, creates a synergistic effect to their skepticism against ACC.

There is no doubt that the political power and media connections of this much smaller group of scientific skeptics are strong. In the science education world, its influence has created confusion among (earth science) students. However, if Sherwood (2011) is correct about its historical progression, the science will eventually be accepted by both scientists and the public. The question that remains of course is how future generations will deal with our lack of action today.

18.9 Designing Curricula Utilizing HPS and the Controversies: Plate Tectonics as an Exemplar

We have given an outline of the development of scientific understanding of four different phenomena through the lens of the controversies surrounding each understanding. In this section, we would like to offer some possible direction for designing instruction that utilizes a modern theory of learning as well as the history and controversies surrounding the phenomena to promote, in students, useful understanding of content as well as aspects of the nature of science.

Researchers have discerned a pattern of learning encompassing the iterative process of developing a mental model of a phenomenon, deriving predictions from the model, testing the predictions, and finally, amending the original model to agree with the new data (Nersessian 2008) or generating, evaluating, and modifying the model (Clement 2009). By starting with this structure, an instructor can utilize historic models and data to encourage students to create their own models of a phenomenon, make predictions from the models, look at the historic data, and determine the usefulness of their models to make predictions. The instructor can also encourage model co-construction (Khan 2008), model evolution (Núñez-Oviedo et al. 2008), and model competition, disconfirmation, and accretion (Núñez-Oviedo and Clement 2008) through the use of personal models, class-generated models, and historic models.

We would start with fundamental concepts or big ideas. They can be garnered from the core disciplinary concepts of the NGSS (Achieve 2012) or one of the big ideas found in the Earth Science Literacy Principles (Earth Science Literacy Initiative 2010). Or, the instructor can discern his/her own fundamental concepts by using the discourse tools found at http://tools4teachingscience.org. For this example, we will use the concept of earth dynamics as it pertains to the theory of plate tectonics. We envision this fundamental concept or primary concept as an amalgam of six secondary concepts (volcanology, seismicity, oceans and continents, geomagnetism, the earth's internal structure, and radioactivity). Of course these are not the only secondary concepts that one could use, nor do they have to be these specific concepts. Finally, we discerned about three or four tertiary concepts from each secondary concept. Tertiary concepts are the learning objectives of individual lessons. For instance, for the secondary concept, "seismicity," possible tertiary concepts are "earthquakes," "elastic rebound theory," and "global seismicity patterns." These tertiary concepts are the foci or instruction using the original documents, data, historical narratives, and inquiry activities.

A brief outline of a possible approach to incorporating HPS and the content material within the structure of model-based learning follows. We would have students read two eyewitness accounts of the 1906 San Francisco earthquake: one by Jack London (1906) and William James (1911). As a follow-up to the readings, we would have students develop an initial mental model of an earthquake, based on their prior understanding and the content of the readings, by asking them what an earthquake is and what causes it. Model competition, model disconfirmation, and model evolution then take place through presentation and class discussion of mental models.

Following student work on their mental models, we would have them read excerpts of H. F. Reid's (1910) report and description of elastic rebound theory. Discussions about Reid's earlier work studying glaciers and how the behavior of glacial ice may have been his model for the behavior of rock could illuminate for students how prior experience can influence thinking about unrelated problems. Subsequent to this discussion, students would break into groups and participate in an activity utilizing the earthquake machine http://www.iris.edu/hq/resource/redefining_an_earthquake_v12, where they can gain an understanding of the nature of the storage and release of elastic energy, as well as the use, strengths, and limitations of models. With the understanding of an earthquake being a release of elastic energy built up in deformed rocks, students can utilize such computer visualizations as the US array record of such earthquake events as the 2011 event in Japan (http://www.youtube.com/watch?v=Kbc0ERoCD7s) and data storage sites such as Rapid Earthquake Viewer (http://rev.seis.sc.edu/) where they can develop a sense of energy released by an earthquake in the form of waves that travel through the earth and be observed by sensitive equipment.

Next, we would ask students about possible causes of earthquakes. Once they have developed their own models, we would have them read excerpts from or summaries of multiple historic models of earth dynamics. These would include Aristotle's porous earth (Şengör 2003), contracting earth (Malaise 1972; Schuchert 1932), continental displacement (Du Toit 1937; Wegener and Skerl 1924), and expanding earth (Carey 1976; Jordan 1971). Students would then, in small groups or whole class discussion, identify the strengths and limitations of the historic models alongside current student models for the cause of earthquakes. Again, we would have students be aware that models of earth dynamics were often dependent on the region used for delineating the model. Aristotle developed the porous earth model within the karstic topography of the Mediterranean. Seuss and Dana developed the contracting earth models during their work in the folded mountains of the Alps and the Appalachians, respectively. Wegener's experience with icebergs may have influenced his model for drifting continents through ocean crust.

Students should also be made aware of the controversies surrounding these models. One issue had to do with the idea that earth dynamics behaved mainly in a vertical direction (porous model and contraction model) versus deformation resulting from horizontal motion (continental displacement and expanding earth models). Other issues dealt mainly with issues surrounding the controversy between drift and permanence theories. Wegener and Du Toit pointed out the difficulties of contraction with the understanding of isostasy and that it could not explain fossil, geologic, and geographic similarities among widely separated continents. The "fixists," on the other hand, accused those in favor of displacement of not having an appropriate mechanism for moving continents, of deciding on their explanation and going in search of evidence to prove the explanation, and of not adhering to the philosophy of uniformitarianism.

We would ask students to use these models, in addition to student- or class-generated models, as multiple working hypotheses. They should determine the implications of each model, and then think of places they would look to find more data to test them. When someone directs attention to the ocean, some readings concerning the history of ocean exploration (Höhler 2003), Marie Tharp (Lawrence 2002, pp. 181–188) and Tharp's discovery of the mid-Atlantic ridge and rift system (Heezen et al. 1959), help students to understand the historical development of physical oceanography. Discussions of continued reticence for accepting drift, as well as the influence of World War II and breaking telephone cables as incentive for exploring the seafloor continue to develop the social and economic factors influencing the direction of scientific investigation. Then students can look at various kinds of seafloor data such as utilized in the "Discovering Plate Boundaries" activity (Sawyer 2010). Here students will look for relationships among patterns of sediment thickness, ocean crust age, bathymetry, and seismic and volcanic patterns. Using these data, students can test their models and the historical models to determine how they hold up to the data.

Then we would introduce students to explorations into paleomagnetic studies (polar wandering and magnetic reversals) and how it tied all the data together (Glen 1982) for those such as Hess (1962) and Vine and Matthews (1963). Finally, discussions into mantle convection, Wilson's prediction of transform faults (Wilson 1965), and the World Wide Synchronized Seismic Network should give students enough information to develop a model of earth dynamics very similar to the current scientific model. A key point throughout the entire instructional series is that the students are allowed to *develop their own model* of earth dynamics as opposed to rationalizing data and identifying "wrong" models because they already "know" the right answer. The questions we would ask are open for students to foster inquiry into the data and model building/testing/amending from the data. In this way, students experience "science in the making" (Conant 1947, p. 13) as opposed to finished science.

18.10 Conclusion

We have accomplished a few goals within this chapter. The first was to highlight the historical and interpretive nature of the geosciences as distinct from the experimental nature of physics and chemistry. All of the models developed by investigators have the purpose of explaining observations of effects of events that have already happened. In some cases, these explanations allow us to peer in the future, but not in any kind of controlled way. Phenomena (shifting plates, long-term weather, meteorite impacts) will proceed as they will and we can only witness them and measure them against our predictions. Second, we demonstrated the global nature of phenomena being investigated within the geosciences. Each of these topics has or has had fundamental effects within all spheres of earth systems and has had impacts that extend around the world. This is not to say the earth scientists do not study strictly local phenomena, but even these local phenomena can be traced back to global causes.

Third, was to demonstrate that it was often the convergence of multiple disciplines involved in independent investigations that led to the eventual development of reliable explanatory models of the phenomena in question. Within this framework, we also found that the interdisciplinary nature of many of the investigations gave rise to the controversies in the first place. This was often the case because the different disciplines operated under different philosophical constraints or followed different rules and politics. Especially relevant were issues surrounding the nature of nature. For instance, do phenomena happen based in uniformity (cyclic) or catastrophe (unidirectional)? In the case of continental displacement, the interpretation by some that it did not conform to uniformity as defined at the time may have delayed its acceptance. We also cited uniformity as an issue to accepting the bolide theory for explaining the extinction of the dinosaurs. Another example of a difference in philosophical stances toward nature was L. Alvarez's interpretation of the extinction event at the end of the Cretaceous. Alvarez, an experimental physicist, believed that impact was the cause of all of the mass extinction events in earth history. According to Gould (Glen 1994c) he sought a universal mechanism for mass extinctions. This approach differs from the historical sciences, which interpret natural phenomena, such as extinction, which are seen as complex and contingent, and dependent on a large series of often interacting factors. In other words, just because a meteorite impact caused a single mass extinction, it does not necessarily mean that all mass extinctions were caused by impact. History has shown that Alvarez's hypothesis of a universal mechanism was not correct.

Fourth, we showed the relationship between scientific advancement and technological advancement. Oftentimes, it was technological advancements responsible for gathering more accurate data and a refinement of methods that increased its reliability. For plate tectonics, it was more sensitive magnetometers, the advancements in seismic recording with the WWSSN, and the enhanced precision of radioactive age dating of rock. El Niño finally gained consensus through the collection of data with the large-scale deployment of better buoys and the strength of computers and models of the oceanic and atmospheric systems. Advancements in atmospheric carbon dioxide detection and atmosphere sampling protocols helped standardize readings leading to the conclusion that carbon dioxide levels in the atmosphere are, in fact, rising and that the carbon dioxide was anthropogenic. The Alvarez groups' development and use of the coincidence spectrometer allowed them to *quickly* analyze the possible iridium concentrations of a huge number of stratigraphic beds, allowing them to show that such beds were anomalous and were indeed the remnants of an extraterrestrial impact.

Fifth, we discussed how explanatory models gained consensus because they accounted best for the collected data. Plate tectonics gained consensus prior to our ability to measure plate movements directly via satellites, but now these measurements record actual displacement. For the ENSO phenomenon, meteorologists utilized computer models to successfully predict long-term weather patterns. For the dinosaur extinction event, the discovery of anomalous iridium layers and most importantly the Chicxulub crater both of which coincided with the end of the Cretaceous were the critical evidences that could only be accounted for by an extraterrestrial impact. Ice cores and tree rings have provided evidence of the greenhouse gas profiles of the earth's past; combined with measurements of present-day gas analyzers and the power of computer modeling, it is possible to predict future planetary warming trends.

A final point we would like to make has to do with the nature of controversy resolution. In analyzing the drift controversy, Frankel (1987, pp. 204–205) argued that "Closure of the controversy comes about when one side enjoys a recognized advantage in its ability to answer the relevant questions…when one side develops a solution that cannot be destroyed by its opponents." For the four controversies described here, we note the overwhelming ability of one model to explain the observations that allowed it to garner consensus from the scientific community. When discussing the *Great Devonian Controversy*, Rudwick (1985) asserted that it was one of the most important and influential controversies in the history of geology. Yet, he also claimed that the controversy is virtually unknown to geologists today. "The paradox has a simple explanation. The controversy has slipped out of sight for the good and adequate reason that the problems it raised were eventually resolved in a way that satisfied almost all participants" (p. xxi). Controversies surrounding the origin of oceans and continents, a meteorite impact causing a mass extinction occurring at the end of the Cretaceous period, and the interaction between the ocean and the atmosphere affecting weather around the world are all considered settled to the satisfaction of most of the interested parties. Where anthropogenic global climate change is no longer a controversial issue for those in climate science and indeed most of the scientific community, there continues to be a lag in consensus among much of the US population.

As we have intimated in the beginning of this chapter and as was evident throughout the discussion, there has been very little published concerning the incorporation of HPS into geoscience instruction. There are small pockets of those who continue to promote the efficacy of using cases as a pedagogical tool for teaching science (For examples, see http://sciencecases.lib.buffalo.edu/cs/, http://www1.umn.edu/ships/, http://www1.umn.edu/ships/, and http://hipstwiki.wetpaint.com/page/hipst+developed+cases). A survey of the three case repositories highlighted above (NCCSTS, SHiPS, and HiPST) shows that of the more than 500 cases housed in these three sites, both contemporary and historical, 24 are earth science related. There are six focused on global climate change. Only one of the 24 cases had any relevance to plate tectonics, and even then tectonics was treated as peripheral to the case. There were none focusing on El Niño nor were there any highlighting the dinosaur extinction controversy. A review of the use of case studies is outside the realm of this chapter, but suffice it to say that of the different types of cases available to use, the interrupted case (Herreid 2007) is probably the easiest to implement and still allows much control to the instructor. See Leaf (2011) for an example focusing on Keeling and the measurement of atmospheric CO2. We gave a brief structure to how one might utilize various activities, original documents, and historic and current data as a way to facilitate student model building for plate tectonics.

Aside from the few publications documenting HPS use as an instructional tool, there are even fewer empirical studies investigating the efficacy of such a tool. One possible avenue to remedy this situation is the development and use of historic case studies (Allchin 2011). This would require collaboration among historians and philosophers of science, geologists, and science educators to develop and test such curriculum materials for teaching.

The main point here is not only is there a need to create such tools for teaching that utilize the history and philosophy of science in instruction, but there is also a need for rigorous evaluation and publication in such journals as the *Journal of Geoscience Education* or *Science & Education.* This would give access to practitioners in the field who can further refine them, enhance their own teaching, and ultimately develop students' useful understanding.

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