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Geology as an Historical Science: Its Perception within Science and the Education System

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Abstract. For much of the 20th century, geology has largely been ignored as a pre-college science subject in many English-speaking nations. In this paper, we examine some of the historical based influences which have affected its status within the educational system. A key factor is that as a science, geology has sometimes been treated as being derived from physics. This is supported by episodes in which geology and physics have interacted. Thus, in the late 19th century, many geologists accepted Lord Kelvin's restricted calculation of the earth's age even though the fossil record spoke differently. More disturbing, are events in which geologists have attempted to replicate physics' methodology. Thus, Charles Lyell defined the principle of uniformitarianism on the basis of Newton's 'Vera Causa' in which only those processes operating today would be accepted as geological causes. Lyell believed that uniformitarianism had to be defined as such, if geology, like physics was to be considered a valid, logically based science. However, the adoption of such restrictive principles is short sighted because it does not consider geology's unique defining characteristics, its historical interpretive nature. These characteristics complement the physical sciences, and also provide students with another route to scientific literacy, a major goal of Project 2061. The environmental crisis, with its large collection of interconnected variables, emphasizes that the systemic methodology of the earth sciences has much to contribute in the future to both science and education, specifically, and the welfare of the planet, generally.

Introduction

In the history of science, there have been a series of 'revolutions' which have greatly influenced man's understanding of his place in the universe (Gould 1987). These revolutions mark the beginnings of modern science because they removed God as a causal agent in nature. They include the Copernican-Galilean redefinition of the universe, in which the earth was displaced from the centre of the solar system, as well as the Darwinian revolution, which recast man as an evolved species, amongst many evolved species. Amongst these revolutions, the least frequently mentioned within the history of science is the discovery of 'deep time', the understanding that man's earthly dominion is confined to the last tick of the metaphorical geologic clock.

There are many reasons why the temporal revolution of the earth sciences has been, for the most part, neglected. Geology is often thought to have many practical and theoretical limitations which 'undercut its claim to knowledge' (Frodeman 1995, p. 960). Such problems include incompleteness of the stratigraphic and fossil records; lack of experimental verification; and the nature of 'deep time' itself, which precludes direct observation (Frodeman 1995, 2000).

However, the main reason for this neglect is related to the fact that geology has often been portrayed as a 'derivative' science whose methodology and logic were provided by the physical sciences (Bucher 1941; Schumm 1991). Indeed, most contemporary philosophers and historians of science have chosen physics as their model of science (Greene 1985; Frodeman 1995; Baker 1996; Mayr 1997). A survey of the major journals concerned with philosophy and history of science lends credence to this argument. It is only in the last twenty years that this lack of historical inquiry has been redressed, but as Frodeman (1995) argues much of this work still accepts the image of geology as a derivative science.

This paper will explore the roots of this 'derivative' label by presenting key episodes from the history of geology, in which this science was reconstituted in the image of the physical sciences, not only by practitioners of physics, but oddly enough by geologists themselves. Concurrently, we see how this philosophical bias is sometimes paralleled within the educational system. For the most part, geology is poorly represented within the current science curriculum of most English speaking nations, especially when compared to the exposure given to the other scientific fields. By neglecting this discipline, we argue that educators inadvertently deprive students of a unique system of scientific thinking which addresses many of this world's most pressing (environmental) problems.

Disciplinary Conflicts: Geology Meets Physics

The impression of geology as a derivative science has sometimes been reinforced by episodes in which geology and physics have interacted. For this discussion, we turn our attention to one of the defining episodes in the earth sciences, the debate over the measurement of 'deep time'.

By the middle of the 19th century, geologists had succeeded in classifying and ordering many of the most important fossiliferous strata, which combined together, allowed the creation of a primitive geological time scale. The sheer magnitude of this scale produced an 'inescapable impression of vistas of time stretching far beyond the scope of human history' (Burchfield 1998, p. 139). However, even though the concept of deep time was now accepted by a growing segment of the public, it had not changed fundamentally, since its formulation by the geologist James Hutton in the mid 18th century, because it 'had no definable magnitude. It lacked measure' (Burchfield 1998, p. 140).

In an attack on the concept of geological time as a vast entity, physicist William Thomson, the future Lord Kelvin, provided the first scientifically accepted calculation of the earth's age. As will be seen, Kelvin's calculation not only subordinated geological time to physics, it also caused serious reassessment of Darwin's interpretation of the theory of evolution. More importantly, it reinforced the image of physics hegemony over geology.

Ironically, Kelvin's attack on 'deep time' was precipitated by Charles Darwin himself. 'Deep time' was a key element of the theory of natural selection, because slow, gradual biological change, which might transform the earth's biota, could only operate through the immensity of geological time (Burchfield 1974). Thus it was important for Darwin that he provide evidence of the vastness of deep time. Unfortunately, rather than basing his argument on a meticulous compilation of evidence, as he had done when discussing Natural Selection, Darwin instead provided one simple example of 'deep time's' passage from a familiar source. In the first edition of *On the Origin of the Species*, Darwin provided a quick calculation, in which he estimated that the marine erosion, which had worn down the Weald Valley (in southern England), had taken some 300 million years to complete (Darwin 1859). Obviously, if this was the age of one valley in England, then undoubtedly the earth was immensely old.

In response, Kelvin apprised of Darwin's calculation, published two short papers in 1862, which provided an age for the earth. To derive this age, Kelvin calculated how long the earth took to cool from its original molten state, based on the Second Law of Thermodynamics. He checked this calculation against figures which accounted for heat from the sun, and tidal friction. Such calculations pointed to a maximum age of no more than 400 million years (Burchfield 1974, 1975, 1998). Later corrections by Kelvin, as well as other scientists of the same period limited this figure to as little as 10 million years (Burchfield 1975, 1998).

Based on his calculations, Kelvin marshalled a two-pronged attack against Darwin. The first relied on the inaccuracies of Darwin's simplistic calculation. Darwin had regretted his remarks about the Weald Valley since he had first published them and had already begun the process of changing it in the second edition of *On the Origin of the Species*. The second part of Kelvin's attack was broader, criticizing as it did the doctrine of uniformity. According to the Second Law of Thermodynamics, all transformations of energy must dissipate a part of that energy and render it useless for further transformations. Translated to the geological plane, this meant that the earth, cooling as it was from its original molten state, must have been running down so that present geological forces must be less powerful and less violent than in the past. The present rate of geological change could therefore not be used as a guide to the age of the world, as many geologists argued.

A close reading of Kelvin's attack shows its inherent flaws. Although justified in attacking Darwin's calculation, Kelvin's argument against the doctrine of uniformity is somewhat hollow. In fact, Kelvin was specifically criticizing Charles Lyell's steady state interpretation of uniformity. However by 1860s the majority of geologists did not themselves support Lyell's (rather unique) interpretation of uniformity (Rudwick 1976; Burchfield 1998), as we shall see.

More importantly, Kelvin's arguments were entirely based on evidence derived from physics; they almost completely ignored the geological evidence for 'deep time', including the fossiliferous strata that are a crucial part of most present day geo-chronological studies. This was based (somewhat arrogantly) on the assumption that physical-mathematical arguments were more important than geological evidence.

With historical hindsight, it is now known that Kelvin's assumptions about the sources of the earth's heat were wrong. The discovery in 1901 of naturally occurring radioactive materials in the earth's mantle provided a source of heat, which seriously undermined Kelvin's age determination. Darwin foreshadowed such a development when he wrote to his colleague Joseph Hooker: 'I cannot think how you can attach so much weight to the physicists', since they disagreed so enormously about the rate of cooling of the earth's crust (Darwin & Seward 1903, p. 5).

In fact, such confidence belied Darwin's true feelings about Kelvin's criticism. He regarded Kelvin as an 'odious spectre' whose chronology was one of Darwin's 'sorriest troubles' (Burchfield 1974; Badash 1989). Darwin had good reason to utter such remarks. Kelvin's reduced chronology could hardly encompass the time required to produce the great explosion of life that Natural Selection had supposedly produced since the beginning of the Cambrian period. More problematic however was Kelvin's attack, based on the Second Law of Thermodynamics, on Darwin's definition of evolution, which postulated a process of descent from lower to higher order organisms. In his 1869 address to the Glasgow Geological Society Kelvin asserted (cited in Thomson 1894, pp. 89–90):

> the limitation of geological periods imposed by the physical sciences cannot of course disprove the hypothesis of transmutation of species; but it does seem sufficient to disprove the doctrine that transmutation has taken place through 'descent with modification by natural selection'.

Unfortunately for Darwin, some of his staunchest supporters, although not retreating from their support of Natural Selection, did attempt to accommodate Kelvin's chronological constraints within the theory of evolution. Both Wallace and Huxley believed that the answer to the problem of 'deep time' was in adjusting the rate of evolution to the new time scale. Huxley admitted as much in an address before the Geological Society of London in 1869 (p. xlviii):

> Biology takes her time from Geology. The only reason that we have for believing in the slow rate of the change in living forms is that they persist through a series of deposits which geology informs us have taken a long while to make. If the geological clock is wrong, all the naturalist will have to do is to modify his notions of the rapidity of change accordingly.

In actual fact, biology was implicitly taking her temporal cues from physics, with grave implications for Darwin's interpretation of evolutionary dynamics.

The geological community, at least at first, yielded with surprisingly little reluctance to Kelvin's diminished chronology, in part because few geologists could fashion an equally sophisticated (mathematically based) counter argument (Burchfield 1975). However, as time passed and Kelvin's (and other supporting physicists') arguments multiplied, a few geologists did attempt to calculate the age of the earth. These attempts were based on measurements of orbital eccentricity, salinity accumulations in the oceans, and erosion rates in rivers.

Remarkably, many of the geologists' results showed a strong degree of agreement with Kelvin's age determination. As Burchfield (1975) notes many of the key parameters that were used in the geologists' calculations were in fact estimates, as they could not be directly measured. It was thus good scientific practice to base their assumptions not only upon the evidence available, but also upon the most reliable opinions available. In this way, it was easier to secure support for their ensuing conclusions. However, such a procedure, 'inevitably introduces into the resulting calculations the unquantifiable influence of accepted authority' (Burchfield 1975, p. 215). And in that period of history, many within the sciences recognized Kelvin as the authority (despite his rudimentary knowledge of geology), so that it is not surprising that the geologists' results agreed with those of Kelvin.

Geologist Archibald Geikie wrote the epitaph to the geological community's opposition to Kelvin's challenge. In reviewing the quantitative results of geologists' efforts to measure geological time, he concluded that the data available were not sufficient to make an independent calculation. Geologists, as Geikie noted, had been 'drawing recklessly upon a bank in which it appears that there are no further funds at our disposal' (cited in Burchfield 1998, p. 141).

'Deep time' was to remain restricted to a figure of no more than 100 million years until physicists Rutherford and Boltwood devised methods of radiometric dating which demonstrated conclusively that the earth was billions of years old.

Lest one think that this dispute was an isolated incident, one only needs to look at the debate surrounding Continental Drift – the earth science's ruling paradigm. In the 1920s, Harold Jeffreys of Cambridge University used physics to attack Wegner's theory of Continental Drift and so advance his competing theory of Contractionism. As LeGrand (1988, p. 105) argues Jeffreys 'imported not only the conclusions of physics, but also it's form and rhetoric into the debate over global theories'.

Perhaps Jeffreys sensed the opportunity to stake a claim 'for physics and himself as the arbiter of disputes in the 'obviously inferior – i.e. non-mathematical – science of geology' (LeGrand 1988, p. 105). He suggested that his book *Earth: Its Origin, History and Physical Constitution* might be too mathematical for geologists but suggested that the 'if the geologist cannot follow a part of the book, I hope he will omit it and go onto the next non-mathematical passage, trusting that someone else will point out any intervening mistakes' (Jeffreys 1924, p. viii).

While noting the absence of experimental data from the earth's interior, Jeffreys argued that it was possible to use physics to extrapolate to a model of its processes and structure, albeit it was necessary to add some 'ad hoc assumptions' (Jeffreys 1924, p. 1). In his view, physics should delineate the boundaries for any acceptable geological theory so that emphasis should be placed upon quantitative 'agreement of theory with fact' (Jeffreys 1924. p. viii). Moreover, according to Jeffreys, in terms of function, the geophysicist provides a general theory; the geologists fill in the details (Jeffreys 1935). In this case, the mathematics of the earth led to one clear conclusion: contraction and not Drift explained the surface features of the earth. However, as we now know, Plate Tectonics (the modern form of Drift) abetted by evidence from the field and the lab swept away Jeffreys mathematical model of contractionism.

Geology Remoulded as Physics: The Logic of Uniformitarianism

Somewhat ironically, the geological community has itself sometimes abetted the perception that geology is subservient to physics. To understand this argument, it is necessary to review the history of the founders of English geology, James Hutton and Charles Lyell.

Trained as a physician, James Hutton (1726–1797) spent much of his early adult life as a farmer. In this work, he took great interest in the nature and development of soils, which in turn led to his interest in geology. In 1768, he took up residence in Edinburgh where he devoted himself to writing and exploring the geology of Scotland.

Hutton's most important contribution to geology was his logical deduction of the nature of geological time. Prior to Hutton, the world was portrayed as a victim of erosion, which ultimately would wear away the continental masses. This image clashed with Hutton's belief in a purposeful world, created by God, which might sustain plant and animal life, so as to benefit the crown of creation, man (Toulmin & Goodfield 1965; Albritton 1980; Gould 1987; Burchfield 1998). Hutton realized that a restorative process must have been operating, so as to maintain the stability of the earth's environment. Thus, he depicted the earth as a machine, which cycled through a continuous process of decay (erosion), continental deposition, and uplift. In such a continuous cycle, geological time was deemed to be an endless, immeasurable entity. He expressed this understanding in his monograph of 1788, 'Theory of the Earth' (Hutton, 1788, p.215):

> Time which measures every thing in our idea, and is often deficient to our schemes, is to nature endless and as nothing.

Hutton's view of geological time is often represented within standard geological textbooks as a victory over the primitive thinking of the 17th century natural philosophers who imposed a Mosaic chronology upon earth history. Indeed, there is truth to this assertion, in that Hutton was among the first thinkers to suggest that geological time was far vaster than the biblically mandated value of some 6000 years.

However, as many historians have noted, Hutton ignored the historical element within his model of geological time, in that he believed that the forces determining the shape of the Earth's surface in the past were the same forces which operated on it today (Rudwick 1976; Gould 1977, 1987; Goldman 1982; Laudan 1987); with such perfect, repeating cycles operating, there was no room for true change or progression.

Hutton's avoidance of the historical was shaped by a variety of influences (Laudan 1987). However, the two most important were his theological leanings, deism, and his adherence to the physical system of Sir Issac Newton. As a deist, Hutton dismissed the Christian concept of revealed religion. Evidence of God was to be found in the natural world, not in revelation. Thus, Hutton rejected the approach of Christian geologists who used the bible and other ancient writings as evidence of the earth's history (Laudan 1987; Dean 1992). Moreover, as Laudan (1987) notes, unlike Christians who advanced a unidirectional history for the earth (which emphasized its creation, the Biblical flood, and its final days) deists were free to consider other patterns of earth history. In this spirit, Hutton proposed that the earth was designed so as to indefinitely maintain an environment suitable for life, without the need of God's intervention.

Hutton's world in balance also found expression in the mechanical theory of Sir Issac Newton. Newton devised an ideal mechanical theory for the solar system in which the planets eternally circled the Sun in timeless perfection. Indeed, Hutton even employed the Newtonian language of 'gravitational matter' to describe the attractive power which helped to drive this cyclical process. In turn, gravitational matter was opposed by a repulsive power, 'solar substance' (in the form of heat derived from the sun) producing a balance of forces, and ultimately a continuously perfect cycling system (Laudan 1987). However, in proposing such a model, Hutton ignored what is most unique about geology-the historical record of change, which is so clearly revealed in the earth's strata.

Hutton's theory attracted relatively few followers within the geological world. Laudan (1987) argues that most geologists rejected both the theological implications, as well as the interpretation of physical powers, which underlay Hutton's theory. Equally important in this rejection was the fact that Hutton's theory was 'entirely causal' (Laudan 1987, p. 134). Hutton showed no interest in historical geology; indeed, as we have seen, his cyclic worldview argued against a unique series of events shaping the earth's development. This is evinced by the fact that he showed little interest in fossils, which were then becoming important in deciphering the (directional) pattern of earth history.

That being said, Hutton's theory did survive and became widely disseminated through John Playfair's (1748–1819) publication, *Illustrations of the Huttonian Theory of the Earth* (1802). A mathematician and physicist, but with no formal training in geology, Playfair treated Hutton's theory as Newtonian science, while eliminating its theological implications (Laudan 1987; Dean 1992; Rudwick 1998). As such, geology was recast by Playfair as a branch of physics, being above all else a 'science of causes of natural processes the same yesterday, today and forever' (Rudwick 1998, p. 4). As Rudwick (1998) notes, the adoption of such

Newtonian principles was commonplace in Enlightenment ideas about the natural world in general, and Playfair's adoption of them within the science of geology was attractive to many in the early 19th century including Charles Lyell (1797–1875).

Using Playfair's interpretation of Hutton as a basis, Lyell attempted to provide a philosophical outlook for the consideration of geological questions, in his most important work, *The Principles of Geology* (Lyell 1830–1833). This outlook, labelled the doctrine of uniformitarianism by philosopher William Whewell (1794–1866) required that geologists assume 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' (K. 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 degree (Rudwick 1998).

Based on this view, Lyell saw the earth as a dynamically balanced, steady state mechanism, in which change was gradual and continuous, but led nowhere (Rudwick 1970, 1976; Gould 1987; Burchfield 1998). Like Hutton, who influenced him, 'Lyell had a vague notion that geological time was vast, but his notion of the earth's dynamics was curiously atemporal' (Burchfield 1998, p. 139).[1] In Lyell's model of a steady state earth, the same forms of life appeared, flourished, went extinct and reappeared in the next geological age.

In contrast to Lyell, most geologists favoured a progressive world of change, and indeed they had much evidence to support their position. By the second decade of the 19th century, geologists were systematically classifying the fossiliferous strata of Europe (Bartholomew 1976). Placed in ordered sequence, such strata revealed unmistakable evidence that the 'actual animal populations inhabiting the earth must have changed strikingly from epoch to epoch' (Toulmin & Goodfield 1965, p. 182).

The reasons behind Lyell's support of such a controversial doctrine are very important for they indicate how he thought geologists should interpret the earth. Equally important, an exploration of Lyell's thinking shows that although controversial in his time his interpretation of 'uniformitarianism' is still influencing the way modern geology is both practiced and even perceived.

Lyell believed that the way to avoid error and inconsistency in geology was through a strict adherence to logic. To do this, he largely relied on two scientific methodologies Vera Causa and enumerative induction (Laudan 1987; Baker 1998; Rudwick 1998). The source for the former was physicist Sir Isaac Newton. In the section 'Rules of Reasoning' in his *Principia* he defines Vera Causa: 'we are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances' (as cited by Laudan 1987, p. 15). For geologists this meant that they must refer only to those existing causes which are sufficient to produce the effect. Regarding the latter methodology, enumerative induction is a pattern of scientific reasoning in which the collection of facts takes precedence, unsullied by any theoretical presuppositions, from which theory might, in due time, emerge (Hull 1973; Laudan 1977). The first President of the Geological Society of

London, G.B. Greenough, urged his members to adopt this strict form of induction, as it was 'unassailably scientific' (Laudan 1987, p. 168).

Lyell's adoption of Newton's Vera Causa and enumerative induction was his philosophical response to those geologists who might invoke catastrophic events as forces that shaped the earth's geological past. Such catastrophic forces were an anathema to Lyell because they implied that geology relied upon unknown causes, thus violating the logical principle of simplicity (which states that the best scientific explanations are those that consist of the fewest assumptions). Lyell believed that the a priori application of uniformity (based on the principle of vera causa) was necessary, if geology, like physics was to be considered a valid, logically based science (Baker 1998, 2000).

Philosopher William Whelwell proved to be amongst Lyell's strongest critics, as he attacked Lyell's adoption of Vera Causa and enumerative induction as unsuitable for a science such as geology. Whewell (1837) considered geology to be a palaetiological science concerned with 'the study of a past condition, from which the present is derived by causes acting in time'. According to Whewell, it was inappropriate to apply Vera Causa, towards specifying the nature of those causes, a priori. Moreover writing about Lyell's inductive logic, Whelwell notes (1837, v.3, p. 617):

> (Lyell's) 'earnest and patient endeavour to reconcile the former indication of change', with any restrictive class of causes-a habit which he (Lyell) enjoins-is not the temper to which science ought to be pursued. The effects must themselves teach us the nature and intensity of the causes which have operated.

In simple terms, Whelwell was denying that the kind of induction advocated by Lyell, which he had borrowed from physics was appropriate to a science such as geology (Baker 1998).

In spite of such criticism, it can be argue from an historical perspective that Lyell's uniformitarian view has had a deep felt effect on the way modern geology is practised and even perceived (Ager 1981; Hsu 1994; Baker 1998). Indeed, as Hsu (1994, p. 218) notes, 'blind faith in the dogma lies at the root of numerous controversies in modern geology.'

For this paper we will briefly document two current controversies, associated with the interpretation of uniformitarianism.[2] Based on uniformitarian logic it was proposed that many landforms in North America and Eurasia were shaped during the last ice age exclusively by the slow gradual action of glaciers. However, more recently it has been recognized that such landforms were equally affected by catastrophic glacial flooding (Baker et al. 1993; Baker 1998). Although more controversial, the debate concerning the extinction (of the dinosaurs) at the end of the Mesozoic has also exposed (at least according to some earth scientists) the flaws with (Lyellian) uniformitarian thinking (Hsu 1994; Gould 1986; Glen 1994). For some earth scientists, the idea that such extinction was due to the impact of a large extraterrestrial body was impossible because it violated their a priori prejudice against large-scale catastrophic events.

These two examples emphasize that a key part of understanding causative process in geology is found by interpreting the landforms, structures and rocks which make up the earth (Baker 1998, 2000; Turner, 2000). In simple terms, the student of geology will find his answers in the concrete materials of the field. As Ager (1981), Baker (1998) and Hsu (1994) argue, Lyell's uniformitarianism with its emphasis on creating a logically valid science of geology may be a historical relic with little place in modern earth sciences.[3]

As can be seen from our brief survey, geology has in the course of history sometimes been treated as a tributary of physics, both by physicists as well as earth scientists themselves. This situation is reflected by the meagre attention that the earth sciences have received by historians and philosophers of science. This neglect was based largely on the assumption that since geology is a synthetic science, which is easily subsumed under the physical sciences, there is little need to study its historical development.

Implications: The Geosciences as an Independent Focus of Study within the Education System

This neglect of the earth sciences (as well as other historical sciences) is also reflected within the modern school curriculum. Prior to the twentieth century, geology was an intrinsic part of the high school curriculum for college bound students in the United States. In part, this reflected the fact that geologists held pre-eminent roles in American science, and wielded their political power accordingly. However, by 1910 such courses had low enrollment, and geology had effectively become an elective (Orion et al. 1999). The conventional wisdom of the time regarded physics and chemistry as having greater social importance than geology because they aided students in developing problem solving skills (Bybee & DeBoer 1994).

In the early 1960s, the domination of the physical sciences within the American education system was bolstered by the belief that the launching of the Soviet Sputnik satellite posed a national security threat. Science education focused on 'the logical structure of the sciences and the processes of the sciences' (Bybee & DeBoer 1994, p. 373) with less emphasis on its personal and social applications. Thus, the sciences which were emphasized, physics and chemistry, were those needed to maintain the United States' (military and) technological advantage over the Soviet Union (Mayer et al. 1999).

Towards the end of the 1960s, a program in the earth sciences reappeared in the American school system, the ESCP (Earth Science Curriculum Project), with a second program following in the early 1970s the CEEP (Crustal Evolution Education Project). In theory, the implementation of such curriculum projects suggested that the earth sciences had achieved equal status with biology, chemistry and physics. However, this was not the case. Although the ESCP received positive evaluations (Champlin 1970), it does not seem to have made a lasting impact in the American secondary school system. The CEEP was specifically designed to incorporate the new paradigm of plate tectonics, but was never successfully implemented in part due to 'a lack of interest in the topic' (Orion et al. 1999).

Concurrently, these units gave the somewhat distorted image that the focus of geology was on the physical rather than the historical. This trend has continued until today; in the *Activity Sourcebook for Earth Science* (edited by Mayer et al. 1980) and later *Earth Science Investigations* (Oosterman & Schmidt 1990), both of which contain some of the material seen in the ESCP and CEEP, the majority of the activities are strongly weighted towards the physical side of the earth sciences. This is all the more puzzling when one considers the fact that:

> these collections are the most widely accepted examples of what scientists and science teachers through their professional organizations have felt important to use in teaching earth science problem solving. (Ault 1994, p. 270)

In other words, even amongst many professional earth scientists and earth science educators, there is a bias towards a geology that is strongly physical, rather than historical. However, if this is truly the case, one might question why it is necessary to teach the earth sciences, when it simply replicates many physics based experiences?

It was not until the mid 1990s that a major curriculum movement in the earth sciences received impetus. This effort is part of the larger AAAS Project 2061. Unlike earlier curriculum projects, which concentrated on specific scientific fields, the goal of AAAS Project 2061 is to develop scientific literacy in all sciences. This project is in its first phase of development so it is still too early to ascertain what effect such reforms will have on earth science instruction (Orion et al. 1999).[4]

We contend that the image of geology as a derivative science is misguided because it does not take into account the unique defining characteristics of this discipline. In contrast to the physical sciences, which tend to be predictive, experimental and reductionist in nature, geology is historical, descriptive, and systems oriented. To a large degree such defining characteristics are both a result of the types of phenomena that geology studies, as well as the types of logic that are brought to bear upon such phenomena.

Much of the work that earth scientists do is based on interpreting natural, uncontrolled phenomena. Such phenomena present a large series of variables, all of which must be considered before arriving at a conclusion. Experimentation and simulation in the laboratory, although an important component of many geological investigations could never be a substitute for evidence gathered in the field.[5]

Due to the large number of variables associated with geological phenomena, geologists rely on an interpretive and narrative form of logic which is used to reconstruct such phenomena (Frodeman 1995; Turner 2000). Such retrospective thinking often requires the geologist to make a meticulous survey of present conditions, which might then be used to explain phenomena of the past. Such historical based explanations emphasize the differences between geology and physics, which primarily focuses on establishing time invariant laws.

The discovery of geological time is a perfect example of this working methodology, in that it required the patient unravelling of uncounted numbers of fossiliferous strata in the field, before science recognized 'deep time's' full implication. Through such efforts, the earth sciences have provided a true sense of the earth's historical development through the creation of an heuristic geological time scale. A single quantifiable number derived in the laboratory and describing the magnitude of the earth's age, although important to this story, could never have established this historical narrative of the earth's development.

Within its framework, the geological time scale represents the vast series of changes (both geological and biological) which have impacted the earth. Psychologists have shown that even small children organize their sense of days, weeks and years around the events that structure those time periods (Friedman 1990). So too, the geological time scale and the events it represents (evolution, environmental change, extinction) provides an organization that permits one to better visualize the magnitude of 'deep time'.

By trying to force geology within the universalism of the physical sciences, both scientists and historians of sciences construct an unnecessarily limited definition of science in general and the earth sciences in particular. Moreover, this definition has also meant that within education, students are necessarily limited to the dominant paradigm of the experimental sciences, with little chance to experience the unique retrospective logic of the historical sciences. This ultimately affects their understanding of subject areas outside of geology, including evolution, ecology and astronomy, which by definition require an understanding of temporally related changes. It also limits students' chances of being scientifically literate (a stated goal of the current educational reforms).

The revolution of 'deep time' emphasizes geology's key role in building an image of the past. The environmental crisis, with its large collection of interconnected variables, emphasizes that the holistic, systemic and historical methodology of the earth sciences has much to contribute in future to both science specifically and the welfare of the planet in general.

Notes

[1] It should be noted that to convince his readers of the vastness of geological time, Lyell in the (1st edition of the) *Principles*, calculated that the most recent volcanic cones on Mount Etna (in Italy) were no less than 12,000 years in age (Lyell 1833, Vol. 3, p. 97). Based on these calculations it was easy to understand that all of Mt Etna was several hundred thousand years in age (Oldroyd 1996). However, as Burchfield (1998, p. 141) notes it was not until the controversy with Kelvin, that Lyell attempted (in the 10th edition of the *Principles*) to provide a 'quantitative scale' to the length of geological time itself. Using the faunal turnover of Tertiary molluscs as a basis he determined that a complete faunal turnover of a species would require 20 million years. Assuming that approximately equal periods of time were necessary for each of the twelve turnovers that he estimated had occurred since the Cambrian, he concluded that the total time required was 240 million years.

[2] Although, we cite only two recent examples, there are many examples of how the 'rare catstrophic event' has played a major role in altering the stratigraphic record of this planet (Ager 1981). Moreover as Ager (1981, p. 54) notes: 'Examples of this sort are in direct contrast to what has been, in effect, the subconscious attitude of most geologists for the last hundred or more years'.

[3] Regarding the pervasive influence of Lyell's uniformitarianism amongst modern earth scientists, Hsu offers the following anecdote (Hsu 1994, p. 218): 'I thought I was being scientifically objective when I indulged in simplistic speculations on the calcite dissolution of ocean bottoms by assuming that the chemistry of the oceans had never changed (Hsu & Andrews 1969). If I had been less ignorant, I would not have lightly dismissed the more valid alternative of postulating ever changing calcite-compensation depth (Hay 1969). I was jolted out of my complacency, however, when I had to write a cruise report on the 1970 deep sea drilling expedition to the Mediterranean Sea. That this inland sea had dried up during Late Miocene time was the only conclusion that is consistent with the implications of a wealth of data on Mediterranean geology (Ryan et. al. 1973). The reactions of many colleagues were, however negative. They said, "I don't believe your story" or "You are way off base because your conclusion contradicts Lyell's uniformitarianism, the fundamental principle of geology" '.

[4] Nonetheless, entrenched attitudes against the earth sciences as a part of the core scientific curriculum still exist. While preparing this article, the first author received a letter from the American Geological Institute protesting the neglect of the earth sciences in the new California high school curriculum. The following is an excerpt from that letter: 'We are writing on behalf of the American Geological Institute regarding the de-emphasis of Earth Science education in the proposed California high school science curriculum. The Institute, a federation comprised of 39 scientific, educational, and professional geoscience societies, is specifically concerned with the proposal contained on page 9 (lines 7–10) of the January 25, 2002 *Draft California Science Framework for K-12 Public Schools*. The proposal states: "All students take, at minimum, two years of laboratory science providing fundamental knowledge in at least two of the following content strands: biology/life science, chemistry, and physics. Laboratory courses in earth sciences are acceptable if they have as prerequisite (or provide basic knowledge in) biology, chemistry, or physics". In our opinion, if this proposal is ratified by the California State Board of Education, it will be a step backwards for the State of California and a detriment to high school students in the State. Earth Science education will provide students a better understanding of the environmental, water resource, and energy issues facing the State of California.

National Science Education Standards developed by the National Academy of Sciences/National Research Council identify Earth Science as a core science curriculum area that integrates chemistry, physics, and biology in an applied context at all grade levels. Earth Science is the discipline that best facilitates an integrated working knowledge of science by all students'.

[5] However, as Turner (2000) notes in her essay 'Rock Logic: The Nature of the Earth Sciences', that many geologists are abandoning the field (the primary source of evidence for historically oriented geological studies) for the lure of the lab and its computer technology: 'Increasingly, field geologists are putting away their rock hammers and relinquishing their field vehicles, believing that field studies will no longer be part of their research. The same geologists who once scrambled over outcrops in search of subtle clues to a geologic mystery are joining the ranks of those who spend their days in front of a computer screen and engage in hallway conversations about the latest software or upgrade'.

As Turner (2000) further notes such trends, somewhat ironically, have developed at a time when earth scientists are most needed to interpret how human activity has impacted upon the natural environment.

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