Using a Historical Controversy to Teach Critical Thinking, the Meaning of "Theory", and the Status of Scientific Knowledge

Keith Montgomery[1]

ABSTRACT

It is important that students understand the "open-ended" nature of scientific knowledge and the correct relationship between facts and theory. One way this can be taught is to examine a past controversy in which the interpretation of facts was contested. The controversy discussed here, with suggestions for teaching, is "Expanding Earth *versus* Sea Floor Spreading." Although this was a short and limited controversy within the mainstream scientific community, it has the advantage of having primary sources that are accessible to students to read for themselves. What makes this controversy intriguing is the later conversion of one of the protagonists (Tuzo Wilson) to tectonics. The controversy is framed explicitly in terms of several criteria for agreeing on the optimal theory: it is an exercise in what has been termed "theory choice" by Thomas Kuhn. Framing the controversy in this way can teach students a great deal about the emergence of scientific theories as well as criteria that can be used to judge ideas in a mature fashion.

INTRODUCTION

Pre-instruction surveys of students reveal that "the majority of students view science as a static body of facts" (Kurdziel and Libarkin, 2002, p.326; also NRC, 1996 p.17; Miller, 2005). Yet, as citizens, students are faced with important and complex social and economic issues that often involve new developments in science and technology (e.g. alternative fuels and energy, bioengineering, climate change) or that entail controversial new proposals (e.g. teaching creationism in science classrooms). Instructors can help students gain the tools they need for making thoughtful and justifiable decisions by incorporating critical thinking skills into course materials (Nelson, 1989). In the long-run, practicing these skills across the curriculum may foster life-long learning and help create citizens who can contribute to society outside of their narrow sphere of disciplinary knowledge (University of Maryland, 2006). A possible immediate benefit of including critical thinking skills in science courses can be that "students actively develop their understanding of science by combining scientific knowledge with reasoning and thinking skills" (NRC, 1996, p.2).

Critical thinking consists of the analysis and evaluation of information and ideas, leading to a belief that one is capable of explaining and justifying rationally (Facione, 1990; Pascarella and Terenzini, 1991, p.32; Scriven and Paul, 2008). Dewey, who termed it "reflective thinking," defined it as the "active, persistent, and careful consideration of any belief or supposed form of knowledge in the light of the grounds that support it and the further consideration to which it tends" (Dewey, 1933, p.118).

Critical thinking requires knowledge of the subject matter under review and its methods might differ depending on the discipline; however, the attitudes and values that underlie critical thinking transcend divisions of knowledge. These attitudes and values include: a healthy, yet reasonable skepticism towards ideas; fair-mindedness and being open to reconsider one's "position;" and, trust in reason and a willingness to set aside emotion as a factor in judgment (University of Maryland, 2006).

Among the various published examples of critical thinking exercises in geology (Wells, 1989; Pinet, 1992; Guertin, 2000; Shea, 2000; Zen, 2001; Rankey, 2003; Taunton and Gunter, 2007), one model is to have students critically examine the validity of mythical and popular pseudo-scientific ideas in light of accepted scientific facts and theories (Soroka and Nelson, 1983; Tepper, 1999; Earle, 2003; Pound, 2007). In contrast, the exercise introduced here has students explore two different theories in mainstream science that were proposed as explanations of essentially the same facts (Expanding Earth *versus* Sea-Floor Spreading): an actual instance in which the interpretation of established facts was contested by two well-respected scientists, one of whom later changed sides. This paper therefore contributes a new type of case for this model of critical thinking exercise. This paper also contributes a set of specific criteria for, and a method of, conducting comparative evaluations like this. Both these criteria and this method can be used in other cases to help students understand how one theory gains acceptance over another in science (or, becomes a justifiable belief).

In addition to its value as a critical thinking exercise, the case studied here also very clearly exemplifies for students three key concepts that are a common source of confusion in recent debates about the status of scientific ideas (Gould, 1981):

- "Facts and theories are different things, not rungs in a hierarchy of increasing certainty;"
- "Facts are the world's data. Theories are structures of ideas that explain and interpret facts;"
- "Facts do not go away when scientists debate rival theories to explain them."

Some initial outcomes are also described but, like Earle (2003), because the class involved was small (18-24 students each spring, on a freshman-sophomore campus), the outcomes are descriptive rather than quantitative. However, this does not negate its value as a potentially useful and interesting example for this kind of pedagogy.

CHOOSING A HISTORICAL CONTROVERSY

There are many historical scientific controversies that

[1]Department of Geography and Geology, University of Wisconsin Marathon County, 518 South 7th. Ave., Wausau, WI 54401; keith.montgomery@uwc.edu

might be taught to illustrate debates about the interpretation of facts and the emergence of scientific theories. Example could include: Neptunism *versus* Plutonism (Porter, 1977); flood geology *versus* the glacial theory (Porter, 1977); Nineteenth Century controversy over the age of Earth (Burchfield, 1975); debate about the interior structure of Earth (Brush, 1979, 1980); the rejection of continental drift (van Waterschoot van der Gracht et al., 1928; Frankel, 1976); the Washington Scablands controversy (Magruder, 1998); the emergence of plate tectonics in general (Frankel, 1988); the K-T extinction (Alvarez, 1997); and, creationism and science (Rankey, 2003).

In choosing a controversy, it is best if students can read and judge the views of protagonists for themselves, and come to appreciate the reasons why one view came to be accepted over another. Kuhn (1977) suggests that controversies are best understood when we can be lead to see the facts through the eyes of contemporaries in the debate rather than judging the "wrong" views of the past from the perspective of the "correct" modern view. What is "obvious" today was not necessarily so in the past, when ideas were still developing: the debate over Wegener's "Continental Drift" makes this clear (van Waterschoot van der Gracht et al., 1928). However, in many, if not most cases, it is difficult to find concise, original statements at a suitable reading level that present each of the alternative views (an apparent limitation in the examples outlined by Earle, 2003, and Pound, 2007).

One interesting, accessible example of a controversy is the theory of "Expanding Earth" (EE) *versus* "Sea Floor Spreading" (SFS). These interpretations of newly available global data were explored by Tuzo Wilson (1960) and Robert Dietz (1961). [Note: Hess' version of sea-floor spreading, published in 1962, was first circulated in 1960 -- see Vine, 1977, p.21, and Frankel, 1988, p.127 -- however, Dietz's publication is shorter, more readable by undergraduates, and more easily available.]

In his 1960 paper Wilson examined "Earth Expansion" in light of "recent observations" from the ocean basins. He concluded that "the foregoing hypothesis [Earth Expansion] has the merit of appearing to explain many features of the Earth's surface" (p.882). Yet, in exactly the same way, in proposing spreading of the sea floor, Dietz concluded that "a novel concept of the evolution of continent and ocean basins has been suggested which seems to fit the 'facts' of marine geology" (p.857).

While others promoted "Earth Expansion" as a unifying global geological theory longer and more aggressively than Wilson (e.g. Carey, 1975), what makes Wilson's (1960) paper exemplary in this pedagogical context is his later conversion to tectonics: indeed, Wilson was one of the architects of tectonics (1963a, 1963b, 1965) and the idea of "supercycles" (1966).

This exercise focuses only on Wilson's expansionist interpretation and examines its consequences. If an instructor wishes, the ideas of other expansionists can be added in as the exercise in theory choice (below) progresses: Carey (1975) and Nunan (1988) present good reviews of later ideas.

There are a considerable number of WWW sites on the topic of EE: a Google search of "Expanding Earth" yields over 250,000 hits and there are some videos available (see http://www.youtube.com/watch?v=VjgidAICoQI for a place to start – in fact, carefully critiquing this video might be a good exercise in itself and a class might usefully produce a response). The theory today attracts a considerable "fringe" following of do-it-yourself theorists: for reasons that are not obvious, many of these theorists are vaguely catastrophist and religious. Other sites explain continental drift in yet other ways (Fischer, 2007).

This exercise can provide students with the tools necessary for critically evaluating web sites such as these as well as others. Instructors can decide for themselves if they wish to extend the exercise in this, possibly bewildering direction.

BACKGROUND: WILSON AND OTHER EXPANSIONISTS

"Expansionists" such as Carey (1975) and Owen (1983) argued that Pangaea covered the entirety of a much smaller Earth, and that very rapid (25%) expansion occurred in the past 250 million years. Wilson (1960), on the other hand, rejected the idea that the entire ocean basins had been created by expansion.

Unlike other expansionists, Wilson argued that the volume of expansion necessary to create the ocean basins in their entirety would be too great according to the most commonly accepted physical constraints: therefore, he limited the expansion to the creation of only the mid-ocean ridge areas and not the abyssal plains. In further contrast, Wilson argued that the creation of the MORs had taken all of geologic time "because there are no important abandoned ridges or any obvious way of disguising them" (p.880-881).

Among other difficulties, as students will discover, in limiting the volume and rate of expansion as he did, Wilson had some difficulty in explaining the parallelism of coastlines across the Atlantic (the fit of the continents) and he could not have gone on to explain the youth of the abyssal plains that later came to light.

Wilson, in a later exploration of new data (1961), suggested that both very slow expansion and sea-floor spreading could be happening together (as did Creer, 1965): he thought that this might explain Africa's situation, surrounded as it is by spreading zones. Without comment, Wilson (1963a, 1963b) then dropped expansion in favor of sea-floor spreading as an explanation of ocean island chains when the pattern of their ages in the Atlantic, at least, seemed to indicate that they had originated on the MOR and that the abyssal plains on which they sat were correspondingly youthful.

THE IDEAS OF WILSON AND DIETZ

Wilson (1960) first established that the idea of Earth Expansion is at least plausible based on some references in the physics literature to a possible decrease in the gravitational constant, and he quoted a rate of increase in Earth's circumference of 0.5 mm per year (p.880).

Wilson then proposed to examine the notion of expansion "in the light of recent oceanographic observations." He noted that "the mid-ocean ridges form a continuous, seismically active belt, extending through the Atlantic, Indian and North Pacific Oceans . . . a median rift valley . . . is a characteristic feature." He thought there were difficulties of scale if one believed that the entire oceanic crust had resulted from expansion, but "If, on the other hand, one postulates that only the mid-ocean and not the whole ocean basins have grown, the expansion would have been much less." He continued: "This would require an increase in the Earth's circumference of about 6 per cent, and the formation of the ridges has probably required all geological time because there are no important abandoned ridges or any obvious way of disguising them." And he concluded: "This does not prove that expansion of the Earth has occurred or if it has that it is due to a change in *G* [the Gravitational Constant], but it is worth considering some of the consequences of accepting that hypothesis."

Wilson then examined certain other observations and answers to open questions that might be a consequence of expansion, including: the centrality of many ridges and the general parallelism between them and the continental margins; heat flow data, from MOR at least; a possible mechanism for orogenesis, involving buckling of the rigid crustal shells; continental drift, to a limited extent (paleomagnetic data were a problem here); and a possible mechanism for major strike-slip faults including the San Andreas Fault (again due to buckling of crustal shells).

Wilson finally concluded that "the foregoing hypothesis has the merit of appearing to explain many features of the Earth's surface, though this does not constitute a proof."

Dietz's (1961) paper presents the now conventional explanation of sea floor topography. This paper is probably best read by students from p.855 onwards, starting at the section titled "Spreading sea floor theory." Like Wilson, Dietz also examines other implications, such as orogenesis on the leading edges of continents, continental drift, and the youthfulness of the ocean floor. Dietz recommended his theory because, "While the thought of a highly mobile sea floor may be seen as alarming at first, it does little violence to geological history" (p.856): For example, the theory requires no volumetric changes of Earth or the ocean basins, in contrast to Expanding Earth and older Contracting Earth theories.

CRITERIA FOR JUDGMENT

The controversy is framed explicitly in terms of several criteria through which the optimal theory might be agreed upon: it is an exercise in "theory choice" (Kuhn, 1977). These criteria are based on epistemic values commonly expressed within the scientific community, but they do not constitute an explicit, formal system of decision-making: there is no "algorithm" that computes the best choice (Kuhn, 1977, p.326). Students will have to learn that judgment is involved.

Going beyond the basic, underlying methodological assumptions of materialism, naturalism, and testability, the attributes of a good scientific theory can be said to include (Kuhn, 1977; McMullin, 1982):

1. Accuracy and unifying power: it must be inclusive of a broad range of observations and in agreement with these observations.
2. Internal consistency: it must be logical and not possess ad hoc elements.
3. External consistency: it must be in accord with other related theories.
4. Fertility: it can suggest new avenues for research and in the long run it can incorporate new facts as they become established.
5. Simplicity and Conventionality: it can accomplish the greatest synthesis with the least complexity and in the most conventional way using existing concepts and theories. [To some extent this attribute sums up 1-3.]

Donovan et al. (1988) present a more extensive, detailed set of criteria that have been applied by Nunan (1988) to aspects of "Expanding Earth," and this is a useful resource for instructors if further background to theory choice criteria is desired.

In addition to the evaluation described below, Expanding Earth theory failed another, critical test of its reality: the "common paleomagnetic meridian" test (Cox and Doell, 1961; Smith, 1978; Schmidt and Clark, 1980). However, the theory had already been largely abandoned by the scientific community for the reasons to be discovered by students in this exercise.

EVALUATING THE THEORIES AND THEORY CHOICE: APPLICATION

The exercise was implemented in an introductory physical geology course consisting of 3 hours of lecture and 4.4 hours of lab. The course is held in the spring semester, so almost all of the students had at least one semester of college-level work. Enrollment varies from 18-24 and the students are, for the most part, "traditional-aged" students. The campus is a freshman-sophomore "transfer" campus and generally none of the students enter with the intent of majoring in geology.

The "Expanding Earth" controversy should be introduced as an enrichment activity only after students have a basic understanding of Plate Tectonics -- in fact, it is also a good vehicle for review of what they know, which is an important, additional benefit. If instructors believe that the writing in Wilson's paper is too difficult, then Heezen (1960) might be substituted, but it is not a wholly original source and neither is it as comprehensive.

As argued, it is most desirable to have students read these sources for themselves, but an instructor may, of course, choose to present the expansionist view in her or his own words as lecture and then proceed with the exercise from that point.

I have students first read Dietz's paper and discuss it alone in the next class period. Dietz's paper is best read from p. 855 onwards and should not present any difficulties in comprehension as it is a review of ideas they are familiar with. I then assign the Wilson paper and in the next session of the class we discuss its ideas to ensure comprehension. We then proceed to the evaluation of the ideas.

Although Wilson's paper is only two pages long, I highlighted the passages I wanted students to pay particular attention to. There are some passages in the

TABLE 2. APPLICATION OF THEORY CHOICE CRITERIA (POSSIBLE RESPONSES BY THE AUTHOR)

1. ACCURACY AND UNIFYING POWER Give examples of data that are explained by one theory and not by the other.	Pangaea, fit of continents (not explained by Wilson's EE).
2. INTERNAL CONSISTENCY a. Note any examples of poor internal consistency.	Heat flow (two different explanations by Wilson).
b. Some "expansionists" accept the existence of Pangaea and its splitting since the Mesozoic. What are the implications of this in regards to consistency?	Why would expansion start in Mesozoic?
3. EXTERNAL CONSISTENCY a. Which theory has the better external consistency with respect to mechanism?	Neither at the time; but expansion insufficient (?).
b. Which theory has the better external consistency with respect to paleomagnetism?	Sea floor spreading: assumes simple, single pole (EE uses special explanation).
4. TESTABLE CONSEQUENCES/FERTILITY a. Which theory best accounts for Benioff Zones? Why are these a necessary consequence of sea floor spreading?	Dietz (not possible under expansion). Earth is finite size under SFS.
b. How fast is the Atlantic and Pacific floor moving? Which theory is the better "fit" for this data?	1.5 - 8.0cm. Sea floor spreading.
c. Which theory best accounts for the Hawaiian-Emperor chain?	In general, both equally, but EE insufficient rate.
d. Wilson argues that expansion accounts for only the oceanic crust that is associated with the MOR and that its generation has taken all of geologic time. • Why does he do this?	To limit expansion within physical limits.
• What does this mean for the age of the ocean crust of the abyssal plains?	It must be ancient.
• Is the ocean crust of the abyssal plains that old? What implications does this have for EE?	Not ancient. Failure of Wilson's version. Data requires full expansion.
e. Which theory best accounts for evidence of crustal shortening or continental collision?	Tectonics (not possible under expansion to same degree).
f. What are the implications for sea level change under either theory?	Continuous fall under EE. Data? Variable under SFS.
g. What implications are there for changes in the speed of rotation of Earth?	Slowing under EE. Data? Constant under SFS.
5. SIMPLICITY and CONVENTIONALITY a. Africa and Antarctica are surrounded by spreading centers; Africa is splitting. Which theory most simply accommodates this?	Expansion (tectonics requires shift in MOR).
b. How are "interior" mountains (such as the Appalachians or Urals) explained by tectonics? Is this consistent with the theory?	Drift over all geologic time. Yes, consistent (more or less uniformitarian).
c. See 3b.	
d. Which theory has the simpler, mechanism?	Sea floor spreading - more conventional, less "violent."

TABLE 3. QUESTIONS FOR FURTHER STUDENT ANALYSIS AND CONCLUSIONS [SELECTED STUDENT RESPONSES IN BRACKETS]

1. **Study the results, above.**
   a. **Which theory do you judge to be best?** [Sea-floor spreading]
   b. **Why?** ["SFS fits the facts better;" "Expansion is weird."]
   c. **Which criteria or facts are the most decisive in your opinion?** ["Benioff Zones;" "Age of abyssal plains;" "India colliding with Asia;" "The speed of movement."]

2. **On the basis of your work, explain your understanding of the relationship between facts and theories.**
   ["Theories explain facts;" "Facts make more sense when you have a theory."]

3. **Scientific ideas are subject to change.**
   a. **Why do you think Tuzo Wilson changed to tectonics?**
   ["Tectonics made more sense;" "He could explain more with tectonics."]
   b. **What contributions did he make to this theory in the 1960s?** ["Hot spots;" "San Andreas faults"]

4. **Are there any other observations you are aware of that might have bearing on the acceptability of one theory over another?**
   ["We can measure the size of Earth from space;" "Various things came up in the 1960s that could be explained by tectonics but not expansion."]

5. **Some expansionists believe that Earth has expanded much more (25%) and very rapidly (breaking up Pangaea) than Wilson was willing to accept. However, they have difficulty finding a mechanism (Carey 1975).**
   a. **How important is the lack of a mechanism?** ["Very important or else you can't explain how it works;" "You need something to make it work;" "Wegener didn't have a proper mechanism for his idea."]
   b. **Is it a violation of criteria #3?** ["?"]
   c. **Or is the lack of mechanism irrelevant to a theory, as Wegener's supporters claimed?**
   ["It's like DNA and Darwin;" "It's nice to have a mechanism - how things work."]

6.
   a. **Prior to Mathews and Vine's paleomagnetic dating of the ocean crust, some researchers argued that sea floor spreading was based on purely "circumstantial" evidence ("Geopoetry" as Hess put it). Is this a valid objection to accepting the idea? That is, do you actually have to see the motion to accept it as happening?** ["No one has seen the Earth's core;" "You can't see evolution but you know it's true."]
   b. **How might this apply to other ideas, such as the Ice Age, or the interior structure of Earth, or evolution?**
   ["You can understand them better;" "It's no different."]
   c. **What role do the theory-choice criteria have in helping you decide?**
   ["It's nice to have some things to think about to help you decide."]

TABLE 4. SOME TEST RESULTS

"How would you answer the accusation, made by some religious groups, that historical theories such as the ice age are inherently weak because no one actually observed the events or changes in question?"

- "Just because one did not observe events doesn't mean there is not evidence that they happened. Nobody has ever seen the big bang, the inside of the Earth, or the inside of the Sun. However there is compelling evidence for each of these about what really happened or is happening. Glaciation is based on the idea that processes remain generally the same over time. As such, we can assume that glaciation caused these features and deposits because there is nothing else that could have."
- "I would counter the accusation, made by some religious groups, that historical theories such as this are weak . . . by turning their question around on them. I would ask if they had a different hypothesis that made sense."
- "Massive ice sheets laid and scraped layers of sediments and created formations and periods of erosion that can not be explained by the concept of the biblical flood, which no one observed either . . . I would have to consider the Ice Age an inferred fact due to its better explanatory qualities than other concepts."
- "[Agassiz] hypothesized that great ice age had extensive and far-reaching effects . . . This implies using the theory of uniformitarianism, or realizing that certain features are produced by no other known processes but glacial action. They could reconstruct the extent of the old ice sheets, based on the present features in the landscape . . . It offered a more compelling explanation than the catastrophic flood . . . it explained the structures in the land that we see today in such a way that no other theory could."
- ". . . the religious groups can say that you need proof of someone seeing the event, but this doesn't hold true. Who witnessed the creation in the first 7 days although religious groups still believe this story? We have compelling evidence that a glacial environment created these landforms . . . even if they disagree, can they offer a reason for this landscape? We can use one theory to make sense of multiple things such as deposits, misfit streams, glacial landforms . . . this is the same as plate tectonics . . . this one theory explains so many things it would be ridiculous not to accept it."
- "The glacial theory is so compelling because the evidence fits the theory so well. His theory can wrap all 3 ideas into one and explain them all [geologic, geochemical, and biologic data], and when a theory can do that, it does it all. It can be compared in magnitude to the tectonics theory. I would say to religious groups that they never saw the god they worship but they still give money every week to somebody. All the evidence that scientists have found in regards to glaciation seem to identify most land as once being covered by mass amounts of ice . . . I would ask them to defend their discrediting remarks and have them show me their evidence that it did not happen. I have a tough time wrapping my mind around the idea, but after seeing the evidence I firmly believe in the idea of glaciation."
- ". . . as far as the argument goes that the glacial theory is weak because no one witnessed these occurrences, I believe that the same can be said about instances in the bible. They might argue that the bible is a written account of the happenings of their religion, but then a geologist can argue that the land forms of earth are the written text of the happenings of natural events on earth. One can read the bible and that Adam ate the apple after Eve who was convinced by the snake said he could. But at the same time one can look at a bumpy kettle moraine landscape and see the obvious signs of a departing glacier's impact on the land."
- "We can observe glacial processes in our own world today and find that they create the same formations and earthy materials just as we suppose they did 17,000 years ago."

SOME OUTCOMES

Written surveys and questionnaires designed to ascertain students' knowledge of, and attitudes towards, science and scientific knowledge (e.g. Abd-El-Khalick et al., 1998; Kurdziel and Libarkin, 2002) are problematic in such a small class (e.g. Earle, 2003). Many responses did reveal a low appreciation of the nature of scientific knowledge, consistent with other sources cited in the introduction: "knowledge" consisted of the facts I was about to teach them, and there was little understanding of the process through which knowledge - at least at the level of theory - emerges in science. While it would have been interesting to follow-up on some individual responses, this was not possible because individuals could not be identified. One thing was obvious: the exercise produced spirited discussion and involvement with the ideas in ways that are often absent in class discussions of pure scientific ideas.

As a limited test of the success of this method, at the end of the semester in which this controversy was used, I posed a question on the final exam as a test of student's abilities to think about ideas critically -- but a question that was not an obvious application of the method: "How would you answer the accusation, made by some religious groups, that historical theories such as the Ice Age are inherently weak because no one actually observed the events or changes in question?" This question was obliquely directed at the on-going entanglement of science and religion.

A representative selection of responses is provided in Table 4. These are very encouraging (and surprisingly hard-hitting): students seem to apply quite readily theory choice as well as the principle of uniformitarianism.

CONCLUSIONS

Further research in a larger class setting is needed to validate the subjective conclusion that this kind of approach to improving students' sense of the nature of science is profitable. The full approach requires two class periods that could be otherwise used for "content," so a trade-off is necessary.

However, in the course, in addition to the EE - SFS controversy, I also applied selected theory choice criteria less formally in other instances. For example, students were asked to use some of the criteria to address the status of knowledge of the interior structure of Earth (e.g. "Why should we accept that the outer core is liquid?" "What kind of knowledge is this?"). And, they were asked to consider the accumulation of independent lines of evidence over the past 170 years for Pleistocene glaciation, and how these strengthen the case compared to flood geology. Students can be lead to see that, in general, "Successful scientific theories synthesize a vast variety of seemingly unrelated facts whose truth is known prior to their invention. But they are [also] able to account for . . . facts whose truth is unknown prior to the formulation of the theory" (Frankel, 1979, p.337). There is clear potential to apply the method to other studies in a less formal manner, if desired: making "theory choice" criteria explicit need not always require a trade-off with traditional content.

Mature or critical thinking is not something that comes naturally to all students (Perry, 1970), but it is a necessary skill in a complex and inter-connected world. Although the class size was small in this case and did not permit quantitative reporting, this exercise in theory choice appears to have potential for providing students a greater understanding of the nature of scientific knowledge and judgment, and a framework for critical thinking concerning debates about theories.

REFERENCES

Abd-El-Khalick, F., Bell, R.L., and Lederman, N.G., 1998, The nature of science and instructional practice: Making the unnatural natural: Science Education, v. 82, p. 417-436.

Alvarez, W., 1997, T. Rex and the crater of doom: Princeton, N.J., Princeton University Press, 185 p.

Brush, S.G., 1979, Nineteenth-Century Debates about the Inside of the Earth: Solid, Liquid or Gas? Annals of Science, v. 36, p. 225-254.

Brush, S.G., 1980, Discovery of the Earth's Core: American Journal of Physics, v. 48, p. 705-24.

Burchfield, J.D., 1975, Lord Kelvin and the age of the Earth: London, McMillan, 260 p.

Carey, S. W., 1975, The Expanding Earth - an Essay Review: Earth Science Reviews, v. 11, p. 105-143.

Cox, A., and Doell, V.R., 1961, Palaeomagnetic Evidence Relevant to a Change in the Earth's Radius: Nature, v. 189, p. 45-47.

Creer, K.M., 1965, An Expanding Earth? Nature: v. 205, p. 539 - 544.

Dietz, R.S., 1961, Continent and ocean basin evolution by spreading of the sea floor: Nature, v. 190 p. 854-857.

Dewey, J., 1933, How We Think. A restatement of the relation of reflective thinking to the educative process: Boston, D. C. Heath, 301 p.

Donovan, A., Laudan L., and Laudan R., editors, 1988, Scrutinizing science. Empirical studies of scientific change: Baltimore, The Johns Hopkins University Press, 393 p.

Earle, S., 2003, Project Atlantis- an exercise in the application of earth science to a critical examination of a pseudoscience hypothesis: Journal of Geoscience Education, v. 51, p. 290-293.

Facione, P.A. 1990, Critical thinking: a statement of expert consensus for purposes of educational assessment and instruction, executive summary ("The Delphi Report"): Millbrae CA, The California Academic Press, 20 p. [Online: http://www.insightassessment.com/pdf_files/Dexadobe.pdf (14 January, 2009)]

Fischer, J.M., 2007, Shock dynamics: A new geology theory featuring impact-powered rapid continental drift as an alternative to plate tectonics -- The key to creation geology: http://www.newgeology.us/ (14 January, 2009).

Frankel, H., 1976, Alfred Wegener and the Specialists: Centaurus, v. 20, p. 305-324.

Frankel, H., 1988, From continental drift to plate tectonics: Nature, v. 355, p. 127-130.

Gould, S.J., 1981, Evolution as Fact and Theory: Discover, v. 2, p. 34-37.

Guertin, L., 2000, Using logic problems in introductory-level geoscience courses to develop critical reasoning and basic quantitative skills: Journal of Geoscience Education, v. 48, p. 423-427.

Heezen, B.C., 1960, The rift in the ocean floor: Scientific American, v. 203, p. 98-110.

Hess, H., 1962, History of ocean basins, *in* Engel, A. E. J., H. L. James, and Leonard, B. F., eds., Petrologic Studies: A

Volume in Honor of A. F. Buddington: New York, Geological Society of America, p. 599-620.

Kuhn, T.S., 1977, Objectivity, value judgment, and theory choice, in Kuhn, T.S., ed., The essential tension: Chicago, The University of Chicago Press, p. 320-339.

Kurdziel J.P., and Libarkin, J.C., 2002, Research methodologies in Science Education: Students' ideas about the nature of science: Journal of Geoscience Education, v. 50, p. 322-329.

Magruder, K., 1998, Great scablands: http://homepage.mac.com/kvmagruder/earth/dwg/scablands.htm (14 January, 2009).

McMullin, E., 1982, Values in science: Philosophy of Science Association, v. 2, p. 2-28.

Miller, Keith, 2005, Understanding the nature of science: A critical part of the public acceptance of evolution: Geological Society of America Abstracts with Programs, v. 37(7), p. 21.

National Research Council (NRC), 1996, National Science Education Standards: Washington DC, National Academy Press, 272 p. [Online: http://www.nap.edu/html/nses/ (14 January, 2009)]

Nelson, C.E., 1989, Skewered on the unicorn's horn: The illusion of a tragic tradeoff between content and critical thinking in the teaching of science, *in* Crowe, L.W., ed., Enhancing critical thinking in the sciences: Washington D.C., Society of College Science Teachers, National Science Teachers Association, p.17-27.

Nunan, R., 1988, The theory of an expanding earth and the acceptability of guiding assumptions, *in* Donovan, A., Laudan L., and Laudan R., eds., Scrutinizing science: empirical studies of scientific change: Baltimore, The Johns Hopkins University Press, p. 289-314.

Owen H.G., 1983, Constant dimensions or an expanding Earth? *in* Cocks, L.R.M., ed., The Evolving Earth: London, British Museum (Natural History), p. 179-192.

Pascarella, P. T., and Terenzini, E. T., 1991, How college affects students: San Francisco, Jossey-Bass, 920 p.

Perry Jr., W.G., 1970, Forms of Ethical and Intellectual Development in the College Years: A Scheme: New York, Holt, Rinehart, and Winston, 336 p.

Pinet, P.R., 1992, A primer on teaching higher-order thinking in introductory geology course: Journal of Geoscience Education, v. 40, p.293-301.

Porter, R., 1977, The making of geology: earth science in Britain, 1660-1815: New York, Cambridge University Press, 288 p.

Pound, K.S., 2007, Use of the 'hollow earth theory' to teach students how to critically evaluate theories: Geological Society of America Abstracts with Programs, Vol. 39, No. 3, p. 17.

Rankey, E., 2003, The use of critical thinking skills for teaching evolution in an introductory historical geology course: Journal of Geoscience Education, v. 51, p. 304-308.

Schmidt, P.W., and Clark D.A., 1980, The response of palaeomagnetic data to Earth expansion: Geophysical Journal International, v. 61, p. 95–100.

Scriven, M., and Paul, R., 2008, Defining critical thinking: http://www.criticalthinking.org/aboutCT/definingCT.cfm (14 January, 2009).

Shea, J.H., 2000, Having students determine whether the Earth is only ten thousand or at least several billion years old: Journal of Geoscience Education, v. 48, p. 584.

Smith, P.J., 1978, The end of the expanding earth hypothesis? Nature, v. 271, p. 301-321.

Soroka, L. G., and Nelson, C. L., 1983, Physical constraints on the Noachian Deluge: Journal of Geological Education, v. 31, p. 135-139

Taunton, A., and Gunter, M., 2007, Introducing medical geology to undergraduates as a critical thinking and risk assessment tool, Journal of Geoscience Education: v. 55, p. 169-180.

Tepper, J.H., 1999, Connecting geology, history, and the classics through a course in geomythology: Journal of Geoscience Education, v. 47, p. 221-226.

University of Maryland University College, 2006, Critical thinking as a core academic skill: a review of literature: Adelphi, Maryland, University of Maryland Office of Outcomes Assessment, 19 p. [Online: http://www.umuc.edu/outcomes/pdfs/CRITICAL%20THINKING%20LITERATURE%20REVIEW.pdf (14 January, 2009]

van Waterschoot van der Gracht, W.A.J.M., Willis, B., Chamberlin, R.T., Joly, J., Molengraaff, M., Gregory, J.W., Wegener, A., Schuchert, C., Longwell, C.R., Taylor, F.B., Bowie, W., White, D., Singewald Jr., T., and Berry, E.W., 1928, Theory of continental drift: a symposium on the origin and movement of land masses both inter-continental and intra-continental, as proposed by Alfred Wegener: Tulsa, Oklahoma, The American Association of Petroleum Geologists, 240 p.

Vine, F.J., 1977, The continental drift debate: Nature, v. 266, p. 19 -22.

Wells, N.A., 1989 Using the illogic of creationism to teach the logic of science: Journal of Geoscience Education, v. 37, p. 317-320.

Wilson, J.T., 1960, Some Consequences of Expansion of the Earth: Nature, v. 185, p. 880-882.

Wilson, J.T., 1961, Reply (Continental and Oceanic Differentiation): Nature, v. 192, p. 125 - 128.

Wilson, J. T., 1963a, A possible origin of the Hawaiian Islands: Canadian Journal of Physics, v. 41, p. 863-670.

Wilson, J.T., 1963b, Evidence from Islands on the Spreading of Ocean Floors: Nature, v. 197, p.536-538.

Wilson, J. T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, p. 343-347.

Wilson, J. T., 1966, Did the Atlantic close and then re-open? Nature, v. 211, p. 676-681.

Zen, E., 2001, What is deep time and why should anyone care? Journal of Geoscience Education v. 49(1), p. 5-9.