PARADIGMS IN COLLISION: HISTORICAL and PHILOSOPHICAL PERSPECTIVES on TEACHING the NEW GLOBAL TECTONICS

John James Murray

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BY

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ABSTRACT

The latter half of the 20th century has been witness to a dramatic shift in the guiding assumptions in our understanding of the dynamics of Earth's crust. Historically, the debate about global tectonics has subsisted in a rivalry between two competing conceptual systems – the "paradigm collision" of fixism and mobilism. The new synthesis of plate tectonics, derived from the mobilist tradition, is the currently accepted model supporting theory, practice, and education in the geosciences. Historians and philosophers of science have taken an interest in the events that led to the emergence of the new global tectonics, and in large measure have viewed this episode in the history of science in terms of a "scientific revolution" in the manner of Thomas Kuhn's paradigm approach in his *The Structure of Scientific Revolutions.* Since the teaching of plate tectonics occurs in virtually all compulsory science education in Canada, the pedogogical potential exists for this great "science story" to be told through the complimentary lenses of the history and philosophy of science (HPS) in the classroom. With increased emphasis in science education on the roles of evidence, argument, appreciation of the nature of science, the development of scientific knowledge, and the importance of how major conceptual shifts revolutionize scientific discourse, it is desirable to construct a teaching and learning model that incorporates these elements into the teaching of tectonics. By focusing on the fixism / mobilism controversy that developed in geology over the years 1910 – 1975, students can be offered a pathway along which HPS perspectives can be introduced in a meaningful, accessible way. The model developed here includes five elements that can be connected to the learning cycle, constructivist pedagogy, and the phases of a Kuhnian treatment of the geological revolution: *recognition, elicitation, paradigm collision, conceptual reconstruction,* and *resolution and emergence.* The motivation for this approach lies in ameliorating two endemic situations: 1) distorted or incomplete historical treatment in standard textbook-oriented learning that results in biased historiography, and; 2) "quasi-constructivist" methods that initially value student conceptions, but eventually work to instill a "scientific correctness" that declares one side of the argument superior and sophisticated, and the unsuccessful paradigm naïve and proto-scientific. A detailed case study of how the five elements in the model could be made operational is outlined, including implications for teacher development, field validation, and avenues for further research. Ultimately, the question that is to be answered as a result of this pathway is *"why do I accept plate tectonics?"*

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"In times of change, the learners inherit the earth, while the learned find themselves beautifully equipped to live in a world that no longer exists."

(Anonymous)

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And to the Blessed Mother, the very flower of creation….and the One who dared to say "yes".

DEDICATIONS

"We shall not cease from exploration, and the end of all our exploring will be to arrive where we started, and know the place for the first time."
-- T. S. Eliot

To my wife, Lorraine.....

...who is the most honest person I have ever known, and sees through everything that I do and hope to do, including what lies in these pages; she is my One, my Love, and my Inspiration when all else seems to be pointless...

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1.0 Introduction

1.1 Towards a Planetary Perspective in Science Education: A Prolegomena

The educational currents of our times suggest a need to reinvigorate science teaching with a view to encouraging students toward the ambitious outcome of *"scientific literacy"*. The methods of science instruction are being reshaped, content reorganized, and the processes through which we communicate to students via the science curriculum are reaching out to fresh alternatives (e.g. entering into "curricular conversation" as advocated by Applebee (1997)). Securing new opportunities at this time can involve viewing the learning of science through a new set of lenses – that is, we are first occupants of a large planet. All else is captured within this broader set of relationships. Consider it the cultivation of an awareness – a *planetary awareness* – a connectedness to the physical environment that closes the gaps among humanity, theory, practice and the philosophy of science. Our planet has been variously described as Gaea, Mother, Oasis in Space, the Theatre of Redemption, Goddess, Terra, "third rock from the Sun", or simply

"Home" through millenia of writings, pictorials, and oral traditions too numerous to enumerate here.

Geological science has periodically revolutionized the manner in which we view the relationship between the human and the "terran". An aptly termed "gaian perspective" is rooted in the consideration of an immense system - planetary cybernetics – an intimate networking of systems that influence one another at the moment of interaction, and beyond that moment (Lovelock and Margulis, 1974a, 1974b; Margulis and Lovelock, 1974). The Gaia hypothesis, as it has come to be known, recognizes that large-scale systems interaction at the planetary level acts to sustain a sort of *planetary homeostasis.* In the case of Earth, homeostasis could in fact act to stabilize the essential conditions for life, not only to permit life to evolve, but to prevail over new, ever-changing conditions (Lovelock and Margulis, 1974a, 1974b; Margulis and Lovelock, 1974; Watson and Lovelock, 1983). It is within the vision, then, of the geosciences to always consider that which comprises Earth and other solar system bodies. How these components came into existence, what may or may not have lived upon (or within) their changing (or unchanging) surfaces, should capture our imagination and interests. Time, then, from the microsecond to the aeon, is of interest to students of planet Earth.

Science education in Manitoba schools is presently undergoing a reform movement not unlike what is occurring in other jurisdictions of Canada and the "industrialized" nations of Western Europe, Australia, and the United States. We have an unique opportunity, that is, addressing the omission of the historical planetary perspective in its secondary-level science programs. As is generally the case in K-12 science curriculum, students from K-6 tend to experience a more integrated, unifying concepts approach in which their science learning is assumed to be interrelated to the other disciplines of science and to foundations beyond the sciences (Toepfer, 1996). In the middle years (grades 7-9), a diversified approach to a "science mosaic" provides synoptic surveys from the traditional disciplines such as ecology, biology, chemistry, and the physical sciences. Since many science disciplines have an affect on our vision of the planet we live on, and if one desires more *geological* literacy among the citizenry, then it can be reasonably argued that a pedogogically sound science curriculum must take account of the need to offer the perspectives just pointed out.

In 1995, the Council of Ministers of Education, Canada (CMEC, 1997) put in place an inter-jurisdictional process that led to the *Pan-Canadian Protocol for Collaboration on School Curriculum.* This was the concrete step toward operationalizing a set of beliefs that the sharing of resources – both human and material – will effect substantial changes on the level of jurisdictional cooperation within Canadian education. Its first curriculum framework document, the *Common Framework of Science Learning Outcomes K-12*, has provided the template from which new course frameworks directed at an earth systems approach could be conceived and developed. Therefore, it is my intention to highlight one of the pivotal episodes in the recent history of the earth sciences for the purposes of securing a position for the history and philosophy of science (HPS) in the teaching and learning environment. The influential science standards documents generated in the United States and Canada (e.g. AAAS, 1989, 1993, 2000, 2001; AGI 1991a, 1991b;

AGU, 2001; BSCS, 2000; CMEC, 1997; NRC, 1996; Rutherford and Ahlgren, 1990), support a vision of Earth awareness that is historically contextualized. An *historically grounded approach* affords an opportunity for Canadian students to connect, in the science classroom, with just how science has progressed without being viewed as "a tale of inevitable progress". The latter implies a *humanistic dimension* to the science curriculum that has often been obscured, neglected, or sidelined by the continuing myth of scientific objectivity, to the exclusion of telling the great "science stories" (see Ornstein and Hunkins, 1998; Stinner, 1995).

It is anticipated that these new approaches will provide the necessary foundation for students to pursue further studies related to the geosciences, astronomy, and planetary sciences, while at the same time foster a preparedness to ask questions, probe for answers, and engage in a life-long relationship with their home planet and its solar system neighbours. In keeping with current approaches to the teaching and learning of science in the wake of standards-based reforms, historical and philosophical aspects of science education should continue to focus on certain aspects. According to the American Geological Institute (AGI, 1991a, 1991b), these include:

- SCIENCE INQUIRY, wherein students are encouraged to converse, ask penetrating questions, and then seek to explore their own constructed explanations alongside scientific explanations through guided research, writing, and planned investigations.

- PROBLEM-SOLVING, where students apply their acquired expertise and knowledge in novel, oftentimes unforeseeable ways.

- DECISION-MAKING, as students identify key, rich, large-context problems, questions, or issues related to the human and robotic exploration of the planets; then pursue new knowledge that will assist them in making informed, rational, defensible decisions that are rooted in the societal and humanistic domains within which science practice operates.

- NATURE OF SCIENCE, where students appreciate and value the understanding that science operates with the consent of personal, social, political, environmental, and multicultural orientations of the global society. Moreover, there are consequences when science circumvents its responsibilities among these societal contexts.

- SCIENCE-RELATED SKILLS, such as initiating, planning, performing, recording, analysis, interpretation, communication, teamwork that have central importance in learning the dimensions of science. It is expressly important for science students of today to not be taught the myth of a single, "scientific method" that leads to a superior "truth" about the material world. If there is indeed an objective "reality", philosophers of science often agree that it may be unknowable. Nevertheless, the methods of science systematically permit new knowledge domains to be constructed.

- SCIENCE CONTENT KNOWLEDGE must no longer be the primary outcome of science teaching, is actively constructed from existing and emerging personal and social knowledge. Creative, integrative linkages of an interdisciplinary nature should now be balanced with the traditional "disciplinary focus" of science teaching and learning. Unifying concepts among traditional, bounded, restricted disciplines should now give form and substance to new views of exploration among the sciences.

In the section that follows, introducing the rationale for the present thesis, I will outline some of the compelling reasons for acting in some manner on the demands outlined above, and why these aspects are particularly attractive to the consideration of the earth sciences struggles of the 20th century. These principles can inform the contexts and provide the template upon which to construct rich, meaningful experiences with students. These same principles are also intended to promote a broader and more authentic appreciation of the nature of scientific inquiry and behaviour.

1.2 Background and Justification for the Present Exploration

Over the past four decades, the earth sciences witnessed the development of its most all-encompassing set of guiding assumptions about the behaviour of the earth since the early uniformitarian principles were laid down in Sir James Hutton's *Theory of the Earth*. The new global tectonics is a powerful, large-scale theoretical framework that has virtually unified every sub-discipline among the earth sciences, and has led to unprecedented progress, knowledge claims, and has led to virtually unequivocal acceptance. So important was this transition to a first genuinely unifying theory for the earth sciences that J. Tuzo Wilson, a leading Canadian geophysicist, called for a renaming of the entire discipline to *geonomy*. This was a courageous declaration that traditional geology can now accept the new, geophysical synthesis and praxis. It is also an admission that it was now governed by a set of unassailable physical laws and attributes (Wilson, 1969a, 1969b). Wilson was unrepentant about announcing that the earth sciences had undergone a "revolution" of the type espoused by Thomas S. Kuhn with the publication of *The Structure of Scientific Revolutions* (Kuhn, 1970a, 1996; hereafter *Structure*). But what really happened over the course of 20th century geological thinking? Can a model be developed to allow students of the earth sciences to become more adept at examining this dynamic past, and determine for themselves a personal level of acceptability of the new guiding assumptions?

1.2.1 Why Geology and History?

Geology is essentially *historical,* and so is often guided by the telling of great stories. These geoscience stories include terrestrial catastrophes such as mass extinction events, extraterrestrial impact events, inundations due to floods (some being of Noachian proportions), explosive volcanism, and seismic events. Historically, such events have been culturally shaped into epic or mythological narratives in a manner that could be described as *anthropic* – we see them through the eyes of a species that cannot fully comprehend or understand the immense scales involved. The measuring scales among planetary systems vary from the subatomic to the astronomical, and temporally from the nanosecond to the aeon. Students and the specialists in the earth sciences have been subject to these same spatial challenges, continually looking for newer views on an old planet. Indeed, geology distinguishes itself among the sciences by its unique appeal to the dimension of time. But not time on a human scale. The planetary scale of exploration and awareness demands a redefinition of time so vast that the field required a new term for it – "deep time".

Geological science is inherently interdisciplinary, often using the theoretical bases and methods of the traditional sciences such as physics (geophysics), chemistry (geochemistry), and biology (paleontology) – what one theologian has described as the "superparadigms" (Kung, 1988). It is also uniquely in possession of its own hermeneutics – a *geosemiosis* – that makes extensive use of a visual literacy rooted in signs (the semiotic), symbolisms, and "lithic narratives" (reading the rocks). These position geology as an interpretive, culture-bound and placed-based science (see Baker, 1999; Murray, 1996a, 1997; Semken, 1997). Mythopoesis –

the generation of myth – has been redefined through modern science as systems of belief that underpin and drive, in a unifying manner, the various disciplines. 'Myth' here is not analogous to allegorical stories, but large-scale sets of guiding assumptions (conceptual systems) that serve to connect an otherwise disparate collection of observations, ideas, or thoughts. Examples from the history of science could include Aristotelian physics, Ptolemaic astronomy, the Copernican system, Harvey's circulation of the blood, Newton's universal gravitation, the kinetic-molecular theory of gases, phlogiston theory, Darwinian evolution, Einsteinian relativity, Wegener's continental displacement, and the kinematic theory of plate tectonics.

In order for a great scientific 'myth' to succeed, it must have the support of an influential community of 'believers'. It does not have to guarantee full acceptance by the vast majority of scientists working within a discipline, provided their allegiance is demonstrated within what is considered acceptable practices. One observer has likened the process – in the realm of curriculum models - to the "great attractors" of chaos theory (non-linear dynamics). MacPherson (1995) argues that such 'attractors' (the myths) await their moment, draw believers who are the articulators of the myth, the new myth thrives for a period of time, grows weary of the struggle to succeed, and inevitably dies out when the architects, constructors, and iconographers leave the scene. The icons of the myth may have lost faith in their cherished view, or attach themselves to yet another novel one. Though the "chaos" analogy has been applied to general curriculum by MacPherson, it may have lesser applicability to science curriculum which does admit to a certain durability – if not a stubborn permanence - of its knowledge claims. One element of MacPherson's argument, though – *curricular lepidopterology* (the "flapping of the wings of butterflies") - does potentially operate in the earth sciences. The butterflies are emerging, heretical thinkers in far-flung archipelagoes who eventually create ripples in the fabric of mainstream geological thought.

Large-scale conceptual systems in science require cogent arguments that defend the system from communities of critics, or act to silence and ultimately defeat serious alternative, rival systems. There also must exist active dissemination of the core ideas in the hope of attracting and retaining converts to a new conceptual system. This is often mirrored by the science education enterprise. More specifically, the traditional process of science education provides for the attachment of students and their teachers to currently accepted ideas in science – an attachment that, at times, borders on dogmatism. Students of science rarely have the occasion, or freedom in the learning environment, to entertain the exploration of alternative worldviews and their own personal conceptual development. They are, however, generously supplied with numerous historical instances of scientific naïveté or "wrongness" that are intended to serve the validation of the current scientific "correctness". Alternative conceptual systems, often held in suspicion or met with undue skepticism in science, are therefore not generally encouraged among students of science, but are to be cast aside as underdeveloped notions, misconceptions, or the reprise of historical *cul-de-sacs*.

1.2.2 What Comes Before Us in Curriculum Today?

Traditional models of teaching and the practice of science education at the upper secondary levels, as expected, give significant stature to the textbook. Essential science knowledge from authoritative viewpoints and a teacher-centred approach places limits on what is possible or desirable. Thomas S. Kuhn, in *The Structure of Scientific Revolutions* (1970 and 1996 editions) remarked that:

> science students accept theories on the authority of the teacher or text, not because of evidence...[the] applications given in texts are not there as evidence, but because learning them is part of learning the paradigm at the base of current practice...[more] than any single aspect of science, that pedagogic form [the textbook] has determined our image of the nature of science and the role of discovery and invention in its advance (p. 143).

Moreover, the sort of historiography that develops from the recollections of the current specialists can foster a "whiggism" that paints a picture of science as inevitable progress. This is a tale of development in ideas from early, pre-scientific naiveté through a chronology of accumulating positive achievement to the presently accepted orthodoxy.[1] Perusal of any currently adopted textbook in introductory geology lends support to the position that the process of teaching global tectonics rests in the "single paradigm" approach, namely the plate tectonic model. It is considered here to be more important and enriching for students to carefully explore the plurality of tectonic models that enlivened 20th century geological thought, including those that have, or still are, viable alternative models to the current leader in the field.

Derek Hodson (1988), among others (speaking in a general sense), suggests that "different kinds of experiences may be required in order to reach the goals of science education". Of these experiences, the following stand out as relevant to this examination of teaching science from a pluralist standpoint:

- Critical scrutiny of evidence and arguments for and against particular theories;
- Appreciation of socio-economic and historical issues concerning science and its applications;
- Appreciation of the nature of science, scientific methods, and scientific practice.

In the Grade 11 and 12 portion of the *Pan Canadian Framework* document, concerned with the earth and space sciences, we find the following student learning outcomes:

- 114-2 Explain the roles of evidence, theories, and paradigms in the development of scientific knowledge *(e.g. describe the historical development of theories to explain the origin and evolution of the Earth)*
- 114-5 Describe the importance of peer review in the development of scientific knowledge *(e.g. describe how the ideas of different scientists contributed to the evolution of the continental drift theory into the theory of plate tectonics)*
- 115-3 Explain how a major scientific milestone revolutionized thinking in the scientific communities
- 115-7 Explain how scientific knowledge evolves as new evidence comes to light and as laws and theories are tested and subsequently restricted, revised, or replaced [2]
- 118-6 Construct arguments to support a decision or judgement, using examples and evidence and recognizing various perspectives *(e.g. prepare arguments, taking into account various perspectives within and outside the scientific community, to defend a position on the age of the Earth)*

The above learning outcomes can be interpreted to support a call for a reconsideration of the teaching and learning of the new global tectonics from new points of view. Additionally, the argument is clearly presented in support of historical, sociological, and humanistic perspectives. From these considerations, a new model can be developed that opens the student of geology to experiencing a synthetic approach to the development of new concepts in global tectonics - one that is authentic, raises the guiding assumptions of a variety of competing models, and permits a clearer vision of what actually took place among the key players in the earth sciences.

1.2.3 History and Philosophy of Science – Is It Time Again?

Considering that the audience for the model to be developed here is senior secondary-level, students are perhaps better placed to shape their conceptual development of novel geophysical ideas through the complementary lenses of the history and philosophy of science (HPS). The multi-model approach is consistent with one recently advocated by Monk and Osborne (1997) wherein "past scientists' views on natural phenomena [are] to be set alongside those of students' views" (p. 406). Among the benefits accorded students through the use of such a pluralistic approach, these authors highlight two:

1) consideration of alternative interpretations of the evidence demands comparison and contrast, forcing teachers of science to raise important epistemological questions such as "How do we know…? and "What is the evidence for…?; and

2) the need for alternative explanations for the phenomena under investigation provides a natural means for science teachers to elicit students' entry-level knowledge and intuitive ideas, an action central to constructivists' pedagogy (Driver and Oldham, 1995).

The synoptic review of Duschl (1994), and its practical classroom applications to the dramatic events of the geological paradigm change of the late 20th century (Kiddell, 1996), pointed to the characteristic "final form" science often portrayed in textbooks as restrictive for students in learning *about* science. It is of equal concern that suggested treatments of significant scientific change presented to students, with the best of intentions to avoid "whiggish" historical accounts, often end up doing just that. They present the historical context as a sort of scientific *hagiography* that highlights the achievements of the individuals who were successful in having their ideas accepted (e.g., see Kiddell, 1996). Utilizing this approach raises a caution related to a potential omission. What could be lost are the deeply penetrating internal, personal, institutional, and cognitive struggles that are coincident with radical developments in the sciences. Part of that omission is the drama involved when students see the models and conceptualisations that were *not accepted* by established scientific norms, and to explore to what extent the "losers" are as important to the advancement of science as are the "winners" (Feyerabend, 1974, 1981). I am reluctant to suggest, as others have, that students must walk the same path as their predecessors and experience the same sequence of events that led to a significant scientific change. This can only be accomplished through a more sophisticated historical treatment, and an inordinate amount of teacher development and classroom time. It is more agreeable to adopt the "vignette" as offered by Monk and Osborne (1997). A carefully selected instance from the history of science can be the basis for a close look at how science conducted its affairs in a given situation. The contexts must be selectively chosen in order to avoid overburdening the curriculum.

In the early 1960's, Schwab and Brandein (1962) outlined an important distinction between the methodological components of scientific inquiry – his *syntaxis* – and the meaningfulness of the evidence – the *semantic* or interpretive component. An over-emphasis on the former leads to an incomplete understanding of scientific inquiry as being primarily method-driven (perhaps read as the hypothetico-deductive approach in science classrooms). In addition, as Monk and Osborne (1997) argue, the constraints of the overburdened curriculum necessitate the "one possible answer from one data set" model. This becomes inconsistent with historical situations where communities of scientists have adopted radically opposing viewpoints while arbitrating the same sets of data. Students, unfortunately, can be caught up in one of two possible outcomes:

- the empiricist belief system that the methods of science lead inexorably to certain knowledge that is trustworthy, or;
- a hopelessly relativistic situation wherein all scientific knowledge is underdetermined by the available evidence, and leads to little certainty whatsoever

Monk and Osborne (1997) hold that the above two end-members characterize the extreme bounds of an *incomplete epistemology.* Students experience some aspects of both the processes and products of science (the context of discovery), but are not necessarily afforded the opportunity to examine the rhetoric and negotiation that occurs as the validity of theoretical interpretations is debated among scientists (the context of justification). Their claim is that the HPS offers the hope of binding these contexts together into a more coherent whole for students. Of interest to this study – and I will take some liberty in adapting it to my interests here - is the use of a geological analogy to describe the importance of including another spatial layer in the development of science literacy. Include not only the landscape, or topology, of acceptable ideas for students, but introduce them also to the underlying elements (stratigraphy) that helps to account for why the landscape looks the way it does now.

1.2.4 What Do We Mean By "Paradigms in Collision"?

Where does the development of a teaching and learning model for 20th century tectonics, through the use of a *"paradigms in collision"* context, come from? The germ of an idea for this exploration grew out of the approach to tectonic viewpoints developed by John Arden Stewart's (Stewart, 1979, Stewart, 1990; Stewart, Hagström and Small, 1981) identification of 'conceptual continents' (the relative movement and association of key ideas as seen in the primary geological literature of the 1960's and 1970's).[3] This thesis does not pursue the complexities as revealed by the geological literature and model them in the classroom setting as shifting 'conceptual continents'. Rather, it takes an approach that subsists in focussing on the significant historical debate that occurred between two major whole-Earth conceptions. These are then linked to an introductory examination (for students and teachers) of how the nature of science (NOS) informs understanding of the behaviour of a scientific community as it wrestles with the single greatest moments in its modern history. In addition, a dimension that provides the appropriate counterpoint to the historical narrative - the 'revolutionary' philosophy of science of Thomas S. Kuhn – will provide the philosophy of science content.

More specifically, two *'colliding paradigms'* are identified from the debate about the earth from 20th century global tectonics models. The two are, namely; the FIXIST traditions of permanent continents and oceans and associated contractionist ideas [7], and; the MOBILIST traditions that include Alfred Lothar Wegener's drift hypotheses, the sea-floor spreading/convection current model, earth expansion hypotheses, and the eventual synthesis commonly known today as plate tectonics. These two large-scale colliding paradigms, then, constitute significant conceptualizations of how the surface features of the earth can be explained, and models that have generated acrimonious debate among earth scientists and influential allegiances. Since these tectonic models do possess a particularly important position historically (e.g., Wegenerian continental displacement in the MOBILIST tradition and the FIXIST accounts of, for instance, a Sir Harold Jeffreys), there will be a natural chronological component. Furthermore, evidence from the literature supports the notion that there are socio-geographical considerations in how ideas related to global tectonics were received – or not received – by the specialists. Hence, there are ideological and social considerations that have, at times, produced a certain "tectonic geography" of ideas. North American and Russian geologists, for instance, were notably hostile to drift theory early in the 20th century, whereas their Southern Hemisphere and (some) europhile counterparts were favourable to the idea. Conversely, during the 1960's and onward, as the plate tectonics synthesis became widely accepted in North America and the United Kingdom, alternative models were being synthesized elsewhere – particularly in Russia, China, South Africa, India, and Australia. Therefore, I offer a model to curriculum developers and teachers of the earth sciences that addresses some of the generally overlooked features of the significant years of change in the debate about the history of Earth. Of particular concern where NOS issues are addressed with students, is a careful examination of the relationships among models, laws, theories, and humanistic aspects contained within this earth science debate.

1.2.5 A Personal Compulsion to Walk This Path of Controversy

As a student of the earth sciences (ca. 1980's) in a major Canadian university geology department, our tectonics courses had already accepted the new conventions of plate tectonics, and operated in a manner expected within Kuhnian "normal science". There were simply no alternative models presented to us when discussing the origin of the Earth's first-and higher-order features. Our historical geology neglected to offer a reasonably thorough treatment of how the shift to the plate tectonics paradigm had taken place within the mobilist tradition, or what the progression of conceptual change was with respect to deeply held fixist belief systems. The following observation from a sociologist of science sums up the experience of most students of geology and the specialists themselves when it comes to the question "why do I now accept the new global tectonics?":

> Most scientists read as little as they can get away with anyway, and they do not like theories in particular. New theories are hard work, and they are dangerous – it is dangerous to support them (it may be wrong) and dangerous not to support them (it may be right). The best course is to ignore them until forced to face them. Even then, respect for the brevity of life and professional caution lead most scientists to wait until someone they trust, admire, or fear supports or opposes the theory. Then they get two for one – they can come out for or against the theory without actually having read about it, and can do so in a crowd either way. This, in a nutshell, is how the plate tectonics "revolution" took place. (Greene, 1984, p. 755)

And again..

> If the plate tectonics model is false, it will nevertheless be difficult to refute or replace, for the plate model is so widely believed to be correct that it is difficult

> to publish alternative interpretations. Lacking well-known alternatives, a dominant model will not be rejected...(Saull, 1986, p. 536)

The preceding two comments shed light on the need for students to personally experience how opinion was actually constructed by geologists. How a new consensus among leaders in the field can lead to strong adherence to a new synthesis on the part of the wider scientific community who now share interests and opportunities offered by the new model (Nitecki *et al.,* 1978). In part, this can be drawn from an introduction to philosophical/historical considerations related to what was experienced by the community of earth scientists during the critical years of significant change, and brought to the classroom. For a variety of reasons such philosophical and historical dimensions of science progress, growth, and change do not commonly find expression within: (1) senior secondary courses in the sciences; (2) undergraduate geoscience degree programs and courses for non-majors; (3) pre-service science teacher education programs; and (4) in-servicing of practicing science teachers. Thompson *et al.* (2000) have identified the following factors as essential to students experiencing the nature of science and its internal controversies:

(1) the great influence of military and political events and trends;

(2) the key role of advances in instrumentation and in techniques of data collection;

(3) the role of competition and/or co-operation among members of scientific sub-disciplines;

(4) the powerful influence of interpersonal rivalries or friendships and co-operation;

(5) the enabling effects and/or barriers provided by native or foreign language and modes of communication;

(6) the social status of scientific institutions, research groups, or individuals;

(7) the vagaries of the literature refereeing process.

A response to the above is to pursue a model for the teaching and learning of global tectonics that allows for student learning experiences that have been shaped by epistemic, historical, and philosophy of science perspectives. The eventual construction of a more personalized account of events that took place as the 20th century change in ideas about the way the earth works is akin to global tectonics itself. That is, there have been episodes of "assembly" of novel ideas and actual "collisions" of competing interests (LeGrand, 1988). Some intellectual connections occurred for a time, followed by inevitable dispersal of "incommensurable" ideas according to what was deemed acceptable, or not acceptable, to the community of workers (see Plates 1-4 throughout in this work). Students can be afforded the opportunity to walk some of these same paths, and it may in some measure offer a less than "final form" aspect to their science learning experiences. One needs look no further than the recent recollections of two of the key protagonists of the plate tectonics development to see an apparent lost opportunity for students' understanding of what has occurred in 20th century earth sciences. Dan McKenzie, one of the key graduate students in the period of the development of early-stage plate tectonic models in the mid-1960's, has recently observed how little is known of the seminal contributions:

> What took me by surprise was how quickly the ideas became detached from their originators as they became accepted. Except for those involved, and for historians of science, no one now knows or cares who was responsible for a particular part of the theory. It is even hard for modern undergraduates to understand that the whole theory is so new and caused so much excitement. They quite reasonably ask, "So, what did people believe before plate tectonics was discovered?" This is a question that I find unexpectedly difficult to answer, because I cannot remove the understanding that people now have to reconstruct our state of ignorance in the early 1960's. One young faculty member in China knew Dan McKenzie had been

> one of the people involved in the discovery of plate tectonics, but was astonished to meet me. He thought it had happened so long ago that all of those involved were dead (McKenzie, 2001, p. 188).

McKenzie's recollections are doubly of concern. First, he is frustrated and bewildered by the state of 20th century historical knowledge on the part of students of the earth sciences. I share that concern only insofar as the geoscience teaching community has the primary role in affording students the *opportunity* to learn. Students cannot be held accountable for the misrepresentation or invisibility of certain geological knowledge. However, McKenzie couples his own thinking with a declaration of a general "state of ignorance in the early 1960's". He betrays his own ignorance while admitting to being beholden to the current orthodoxy that obstructs his (and his students, I suppose) ability to properly appreciate pre-plate tectonic models.

Similarly, Walter C. Pitman III who, in the early 1960's as a graduate student at the Lamont Geological Observatory of Columbia University, was a key figure in establishing the validity of sea-floor spreading from ocean-floor magnetic data, recollects:

> We had been fed some notion of the idea of continental drift sometime back in grammar school geography class ("see how South America and Africa seem to fit together like pieces in a puzzle?"), but it was not until 1965 that I began to be aware of the immense controversy this idea had provoked. In effect, I was learning about the problem as I was helping to solve it. (Pitman III, 2001, p. 94)

These anecdotes alone give impetus to the need for an historically representative and epistemologically rich treatment of teaching and learning the new global tectonics – both inside and outside of the experiences of the scientists themselves. Placing that rich episode of scientific change back into the hands of students – as it was in the hands of the graduate students during the critical periods historically – constitutes an eminently teachable insight into many aspects of the nature of scientific debate and the emergence of new knowledge claims. An earlier foray, directed at the professional geological community, for such visibility of historically grounded geoscience teaching has been outlined by this writer, but has not yet been developed substantially (see Murray, 1996b; Murray and Smerchanski, 1996). The substance of the treatment here is to refine the characteristics of this historical teaching and learning approach to modern global tectonics for students in the classroom. And to do so in such a fashion that the great struggle between the fixist and mobilist traditions provides students a more representative view of how events unfolded. There also exists here a potential in fostering awareness of how geoscientists behave as a community, reacting to crisis. Glen (1982, 1994) for instance, has published highly personal accounts of the development of plate tectonics and the recent controversy over the causes of mass extinction events – both exemplifying that the geological community was deeply divided.

1.3 The Guiding Questions

Primary Questions :

1. Can teaching and learning experiences drawn from the significant historical struggle between FIXIST and MOBILIST ideas in geology be considered an opportunity for students to examine how science progresses through struggle and controversy?

2. Can the historical context generated by the two dominant paradigms in 20th-century geology become, for students, an exploration of Thomas S. Kuhn's ideas of revolutionary scientific change in the science classroom?

Secondary Questions for Consideration:

1. What are the key relationships between the FIXIST and MOBILIST traditions in the earth sciences? Do we consider them as the two competing "big ideas" for students to examine within a Kuhnian philosophy of science?

2. What are the expectations for students in generating their own personal understanding of scientific change through examining the multitude of approaches taken by geoscientists in the years 1950 to 1975 to the problem of continental drift? (cf. Monk and Osborne, 1997)

3. To what extent can the conceptual change in the earth sciences be applied to students' Kuhnian understanding of the geoscience "revolution", and is it analogous to what was experienced within the *contexts of discovery and justification* by the specialists themselves?

4. Can the methods by which students review and evaluate the evidence from a plurality of models – based on an adequate historical representation of geologists and their ideas – be incorporated by earth science educators and curriculum developers into a teaching and learning model that more authentically represents revolutionary scientific change for students?

1.4 Limitations of the Exploration

1. It will be important to provide an appropriate context for the present study. This context will be based on a review of current literature related to geoscience education, a brief overview of the 20^{th} century developments in global tectonics, the relevance of history and philosophy of science perspectives to the science teaching and learning environment, and what constitutes a student's role in experiencing the significant struggle between two competing world views from the recent geological revolution. The nature of these contexts will be outlined in some detail in a succeeding chapter.

2. Since the scope of this study is to develop a teaching and learning model in global tectonics based on an historical approach with appeals to the philosophy of science, access to students' thoughts, reflections on the model, and its generative abilities (e.g. performance task assessments) will not be included at this time, but could constitute a further research problem.

3. An example case study, for eventual curriculum development and classroom use, will be outlined (in Chapter 4) that will detail an approach to tectonic models with students' needs in mind. The case study will include the personalities (icons) who drove novel theoretical developments, the relevant geological content as teacher background, HPS perspectives, suggestions for student activities, and exemplars from this episode of scientific controversy that may be embedded in the learning process.

4. Historically, the crucial period 1950 – 1975 will be the focus of this case study of the "geoscience revolution", with specific treatment of how the two predominant competing models of the time – the FIXIST and MOBILIST traditions – treated the available evidence. Analysis will concentrate on a Kuhnian vision of revolutionary scientific change.

1.5 Guiding Assumptions of the Study

The following guiding assumptions are being made in developing this teaching model:

1. The manner in which students develop awareness of conceptual change in science could be modeled closely to the manner in which the same processes have occurred in actual scientific practice. Initially, though, the process of change is introduced within an historical context, with students not expected to behave as practitioners would.

2. Students generally *acquire* new models and concepts in science without being given adequate opportunity to compare their earlier systems of belief - and acceptance of them - to the new models presented. Prior systems of belief are too often simply abandoned, to be used in non-academic contexts and discourse (Thagard, 1992).

3. The internal coherence and problem-solving success of alternative models to a reigning paradigm are generally underrepresented to students, and their significance unknown to teachers. Teachers, therefore, are often indifferent or hostile to exploring the details of alternative explanations of phenomena with their students.

4. Students do not customarily have the occasion to develop the sophisticated knowledge required in order to have greater sensitivity to issues related to a particular model's explanatory coherence. This impedes their ability to adequately learn novel scientific theories, and in particular, to appreciate the arguments presented by alternatives to the dominant theory within a discipline. Teachers have played a dominant role in perpetuating this situation through a narrow view of the *context of justification*.

5. Students do not naturally pass through the necessary historical stages that the scientific community does (or did) in order to arrive at their worldviews. Therefore, the history of ideas in science must be formally taught and experienced by students together with their teachers.

6. Direct exposure to the geological tradition of "multiple working hypotheses" permits students of the earth sciences to position themselves to ask questions about why they accept certain models and reject others without having the opportunity to seriously consider them (cf. Monk and Osborne, 1997).

7. The context of justification for students of the earth sciences – particularly with reference to the recent development and acceptance of the plate tectonics paradigm – is one of classical "whiggish" historiography. Judgements about former models and manners of thinking and persuasion are done in the light of modern interpretations. So long as students are consistently presented with the view that science progresses in a cumulative fashion, and that the role of science is the development of "successive approximations toward a clearer truth", the revolutionary structure of the ideas in global tectonics will act toward a fundamentally incomplete epistemology for students of the earth sciences (Kuhn's *systemic invisibility of scientific revolutions)*.

Notes – Chapter 1

1. For an interesting discussion of "whiggish" tendencies in the writings of one of the leading figures in modern tectonics, Claude Allegré, see the article by David J. Leveson, "Whiggism and its Sources in Allegré's *The Behaviour of the Earth*", Earth Sciences History, vol. 10 (1), p. 29-37.

2. It is difficult to envision an instance wherein a scientific "law" could be restricted, revised, or replaced.

3. Earlier sociological analyses of the geoscience revolution by John Arden Stewart coined the term *conceptual continents* in quantitative modeling of citations in the geological literature related to plate tectonics. This, while working on his doctoral dissertation in the sociology of science at the University of Wisconsin-Madison (Stewart, 1979). In a unique and insightful manner, Stewart traced the development of the emerging literature of the 1960's and 1970's related to various key aspects of plate tectonics through what he called a *co-citation analysis.* The basic assumption in co-citation analysis is that two references are considered more closely related to one another if they are cited together in another related article. What emerged for Stewart was a very large, 'conceptual plate tectonics continent' comprised of a large and growing body of literature related to plate tectonic theory by the late 1960's. By mapping the number of citations onto a three-dimensional "hill model", Stewart was able to draw 'topographic pictures' of these conceptual continents – the more citations an article received, the greater its elevation as a "hill". A 'continent' was, in turn, comprised of an agglomeration of these citation 'hills'. According to Stewart's analysis, the 1970's saw a maturation of the plate tectonics literature that led to the emergence of new, sometimes smaller "conceptual continents" that dispersed away from the main body of geophysical literature. For instance, some of these new conceptual continents are in fact related to characteristic elements of the plate tectonic heuristic, or are auxiliary hypotheses required by the theory (e.g. subduction zones, mantle plumes, 'hot spots', island arcs, etc.). The assertion is made that such quantitative studies of the literature can identify dynamic, changing interests within research fields, and the maps of the 'conceptual continents' illustrating the co-citation analyses may serve as useful tools for historians and sociologists of science. Further developments of the conceptual continent idea can be found in Stewart (1990) and Stewart, Hagstrom and Small (1981).

4. Henry Frankel, perhaps one of the leading historians of 20th century geology, pursued one of the earliest treatments of the geological revolution through a *non-Kuhnian* thesis (see Frankel, 1981). He identified the two great traditions in geology as being FIXISTS and MOBILISTS, with the former claiming that large-scale relative horizontal movements were plausibly deniable on strong geological and geophysical grounds – vertical motions in the crust accounted for all important geological phenomena. Within the fixist tradition, two views dominated the literature and the debate – those who could be described as "permanentists" (those who considered that the continents and ocean basins were extremely durable features and may have been primordial) and the "contractionists" – mostly geophysically oriented earth scientists – who accepted that cooling of the outermost crust, and the consequent compensation via compressional folding, held the most promise. The mobilists, alternatively, accepted and strenuously proposed horizontal displacements of the continents, and believed that such movements provided unique solutions to various vexing problems across all earth sciences specialties.

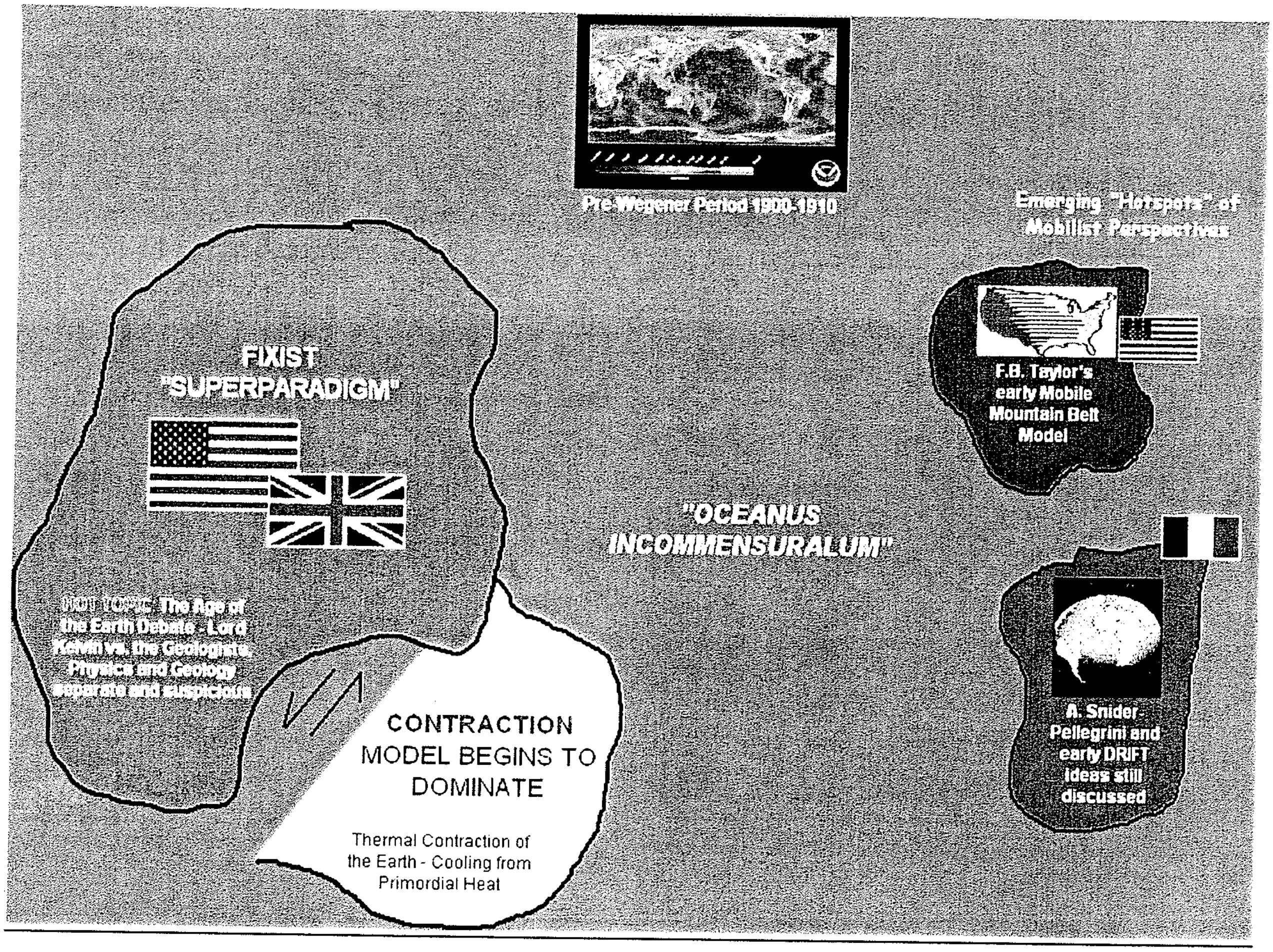

Plate 1: In the period 1900 – 1910, prior to the publication of Alfred Wegener's *On the Origin of Continents and Oceans,* the contractionist model was beginning to diverge from the major contributors to the fixist paradigm, including those who were aligned with Lord Kelvin's estimates of the age of the Earth. New mobilist arguments had begun to surface in America and continental Europe.

2.0 A Review of the Literature

2.1 Introduction

In order to define the classroom context for which this work is ultimately intended, it is necessary to outline certain details. These are the historical, philosophical, and geoscience education aspects of the development, acceptance, rejection, and further modification of tectonic models. Additionally, this thesis takes characteristic elements of science education practice found in the literature, and develops from them an approach to geoscience teaching and learning that is grounded in the history and philosophy of science. This linkage will provide for a framework from which more detailed curriculum and instruction models can be generated, and classroom-based activities and observations can be carried out. This, then, will lead to an awareness of, and appreciation for, alternative conceptual models in the earth sciences, and how these models faced the tests of controversy and collision.

What follows is a necessarily introductory literature review, but one that is intended to support the reader in the important background features connected to the arguments within this thesis. Elements that comprise this review are:

- Connections to currents in the history and philosophy of science;
- The role of science teachers' knowledge and beliefs about the philosophy of science and teacher practice;
- The contexts of discovery and justification;

- Integrating the history and nature of science into models of teaching and learning in geology;
- How has the new global tectonics been taught?;
- Identifying two colliding paradigms in 20^{th} century geology for students and kuhn's analysis of scientific change.

2.2 Connections to Currents in the History and Philosophy of Science

"School science" is often divided into categories pertaining to inquiry or investigation, technology, and decision-making. In addition, the history of school science education is a recursive cycle of periods in which the methods of science have been strongly emphasized in curriculum rhetoric, interspersed with periods when content coverage figures more prominently (Millar and Driver, 1987). Finally, whether the classroom focus is on content, process, or a combination of the two, what are considered acceptable means of imparting knowledge to students may be located anywhere along a continuum between didactics (teacher-focused) and heuristics (student-generated learning) (Schmidt, 1999). Recently, there has been an increased emphasis on constructivists' notions of activating the prior knowledge frameworks of students, exploring these more deeply, and then attaching new or unique understandings onto them (Driver, 1989; Driver *et al.*, 1994). Space does not permit an exhaustive treatment of the theoretical constructivist approaches to teaching and learning here. These have been largely found acceptable to the educational community at large, and argue persuasively in the realm of qualitative educational research (McMillan, 2002, pers.comm.). Nevertheless, connecting the two end-members (content and process) in the teaching and learning continuum is where many observers see the role of the history and philosophy of science (HPS) as an important third element. Finding the proper place in the curriculum for HPS has been an enduring difficulty since the 1960's (Bybee *et al.*, 1991), and generally-speaking, it has been an issue problematic on three major fronts:

1) teacher development and background knowledge to adequately address HPS in the classroom;
2) seeing it as a priority for teaching and learning on a level similar to issues of classroom management and essential science knowledge coverage, and;
3) noting that HPS in science teaching will not noticeably improve student achievement in science (Monk and Osborne, 1997).

The last of these counterinstance*s* bears some examination, with the desire to turn all three of these counterinstances into solved problems. In declaring that HPS in the science classroom will not "improve" student achievement begs the question: "upon what achievement indicators does such a statement rest?" Is it measured through higher standards test scores, a survey of student attitudes toward the learning involved, levels of demonstrable enthusiasm for further inquiry? I believe that there are other motivations for HPS in the science classroom that may not be easily measurable through traditional means.

2.2.1 The Role of History and Philosophy of Science, Teacher Practice, or, Why the History of Geology Matters

Though HPS in science teaching can be shown to possess a desirability, its practice within the learning environment has, at times, seemed less than satisfactorily accomplished. Nevertheless, current science education initiatives continue to recognize the importance of some exposure to the historical context in our schools. The following, taken from *Science for All Americans* (AAAS, 1989), is worth noting in some detail.

> There are two principal reasons for including some knowledge of history among the recommendations. One reason is that generalizations about how the scientific enterprise operates would be empty without concrete examples. Consider, for example, the proposition that new ideas [in science] are limited by the context in which they are conceived; are often rejected by the scientific establishment; sometimes spring from unexpected findings; and usually grow through the contributions from many different investigators. Without historical examples, these generalizations would be no more than slogans. A second reason is that some episodes in the history of scientific endeavor are of surpassing significance to our cultural heritage. Such episodes certainly include Galileo's role in changing our perception of our place in the universe; Newton's demonstration that the same apply to motions in the heavens and on earth; Darwin's lengthy observations of the variety and relatedness of life forms that led to postulating a mechanism for how they came about; and Lyell's development of the principles of geology that laid the foundations for a modern examination of the history and evolution of our planet. These [science] stories stand among many other milestones of the development of all thought in western civilization. (AAAS, 1989: p. 111)

The importance of HPS to the development of a broader social context in general education has been seen through the lens of social studies educators. For instance, Bragaw and Hartoonian (1988) outline the need for students to become competent decision makers in both the personal and civic arenas, for increasingly they will be called upon through participation in the political process to express some level of understanding in science-related concerns in public policy.

Research related to the status of HPS and the nature of science in the curriculum, according to Bybee *et al.* (1991), identifies four key areas for examination: 1) student and teacher understanding of the subject; 2) curriculum guidelines; 3) studies of actual classroom practice, and; 4) current instructional materials. Here in Canada, the *Common Framework of Science Learning Outcomes K-12* (CMEC, 1997) has provided refreshing new support for the incorporation of historical and social contexts, and the nature of science (NOS) into science teaching and learning. Perhaps less visible are the perspectives from the philosophy of science. I would tend to agree that specific and overt treatment of the philosophy of science should be done in only the most careful and introductory manner at the senior secondary level. The model being developed here will concentrate primarily on the Kuhnian perspective of the geological revolution, even though currents of thought from other philosophers of science (e.g., Feyerabend, Popper, Lakatos, Laudan, Giere, and Thagard, to list some notable members) can at times offer a more coherent treatment of certain episodes in that debate about Earth's behaviour.

Most science educators would agree that there is merit in exploring the issues of HPS and NOS as critical linkages in fostering an increasingly balanced and relevant treatment of school science. There are, however, few examples of successes that have come from the creation of curriculum materials expressly for this purpose. For instance, James Bryant Conant introduced historical case studies through his development of curriculum at Harvard University in the 1940's and 1950's. His thesis was that students would understand the methods of science through the examination of the progress and problems as these occurred historically. The *Harvard Project Physics Course* developed by F.G. Rutherford, Gerald Holton and Fletcher Watson (1970) has recently been observed to have been a "glorious failure" (A.O. Stinner, pers.comm. 2002), even though it was an exceedingly well-intentioned and designed program that pursued the historical approach in significant detail. Though recent decades of effort in nurturing HPS in the science classroom have not yielded the level of implementation that advocates had hoped for, some signs of continued emphasis continue. For instance, in the province of Manitoba in Canada, there will appear, early in 2003, a physics curriculum approach developed out of the Pan-Canadian framework that will incorporate some introductory-level strategies related to NOS and HPS (Metz, 2002, in press). This new program will encourage teachers and their students to explore the parallel development of the wave and particle models of light within an historical context, while at the same time examine these complimentary or competing models of light in terms of some of Kuhn's characteristics of an attractive theory. A sample student learning outcome illuminates the overt status now given to historical and philosophical perspectives within this forthcoming document [1]:

> Analyse competing explanatory models from history used to explain the nature of light in terms of Thomas S. Kuhn's five characteristics of a good theory *(accuracy, scope, consistency, simplicity, fruitfullness).* (Metz, 2002, in press)

By virtue of expressing an interest in the pusuit of historical and philosophical perspectives within science curriculum, it is necessary to emphasize the present state of teacher preparedness and systems of beliefs related to NOS and HPS. Equally important, from a Kuhnian point of view, is the enduring role and influence of textbooks in presenting improperly the nature of science to students. About a decade ago, Gallagher (1991) looked at the knowledge and beliefs about the philosophy of science among pre- and in-service science educators. He stressed the importance of how these individuals form, along with the media, the lasting images of science contained within the general public. It was determined that both groups of teachers possessed limited knowledge of HPS, primarily due to lack of opportunity to experience this field and its scholarship. In terms of NOS, the two groups held deeply positivistic views on the generation of new scientific knowledge, accepting for instance that there is an external reality beyond that of the observer's physical intervention that is knowable. Among the undesireable results for Gallagher, these two are notable:

1) the overemphasis on factual science remains the cornerstone of science teaching; and
2) a failure to recognize the tentativeness of scientific knowledge and the creative and social aspects of how scientific knowledge is generated, negotiated among peer groups, and ultimately validated with inclusion into an existing corpus.

There is a possible criticism, or at least a caution, that can be directed at those who are beginning to advocate for, and encourage the adoption of, a particular synthesis related to the nature of science. Some views are touted as having a degree of status and consensus within the science education community that cannot be certified. In a revealing and important quantitative study of the tenets held by a variety of philosophers of science, Brain Alters of Harvard University noted some significant disagreements about what are considered the fundamental tenets of the nature of science (Alters, 1997). Therefore, as the argument proceeds, since philosophers of science cannot agree on the basic tenets of NOS, then why should science curriculum formalize definitions along one particular line of reasoning or set of tenets? This fits into a pluralistic approach that is very appealing to the earth sciences. As we see the 20th century geoscience revolution unfold in subsequent chapters, we will find that some of the difficulties that caused intense confrontation were rooted in those who wished to maintain the tradition of *multiple working hypotheses* in geology (see Chamberlin, 1890). The mobilists desired that geology adopt a *single* set of fundamentals (laws, if you will) that argued for a new *geonomy* – a new science altogether - underpinned by physically grounded, immutable principles (see J.T. Wilson, 1968a, 1969a).

2.2.2 Whose Philosophy of Science?

A difficulty that naturally arises with the present study, then, is to make some important decisions about *whose philosophy of science* and *whose nature of science* will inform the development of a teaching model for global tectonics that pays heed to HPS and NOS considerations. Episodes such as the rejection of Wegener's drift hypotheses earlier this century, the marginalisation of the "drifters" in the period 1930 to 1960, the resurgence of an interest in mobilist models in the late 1950's, and the reception and widespread adoption of plate tectonics in the 1970's, all take on unique dimensions when in the hands of certain philosophers of science. Chronologically, as one peruses the differences among the works of Kuhn (1970, 1996), Lakatos and Musgrave (1978), Feyerabend (1974, 1981), Laudan (1977), Frankel (1981), Thagard and Nowak (1990), Thagard (1992), Giere (1999), and Oreskes (1999, 2001) in light of the revolution in geology, a variety of interpretations are clearly possible.

There have indeed been a number of historians who have adopted one or more of these notable currents in philosophy of science, and agreement on which is a "best fit" for geology in the 20th century is far from certain. If it is then unexpected that agreement will be soon found on a common basis for understanding this episode of scientific change, then we should be equally reticent about imposing a particular epistemic viewpoint on the students, as if it were the more informed or unchanging. Some science curriculum developers, for example Jenkins (1996), advocate having the students themselves engage the competing views of those who study science. The existing plurality among philosophers of science, contends Jenkins, "need not be regarded as an insurmountable problem for science education. It can, instead, be seen as an aspect of science which students should be taught and encouraged to explore" (*ibid.*, p.146). Nevertheless, I am not sanguine about offering students the fluidity and potential murkiness that could result from a treatment of the geoscience revolution from a host of available HPS currents of opinion. Rather, this thesis focuses on the development of ideological and evidential arguments that drove an important controversy, one that could well be continuing today, from only *one* perspective – the Kuhnian. In offering this restriction, it is not an intention to close debate on whose philosophy of science produces the best "fit of the conceptual continents", but recognize that the Kuhnian model of scientific change is powerfully explanatory. It also offers a degree of simplicity and accessibility for students, is fruitful, and accounts for much of what occurred historically in the debate about global tectonics. It is a promising point of departure from which to *begin* the students' journey into the HPS landscape [2]. In a sense, the choice is made by appealing to many of the characteristics of a sound theory that would have been advocated by a Kuhnian analysis in the first instance. If it is considered axiomatic in science to not unnecessarily confuse an otherwise simple set of circumstances, than one could at least recommend that we not similarly confound the initial steps of students as they are exposed to the philosophy of science in the classroom.

2.2.3 Is There a Philosophy of Geology to Share With Students?

There has been very little accomplished with reference to a particular *philosophy of geology,* whereas physics and biology enjoy significant treatment by philosophers of science. So neglected has geological science been within HPS, that one can identify only three significant contributions of the last thirty years: David B. Kitts' *The Structure of Geology* (1977); W. Von Engelhardt and J. Zimmerman with their volume *Theory of Earth Science* (1988); and the excellent overview given by Robert Frodeman in his publication "Geological Reasoning: Geology as an Interpretive and Historical Science" which appeared in the *Bulletin of the Geological Society of America* (Frodeman, 1995).

In the latter, Frodeman declares that the standard account of the reasoning process within geology is lacking in a distinctive methodology to call its own. It is, rather, viewed as a "derivative science" relying upon the techniques of, say, physics. Kitts and Von Engelhardt and Zimmerman would be comfortable within such a view. However, Frodeman counters with a reasoning process that actually sets geology *apart* from its contemporaries for quite good reason. He rejects the view of geology as being mere applied or imprecise physics, in the traditions of analytic philosophy and its application in logical positivism. He has identified two distinctive characteristics (or paths of reasoning) that are unique to the earth sciences [3]. First, geology possesses a *hermeneutic,* or interpretive, instructional aspect that derives from drawing meaning from the signs contained within the field evidence (rocks, etc.), and seeks to decipher the past from these remains. Kitts referred to this quality as *retrodiction in geology,* and this quality sets the parameters for what is certain and uncertain in geology (Kitts, 1977, p. 39). In short, all geological understanding is best considered as an interpretive process, and has analogs in how the physician interprets the signs of the disease state or how circumstantial evidence is assembled for trial.

For a science like geology, relying as it does on an excessive use of iconographic representations (e.g., geologic maps, stratigraphic charts, block diagrams, cartoons of subduction zones), one must bring to the science some precepts of what such art forms are intending to convey [4]. As we will discover later on, the existence of young, Tertiary-age mountain systems mean one thing to a contractionist thinker (failure of the crust near continental margins following millions of years of sedimentary deposition), and quite something else to an advocate of plate tectonics (ophiolite complexes or accreted, exotic terranes). Geological interpretation argues that original goals and assumptions will determine from the outset what facts are set forth as important and requiring explanation by theory. What, then, of the eschewed "facts", avenues of research, or areas of potential importance that go unexplored? As these omissions accumulate over decades, a science identifies itself through a particular *recorded or sanctioned history,* but can never account for what may have been, and lost to that history. These omitted or excised points, however, should not be lost with respect to how students are taught to understand and appreciate the role of evidence in the case of accepting a new global tectonics.

This takes us to the second of Frodeman's aspects – that of geology as *history.* It has been said that geology differs from most other sciences in one, vast sense – that of its immense fourth dimension of time. Geology seeks to chronicle events that have actually, or apparently, taken place over aeons in the case of continental movements, or days in the case of volcanic eruptions and inundation events. In this respect, geology cannot adopt the hypothetico-deductive experimental approaches that could otherwise occur to test an hypothesis or evaluate a prediction. The event has already taken place, and proxies have been left behind for the "observer" to glean possible explanations.

Faced with such temporal and spatial difficulties, not to mention the complexities and oftentimes singular nature of events, modeling the geologic past must turn itself to other types of reasoning, such as analogy, multiple working hypotheses (Chamberlin, 1890; outrageous hypotheses (Davis, 1926), and (with apologies to the physicists) eliminative induction (Frodeman, 1995). It is also important to note that geology has begun to extricate itself from the conventions of its *uniformitarianism* that was one of the traditional hallmarks of the discipline going back to James Hutton and Charles Lyell. This, because the principles of uniformitarianism (ostensibly considered as interpreting past events within the context of what one observes happening geologically at the present time) have been unable to account for occurences such as sudden mass extinctions of life, the Cambrian explosion of new body plans in the fossil record, extra-terrestrially-induced catastrophes, and the periodic nature of volcanism and mountain building (orogenies). The late Stephen Jay Gould (1987; 1989) has reduced past reliance upon a predictable gradualism and encouraged an embracing of a new *contingency model* wherein geological events are likely probabilistic in nature. We can now freely deal with past geological environments that have no modern analog, and can separate our brief human time spans from the immeasurable expanse of geologic time. Nevertheless, there is a new uniformitarianism, presently powered by plate tectonics, as the "new present as key to the past". Brian F. Windley, in *Uniformitarianism Today: Plate Tectonics is the Key to the Past* (Windley, 1993), summarizes what he considers to be compelling evidence that:

> ...confirms that the plate tectonic paradigm can be applied convincingly back to the beginning of the geological record...processes that produced oceanic and continental rocks since the early Archaean (4.0 Ga) have not been fundamentally different from those that operate today. (Windley, 1993, p. 7)

Windley did caution against applying his analysis too liberally, and did not claim that the present and the past are *identical.* As has often been the case in geology, the spectre of Lord Kelvin and thermodynamic principles appears, and we read the cryptic "with this thermal caveat, it is possible to say it is unlikely that any of the continental material preserved on Earth today was produced by processes significantly different from those that operate now." (*ibid.*, p. 16).

2.2.4 What is Happening in Geology Classrooms Now?

There exists some recent evidence in support of, among one group of science students observed recently, another form of uniformitarianism. This brand may colloquially be summarized as *"the present misconceptions are the keys to the past"*. In a study of what the authors term "alternative ideas and misconceptions" among Portuguese science students related to the earth sciences (Marques and Thompson, 1996, 1997), the following were identified as misconceptions:

- Continents are rooted hundreds of kilometers deep;
- A progressive slope is present from the centre of the continents to the centre of the bottom of the oceans;
- The cooling of the Earth causes the appearance of topography;
- A fixist view about the location of continents is held;
- The same tectonic mechanism causes both the continental and oceanic mountain ranges;
- Vertical forces push up the crust and originate the continents.

The intent of the next phases of instruction was to, in effect, remove all of the above misconceptions and then claim that the students have now adopted the consensus view. A remarkable and powerful opportunity to link these students' prior knowledge (I am willing to admit these as *alternative ideas,* but not *misconceptions* for reasons to be stated momentarily) with the tenets of the FIXIST paradigm – and particularly its contractionist manifestation –

was missed in their treatment phase. Each of the characteristics of Earth's behaviour or constitution listed above has, at one time or another, been a deeply held conviction of geology until the upheaval that was the 1960's and 1970's. To hold these conceptions as acceptable was, in the first half of the 20th century, not only consistent with alignment to the reigning synthesis, but what could be held as the only *conceivable* interpretation of the available evidence. In short, these misconceptions of today were the system of orthodoxy in geology yesterday. One of the conclusions drawn from the study of Marques and Thompson (1996) was that "traditional teaching strategies in earth science classes do not eradicate students' prior misconceptions" (p. 212). A casual glance at what were deemed student misconceptions by these authors does not necessarily reveal their intractability, but constitute a set of views remarkably parallel to those once at the heart of geological thinking. One could expect that pedagogical techniques alone could put the students into a situation where their entry-level beliefs will at least be called into question, if this were a desired end. As we will observe in Chapter 3, however, the rootedness of these conceptions among students is reflected historically in how remarkably similar views were upheld and vigorously defended by the leading earth scientists of the times when these ideas were popularized. More than simply common-sense or pre-scientific views about the nature of planet Earth, such student conceptions comprise excellent opportunities for teachers to access the historical perspective.

At least one of these 'misconceptions' – that of deep continental roots – is worthy of some additional treatment here. In a seminal paper that was potentially devastating to the possibility of large-scale mantle convection in 1963, Gordon J.F. MacDonald outlined in his *"The Deep Structure of the Continents"* that heat flow data mitigated against any significant migration of continental blocks beyond a short distance along the Earth radius line upon which they were located. Without a sound geophysical probability that the planet can convect, almost any consideration of continental drift comes to a rheological halt. MacDonald was held up as an obstinate "anti-drifter" by his colleagues who attended NASA's Goddard Symposium of 1966. In the words of Sir Edward Bullard – one of the key protagonists in support of drift theory among geophysicists – "many precedents suggest the un-wisdom of being too sure of conclusions based on supposed properties of imperfectly understood materials in inaccessible regions of the earth." (quoted in Oreskes, 2001, p. 124). This was, for MacDonald, seen as a masterful putdown, and not long after this confrontation, he found himself disengaging from the solid earth scientists as a community, and began devoting his energies to the study of the atmosphere and long-term climate change.

It is notable for Marques and Thompson to now observe that recent evidence on the deep structure of continents (Fischer and van der Hilst, 1999) puts their roots on the order of 250 kilometers, and places MacDonald's earlier arguments on a renewed, firmer footing. It is no longer tenable to hold, as a student misconception, support of the notion of a deep structure of continents. It may in fact be an opportunity to examine with students how tentative certain features of the new global tectonics have been of late. The teaching model advocated here is intended to encourage students to confront both *themselves* and *one another* when it comes to geological ideas in collision. This can best be accomplished by setting before them the two, competing paradigms that fuelled the debate, and do this with particular attention to the historical perspective.

2.3 The Contexts of Discovery, Justification, and a Search for an HPS Model

As early as the late 1930's, Reichenbach (1938) differentiated between two important contexts – the *context of historical discovery*, and the complimentary *context of epistemological justification.* The former is thought to include the set of imaginative ideas, unconventional techniques, and novel ways of thinking that direct a scientific community to previously unknown conclusions or applications of their knowledge. Within this context can be found speculative arguments, neologisms (new terminology), metaphorical language, and descriptive accounts. The context of justification, however, is more properly evident in the traditional role of science education – the transmission of established bodies of knowledge that answer the question "what do we know?". This view does not require a "sophisticated epistemology" on the part of science teachers (Elby and Hammer, 2001), who are generally comfortable with the products of science, requiring little or no substantial justifications to be passed on to their students. According to Duschl *et al.* (1992), the context of justification emphasizes the development of an understanding of the evidence supporting current scientific theories "*without regard* to predecessor theories" (p.28, emphasis my own). A more recent interpretation (Monk and Dillon, 2000) operationalizes this context as the combination of evidence, logic, communications skills, rhetoric, and personal connections important to the success and acceptance of one's ideas.

From Duschl's limited processes (investigative procedures) and products (concept instruction) model, one important component can be adopted – that of the scientific chain of reasoning that leads to adoption of a single paradigm. It can be used to illustrate what may constitute a fundamental weakness of such an approach. Duschl argues that what is best for students, in order to capture the context of discovery, is to explore at least one episode from the history of science that involves significant paradigmatic change. Recently, Kiddell (1996) responded to this invitation of Duschl within the context of the development of the theory of plate tectonics as a classroom-based case study with students. However, since Kiddell concentrated on the single-model approach advocated by Duschl, her students were left with the enduring impression (and the one perpetuated in a considerable number of geology textbooks and learning materials) that this episode of scientific change was one of progression from earlier, naïve models, to a more sophisticated picture. Such interpretations have already surfaced among some influential members of the geological community (Leveson, 1991). Despite the advocacy of this teaching approach by Duschl, and others who have applied it, I am now suggesting that the more comprehensive, internally consistent, historically representative, and philosophically valid (Hodson, 1988) approach to examination of the events in 20th century earth sciences is to adopt some form of the pluralistic teaching model articulated by Monk and Osborne (1997).

What the primary literature suggests, together with a large number of historical case studies and recollections of geoscience community members (see Allegré and Courtillot, 1999; Glen, 1982; Hallam, 1973, 1983; LeGrand, 1988; LePichon, 2001; McKenzie, 2001; Menard, 1986; Nunan, 1988; Oldroyd, 1996; Oreskes, 1999, 2001; and Stewart, 1979, 1990) is, that in the case of the earth sciences of the 20th century, the more appropriate viewpoint is one of a multiplicity of competing, contemporaneous models of the way the earth evolves and behaves near its surface. Many of these competing conceptual models can be subsumed within the simplified boundaries set out by the two large scale worldviews of "fixism" and "mobilism". It is in this sense that the argument here intends to make a clear break with some of the conventional presentations of the new global tectonics as having been the natural consequence of inductivist methods in geology, together with a tale of steady approximations toward an inevitable breakthrough to the "truth" about the way Earth dynamics works.

2.3.1 The Pluralist Model of Monk and Osborne

Prior to assessing how Monk and Osborne's pedagogical model could (with appropriate adaptations) be applied to the phenomena of global tectonics, it is appropriate to briefly lay out the six phases that these workers suggest, and point out certain limitations in the applicability of the model to our purposes:

Phase 1 : Presentation of the phenomenon to students;

Phase 2 : Elicitation of students' ideas related to the phenomenon;

Phase 3 : Historical Study – teacher presentation, or student research into the historical ideas related to the phenomenon;

Phase 4 : Devising experimental tests;

Phase 5 : The Scientific Idea and Empirical Tests – how did the scientific community conduct the tests?;

Phase 6 : Review, Evaluation, and Discussion of the different forms of interpretation.

In terms of Phase 1:

In keeping with the constructivist ideals of appealing to, and giving status to, students' entry-level thinking, it is appropriate to introduce the story of global tectonics as a topic worthy of the students' attention and interest. This has been captured well by Betty Anne Kiddell's "real world applications approach" (Kiddell, 1996), and appeals to the ground-breaking work of Driver and Oldham (1985). Both historically and philosophically speaking, the earth sciences has always maintained a strong tradition of what used to be termed "multiple working hypotheses" (Chamberlin, 1890), and more recently it has been considered a key component of the disciplinary matrix of geological thought (Kitts, 1977) or in a post-modern sense, an aspect of a broader '*geosemiosis*' – one of the "signs" that identifies geology as an uniquely historical science (Baker, 1999).

Toward Phase 2:

Some researchers have questioned the value of approaching science education with a rationale based on "the way scientists work" (Caravita and Halldén, 1994; Hodson, 1996; Millar and Driver, 1987; Osborne, 1996). They criticize the manner in which the parallels between the development of students' ideas and the development of scientific ideas over the course of history have sometimes been used to falsely equate students' science with scientists' science. Caravita and Halldén (1994) attempt to draw distinctions between students and scientists on numerous grounds. Many of their arguments underestimate the sophistication of the ideas and arguments that students are able to generate. Duschl *et al.* (1992) compare the merits of "context of justification" and "context of discovery (development)" approaches to science education . They define a 'context of justification' as a method of teaching science in which students either generate or are taught evidence for existing theories, and a 'context of discovery' approach as one in which students are expected to understand the historical development of the ideas that they are studying. However, these are not the only possible rigid alternatives. Understanding the nature of science is an important goal, and students will likely gain a better understanding of this process if they reflect on their own contexts of development that can occur through a re-visiting of the evidence that was made available to the scientific community. As a result of this action, though, we may not wish to be overly concerned that students' views will not always mirror those of the historical development of the ideas themselves. Of greater interest is to offer students the opportunity to articulate their own creative and imaginative responses to the available evidence, and perhaps, if the opportunity arises, see if their thinking in any way parallels that observed historically by the scientific community through its interactions.

Students today are surrounded with evidence of scientific principles in action, through their interactions with the environment and their participation in the society in which they live. However, one of the key difficulties facing *geo-scientific* principles in action is that these often occur on time and dimension scales that are orders of magnitude beyond what is customary in human experience. Public understanding of tectonics, it seems, is constrained by these spatial demands (Jacobi *et al.,* 1996). It seems likely that students could gain a better appreciation of the "false starts and misdirections" (Duschl *et al.*, 1992, p. 36) of 20th century global tectonics if they actually experienced some of these vicariously, through participating in a re-creation of those experienced by scientists historically, and concentrating less on the potential barriers imposed by the difficult spatial considerations.

Within the context of discovery, it may prove difficult to have students offer their own whole-earth models as complimentary to those already espoused through past geological efforts. Prior knowledge will likely bring forth strongly biased models that are not necessarily connected to their place in the history of geological ideas. This is not considered a fault of the students, but a critique of the manner in which their prior conceptual knowledge in the earth sciences was laid down (the stratigraphy of the "landscape" outlined previously). Nevertheless, this does not argue for the non – inclusion of student-generated models, but simply a careful assessment of the characteristics of those that are generated. One manner in which this could be synthetically accomplished is for the actual historical models to be "elicited" alongside the models offered by the students.

Phase 3 considerations:

It is this phase that is considered crucial in relation to the development of ideas that eventually culminated in the rapid move to plate tectonics by the geoscience community. It is also the point at which most previous attempts at capturing the nature of this scientific change have remained within the HPS literature, and not adequately brought to the classroom experience for the benefit of students. The transition from earlier FIXIST commitments to the now influential MOBILIST paradigm in the earth sciences was by no means smooth, fluid, or even expected. As the debate unfolded, it is at the most fundamental level that we find the most intense personal and professional commitment to one or the other – syntheses having characteristics of both paradigms are more recent developments (e.g., Lowman, 1985a, 1985b, 1992). Consequently, the only manner in which the history of this debate can be viewed, and kept historically integral for students, is to recognise that it is the tale of two completely independent conceptual arguments destined to collide in the face of the new evidence that poured forth from the world's ocean basins in the post WW II era. Each view carried with it secondary research traditions (or programs if we appeal to Lakatos) that can be subsumed within either the fixist or mobilist traditions. For the sake of brevity, we will not have the scope to exhaust all the identifiable features of some of these subsidiary research programmes, but will focus on what could be described as the two great "conceptual supercontinents" of the FIXIST and MOBILIST paradigms.

Monk and Osborne (1997, p. 416) outline the following "multiple inputs" as essential for teachers, and these can be summarized as follows:

- An example of early thinking on the phenomenon as yet one more view to consider (I would suggest that more than one example of that *early thinking* would be beneficial in the case of global tectonic models)
- Background information on the economic – social – political conditions of the time (in the case of geological thinking, the geographic location of researchers is of prime importance, as is their country of origin and institutional affiliations)
- An example of competing ideas from other scientists and not necessarily the modern textbook version (I would take this a step further by suggesting that among the competing ideas, there should be included at least one model that was rejected on a basis outside of rational or evidential arguments)

- Some discussion or exploration of the data or other background that might have added support for the historical view; and
- A brief chronology in terms of dates and events that need some sorting

It is with the above characteristics in mind that an interesting, rich, and multi-layered "science story" could be constructed as an exemplar lesson for classroom use (e.g., Matthews, 1994; Stinner, 1995). On occasion, however, such "science stories", as rewarding as they are intended to be by their creators, offer a narrative that may still be outside of the realm of the students' imagination and interests. If the students themselves are afforded the opportunity to create these narratives, there can be some sophisticated, and at times, dramatic results. [5]

Problems and Potential Successes with Phases 4 and 5 :

Monk and Osborne (1997) openly declare that students will be able to design their own experiments in order to assess the available evidence, and act realistically as a community of researchers, thinking creatively and imaginatively as they conduct themselves in a collegial manner (p. 418). They go on to indicate that carrying out these experimental designs is beyond the limited time constraints imposed by school science. The recommendation, then, is to be very selective about what topics easily lend themselves to such practical investigations. One cannot be sure about how successful this will be unless one defaults to the imposition of teacher-directed experimental design. Then, we may have lost any potential gains that a more student-directed inquiry process offers. Rather than having the expectation that students are to be directly involved in Kuhnian "normal scientific" pursuits, it is perhaps more desirable (and this is not intended to denigrate student abilities and freedoms) that they be presented with certain key investigations or crucial tests that were conducted historically, and seek opportunities to add to the variety of alternative explanations that emerged. Their impression that this is a form of "window" on the generation of auxiliary hypotheses that can be developed to explain a body of evidence. The projected timelines to accomplish all of these aspects are potentially too ambitious – *more* than one or two classes, experience shows with this approach, will be normative to have modest accomplishments.

Their treatment of the closure of the scientific story is exceedingly important, and has direct implications to the teaching approach advocated in this present study. What they intend to leave the students with is the impression that available data supports a resolution of the conflict in terms of the currently acceptable model. Moreover, students are encouraged to accept this consensus as sufficient for now, but must remain open to reinterpretation of the evidence and discuss the treatment of anomalous results. They properly advocate a rejection of the notion that modern consensus equates with durable, lasting *correctness.* The adoption of the instrumentalist view that a modern explanation is indicative of superior predictive ability, or has wider application, or is a unifying influence among disparate subdisciplines, is certainly acceptable. More problematic, however, is whether students will have the necessary position to question *how the scientific consensus* was reached. I suggest that the sociological, personal, and institutional elements need to be included in any treatment of scientific consensus-building. This takes us logically to their stage six.

Stage 6 : Consideration of the Implications of the Evidence

It is at this final stage that students are afforded the opportunity to weigh evidential arguments, deciding on issues such as, "is it fruitful?","is it logical?" (Posner *et al.*, 1982). In the case of this study, students ultimately must be engaged, as the geoscience community was in the period 1950-1975, in an intense struggle between two dynamical models of earth history. It comes down to us in the established literature as Wegener's original (1912, 1924) *"The Origin of Continents and Oceans",* Samuel Warren Carey's *"The Tectonic Approach to Continental Drift* (Carey, 1958), Harry Hess's *"The History of Ocean Basins"* (Hess, 1962) – all geological thinkers – and the great opposition posed by the geophysical community (led by physicist Sir Harold Jeffreys at Cambridge) who declared that it was an impossibility on compelling physical grounds. With some poignant parallels, it is somewhat of a reprise of the arguments in the age of the Earth debate that occurred in the late 19th and early 20th centuries. This is the essence of this "science story" that is to be presented to students, such that...

> ...in our model, the final review will require an opportunity for students to reflect on the products of the resolution of the conflict, which have now become the products of the context of discovery, and compare them with their own thinking. Hopefully, such a phase will enable them to note that historical thought cannot be considered ignorant or stupid, for they too have had similar ideas. It may also become apparent that the ideas of science are not often based on what seems self-evidently salient. Rather, that it has taken imaginative and creative leaps of thought to transcend the limitations of commonsense thinking, and scientific ideas are the contingent product of a socio-historical and geopolitical context and culture. However, most importantly, this approach does focus on *what we think now* – that is, the science concept that is in the curriculum, whose knowledge and understanding by [students] is the main aim of the science teacher (Monk and Osborne, 1997 p. 420).

Carr *et al.* (1994) also emphasize the importance of this form of knowledge acquistion by students:

> The most important feature of an approach to science classes which addresses the difficulty of changing ideas is conversation. Science lessons which continually seek learners' ideas, which help to clarify them, and which provide an open and unthreatening environment for changing these ideas through conversation are classes in which learning in science can be improved. The false idea that science is exact , and therefore that concepts in science are unproblematic, can be argued to have trapped science teaching into a pedagogy which misrepresents both the content of science and the process whereby this content is constructed (p. 158).

2.4 Integrating The History And Nature Of Science Into The Geology Classroom

Geology is an eminently historical and descriptive science, and at times has had its arguments calling for the reformulation of the fundamentals of physics (e.g., see Hunt, 1992). In perhaps one of the earliest accounts that discussed a *philosophy of geology*, Kitts (1977) submits that geological science can only be fruitful by operating within established, immutable natural laws that have their source in the physical sciences. Indeed, he was convinced that what most were calling a Kuhnian overthrow of the prior fixist hegemony (e.g. Wilson, 1968a,1969a) was not revolutionary at all. In Kitts' manner of thinking, there were no physical "superparadigms" that were dismantled or made subordinate to a new, sweeping synthesis. Therefore, even though the new plate tectonics was a crucial theoretical breakthrough, it acquired its explanatory influence not from geology, but from the established physical principles (e.g. Euler's Theorem related to the rotation of crustal plates) of a much older physics and chemistry that are generally found acceptable to geologists anyway [6]. In an important critique of Kitts' analysis, Laudan (1980b) counters that it has not been uncommon for geology to find a kinematic representation of crustal movements acceptable even when a dynamical mechanism remains to be worked out.

Analogously, Hallam (1973) points out that "gravity, geomagnetism, and electricity were all fully accepted before they were adequately explained" (p. 110). What may have separated these comments from the situation related to drift ideas is important to state here. What may have undermined the earlier mobilist ideas was not that there was no *acceptable* mechanism that could explain the evidence, but that there was no *conceivable* mechanism that would operate within accepted physical theory. Laudan (1980a) correctly observes that it is more likely that a novel hypothesis will be deemed acceptable, without a known cause or mechanism, provided that any potential causal mechanisms will not be ruled out *a priori* on physical grounds. In the case of mobilist ideas, strong evidence for a substantially solid mantle down to appreciable depths was certainly going to place the burden of proof on there being extraordinary or overwhelming field evidence for drifting continents. The situation for Alfred Wegener, and other supporters of drift theory, though, could be said in this way - if it *did* happen, it *can* happen.

From a NOS perspective, it is important for students to experience the inevitable friction that occurs when one discipline is calling upon another to begin thinking radically about altering its fundamentals. For instance, geology has a particular epistemological manner in which it views the world, and has recently been called a *geosemiosis* by Baker (1999). By interpreting in a semiotic (through signs and symbolisms) way, geological knowledge complements and contrasts with other ways in which scientific knowledge is developed and organized [7]. These are important contrasts for students to gain experience in the NOS as a key purpose in their science education. By designing curriculum materials in geology that present students with differing, if not completely opposing, sets of arguments (e.g. about the permanence of ocean basins on the one hand, and the impermanence of oceans in the drift hypotheses; contractionism versus expansionism; polar wandering with permanent continents or continental drift with mobile lands), there may be enhanced potential to see the rhetoric of science in action first hand (Erduran *et al.*, 2001). It is argued here that such point-counterpoint features in the delivered science curriculum serve students well in formulating their first impressions of how scientific communities behave, how individuals respond to novel facts that may erode cherished systems of belief, to understand the role of critical tests, evaluating the rhetoric during a crisis period, and having some opportunity to personally assess how the evidence was indeed validated, evaluated, and subsequently codified (Glen, 1994).

This historical contextual approach avoids "final form" science, with the teacher availing the students of only the *latest* facts, interpretations, and the traditional acceptance of the current orthodoxy. Recently, Mayer (1996) and Mayer and Armstrong (1990) have observed that the historical perspective, particularly within the earth sciences, could assist in avoiding the deterministic and reductionist view of science in general, or the isolation that comes with examining a constructed world rather than the natural world.

The kind, nature, and history of ideas related to Earth's crustal relationships have been important to science in the past century and a half – and not confined to the earth sciences alone. By virtue of having a meteorologist and aeronomist, in Alfred Wegener, set the tinder alight with radical thinking on the movement of Earth's surface features, there is an immediate cross-disciplinary aspect to the controversy that ensued. The topic of continental drift now appears in the new Grade 7 science program for all Canadian students who are in schools aligned with the *Pan-Canadian Framework* (CMEC, 1997). This is a crucial period for students, as they are very likely to be expected to adopt a style and set of learning experiences that are grounded in a textbook treatment of science, and one that is now seen as perhaps the earliest stage of what will become a formalized treatment of science that continues until the senior secondary level and beyond. Once students have reached the expected levels of sophistication at the senior secondary level, we can incrementally introduce them, in a sort of initiatory way, to aspects of scientific change as revealed by philosophers of science. A Kuhnian analysis, as mentioned previously, is open to debate as to its robustness in accounting for all vagaries contained within the geoscience revolution, but does constitute an accessible first step for students. This, along with the unique characteristics of global tectonics itself – capable of distillation into an excellent, first-order simplicity with accessibility and great visual appeal – make it a good fit for students of this age.

2.5 Some Current Efforts In Teaching The Historical Development Of The New Global Tectonics

Thompson, Praia and Marques (2000), when field validating new curriculum materials related to the development of plate tectonics theory for Portuguese science students aged 13-14 years (grade 7), outlined the following characteristics as being encouraged by textbook teaching and whole-class pedagogical practices:

- A strong empirical perspective, stressing pure, unbiased observation as the fundamental starting point in the construction of this [particular to geology] and indeed any, scientific knowledge;
- A lack of mention of the historical and social aspects of science, which are quite crucial to grasping the main points of the controversy concerning the fixist and mobilist paradigms;
- The consideration of drift as an important stepping stone on the way to explaining global plate tectonic theory which is perceived to have much more educational value than the precursor Wegenerian drift theory; and
- The existence of two major opposing camps amongst the scientific community of the time – one fixist and orthodox, the other mobilist and somewhat heretical.

To these characteristics, I would add the following within the purview of traditional teaching characteristics in global tectonics:

- An over-emphasis on the view that prior tectonic models were naïve, lacking in predictive and explanatory power, and would be expectedly overturned at some point;
- The fixist position was essentially grounded in the "shrinking, wrinkling apple" phenomenon attributed to the American geologist Frank Bursley Taylor;

- The existence of a sophisticated, convection current-driven global tectonics is viewed as a recent development, whereas its roots go back to the 1930's with the prescient models of Arthur Holmes (Allwardt, 1990);

- The *sea-floor spreading hypothesis* of Harry H. Hess (1962) is viewed as contemporaneous with the development of plate tectonics, and part of the theory – the two are quite distinct;

- That plate tectonics is taught to students through powerful heuristic devices (e.g., block diagrams, puzzle-like fits of crustal plates, cartoons, etc.) that render a simplified description of dynamical principles that are not yet robust postulates of the theory itself;

- That plate tectonics developed through a sequence of inductions based on novel facts brought to light through heretofore unavailable technologies; that observations, and the steady accretion of data moved the community of scientists to embrace mobilism;

- There were no significant names of geoscientists to attach to the schism that came to pass between the fixists and the mobilists – the endeavors are portrayed as collectives among indeterminate individuals, often without mention of geographic location or institutional affiliations.

Over the years of its exciting evolution, when giving consideration to how the development of the new global tectonics has been treated in classroom settings, it may be crucially important to note how it is being treated today. Perusal of an influential introductory-level textbook in tectonics published recently (Moores, 2002), there is *no mention* given of the historical background to plate tectonics theory. It is treated as, *de facto,* the only paradigm to be taught to the next generation of geologists, and is considered so robust that only the principles of the theory (e.g., plate kinematics, relations to ore deposits geology), and not its interesting historical development, are examined. This could well constitute an unprecedented pace of enshrinement of a new paradigm in a modern science discipline, and a clear vindication of the role ascribed to texts within "normal science" by Thomas Kuhn in *Structure.* As recently as the mid-1970's, there existed textbooks in geology – though few – that advocated a more cautious tone, respecting equivocation over hurried or blind acceptance of the new global tectonics (Wyllie, 1976). It seems that, even in the shorter term, haste and expediency will soon re-write all geological texts, including those that claim that the principles of plate tectonics are transportable to other 'terrestrial' planets (e.g., Venus and Mars) and the moons of the Galilean planets (Jupiter and Saturn) .[8]

2.6 Identifying Two Colliding Paradigms In 20th Century Geology For Students, And Kuhn's Analysis Of Scientific Change

When invited to comment upon the reasons for the success of an introductory course in geology for non-majors, Stephen Jay Gould (the late Alexander Agassiz Professor of Geology at Harvard University) identified two key strategies:

> I try to follow five principles in this general quest to make science accessible, especially to people who think they are bored with or afraid of the subject. The strategy is basically two-fold: appeal to the mind (attack boredom) by showing how intriguing the material can be; appeal to the emotions (attack fear) by displaying science as a quintessentially human enterprise done by fallible people with all the motivations, base and noble, that propel us all. (Stephen Jay Gould, 1984; commenting on what made his introductory geology course at Harvard the most sought-after elective in that institution's history, turning away over 400 aspirants per year)

Continuing on in that paper, Gould illustrates five principles in a quest to make science more accessible to students. These include:

- Conveying to students the excitement of the subject; he claimed that general theories such as catastrophism or plate tectonics acted as wonderful exemplars that had the potential to alter a student's perception of the world – permanently;
- Choosing topics carefully that were both current, or controversial, or both; demonstrating how scientists can argue, debate, make mistakes, get intensely and personally involved in bitter rivalries, and destroy careers; include key protagonists (and their antagonists) by name, and connect them to their cherished belief systems;

- Use an historical approach to emphasize the humanistic character of science; cultural presuppositions of the age tend to connect to the content of contemporary theories;
- Emphasize the differing styles of scientific inquiry, from the mathematically-oriented and deductive sciences to those that are more descriptive and tend not to "traffic in prediction";
- Convey the actual practice of science to students by focussing on the primary literature of research (or very good secondary sources) – not placing emphasis on what he calls "watered-down and often falsely abstracted textbooks and popular science articles". Gould maintains that judicious selection of the primary literature can still be very readable to the general student audience. For instance, if we wish to understand more fully J. Tuzo Wilson's "conversion" from the fixist to the mobilist perspective, we should do that by reading *Wilson*, not a contemporary commentator.

Given Gould's best practices for invigorating a course in the earth sciences, we can now focus and refine these to consider their utility in light of the philosophy of science perspectives advocated here. One may wish now to include the perspective that comes from introducing to students, in introductory fashion, the connections that exist between a Kuhnian approach to the philosophy of science (ideally, those ideas that he was an exponent of prior to his partial recantation) and the revolutionary changes that took place among geologists, geophysicists, and other earth scientists during the period of global tectonics upheaval.

We have reached the point where some specifics of why I am advocating the teaching and learning potential of global tectonics through a *"paradigms in collision"* model is particularly appealing. Furthermore, the simplicity of describing 20^{th} century geological debate through the lenses of but *two* paradigms locked in a struggle for dominance is not far from the manner in which things unfolded. Though it is always possible to concentrate on and critique the fuzzy edges, lack of a perfect fit of ideas, and the finer details that attract the interests of historians and philosophers alike, a good case can be made for considering what is manageable and of interest to students.

2.6.1 Towards A Classroom-Based Kuhnian Philosophy Of Geology

Certainly in the wake of the second release of *Structure* (Kuhn, 1970), intense interest in the paradigm concept by philosophers of science eventually found its way into the sphere of science educators by the 1980's. Christopher Ray (1991) in his *Breaking Free from Dogma: Philosophical Prejudice in Science Education* remarks that the diversity of opinion among philosophers of science makes it unwise to entrench a particular view of science in the classroom with students. He contends that partisan views – if not forceful proselytisation efforts – about what science is and is not do not allow students to grasp that there exist fundamental disagreements about the nature of the scientific enterprise. A very clear example of the plurality that exists can be found among those who have interpreted the 20th century geological debate in the literature. The acceptance or rejection of continental drift theory or plate tectonics have variously been described and interpreted by historians and philosophers alike through the lenses of Kuhn (Hallam, 1973; Laudan, 1980a; LeGrand, 1988; Stewart, 1979, 1990), anti-Kuhn (Frankel, 1981; Kitts, 1977; Oldroyd, 1996; Ruse, 1981), Imre Lakatos (Frankel, 1979), Larry Laudan (Frankel, 1980), and Bayesian rationality (Nunan, 1984). Thus, decision-making about a particular approach to the philosophy of science with respect to geological matters in the classroom setting with 17- 18 year-olds must ensure sensibility, comprehensibility, and a degree of simplicity to make the ideas accessible. My sense is that the Kuhnian perspective on the geo-science revolution is a good enough first approximation to make it work well.

The paradigm approach to the history of science (Kuhn, 1970) offers the suggestion that there is a distinct difference in the practices of scientists during "normal" or "paradigm-directed" science and "revolutionary" science – an interesting period when a novel paradigm is displacing, subsuming, or completely eradicating an older one. The paradigm concept, admittedly re-worked and modified by Kuhn himself, is a constellation of beliefs, values, procedures, and methods of inquiry that are the shared deposit of a community of workers. It is powerful in the sense that it is *learned* through an initiation process or training through common research experiences. Kuhn has identified this set of beliefs and practices as the *disciplinary matrix*, comprised of elements such as: symbolic generalizations, metaphysical models, values, and exemplars.

Normal science permits rapid advancement of a field of knowledge due to increased and sustained motivation among the research community in a narrowly-defined set of possibilities and problems within the context of justification. The paradigm, then, sets the expectations by which the validity of further research will be assessed, evaluated, and justified. If results fall short of, or external to, the paradigm commitment, it is not the paradigm itself that is failing – there must be found other causes of the anomalous results. A good geological example of current normal science would be studies that refine the velocity vectors of present plate motions, application of the plate tectonics model to the evolution of life, and accounting for the causes and distribution of global seismic activity (Stewart, 1979).

The values aspect is an important consideration for students. Typical values include those that impact the evaluation (elegance ?) of theory structures: simplicity, accuracy, quantitativeness, scope and range of applicability. Visual models could be considered, particularly in geology, as being within the compass of value statements. For instance, the schematic representation of tectonic plate boundaries (see Figure 2.1) is perhaps the leading metaphysical representation of the plate concept – a true Kuhnian *exemplar*.

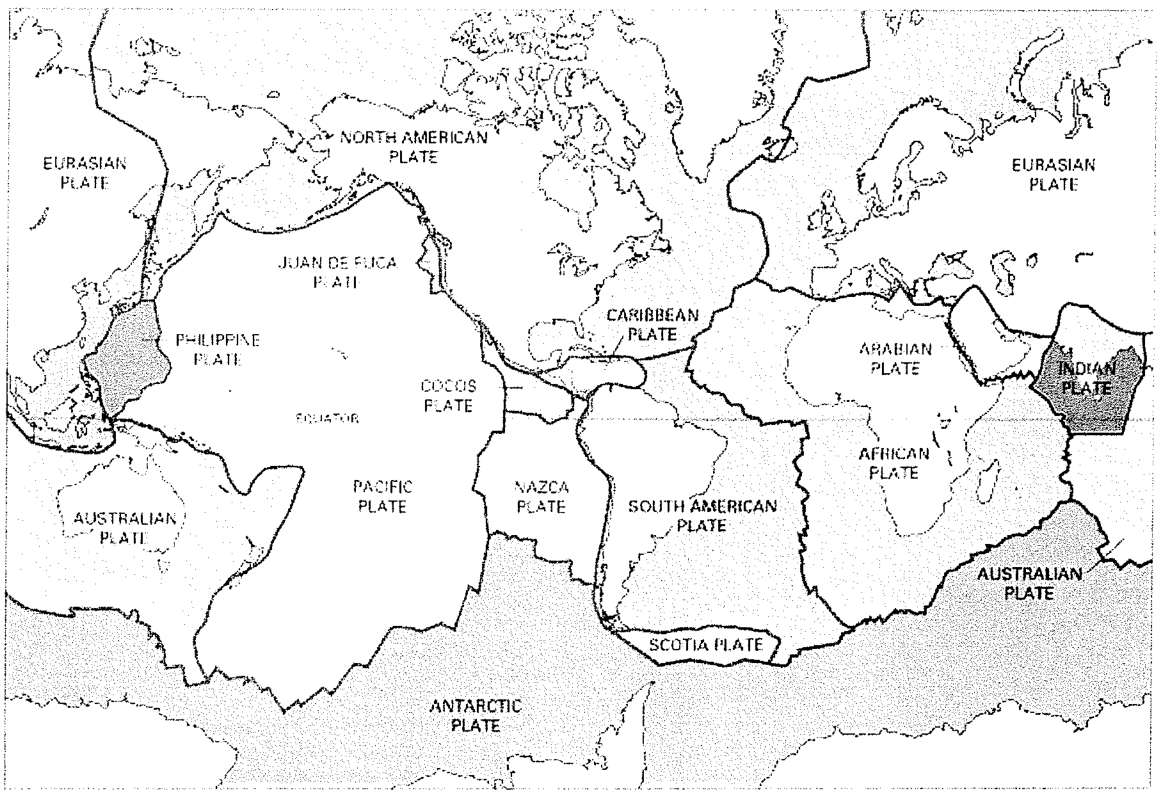

Figure 2.1 Diagrammatic representation of the world's major plate boundaries as determined from the abundance of earthquake foci.

(USGS, used with permission)

The above representation of plate boundaries is an abstraction determined by the definition of what a plate boundary actually is. Operationally defined, it is a narrow zone of intense seismic activity. If regions of high seismicity are deemed to constitute crustal plate boundaries, than the existence of plates is dependent upon the location of earthquake epicenters (see Figure 2.2)

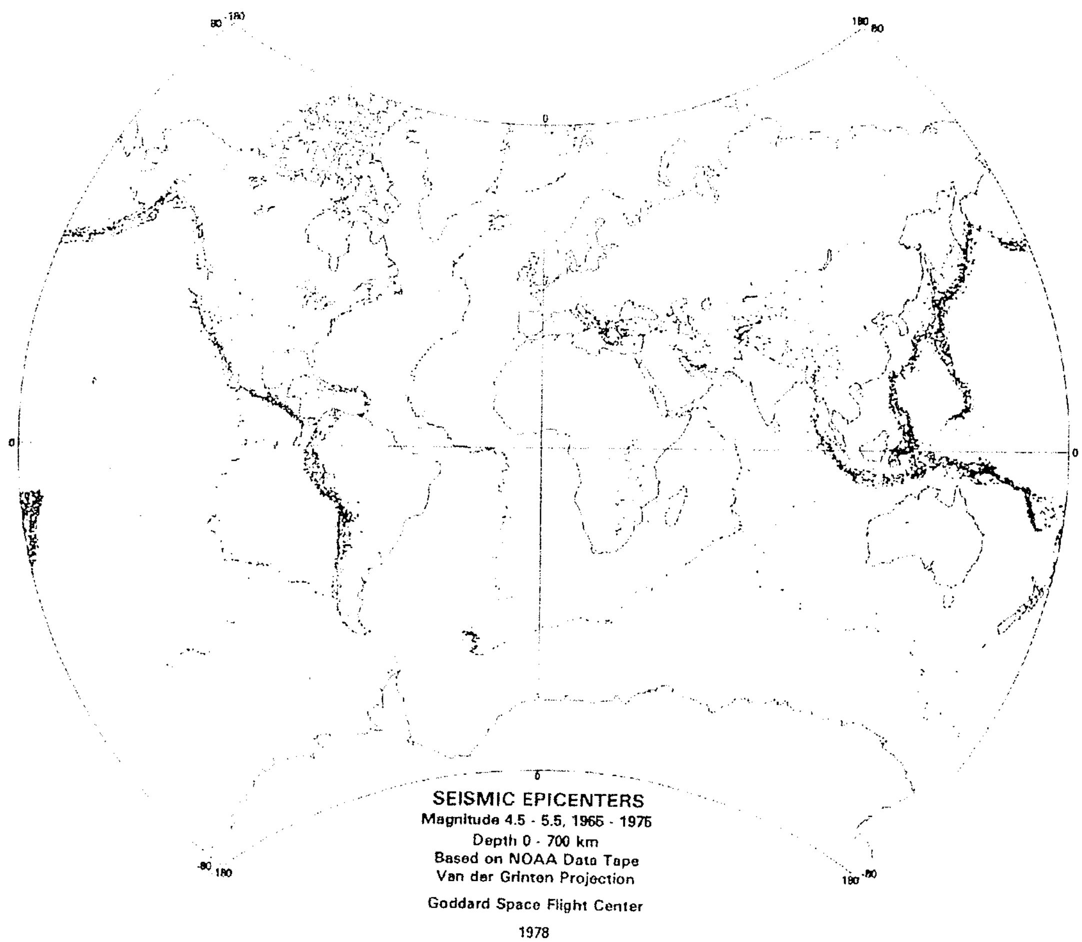

Figure 2.2 World seismicity map of earthquake epicenters over the years 1965-1976. Compare the regions of high seismicity on this map with the location of plate boundaries seen in Figure 2.1. This arrangement of dots constitutes another Kuhnian-type exemplar.

(courtesy NASA Goddard Spaceflight Center, Greenbelt MD. Used with permission)

Such schematic pictures are also supported by traditional algorithmic, symbolic generalizations. Such formalized expressions as **F = ma** can be found in geophysical representations of the kinematic motions of crustal plates. For instance, transform faults slip in a direction that is opposite to the direction that the plate is being displaced – an instance of a verbal symbolic formulation. Mathematically, we may see such expressions as $V = V_x sin\theta$ which relates to the velocity of the spreading of the ocean floor, V, the number of degrees, θ, from the pole of rotation, and the maximum observed plate velocity, V_x. This latter example is an equation that can be used to *define* the pole of rotation, and could be interpreted as a more symbolic mode of representing a Kuhnian exemplar.

Exemplars are, for our purposes here, specific scientific publications (or perhaps more fitting, the ideas and conceptual steps contained within these benchmark papers) that illustrate how elements such as the ones just outlined can be applied to specific research problems. They are widely recognised within the scientific community as major accomplishments in the field. [9] As has been noted earlier from the experiences of Gould (1984), such exemplars can be within the grasp of students who may not have yet had the opportunity to be enriched by the primary literature. More will be said about the role of scientific literature in Chapter 4, where the model for treatment of the geoscience revolution with students is outlined in detail.

According to Kuhn, there is a great deal of tacit knowledge that is communicated to students as they are socialized into a research community. This is done by studying carefully the exemplars of the past and following select, approved research pathways. There is more than a subjectivity to this tacit knowledge, since it is a shared commodity that has been established as useful to prior research. Somewhat closer to the science classroom, one may find an analog in how we socialize our own students into the nature of *our* science experiences through shared values, methods, and how problem-solving is constituted. According to Rudolph (2000), in a recent critique of the hoped-for inclusion of the philosophy of science and NOS in the science classroom, the application of Kuhnian or Lakatosian analyses of large-scale shifts in the theoretical structure of a science over an extended period of time will "fail miserably" unless the attendant historical analysis of the content knowledge is also developed with students. The developments in global tectonics, however, have the distinct advantage of being compressed into a remarkably brief time period (1920's to the 1970's) such that an individual's life could span the entire period. This makes the accessibility of the historical components an easy task, and since many of the protagonists hailed the changes as "revolutionary" or "Kuhnian" in nature (e.g., Wilson, 1968a, 1969a), it is sensible to consider the period with students in a similar manner. There may not even be a need, as described by Matthews (1994), for a synthetic or distillation approach that gleans from a variety of workers within the HPS a sort of lower-level, agreeable core set of statements about science around which educators can rally and apply directly.

Returning then, to the Kuhnian characteristics that make his ideas attractive for use in examining 20th century geological thought, the concepts of "anomalies", "crisis", and "revolutionary science" are addressed. It was made quite clear by Kuhn that paradigms are not generally subjected to tests once one has taken hold of the specialists who are bounded – or constrained – by it. When anomalies surface – manifest failures of the paradigm to account for new evidence, for instance – that does not mean the end of the fruitfulness of the paradigm so long as other areas of research remain fecund. Nevertheless, if the kind or number of anomalies accumulate to the level where there is a severe threat posed to the basic, guiding assumptions of the paradigm, then the community of workers could be said to enter a period of "crisis". One excellent example of an external threat to turn-of-the-century geology came from physics, when thermodynamic principles – and the persuasive influence of Lord Kelvin – placed severe new constraints on the conceivable age of the Earth. Stewart (1979) referred to this as an instance when one research group exerts a *conceptual pressure* that precipitates a crisis situation in another, non-aligned group of workers.

As the crisis period continues, elements of the paradigm become subject to modification, some being of an *ad hoc* character, and this can be a particularly fertile period of "wild theories", or perhaps what Davis (1926) considered "outrageous hypotheses". New, emergent reorganisations of key cognitive elements among working groups can spawn nascent, rival paradigms that contain their own different assumptions, exemplars, and suggestions for a new "normal science". If a significant competition, or confrontation develops between two or more communities, we can then enter what Kuhn described as a "revolutionary science" period. Revolutionary science is thought to exist when competing paradigms claim that their view offers the best solution to some of the outstanding anomalies in addition to subsuming the required solved problems of the prior hegemony. Since research must occur within a paradigm, a state of great tension can develop as the landscape accommodates more than a single one at one time. Identification of what constitutes an important problem is paradigm-specific, as are the new meanings and assumptions that characterize each alternative view. Communication among rival groups becomes difficult, and this Kuhn termed *incommensurability*. Persuasion, or the context of justification, then, becomes a significant operand as rivals seek to convince within the literature, symposia, and various fora. This ideological aspect of peer persuasion warrants a look at the following:

> The effects of shared ideology.....are less uniform, for its mode of application is of a different sort. Given a group, all the members of which are committed to choosing between alternative theories and also to considering such values as accuracy, scope, simplicity, and so on, while making their choice, the concrete decisions of individual members in individual cases will nevertheless vary. Group behaviour will be affected decisively by the shared commitments, but individual choice will be a function also of personality, education, and the prior pattern of professional research (Kuhn, 1970: p. 241).

How the above dynamic was actually seen to occur depends on point of view. The above perspective is accessible to students in the classroom, and in particular it is important to carefully address the sociological aspect, as students rarely have the opportunity to witness how professional scientific communities arbitrate competing views. Nor does the practice and pedagogy of science offer adequate opportunity for students to vicariously put themselves in a position to consider the evidence independently of their paradigm-driven texts. For instance, when it comes to making that critical choice, Kuhn considers diversity of opinion a strength, for "if a decision must be made under circumstances in which even the most deliberate and considered judgement may be wrong, it may be vitally important that different individuals decide in different ways. How else could the group as a whole hedge its bets?" (Kuhn, 1970, page 241). Interestingly, Lowman (1992) sees this diversity aspect of the decision to accept plate tectonics a real problem pedagogically for students when he asserts "the most serious charge against plate tectonics as an educational device is also the simplest: the theory may be wrong" (*ibid.*, page 6). Lowman uses this comment as a precursor to his advocacy of teaching all competitive theoretical models that still exist within the literature today, including the plate tectonics paradigm as one of a broader array of working hypotheses. He sums up with the statement "it is unfair to students not to prepare them for this possibility [that plate tectonics will be overthrown]" (*ibid.*, page 7).

One of the principal criteria or value set used to persuade others to adopt a paradigm is its perceived fruitfulness (i.e., the number of interesting and potentially soluble problems (Kuhn would call them "puzzles")). The manner in which fruitfulness is measured or applied is, of course, subject to the characteristics of certain group memberships within a discipline. In some cases, only full acceptance of the paradigm can then initiate an evaluation of its fecundity. Kuhn has offered that there is a chronological aspect to acceptance propensity – he suggests that younger scientists, or newer recruits to a field, are more amenable to socialization into a new model than their older, entrenched colleagues. Outsiders are also perhaps more prone to accepting a novel set of guiding assumptions. The history of the geological revolution reveals some anomalous behaviours with respect to these indicators – some older, established geophysicists (e.g., J. Tuzo Wilson, Sir Edward Bullard), geologists (S. Warren Carey, Chester Longwell), physicists (Pascual Jordan, P.A.M. Dirac, R.H. Dicke) and the mentors of key graduate students (Drummond Matthews) were among the early proponents of the new mobilist perspectives. Planck's Principle (that the older generation must "die off" before a new theory can be accepted by the next generation) did not apply particularly well to these groups of senior researchers in the earth sciences, and this nicely bears out the thesis argued by Hull *et al.*(1978) against the untidy application of the "elderly holdouts" phenomenon.

The switch from one paradigm to another, for Kuhn, is not a Lyellian gradualism, but an epiphany – a conversion experience that includes a significant "*gestalt switch*" as if scales had fallen from one's eyes. The shift may be even more dramatic when it occurs in older, established workers who have held deep commitments to the former paradigm that they may have been instrumental in developing, propagating, and teaching to students. The following recollection of Xavier LePichon, from his retrospective *My Conversion to Plate Tectonics* (in Oreskes, 2001), is illuminative:

> It was during a conference organized by NASA in New York in November 1966 that the victory of mobilism was clearly established. Teddy Bullard, who presided, could not find a single scientist to defend fixism.[10] But it was during the April 1967 American Geophysical Union meeting that, to use Bob Dietz's phrase, "the total and instantaneous conversion of the American community to continental drift occurred. You could see it on their faces and even in their eyes". It was there, too, that the mobilist model had [finally] become quantitative (LePichon, 2001; quoted in Oreskes, 2001, p. 213).

The revolutionary period ends when a new paradigm succeeds in gathering the majority of practitioners in the various groups affected by the emerging new synthesis. One enduring misunderstanding drawn from Kuhn's analysis of scientific development, and one often implicitly (and unknowingly) espoused in the science curriculum as whiggish tendencies, is that the new paradigm constitutes an *improvement* on the pre-existing one. Lakatos and Musgrave (1970) provide some fine examples of how this error has been made manifest in the history and philosophy of science. Kuhn does not lay claim to the assertion of his critics that his position is hopelessly relativist, but he does defend this notion by saying that one cannot be entirely certain that a new paradigm is a closer approximation of some "truth" or "what is really out there". Nevertheless, he does support the view that *progress* results from paradigm change by appealing to his criteria of simplicity, scope, accuracy, and success at making quantitative predictions. There is a caution here, though. According to Kuhn, it is the textbooks (rewritten ones in particular) that offer the appearance of rapid, progressive advancement by being exponents of the major, newly-solved problems that troubled the antecedents. The actual, nonprogressive developments lurking within a scientific revolution become invisible in the new texts, and are completely lost to students. It comes down to what are deemed critical anomalies in need of treatment, and those which can be safely ignored as text becomes the vector of educational change (cf. Jacobs, Russell and Wilson, 1959, 1974).[11]

In their volume, *Scrutinizing Science: Empirical Studies of Scientific Change*, Donovan *et al.* (1988) and (simultaneously) in Laudan *et al.* (1988) a number of 'theses' about guiding assumptions were outlined, and a set of 'theses' about theories, their interrelationships, and appraisal by workers within a research program. Many of their theses will find their application to certain episodes in the development of the new conceptions that emerged among communities of geoscientists in the development of whole-earth tectonic models. If we were to select from this list those that are particular to the historical analysis of Kuhn as revealed in *Structure,* one can offer to students a shortlist that works particularly well for our simplified epistemic purposes here:

- empirical accuracy and coherence within a theory;
- a theory's ability to solve problems outside the domain of its initial success;
- scientists are prepared to leave empirical difficulties unresolved for years;
- empirical difficulties become acute only if a rival theory explains them better;
- scientists associated with rival theories fail to communicate with one another;
- guiding assumptions change abruptly and totally, and the entire scientific community changes its allegiance to the new guiding assumptions;
- younger scientists are the first to shift and then conversion proceeds rapidly until only a few elderly holdouts exist;
- scientists prefer a theory that can solve problems not solved by its predecessors;

Another valuable asset rests with offering the *teacher* a manageable first foray into HPS in the classroom experience. A potential shortcoming, outlined by Laudan *et al.* (1988), is that most case studies attempt to apply one particular theory of scientific change (e.g. Kuhnian, to cite a perceived over-applied example) *in toto* rather than in a synthetic manner to assess the relative adequacy of a set of otherwise rival theories of scientific change. Most case studies rely upon secondary and tertiary sources of information rather than the primary literature and accounts involved. In the case of global tectonics, however, we possess the unique advantage of having many of the key protagonists still living, and their vast literature readily accessible. Hence, the teaching model developed for this thesis could be expanded to draw attention to a set of theories of conceptual change overlapping the disciplines of science, science education, science pedagogy, and currents from the philosophy of science (here, however, we apply primarily Kuhn's analysis).

Returning to the foregoing discussion, when members of the geoscience community assess the merits and/or demerits of both current plate tectonics and extant rival theories, scant attention is given to the important guiding assumptions concerning what constitutes an 'anomaly'. As outlined above, when empirical difficulties surface for a particular paradigm (to put it in Kuhnian terms), the discipline should be faced with what Kuhn described as a "crisis" situation. If there exists a serious rival theory that can resolve the anomaly, we now have an "acute" problem situation. There have been a host of instances where plate tectonics has failed to adequately solve anomalous problems stemming from empirical evidence (see the volume edited by Kahle, 1974), but its overall effectiveness at solving what are considered more important problems has likely deflected or ignored most of the criticism that arises from any unsolved irritations. This is, of course, classically Kuhnian.

With an increasing emphasis being placed now on the history and philosophy of science as a component of curriculum development in science (e.g. AAAS, 2000; Duschl, 1994; National Research Council, 1996), and an awareness that understanding issues in the HPS may be critical for the development of scientifically 'literate' persons (e.g. Bybee *et al.*, 1991), it may be important now for geological education to create for its students a more balanced treatment of the present state of global tectonics, and how it is defending itself in the face of new rivals (Hallam, 1980).

When viewed as a continuum, from the early fixist models to Wegenerian continental displacement, and eventually to sea-floor spreading coupled with mantle convection, and ultimately to plate tectonics (PT), it seems reasonable that each new approach preserved the major successes of its former rivals, while at the same time reducing the number of conceptual difficulties and empirical anomalies of its predecessors. In the 1960's, tectonicists were faced with a clear choice of a mobilist paradigm that seemed, in most respects, superior to the permanence of the fixist alternative. What is more obscure is the rationale behind the acceptance of PT over the expansionist alternative, when both were powerful explanatory models. Ultimately, the choice of PT by certain influential individuals may have been just that - individual assessments linked to the fortunes of influential professional interests. Nunan (1988) submits :

> Researchers tend to commit their energy and resources to one research tradition, ignoring or denigrating serious rivals. But that fact still doesn't explain why the bulk of earth scientists linked their professional fortunes to plate tectonics rather than expansion. I suspect that familiarity breeds adherence (Nunan, 1988, p. 309).

Was the geoscience community's familiarity with lateral motions and compressional orogenesis linked to the familiarity of English-speaking and influential figures such as Harry Hess and J.Tuzo Wilson? The rivals were less mainstream 'Gondwanalanders' such as S. Warren Carey, the Hungarian, Laszlo Egyed, and German expansionists like Otto Hilgenberg and the physicist Pascual Jordan.

A case in point is the German school, whose work was all but forgotten until it was resurrected by Carey in the 1950's. These, and others who were on the 'fringe' of geology, generally worked in regions that were geographically isolated from the professional communities in America and Western Europe (Nunan, 1988). Is adherence to PT a completely rational theory choice, when serious rivals (for instance, expansionism) did exist, but have been paid scant attention or dismissed in ridicule? There exists plenty of assurance in the field that PT has a great deal to commend it, both conceptually, and according to the field evidence - particularly its applicability in the world's ocean basins. Nevertheless, there were seriously competitive, comparable models outside of the fixist alternative that are now considered moribund and unacceptable. I think a case can be made that the geoscience "revolution" is still going on (Owen, 1981), though that is a matter of debate, and the prospect leaves the potential for obscuring the major conflict that has left us where we stand at present. For if new evidence convinced advocates of PT that serious anomalies do exist (and there are some unattended to), and an alternative became the more progressive research program (in the Lakatosian view), current advocates of PT could consider abandoning – or at least modifying - PT in favour of the more progressive alternative. It appears that the examination of this case study in geology points to a situation where serious rival theories have been dismissed (or marginalized) on insufficient empirical grounds. It is not desirable for students to be in the situation of a McKenzie or Pitman as outlined earlier. As LePichon (2001) recounts in a repentant moment:

> I also regret the oblivion into which [Samuel] Warren Carey and Bruce Heezen have fallen. I believe, furthermore, that not enough attention has been paid to the priviledged relationships existing among a few key laboratories. In a sense, the history of the elaboration of plate tectonics can be read as a concerto for three instruments in which Princeton, Cambridge, and Lamont (Columbia) successively held the soloist role until they joined together in the final chorus (quoted in Oreskes, 2001, p. 221).

LePichon's reference is to the destruction of the expansionist group in America – and in particular the reputation of Bruce Heezen at Lamont - and the limited access to data in the worldwide community of workers. Small wonder students today are a "one-paradigm" classroom in the realm of global tectonics. The paradigm itself was likely generated in a parochial environment.

According to the recently released National Research Council (1996) *Science Standards:*

> The solid Earth is layered with a thin brittle crust, hot converting mantle, and dense metallic core. Crustal plates on the scale of continents and oceans constantly move at rates of centimetres per year in response to movements in the mantle. Major geological events, such as earthquakes, volcanoes, and mountain-building result from these plate motions (NRC, 1996, pg. V-89).

Further on in the document, in the section on *"History and Nature of Science"*, we read:

> Scientific explanations must also include a logical structure, rules of evidence, openness to criticism, reporting methods and procedures, and making knowledge public. Explanations on how the natural world changes based on myths, personal beliefs, mystical inspiration, or authority may be personally useful and socially relevant, but they are not scientific.....all scientific knowledge is, in principle, subject to change as new evidence becomes available. In areas where data or understanding are incomplete, such as the questions surrounding (our planet), new data may well lead to changes in current ideas, or resolve current conflicts (*ibid.*,p. V-167).

The above statements are mutually distinct, and presented in a major curricular document serves to highlight the on-going difficulty in making room for alternative points of view in the teaching of geology. All important curriculum documents in recent years that have dealt with the teaching of the 'mobilist' perspective in geology do so from one point of view - plate tectonics. It is hoped that it would be more enriching for students of the geosciences to entertain on-going, parallel research traditions that do not subscribe to the plate tectonics paradigm exclusively – if this were possible. This is both informative, stimulating, a balanced treatment of the current issues, and is more aligned to my earlier point about presenting the key ideas as a conflict between two influential paradigms.

It has been made clear from a number of quarters within the HPS community that serious reservations about the Kuhnian paradigm approach – and its validity or applicability to the geological history of ideas – do exist. I resist the temptation to enter into that finely structured debate here (to include the alternative views of other philosophers and observers) for reasons outlined earlier, and for the reason of my own particular need for simplicity. It is hoped, however, that the preceding discussion of Kuhn's chief characteristics of the paradigm approach will act as important teacher background discourse of how his seminal contributions could contribute to the science student.

2.6.2 The Need For A "Colliding Paradigms" Approach For Students Of The New Global Tectonics

In his *Conceptual Revolutions* - on cognitive and conceptual change in children - Thagard (1992) advocates a lengthy list of episodes from the history of science as being potentially useful in examining the manner in which young people accommodate, adapt to, or acquire scientific theories. Some of the more interesting and compelling of these, for Thagard, were phlogiston theory, Darwinian evolution, Harvey's circulation of the blood, Newtonian kinematics, and the continental drift debate. Though Thagard's interests were primarily in the realm of conceptual change in children, he was confident that the history of science could provide a wealth of opportunities to examine whether children's theoretical development mirrors that of the scientific community. This aside, I am attracted to his proposal that students of science can be taught a "greater sensitivity to explanatory coherence issues, and whether this sensitivity can lead them to learn new scientific theories more readily" (*ibid.*, p. 261) Further on, he asserts that scientific theories fall generally into one (or more) of three categories: 1) data-driven; 2) explanation-driven, or; 3) internal coherence-driven. There also exist differences in how conceptual models change amidst scientific revolutions, with the most radical conceptual leaps being taken by the most dramatic scientific revolutions. My sense is that the geological revolution is best presented from the simple, but powerful standpoint of *two colliding paradigms* – the FIXISTS versus the MOBILISTS – with the result of the collision a great conceptual leap of faith among the geoscientists. Consideration of the motivations for doing this, the following are important. I look for students to:

- Come to explore and appreciate the interesting history, and related discussions and debates which have taken place within the geological community during the last 100 years;
- Develop their own responses to the historical episodes, in a simplified introductory manner, that contain discussions around the role of evidence, models, theory-dependency, and the role of personality in scientific persuasion;
- Examine the exemplary data from geodesy, topography, stratigraphy, paleontology, paleomagnetism, and paleoclimatology as these drove the geological revolution;
- Become increasingly aware of, and responsive to, how scientific problem-solving provides for inter-group co-operation, rivalry, the revelation of long-sequestered schisms;
- Appreciate more fully some of the immense theoretical obstacles that geoscientists had to overcome in order to change their allegiance from the fixist to the mobilist side;
- What are some of the less well-known scientific, political, sociological, and cultural contexts that led, for instance, to the exclusion and isolation of certain individuals (and their ideas) from the fixist-mobilist debates?;
- Examine and clarify, for their particular interests, those aspects of the nature of science that we wish to emphasize in the classroom. This, through understanding the biases, commitments, and theoretical adhesion that can be observed within the earth science communities of workers in the period 1915 – 1975.

Taken in sum, this list of learning experiences produces a depth of treatment of the geological revolution that assists in maintaining a balance between delivering the important content while addressing many of the compelling historical details that make science a human endeavor.

Notes to Chapter 2:

1. It may be useful to see how this entire unit of study related to the wave-particle models of light has been constructed by Don Metz (2002, in press). What follows here, however, is one further example

   The student will be able to:

   Explore, examine, and discuss the consensus on the wave-particle duality of light that was arrived at within the physics community.
   Include: Principle of Complimentarity and the Copenhagen Interpretation

2. For the reader who is interested in analyses of scientific change in geology through the lenses of other philosophers of science beyond Thomas S. Kuhn and *The Structure of Scientific Revolutions*, the following are important (see refs. for full bibliographic information):

   Michael Ruse (1981). What Kind of Revolution Occurred in Geology?

   Henry Frankel (1981). The non-Kuhnian Nature of the Recent Revolution in the Earth Sciences; (1982) The Development, Reception, and Acceptance of the Vine-Matthews-Morley Hypothesis;

   Larry Laudan, A. Donovan, R. Laudan, P. Barker, H. Brown, J. Leplin, P. Thagard, and S. Wykstra (1986). Scientific change: Philosophical models and historical research.

   Rachel Laudan, Larry Laudan and Arthur Donovan (1988). Testing Theories of Scientific Change; in A. Donovan *et al.* (eds.) *Scrutinizing Science: Empirical Studies of Scientific Change*

   Rachel Laudan (1980a). The Recent Revolution in Geology and Kuhn's Theory of Scientific Change. Rachel Laudan (1980b). The Method of Multiple Working Hypotheses and the Development of Plate Tectonic Theory. (It is notable that Rachel and Larry Laudan are spouses).

   Ronald N. Giere (1999). Visual Models and Scientific Judgement.

   Homer E. LeGrand (1988). Drifting continents and shifting theories: The modern revolution in geology and scientific change.

   Richard Nunan (1984). Novel facts, Bayesian rationality, and the history of continental drift.

   John Arden Stewart (1990). Drifting continents and colliding paradigms: Perspectives on the geoscience revolution.

3. The terms "geology" and "earth sciences" are sometimes considered synonymous. I will identify geology as a particular set of viewpoints that are underpinned by field evidence and interpretation, and containing an important historical dimension (geologic time). In this manner, geology is behaving as one of the family of earth sciences. The other earth sciences could include, but are not limited to, geophysics, geochemistry, paleontology, glaciology, stratigraphy, etc.

4. For an excellent treatment of the iconography of geology, and in particular, the influential role that the visual aspects of the plate tectonics revolution had on the scientific community, see Ronald N. Giere (1999). Visual models and scientific judgement. in R.N. Giere (ed.) *Science Without Laws.*

5. For samples taken from the author's classroom in Winnipeg, Manitoba, see Murray (2000). For examples of student-generated one-act short plays involving key protagonists of the new global tectonics, including Alfred Wegener (the "drifter"), Sir Harold Jeffreys (the staunch defender of the contractionist model), Hugh Gwyn Owen and S. Warren Carey (expansion tectonics), see those presented in Appendix 'B'.

6. As will be noted in a subsequent section, one of the primary reasons that early drift ideas were found to be approaching an heretical status – and the same can be said for concepts involving expansion of the Earth's interior in the 1960's – was that an appeal was being made for a *new physics* to be applied to the geological evidence. Even though the age of the Earth debate had left geologists somewhat circumspect about geophysical improbabilities around the turn of the 20th century, it has been perennially difficult for geology to convince others – particularly physicists – that the field evidence at times calls for a re-examination of what are thought to be immutable laws.

Some physicists, however, have shown an inclination in the past to consider such profundities (see Pascual Jordan, (1966; 1971 in translation from the German by Arthur Beer.), *The Expanding Earth* ; Dicke, R.H. (1959). Gravitation – an Enigma, *American Scientist,* March 1959, p. 25–40; Dicke, R.H. (1957). The Principle of Equivalence and the Weak Interactions, *Reviews of Modern Physics, vol.* 29., p. 363; Dirac, P.A.M. (1938). A New Basis For Cosmology, *Proceedings of the Royal Society, Series A,* p. 199-208; Dirac, P.A.M. (1937). The Cosmological Constants, *Nature,* vol. 190, no. 4781, p. 323; Egyed, Laszlo (1957). A New Dynamic Conception of the Internal Constitution of the Earth. *Geologische Rundschau,* vol. 46, p. 101-121.

7. For a fuller treatment of how the concept of reading the "signs" of the Earth – a geosemiotic point of view, see Victor Baker (1999) and Ronald Giere (1999) whose interests often are directed at the iconography found among the earth sciences.

8. See, for instance, the application of plate tectonics to Mars' tectonic history in : Cowen, Ron (1999). Plate Tectonics on Mars – Magnetic map reveals ancient activity on the red planet, *Science News,* vol. 155 (18), p. 284-285; McKenzie, Dan P. (1999). Plate Tectonics on Mars?, *Nature,* vol. 399 (6734), p. 307; Sleep, Norman H. and Kenneth L. Tanaka (1995). Point-Counterpoint – Did Mars have plate tectonics? *Mercury – Journal of the Astronomical Society of the Pacific,* vol. 24 (5), p. 10-12; Norman H. Sleep (1994). Martian Plate Tectonics, *Journal of Geophysical Research – Part E – Planets,* vol. 99 (3), p. 5639-5656.

9. W. Jason Morgan's 1968 paper, "Rises, Trenches, Great Faults and Crustal Blocks" that was published in the watershed year of 1968 in the *Journal of Geophysical Research* has all the hallmarks of a Kuhnian exemplar. This work sets out the first quantitative models of relative plate motions on a spherical surface. Morgan used the symbolic generalization, $V = V_x \sin\theta$, and illustrated plate motions with great simplicity, together with relations to a wide range of geological phenomena and the potential of the model to yield significant, testable predictions. This paper, as shown in Stewart (1979, 1990) was one of the most highly-cited solid-Earth papers over the years 1970 – 1976. For a fascinating account of how Morgan's work almost went unnoticed in 1967 at the annual meeting of the American Geophysical Union, see the historical accounts of William Glen (1982), H. W. Menard (1986), Stewart (1990) and LePichon (2001; Chapter 13 in Oreskes, 2001).

10. This statement is either incorrect or LePichon has not remembered that Gordon MacDonald was the presenter of a key address at this Goddard Symposium on his "*deep roots of continents*" hypothesis – and the need for fixed continents. MacDonald was so roundly criticised by attendees for holding back progress in the new global tectonics – based on a sort of geophysical obstinacy

similar to a Sir Harold Jeffreys – that he left the meeting prior to the final plenary session in disgust and bewilderment (see MacDonald, 2001). In the published proceedings of the Goddard Symposium (see Phinney, 1968), which did not appear until almost two years after the meeting, the editors did not see fit to even publish MacDonald's paper. It was as though no trace of a sound fixist argument could be left in the volume. Moreover, some papers in the published proceedings were written by invited authors who were not in attendance at the meeting. The transcripts of discussions are particularly revealing in the appendices of this volume edited by Phinney.

11. For detailed treatment of the anomalies that have periodically surfaced – to little avail – within the plate tectonics paradigm, these are well laid out in the volume *Plate Tectonics: Assessments and Reassessments, AAPG Memoir 23,* edited by C. Kahle (1974). The paper by Arthur and Howard Meyerhoff (son and father in that order) contained within this volume, "Tests of Plate Tectonics", is a major critique of dozens of anomalies that, in the authors minds, are serious enough to warrant careful reassessment of the plate model.

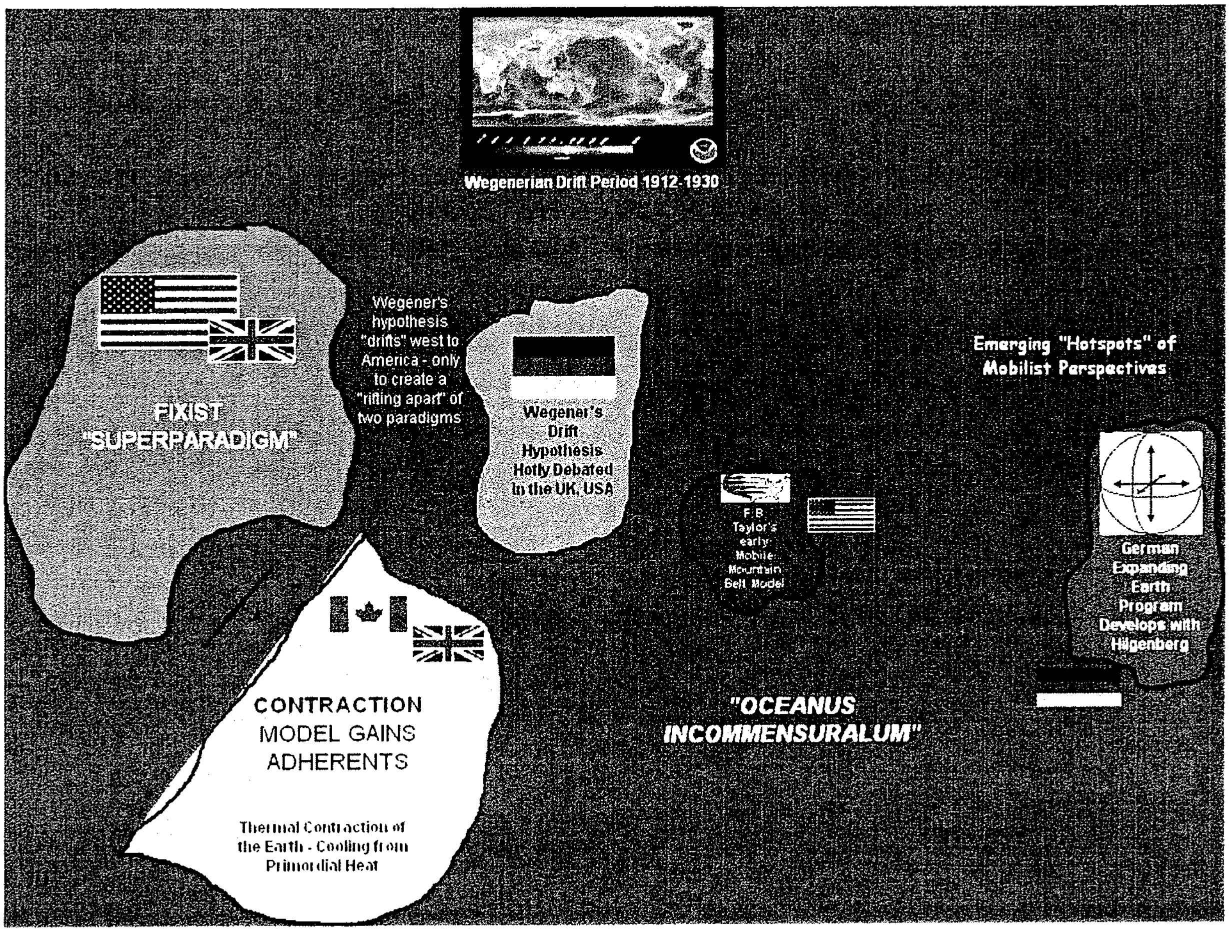

Plate 2: In the period 1912 – 1930, with the publication of Alfred Wegener's *On the Origin of Continents and Oceans,* the new theory was given a hearing among American and British geologists, and met with vehement hostility from most. With the rejection of the early versions of drift theory, and the untimely death of Wegener in 1930 on an expedition to Greenland, his ideas drifted into relative obscurity. At this time, a radical new mobilist hypothesis —that of an expanding Earth – developed out of Germany with Otto Hilgenberg.

3.0 The Emergence of a Duality in Geology

3.1 Historical Development of Plate Tectonics: The Collision of Two Great Paradigms

> The very configuration of the world itself in its greater part presents conformable instances which are not to be neglected. Take, for example, Africa and the region of Peru with the continent stretching to the Straits of Magellan. In each of which tracts there are similar isthmuses and similar promontories, which can hardly be by accident (Bacon, *Novum Organon,* 1620).

> No idea that has been discussed for three-hundred years, has been debated vigourously for fifty, and is today the centre of controversy, can properly be ignored. So it is with the observation that the shores on the two sides of the Atlantic ocean are similar in shape and nearly parallel, and the theory that this may have been caused by the drift of continents (Wilson, 1963a).

In order to examine more fully the historical development of modern global tectonics, and link it to geological education and HPS, it will be important to enter into a discourse concerning the historical perspectives surrounding paradigms in geology, and examine in detail some of the key players (I will call them "icons") who shaped the crucial arguments :

THE FIXIST TRADITION:

- CLASSICAL CONTRACTIONISM
- PERMANENTISM (FIXED CONTINENTS AND OCEANS)

THE MOBILIST TRADITION

- WEGENERIAN CONTINENTAL DISPLACEMENT
- EARTH EXPANSION TECTONICS
- PLATE TECTONICS

The idea of drifting continents is not a new one. In fact, its history predates by at least a century the early syntheses in European geology.[1] It is generally assumed that the watershed experience was the New York meeting of the American Association of Petroleum Geologists held in November, 1926. That meeting had Alfred Wegener (German meteorologist) and Frank Bursley Taylor (an American geologist) in attendance, along with a number of other influential American geologists. There, theory of continental drift faced perhaps its first public scrutiny - and its most devastaing attacks at the hands of the North American geological establishment (see van Waterschoot van der Gracht, 1928a, 1928 b; Oreskes, 1999, 2001). Despite Wegener's cogent arguments, and the marshalling of a tremendous amount of paleontological, paleoclimatological, and "continental fit" supporting evidence, his model met with, at best, a cool reception on the western side of the Atlantic. By the time of his untimely death in Greenland in 1930, his ideas were already facing the path to oblivion. This may seem unusual, but at that time, the influence of contractionism was the orthodoxy in geology. It held that the large-scale topological features on Earth's surface were due primarily to the steady thermal contraction of the outer spherical shells of a planet that was still primordially hot in its deep interior, supplemented by crustal heating from the decay of radioactive isotopes. As a result, the forces that drove mountain - building (orogenesis) and other tectonic processes were primarily *vertical* motions of the Earth's crust. There was little in the way of support for lateral motions as implied by the drift model, and such a guiding assumption virtually ruled out continental displacements *a priori*. Nunan (1984) has argued that, since contractionism was theoretically progressive at the time of Wegener's alternative, the latter would only supplant it if it was more progressive. It was not. The lack of a plausible mechanism to move continent-sized land masses, no matter how compelling the empirical evidence was (eg. fossil remains, circum- Atlantic similarities), left drift theory with seemingly insurmountable geophysical obstacles. Though lack of a mechanism is the conventional wisdom on the dismissal of Wegener's ideas, more recent reviews of this period (e.g., Oreskes, 1999, 2001) concerning his rejection by the American geological establishment point less to this issue than the deep theoretical commitment to the fixity of continents. Geology, in essence – particularly in North America – was a substantially conservative activity that was quite suspicious of ideas that raised the spectre of a new catastrophism.[2]

As often occurs in the history of science, historians are attracted to a single large event or controversy (e.g., oxygen theory vs. phlogiston, uniformitarianism vs. catastrophism, mechanism vs. vitalism, or mobilism vs. fixism in geology). One side of the controversy is generally viewed as the "winner", and the historical situation that was actually at hand was much more complex than such a dichotomous approach would imply. With the arrival of a highly-successful plate tectonics, geology too could be viewed as having its "winners" and "losers", and we could simply move on. What is then missed – and this is particularly important for students of science – is that supposedly peripheral ideas and events are quite at the heart of matters, and may be central to a clearer understanding of great debates in science history. Global tectonics, in my view, is no different. It can be demonstrated to students that the move from committed fixist notions of the planet to the novel mobilist perspectives was not an easy transition for geologists, and was far from over in the wake of Alfred Wegener. When we hear of recollections from scientific meetings such as "have you heard about what so-and-so is talking about right now? He has changed his abstract at the podium!!" (Menard, 1986) and stories of people then running down hallways to get into a conference room to hear about outlandish new ideas of moving crustal blocks, there is plenty to capture the interest of students. Though there is some truth to the argument that new ideas in geology have an evolutionary character to them, the conflict between the fixists and the mobilists occurred over an instant in geological time. It is my intention to adopt that abrupt telescoping of time, and for the sake of brevity I will refer the reader to the more detailed historical accounts whenever necessary. However, there are certain salient features that do suggest what should not escape the awareness of the student, and these will provide the basis of treatment in the subsequent historical details.[3] The extensive treatment in the subsequent sections provides for important –

and often little known – historical material that can eventually find its way into teacher-designed materials related to the geological revolution.

3.2 The Initial Collision - Continental Drift Theories And The Response To The Mobilists In The Period 1915 – 1950

Prior to about 1910, when Frank Bursley Taylor published his mobilist ideas in the landmark paper *Bearing of the Tertiary Mountain Belts on the Origin of Earth's Plan* (Taylor, 1910), it was the early iteration of *contraction* theory that supplied the then acceptable picture of the evolution of the earth's crust. The periodic foundering of the crust to produce ocean basins along with the elevation of intensely deformed landmasses to provide continental geodetic "highs" was satisfying enough to be a sort of *"la jour de synthese"* for geological thought. Just prior to the turn of the century, however, geologists and geodesists (those who specialize in accurate measures of the planet's surface topology), together with the structural geologists, had determined that the degree of overthrusting at mountain ranges and concomitant crustal shortening was dealing a serious blow to classical contractionism. It became apparent, through calculations, that no estimate of the cooling and contraction of the earth could account for the observed folding (Greene, 1982). This new challenge to conventional contraction theory demonstrated that all new hypotheses about the behaviour of the earth could no longer be made on scanty mathematical and physical foundations – the time of physics *and* geology had now arrived to replace the rivalry of physics *versus* geology.[4]

The first radical theory, arguing from a variety of diverse and somewhat disparate evidential points, was clearly arrived at in 1912 with Alfred Wegener's initial version of his *Die Enstehung der Kontinente und Ozeane (The Origin of Continents and Oceans)*, published book-length in German by 1915 (Wegener, 1915).[5] According to Wegener's own recollections, he first arrived at his ideas in 1910 by meditating on a globe and the apparent jigsaw-like fit of the continents around the Atlantic Ocean (Oldroyd, 1996).[6] At this time, particularly in North America, the principles of isostasy that had been outlined by Airy and others was to be reckoned with in any new theory of the earth. By virtue of recognizing that continental material was less dense than that of the ocean basins, and appealing to a substratum that behaved as an extremely viscous fluid that could yield under stress, Wegener appeased those who would have objected to his hypothesis of continental displacement on the grounds of an indifference to isostasy. [7]

In the 1924 English translation of Wegener's book, he took up the evidence for contraction theory and its relations to his mobilist model. He considered the evidence for contraction theory in the light of isthmian "land bridges" (used to explain faunal distributions both ancient and modern), the suggested permanence of the continents and ocean basins, and how these ideas would be modified by the new theory. Though he acknowledged that classical contraction theory had served geology well, the following evidence was mounting against it: radioactive heating of the Earth's interior, extensive folding and thrusting in young mountain ranges, the non-uniform distribution of those same Tertiary-age mountain systems. He also noted that the uniformitarian concept of subsiding continental areas, or the subsidence of land bridges to become seafloor stood in violation of the principle of isostasy. Therefore, if contraction was to have not occurred, then the horizontal compression assumption required the rifting of contients somewhere else on the planet's surface. Wegener was conservative, then, on two fronts: he supported the permanence of the continents insofar as areal extent was concerned, and; he recognised that crustal shortening in one area had to be compensated for by extension somewhere else – a sort of *conservation of diastrophism.*[8]

It was in the second portion of the work where the Wegener "bombshell" (Carey, 1976, 1988) was levelled at geology. In this section, the now classic sets of diverse evidence from the earth sciences was presented: from geophysics, geology, paleontology and paleobiology, paleoclimatology, and geodesy. One of the most penetrating (and visionary) assertions was that the Earth's surface was comprised of two types of chemically distinct crust – the continents (sial) and the ocean basins (sima) [9]. From geodesy (the science of the shape and dimensions of the Earth), it was clear that some of the earth's crust was at or just above sea level (the continents), and most of the rest was at a level consistent with the ocean basins – the so-called hypsometric argument. From geophysics, gravity measurements showed that the continents and oceans were in isostatic equilibrium; seismic studies indicated that these "two crusts" had differing properties; dredge hauls of the seabed invariably brought up simatic rocks (e.g., basalts, amphibolites). So confident was Wegener of his geophysical evidence and how well it fit his theory, that he enunciated "these ideas have been accepted by most geophysicists" (Wegener, 1924, p. 41).

It was the final section of Wegener's book that caused considerable difficulty for the geophysical community, for it was here that his guiding assumptions were laid out in full. Final chapters tend to be speculative, and his were no different. Since he was advocating the idea that the continental land masses could "float" on the denser sima, Wegener required a sima that could *flow* over geologic time. The one aspect that has received far too much attention by historians, according to recent analyses of the period (Oreskes, 1999), is the issue of the mantle's resistance to flow even under inconceivably immense, directed forces. Wegener recognized it as a potential problem, but not a fatal blow to the theory. He felt the evidence was so overwhelming that it was up to the physicists to assist him in explaining how it *could happen* (Stewart, 1979, 1990). What he did offer were two auxiliary hypotheses that could possibly explain forces driving the continents westward and also equatorward. To explain the latter, Wegener suggested *polflucht,* or a pole-fleeing force that was zero at the poles and maximal at the equator, and thought to be responsible for the Earth's tidal bulge. For the westward drift, he invoked the same tidal forces that are thought to be responsible for the Earth's tidal bulge, but appealing to some sort of viscous drag imposed on the continents by the Moon. These forces were appallingly weak to seem sufficient, but Wegener argued that even small forces directed over long periods of time could have caused noticeable movement.

Having briefly outlined these important features in Wegener's volume, it could be useful to close this section with some comments on Wegener's style of presentation. He patently followed most conventions of the time in his argumentation: pointing out the inadequacies of competing theories and how these could be explained better by his own.

In subsequent editions of *Die Enstehung der Continente und Ozeane*, he deliberated with his critics and responded to their critiques, and; he recognized that a keen geological eye would spot weak evidential arguments, but on the whole he felt that the new synthesis had merit. It is equally important – and this should be stressed to students – that many similar arguments fostered by Wegener (e.g., matching of continental coastlines, across-ocean continuity of geological features, continuation of mountain ranges, fossil assemblages, and the evidence for the Permo-Carboniferous glaciations prior to the breakup of Pangaea) are used in textbooks as support for plate tectonics. For an extensive treatment of both the theory and supporting evidence given by Wegener, see Marvin (1973).

In the period 1920 – 1945, a number of theoretical constructions that could be described as "mobilist" were in existence. It is apparent, however, that only two figures emerged as the ones worthy of extensive debate – Alfred Wegener and a South African contemporary, Alexander du Toit who published his *Our Wandering Continents* in 1937. Not long after the publication of his German editions, the tone in England and America was hostile to Wegener - it was first considered at a meeting of the Royal Geographical Society in 1923 – and at this time, one of his chief antagonists surfaced. Harold Jeffreys, a British geophysicist, spoke earnestly against the prospect that continents could move at all. [10] His arguments were adopted wholesale at the truly watershed experience of the 1926 American Association of Petroleum Geologists' (AAPG) symposium on continental drift. That single event convened so many influential opponents (and specialists, it is important to add) to drift, that this meeting is cited as the "key event producing the decline of interest in drift theory in North America and Britain" (Stewart, 1979) [11]. It is worthwhile for students to have some of these published proceedings offered to them, for they provide valuable illustrations of how scientists attempt to persuade one another (the context of justification) or even talk past one another in an effort to avoid the pitfalls of addressing the data, what count as "facts", and especially the guiding assumptions of opposing research communities. Yet another irony emerges later on in the 1960's and 1970's when the mobilists are in the clear majority, and the minority opposed to drift theory cannot be adequately heard.

Some of the acrimony quickly emerges upon viewing some selections taken from van der Gracht (1928):

> When we consider the manner in which the theory is presented, we find: that the author offers no direct proof of its verity; that the indirect proofs assembled from geology, paleontology, and geophysics prove nothing in regard to drift unless the original postulate of drifting continents be true....thus, the book leaves the impression that it has been written by an advocate rather than by an impartial investigator [p.82]
>
> (Bailey Willis, Professor Emeritus at Stanford). [12]

> Can we call geology a science when there exists such difference of opinion on fundamental matters as to make it possible for such a theory as this to run wild?...Wegener's own dogmatism...makes categorical comments somewhat less objectionable than would otherwise be the case [p. 83]
>
> (R.T. Chamberlin, Professor of Geology at the University of Chicago).

> Wegener's hypothesis in general is of the foot-loose type, in that it takes considerable liberty with our globe, and is less bound by restrictions or tied down by awkward, ugly facts than most of its rival theories. Its appeal seems to lie in the fact that it plays a game in which there are few restrictive rules and no sharply drawn code of conduct. So, a lot of things go easily. But, taking the situation as it now is, we must either modify radically most of the present rules of the geological game or else pass the hypothesis by. The best characterization of the hypothesis

> [is] if we are to believe Wegener's hypothesis, we must forget everything which has been learned in the last 70 years, and start all over again [p. 87]
>
> (R.T. Chamberlin, at the conclusion of his paper at the AAPG Symposium on Continental Drift, 1926).

Chester Longwell, a Yale geology professor, and the one who perhaps held up best under the temptation to move against Wegener at the meeting, cautioned all with his ability to beware of the "zeal of the advocate" and the "prejudice of the unbeliever":

> Very naturally, we insist on testing this hypothesis with exceptional severity; for its acceptance would necessitate the discarding of theories held so long that they have become almost an integral part of our science [*ibid.*., p. 146].

> [If] the doctrine of continental displacement is accepted as a working hypothesis, to be tested and tried fairly along with others, it may be productive of valuable results [*ibid.*, p. 157].

3.3 The Second Convergence – New Evidence for Mobilism in the Period 1950 – 1960....the Response of the Fixists

The geological sciences grew rapidly after Word War II. Through the efforts of the Office of Naval Research of the U.S. Government, knowledge about the nature of the world's oceans and the remarkable character of the ocean floors made unprecedented progress (Wood, 1985). Oceanographic research revealed the world's largest linear feature – the mid-ocean ridge system – to be an almost 46,000 kilometre long, sinuous mountain range through all the major ocean basins. With the appearance of being under tension, and displaying anomalously high heat –flow values, here was an unexpected feature that would have to be explained by any acceptable global theory. It seemed, now, that the convection-current model developed by Arthur Holmes in the 1930's could indeed provide the plausible dynamical mechanism that could account for drift, gravity anomalies at the surface, the opening of ocean basins, and the high heat flows observed at the mid-ocean ridges (see Figure 3.1 for Holmes' model of mantle convection).

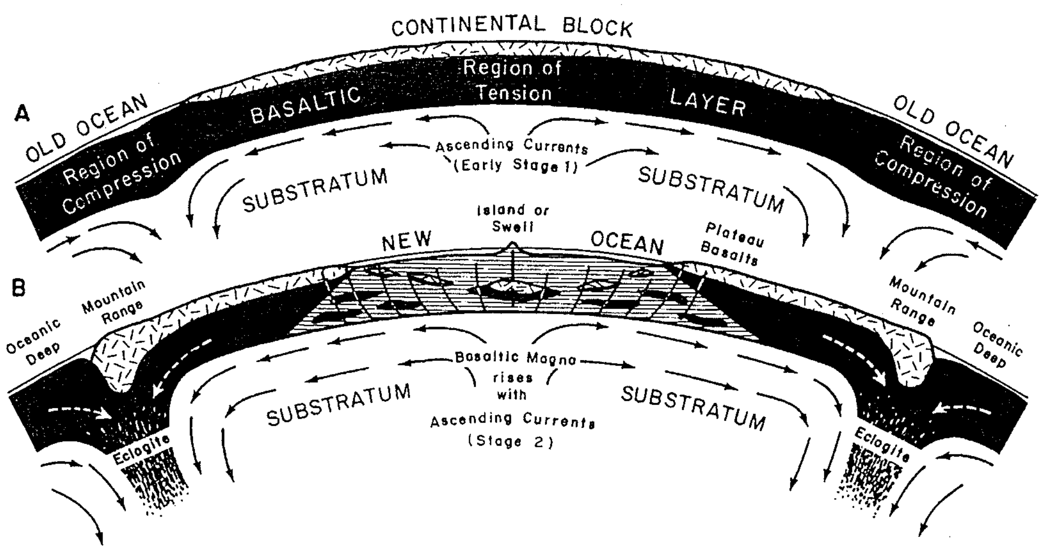

Figure 3.1 Arthur Holmes' convection current model, published in 1944. It predicts with remarkable foresight the existence of regions of high heat flow under the centres of ocean basins, and how these could produce oceanic islands and downward movement of material at the margins of continents. The figure, first produced around 1930, appeared as an icon in all of his editions of the very popular *Principles of Physical Geology.*

(from Holmes, 1944; used with permission)

Holmes did have periods of grave doubt about mobilism, all the while attempting to breathe sustenance into his convection current hypothesis. For instance, in his 1953 article appearing in *Nature,* wherein he debates the merits and demerits of the two opposing options of trans-Atlantic land bridges or continental drift, Holmes' betrays some agony in making the decision:

> Despite appearances to the contrary, I have never succeeded in freeing myself from a nagging prejudice against continental drift; in my geological bones, so to speak, I feel the hypothesis to be a fantastic one (Holmes, 1953, p. 671)

It would seem that the influential Holmes was attempting to consider all reasonable theoretical arguments without betraying an open endorsement of continental drift, even though it caused him to have several confrontations with Harold Jeffreys (Frankel, 1978). The loss of a profile in Britain for the "drifters" was largely due, one would suspect, to the towering profile of Jeffreys, whose cogent mathematical arguments supporting the contractionist model were popular in Britain at the time.

Curiously important, as drift was on the wane in the northern hemisphere up until the late 1950's, it was a major working hypothesis for southern hemisphere geologists, led by Alexander Du Toit and his *Our Wandering Continents* (1937), and later on by one of his students – Lester B. King of the University of Natal in South Africa. King gave a series of lectures on the topic of drift in the 1950's to American audiences, setting the stage for an even more vociferous proponent of mobilism, Samuel Warren Carey of the University of Tasmania (King, 1983). S. Warren Carey's activities demand some mention here. Carey, unlike many of his contemporaries, was a global thinker who continually looked for explanations of the Earth's larger-scale features – e.g., the relationships between the major belts of young, folded mountain ranges and the gross fit of the continents. He always claimed to be irretrievably drawn by the evidence toward one of the most conceptually revolutionary hypotheses yet seen in modern geology – that of the expansion of the Earth. Carey, using an elaborate set of constructed models, demonstrated that the fit of the continents improves significantly on a globe of reduced radius. Moreover, he maintained that the planet had expanded exponentially since Permian time, and it was up to the physicists to determine the mechanism. [13]

Carey's influence on other geoscientists was remarkable for several reasons. First, he instigated renewed interest in solving global-scale geological problems when most of the field had become reductionist, provincialist, or, in the case of American geology, immersed at the quadrangle level of scale (Hallam, 1973). Second, he was an effervescent, dynamic speaker who made deep impressions on the graduate students during his informal talks at American universities in the late fifties and earliest sixties, much to the dismay of their advisors (Le Pichon, 2001). Finally, he convened the first modern-era symposium on the issue of continental drift in 1956 (Carey, 1958) that saw his *The Tectonic Approach to Continental Drift* occupy more than half of the published proceedings. Carey's works must be read in order to be appreciated, and it is clear that both the fixist *and* the mobilist hegemonies, in their turn, sought to set Warren Carey adrift toward an *archipelago of ignominy.* [15]

In the late 1950's, there still existed a sophisticated response to the emerging data related to the ocean floors from the traditions of fixism, and within the contractionist approach in that paradigm. Perhaps the most global theory in this vein, which systematically attempted to account for new evidence from seismology, paleomagnetism, structural geology, and oceanography – within contractionism – was the treatment offered by J. Tuzo Wilson, professor of geophysics at the University of Toronto. In an important series of articles (Wilson, 1951, 1959a, 1959b) and as co-author of the popular textbook *Physics and Geology* (Jacobs, Russell and Wilson, 1959), he proposed that contraction of the outer spheres of the Earth was not due to thermal cooling, but to the upward displacement of mantle material along major fault zones. In this model, the upper 70 km or so of the crust was not primordial, but had been derived from the mantle below (see Figure 3.2). On the surface of the Earth, these faults form a system of interconnected *arcs*, which certainly may have predisposed Wilson to his later ideas about *plate boundaries* less than a decade later (see Figure 3.3 below).

J. T. Wilson's theoretical approach was likely the most global synthesis of this period, and was squarely directed at explaining surface *geological* features through a *geophysical* set of approaches. In the next section, we will examine somewhat more closely how Wilson's evolution of thought can make for an appropriate context for students to experience their own vicarious historical development within a pluralistic conceptual model.

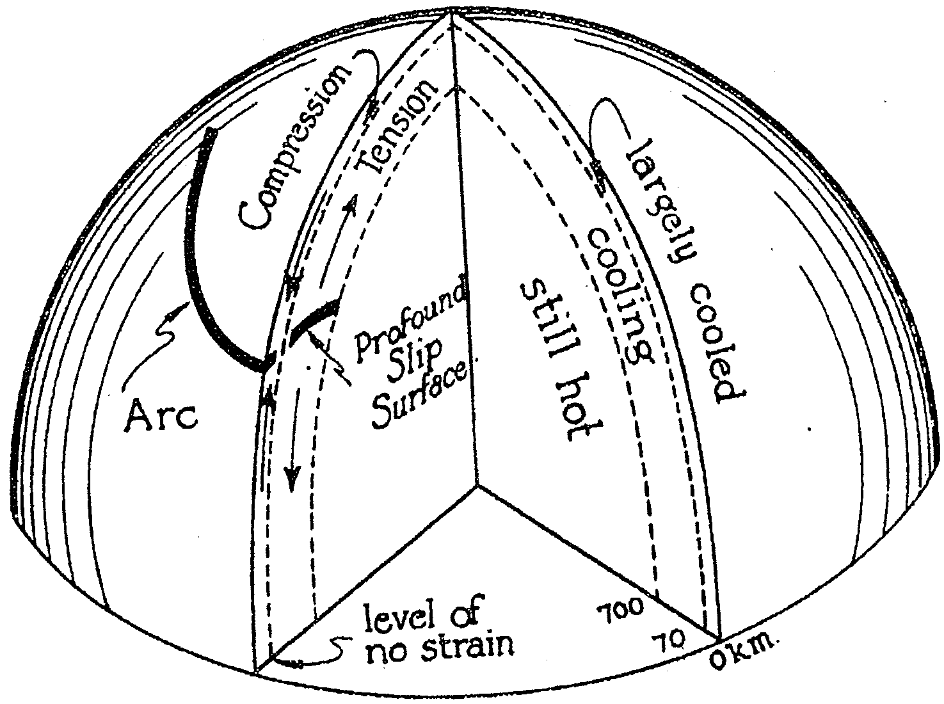

Figure 3.2 J. T. Wilson's model of the outer spherical shells of the Earth as it appeared in the *Proceedings of the Royal Society of Tasmania for 1950* (Wilson, 1951) and in a subsequent sequence of publications throughout the 1950's (Wilson, 1959a; 1959b) . The outermost 70km of the crust was a zone of compression due to contraction of cooled material. The zone extending below that, down to 700 km – the zone of deep earthquakes – was under tension due to thermal cooling. The model developed out of Jeffreys earlier work from the 1920's, and was modified to accommodate the new seismic data indicating two distinct compositional layers in the crust – an outer "skin" where shallow-focus earthquakes occur, and a deeper layer where the deep-focus quakes occur along major,continent-rimming thrust zones (fault planes) (from Wilson, 1951; used with permission)

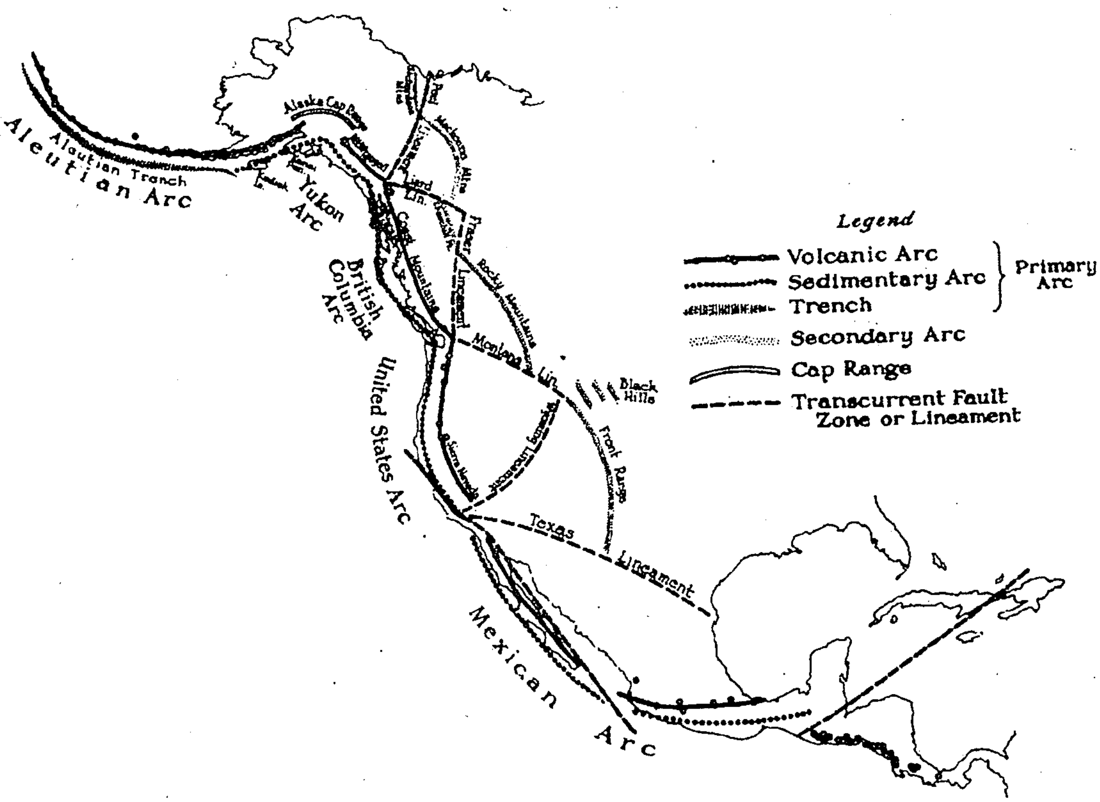

Figure 3.3 A visualization of the "interconnected arcs" as these rim the west coast of the Americas. Note that the arcs are convex toward the ocean, and are the surface expression of what were thought to be conical fault systems within the top 700 km of the deeply-rooted continental ,masses (sial). Imagine a ping-pong ball that has depressions imprinted on it, and the analog is a close one.

(after Wilson, 1959b; used with permission)

3.4 J. Tuzo Wilson – Pluralist Thinker and Canadian Icon in Global Tectonics

If there exists an individual who has embodied how rapid scientific change can transform a veteran scientist – and without loss of stature in these transformations – J. Tuzo Wilson represents an interesting model for students to examine. Being the first graduate in geophysics from the University of Toronto in 1936, Wilson was, early on, applying a synthesis of physics *and* geology to his view of the planet. Moreover, if we chart the path of the literature over the period 1959 – 1969 that is attributed to Wilson and his ideas, and can safely eschew the problems of the published paper as being "fraudulent" according to Peter Medawar, then Wilson becomes somewhat of an iconoclast who managed to avoid the perils of changing one's mind. One sociologist of science, Mott T. Greene (1984), has remarked that "to have changed his views so radically in so short a space of time, and done so openly for all to see without loss of stature in the geological community is an episode of prime importance to the sociology of science". One philosopher of science, Rachel Laudan (1980), has produced a case study of Wilson's behaviour over this period and concluded that he was operating within the venerable "method of multiple working hypotheses" of Thomas Chrowder Chamberlin (1890). In that analysis, Laudan erroneously claims that Wilson was working simultaneously among three major "maxi-theories" of the Earth – the contracting earth, the expanding earth, and the convection-current model of Arthur Holmes – and comparing and contrasting each model's efficacy at solving problems. I would suggest that, in the customary Wilson style, it was indifference to negative peer perceptions and the attractiveness of unique global theories that made Wilson *appear* to be multi-tasking with global tectonics. An alternative interpretation – and one to be upheld in the teaching model presented in Chapter 4 – is that Wilson's geographic movements, key sabbatical scheduling, and openness to radical interpretations allowed him to pass through a gauntlet of global theories *in succession*, not *simultaneously*.

Wilson always demonstrated an insight that permitted him to recognize a fertile idea in its earliest stages, and then possessed the industry and editorial board connections to see his thoughts rapidly published. In addition, he regularly used a cautious, skeptical tone in order to avoid coming out in glaring support of alternative conceptual models too early on. He seemed to have an interest in offering new, potentially fruitful avenues of research to be followed by other workers. For instance, with respect to contractionism (ca. late 1950's), we read (and note the cautious, almost evasive tone):

> This discussion has not proved that contraction is the cause of mountain and continent building, but it has shown that it can explain details of the earth's surface features in a way that no other existing theory has done. The extent to which details can be explained, and the absence of any other adequate explanation make the contraction theory very attractive. Convection currents may exist deep in the mantle and probably were important in the earth's early history, and polar wandering may well be occurring. But, neither one of these nor any other proposal yet made provides an account of the development of the earth's surface features comparable to that now possible by using the contraction theory (Wilson, 1959; in Jacobs, Russell and Wilson, 1959, p. 360-361).

and, in the case of the earth expansion hypothesis of Warren Carey as inspired by the possibilities enunciated by Dicke and others in the 1930's:

> The point that has just been made [the physical and geological consequences of earth expansion] does not prove that the expansion of the Earth has occurred or if it has, that it is due to a change in 'G', but it is worth considering some of the consequences of accepting that hypothesis. It [the expansion hypothesis] has the merit of appearing to explain many features of the Earth's surface, though this does not constitute a proof. Even if true, expansion at the rate here postulated could conceivably be due to phase changes in the Earth's interior, or perhaps to differentiation of the core and mantle, but a decrease in 'G' remains an inviting idea (Wilson, 1960, p. 881-882).

After another couple of years, Wilson (1963a) had by then turned his attention to the question of the movement of continents by convection currents, but only after being convinced that convection in the mantle was a conceivable geophysical reality. By suggesting a test of oceanic extension via convection currents – the age of volcanic islands should be progressively older away from the mid-ocean ridges – Wilson was again offering a new avenue of research. This he took on himself, but could not get the paper published in a leading journal (it was uncharacteristically rejected by the *Nature* editorial board, who were well connected to Wilson's inkwell, as being too speculative). Eventually, the work appeared in the *Canadian Journal of Physics* (Wilson, 1963b) but was not particularly convincing within, or well known to, the geological community.

Without openly accepting or believing any of these hypotheses to be true, Wilson did succeed in pointing out each one's explanatory potential and predictive capacities (Laudan, 1980b). It is clear that his contributions were atypical and made geology a more exciting discipline among his contemporaries, for instance:

> Scholars who change their opinion too often usually lose the respect of their colleagues, but Wilson's insight and originality appear to have made him an exception (Uyeda, 1978, p. 65).

Though Wilson may not have been using a set of 'multiple working hypotheses' in simultaneous action, he was certainly a pluralist thinker and very cogent in broad, synthetic arguments. It would be difficult to imagine how progress would have occurred so rapidly in geology at that time had there not been one with his stature pursuing the risks that he did. Historically, Wilson has a secure place by virtue of generating interest in novel models, and his methods were – and remain today – notably rare and non-normative among geologists. There may yet emerge some weaknesses in the current synthesis, and plate tectonicians will in all likelihood alter some of the fundamentals (Hallam, 1980). It is unfortunate that a J. Tuzo Wilson has left the scene prematurely, for if he were to be shown as incorrect, he merely would have attached himself to a newer, more progressive development.

3.5 Vladimir V. Beloussov – Entrenched Continental Conservatism or the Remoteness of the Russian Archipelago?

If one were to look for a geological icon who was willing to collide with the interests of a J. Tuzo Wilson, and transfer this personal debate to the larger one of the Fixist – Mobilist collision of ideas, then Vladimir Vasilievich Beloussov is that icon. Almost synonymous with the Soviet scientific establishment in geology, his influence came from his ability to communicate and publish in the English language, and his regular presence at international scientific meetings. His was a quintessentially "Continental" approach to geology, perennially frought with complex geological structure, ancient internal shields, and that mixed with the professional isolation that came from being a Soviet geologist in the fifties and sixties. Beloussov's tectonics was a vertical tectonics along major faults orthogonal to the surface, and this was to put him in an unlikely position to adopt the *horizontal* assumptions that were emerging from the mobilists in America, western Europe, South Africa, and India.

The core idea of his tectonic modelling was the concept of "oceanization", essentially the transformation of continental crust (sial) into denser basaltic (oceanic sima) material that has undergone subsidence to become the ocean basin substratum.[16] What creates for an interesting feature for students, where Beloussov and his entrenched views are concerned, is that more than any other opponent of drift, he engaged in unusually candid written dialogues with Western geologists – particularly having a fondness for Wilson as an sparring partner .[17] In particular, Beloussov demonstrated a deep aversion to Wilson hailing the new global tectonics as a "scientific revolution" that would have sweeping implications for textbooks, training of geologists for industry, and academic research programmes (Wilson, 1968a). Beloussov – though he had accepted that the contractionist version of continental fixity had serious difficulties – still articulated that "the store of particular ideas and concepts still remains…and up to the present [the foundations of contraction theory] have been strongly reflected in the majority of ordinary regional geological papers" (Beloussov, 1968, p. 17). The use of the phrase "ordinary regional geological papers" is telling, as these were the stock-in-trade of most practising geologists in the Russian establishment. The emphasis on sea-floor data in support of the new mobilism would have been worrisome for Beloussov, who would desire an equally relevant treatment – in any theory – of continental geology. In a great irony for Wilson, who was as eclectic in his thinking as any dared to be at the time, Beloussov attacks Wilson in the 1968 exchange in *EOS : Transactions of the American Geophysical Union* as not being supportive of the "method of multiple working hypotheses" which, presumably, would now have to include his "oceanization" model. In sum, the following final word on the issue from Sengör and Burke in the 1979 exchange shows how philosophically distant the two groups had become (Kuhnian incommensurability):

> Our emphasis has not been on citing detailed evidence that shows the weaknesses of Beloussov's position, because we believe that such evidence is both ample and familiar. Rather, we draw attention to what we see as his philosophical attitude and historical perspective which, we conclude, derives from those of the German masters of contractional tectonics. Long before the advent of plate tectonics, the inadequacies of this approach had been recognized and its place taken by hypotheses involving large-scale continental displacements in the writings of such *tectonicians as [Edouard] Suess, [Ēmile] Argand, and [Alexander] Du Toit. Our*

general feeling is, that dialogue with Beloussov is unlikely to be very fruitful, since the premises on which his interpretation stands are so different from those on which both plate tectonics and the mainstream of tectonic studies rest (Sengör and Burke, 1979, p. 207).

In exploring, for a moment, the above commentary of Sengör and Burke and its pessimism, there is an interesting re-interpretation of geological facts. Suess had actually argued for the *contraction theory* of mountain belts (see Hallam, 1973, p. 7-8). Émile Argand did have some reservations about the contraction theory, and had advocated an early form of drift, but these aspects of Argand's model, and very little of what is found in Du Toit's work, had any credence among the "true drifters" until the 1960's. These two opponents of Beloussov (and his entrenched fixist stance) show clear evidence for how quickly history can be distorted upon the arrival of a new, influential paradigm (cf. Marvin, 1973, p. 86-87).[17]

3.6 Struggle and Revolution: The Period 1966 – 1975 and the Emergence of the New Synthesis of Plate Tectonics

As outlined earlier, throughout the thirties and forties, drift was essentially absent from serious consideration. However, in the decade of the fifties, the emergence of paleomagnetism in geophysics breathed new life into mobilist theories.[18] Early investigations seemed to reveal that certain land masses had migrated thousands of kilometers from their original locations, or, that the Earth's magnetic poles actually migrated over long periods of time ("polar wandering"). The assumption, however, was that the dipole field was a long-term characteristic of the Earth, and little in the way of polar-wandering was reasonable on physical grounds. And yet, under the influence of Sir Harold Jeffreys, and other persuasive skeptics of the new science of paleomagnetics, it would be another ten years before rock magnetism was taken very seriously (see Jeffreys, 1959; and Takeuchi *et al.*, 1967).

During the 1950's and 1960's, geology was faced with new oceanographic data that almost immediately called into question the traditional fixist approaches (e.g. contractionism) to the Earth's continents and ocean basins. The prior tradition was that surface features were almost immutable, fixed in relative positions, and immoveable on the basis of strong geophysical arguments. The novel facts coming to light from sea-floor studies were incompatible with the hegemony of fixism, and resurrected the mobilist ideas of Frank Bursley Taylor (1910) and Alfred Wegener (1915, 1924, 1929) that had been discredited earlier in this century. That earlier rejection was supposedly on the basis of having no plausible mechanism to move huge continental land masses.

In this period of arguably "revolutionary" transition, two equally viable hypotheses were competing for acceptance among geologists, and geophysicists: 1) an emerging synthesis that has come to be known as plate tectonics (hereafter PT), and; 2) an expanding Earth, which holds that the Earth's radius (and hence surface area) has been exponentially increasing over geologic time (hereafter called EXP). To explore the circumstances of just how PT theory came to be accepted, and its rival, EXP, was rejected (or ignored?) could provide an inviting context as a case study in the history and philosophy of science, but will not be considered in detail here. There are, however, profound implications for geological education, in that EXP is completely absent from current geology textbooks, the current mainstream geological literature, and hence the training of future students of geology. For the sake of the present study, the expansionist model will be considered as an auxiliary research programme within the mobilist tradition.

Also during the 1950's, mapping of the ocean floors revealed an extensive, globe-encircling system of "ocean ridges", with associated anomalous high heat flow along the central axes of these ridges (see Heezen,1960). Dating of rocks on ocean islands indicated that these become progressively older as their distance to the axis of the ocean ridge increases, and sediments supported the startling conclusion that the ocean basins were much younger than the continents. There is apparently no oceanic crust older than about 200 million years, and this on a planet with continental rocks as old as 3,800 million years (see Wilson, 1963a). These new revelations came with such rapidity, there were few in a position to provide for a synthesis of all the new oceanographic results. Bruce Heezen, then of the Lamont Geological Observatory of Columbia University, was the first to incorporate the new geophysical data into a theory of earth expansion.

Heezen was not the first to invoke an expansion hypothesis to explain the information relevant to drift, and his published literature appears to be less than comfortable with the possibilities emerging from his own data. This was done more visibly by Samuel Warren Carey of the University of Tasmania in 1956, and by Laszlo Egyed of Eötvos University in Budapest in 1957 (see Carey,1958; Egyed, 1957). Heezen's model argued that the crustal regions bounded by the ocean ridges were rigid blocks of crust that extended into the underlying mantle, and as new material welled up along the axes of the ridges, continents would necessarily be displaced from one another. Since he had no evidence for the destruction of oceanic crust, the only conceiveable alternative was an expanding globe. The concept of *subduction*, the process by which oceanic crust is returned to the mantle at regions of low heat flow, had not yet been conceived. It became an *ad hoc,* or auxiliary, hypothesis necessary in the later plate tectonic model to account for the lack of ancient (> 200 Ma) oceanic crust on a planet of fixed radius. The rate of expansion would account for the amount of new surface area erupted on the ocean floors, and the world's ocean basins would consequently increase in size over geologic time periods (Heezen, 1960). Heezen and his students at Lamont are credited (or perhaps discredited) with adhering to a new, mobilist *expansionist tectonics* in the face of significant internal opposition from colleagues – mostly geophysicists – who remained committed to the fixist paradigm (Le Pichon, 2001).

A second, and eventually more persuasive model came (independently?) from Robert S. Dietz (a Canadian geologist) and Harry Hammond Hess at Princeton. This was the hypothesis of seafloor spreading, first proposed in 1960. In the 1930's, it had been modelled by Arthur Holmes that convection currents in the mantle could influence crustal movements (see Figure 3.1 in this chapter), and Hess suggested that this was just the sought after mechanism to account for high heat flow at the crests of the ocean ridges. Furthermore, his "conveyor-belt" model of oceanic crust movement away from the ridge axis argued for a destruction of older crust elsewhere on the planet's surface. Seismic evidence at the time indicated that the ocean trenches were sites of deep focus earthquakes, and these occurred in belts that paralled the trenches.

It had been known from paleomagnetic studies that the Earth's geomagnetic field undergoes periodic reversals of polarity - a phenomenon that still lacks an appropriate explanation. Nevertheless, it was predicted early in 1963 (Morley and Larochelle, 1964) that oceanic crust should contain a record of these reversal events in the ferromagnetic minerals of the rocks. This was outlined in a little recognized 1963 paper by Fred Vine (a graduate student at the time) and Drummond Matthews (his advisor) of Cambridge University, and independently predicted earlier by the Canadian geophysicist, Lawrence Morley. Morley, who had independently submitted a paper (in 1963) outlining the manner in which paleomagnetism could be used as a means of dating geological events, had it rejected by the editors of *Nature* and the *Journal of Geophysical Research* just six months before the Vine and Matthews paper was accepted for publication by the same journal late in 1963. Any account of this regrettable episode of "priority" is an important, though unflattering, peering into the nature of scientific practice, and the acrimony of certain debates in these pivotal years has been dramatically told by Glen (1982). In his own retrospective of the affair, H. W. Menard comments that Morley's paper "may just be the most significant geophysical letter to have ever been denied publication" (Menard, 1986). As a recent postscript to the affair, in another retrospective account (Morley, 2001), Morley contends that this experience irrevocably sidelined him from the mainstream of ocean-floor geophysics, and encouraged him to abandon research in this area altogether. He turned to satellite-based remote sensing research early on in 1964, never to return to solid-earth geophysics.

At this point, geology was faced with three competing rival theories: contractionism on the fixist side of the debate, and drift with the possibility of expansion on the mobilist side. The new sea-floor data were increasingly creating empirical problems for contractionism, and Hess and others (e.g., Le Pichon, 1968) were sharply critical of EXP as a viable alternative (likely on grounds of not being comfortable with appealing to a new physics unless absolutely required). Still, the geological community was hesitant in choosing between the sea-floor spreading hypothesis that supported drift, and Heezen and Carey's equally plausible rival EXP that could also account for all of the observed sea-floor data and anomalies. Due to this problem, there was a general reticence about accepting drift in general, particularly if one differentiates the two competing theories within the mobilist sphere as being independent, Laudanian research traditions, as is done by Nunan (1984, p. 302-303). According to Nunan's analysis, EXP belongs to a completely different research program, in that its mechanism involves radial movements within a spheroid. The true drift theory, which involves lateral movements at and near the surface of the spheroid as the "hard-core" of the tradition, is clearly distinct. In the EXP version, continents are *displaced* as new ocean floor is created on an expanding planet. In the extreme, EXP does not necessarily have to allow for the destruction of old ocean floor at the trenches.[19] Because of this, it was pointed out by Xavier Le Pichon (1968) that the preponderance of north-south ocean ridges would lead to an unacceptable asymmetric expansion of the Earth (there are far fewer east-west spreading centres). The rate of expansion in an east-west direction would far outstrip the north-south expansion. Le Pichon, one of the key architects of the kinematics of plate theory, dismissed the expansion alternative quite openly with a devastatingly brief comment in his 1968 paper in the *Journal of Geophysical Research* :

> ...the expansion hypothesis loses most of its appeal. Other strong arguments have previously been advanced against the expansion hypothesis, and it will not be considered further here (Le Pichon,1968, p.3674).

Nunan (1984) submits that that single statement was the demise of the requirement for an expanding earth (for subduction would now assume the role of how to account for the excess of oceanic lithosphere on an Earth of constant radius), and it was the combined weight of influential writers that contributed to the accelerated acceptance of sea-floor spreading (and by association, drift theory).

All that remained was for someone in the geoscience community to come up with a kinematic synthesis. Two key papers - one by Jason Morgan (1968), and the other by Dan P. McKenzie and R.L. Parker (1967) - provided the unifying principles of plate tectonics to pull all of these diverse pieces of evidence into a single, all-encompassing theoretical model. It is often assumed, and incorrectly so, that plate tectonics and continental drift are synonymous. They are somewhat distinguishable in that plate tectonics is the synthesis that derives from the concepts of continental drift and spreading of the sea-floor (Laudan, 1977). These two complimentary ideas – continental displacement and sea-floor spreading – could be considered as examples of 'conceptual continents' that had collided in order to form a significantly new, and larger, 'mega-scale conceptual continent' called plate tectonics.

Notes – Chapter 3:

1. Ursula B. Marvin's *Continental Drift: Evolution of a Concept* (1973) is a very readable and interesting treatment of the concept of the figure of the Earth (going back to Crates, ca. 150 B.C.) and drifting continents from the period of Bacon and his *Novum Organon* (1620) to the 20th century. One of the earlier attempts to reconcile the opposing coastlines of the Atlantic was accomplished by the French geologist, Antonio Snider-Pellegrini in his famous treatise *Des Mystères de la Terre Devoilées* (1858). He claimed that the continents were at one time joined, but were subsequently split apart by the Noachian deluge. Several other drift theories were attached to the catastrophist viewpoint, for instance by the passing of a large celestial body that ripped the Moon from the crust of the Earth. Osmand Fisher and William Pickering were leading exponents of these extra-terrestrial hypotheses.

2. Charles Lyell, whose *Principles of Geology* passed through no less than eleven editions in the years 1830 to 1872, saw it as a duty to rid geology of its "Mosaics" (his pejorative term for the catastrophists who were advocates of the Noachian deluge) and the "nonsense" that kept geology from doing what was right for it – work out the mineralogical constitution of the Earth. Lyell's Earth was a steady-state, perpetual motion machine that never ran out of interior heat due to what he described as reversible "thermo-electric" changes at depth (in retrospect, a remarkably advanced insight that led to a search for the "geodynamo" among later geophysicists).

   Hence, Lyell's brand of uniformitarianism was one of endless, cyclic periods of slow, gradual change. Catastrophist-seeking hypotheses such as meteoritic impacts and moving continents were, then, understandable anathemas to the geological establishment. More particular to drift hypotheses, it appeared to most that Wegener's ideas were profoundly anti-uniformitarian to the point of being insulting to the icons of geology – James Hutton (*Theory of the Earth*) and Charles Lyell (*Principles of Geology*). It was shocking enough to consider that the continents had 'drifted' about the surface of the globe; but, to assert that this has occurred only once – late in geologic time – was the rearing up of a new *catastrophism* for many geologists. Either continents have always been moving or they do not move at all in the uniformitarian view. It is interesting that, in recent years, the notions of a repeating *supercontinent cycle* or the Wilson cycle (opening and subsequent closing of a major ocean basin) have breathed continuing life into the traditions of uniformitarianism.

3. A number of scientists, historians, and philosophers have written about the scientific developments from continental drift to plate tectonics, among them Homer LeGrand (1988) *Drifting Continents and Shifting Theories;* Naomi Oreskes (1999) *The Rejection of Continental Drift: Theory and Method in American Earth Science* and her 2001 retrospective *Plate Tectonics: An Insider's History of the Modern Theory of the Earth;* Claude Allegré (1988) *The Behaviour of the Earth;* William Glen (1982) *The Road to Jaramillo: Critical Years of the Revolution in Earth Science;* Rachel Laudan (1980) The Method of Multiple Working Hypotheses and the discovery of plate tectonics theory. In *Scientific Discovery: Case Studies, Boston Studies in the Philosophy of Science 60;* Xavier LePichon, Jean Francheteau, and Jean Bonnin (1973) *Plate Tectonics;* Ursula B. Marvin (1973) *Continental Drift: Evolution of a Concept;* Henry William Menard (1986) *The Ocean of Truth: A Personal History of Global Tectonics;* John Arden Stewart (1990) *Drifting Continents and Colliding Paradigms;* Robert Muir Wood (1985) *The Dark Side of the Earth: The Battle for the Earth Sciences;* a new volume chronicling the life of Alfred Wegener has just been published by Mott Tuthill Greene (2002) entitled *Alfred Wegener and the Origins of Modern Earth Science;* perhaps one of the most interesting, from the perspective of how history is recalled even by the protagonists who were there when it all happened, is Naomi Oreskes' retrospective listed above.

4. For detailed accounts of the history of geology prior to the Wegener era of post 1915, see the works of Ursula Marvin (1973), Anthony Hallam (1973; 1983) and Mott T. Greene (1982; and 1984). David R. Oldroyd's *Thinking About the Earth: A History of Ideas in Geology* (1996) does a particularly good job of exploring the "big ideas" of geology in a synthetic manner with some sympathies for the Kuhnian interpretation of the transition from fixist to mobilist thinking. Other Kuhnian interpretations of the history of continental drift and plate tectonics can be found in Anthony Hallam (1973), Rachel Laudan (1980a), and John Stewart (1990).

5. The first English edition to be published was not available until 1924, and translated from the third German version of Wegener's treatise. By the time this version had been made available, Wegener had already made some substantial modifications of what had been deemed "naïve and erroneous" interpretations of the evidence. These later editions also coined his now famous "pangäa" – *Pangaea* – a term referring to the assembled supercontinent that, according to a later "drifter", Alexander Du Toit (1937) was comprised of Gondwana in the south and Laurasia to the north during Mesozoic time. The fourth edition of Wegener's volume (1929) was not translated into English until 1966 – the year that the new global tectonics was quietly in the hands of two young graduate students (W. Jason Morgan at Princeton and Dan P. McKenzie at Cal Tech).

6. It seems as though identifying this "jigsaw fit" is the first rite of passage prior to producing a radical new hypothesis of the Earth's plan. Historians have identified dozens of persons who have commented on the puzzle-fit, going back as far as the first reasonable accurate trans-Atlantic maps and Francis Bacon (ca. 1620). It seems that even in the late 20th century, this rite continues. Karl Luckert, an historian of religions by profession and a latent supporter of the earth expansion hypothesis in the 1990's, claimed that he first had this fit pointed out to him in 1979. It left an indelible mark on him. Conversely, for those who wish to be more circumspect of such continental fits, a contributor to Kahle (1974) has described no less than *forty* such coastline fits worldwide – none of which would be of interest to those who continue to give us plate reconstructions going back at least 1.8 Ga.

7. An extensive treatment of the American commitment to the principles of isostacy, which claimed that the outer crust rises in some places, falls in others, but on the whole there is a sort of isostatic equilibrium, see Naomi Oreskes (1999).

During the late 19th century, the concept of isostasy was developing in order to account for various geological phenomena. The concept was based, to simplify, on the idea that the crust of the earth would respond to increased sediment loads, or glacial ice, that were on the order of a few kilometres in thickness. These regions would respond by sinking deeper into the mantle below as if the upper layers were "floating" on the denser substrata. The thought is akin to the displacement of a ship at sea. It explained, for example, significant crustal thickening under the roots of mountains in order for these to remain in equilibrium at the surface. Similarly, it was known that the Fenno-Scandinavian region was rebounding in the wake of the removal of large ice sheets that retreated about 10,000 years ago. Isostatic equilibrium would produce a geoid that was uniform in terms of its gravity field. Small vagaries in the local or regional gravity fields – known as gravity "anomalies" – would be indicative of crustal material *out of equilibrium*. Thus, downward or upward movements of material would show up as gravity lows or highs respectively. The horizontal compressive forces required for overthrusts would be provided by the contraction model of the Earth's interior (see, for instance, Jeffreys (1924) and Wilson (1959).

8. Diastrophism is the term used to describe, collectively, all types of crustal distortion such as folding, rifting, faulting, etc.

9. "Sial" refers to rocks enriched in silicon and aluminum such as granites, and "sima" for enrichment in silicon and magnesium such as basalt.

10. Harold (later Sir Harold) Jeffreys has often been portrayed as the villain in the mobilist vs. fixist debates. His six editions of *The Earth: It's Origin, History and Physical Constitution* were standards in the field of geophysics from the first edition in 1924 to the last – the sixth – published in 1976. His longevity and stoic commitment to partial differential equations never permitted him to be sanguine about drift hypotheses. Geologists opposed to drift quickly adopted Jeffreys as their standard-bearer, and this became very clear at the 1926 AAPG symposium in New York. It is ironic, though, that many of the eventual leaders of the mobilist movements in the 1950's and 1960's were geophysicists themselves, some even former colleagues or students of Jeffreys. In 1983, Jeffreys died unrepentent and still extolling the virtues of his fixist commitment.

11. The proceedings of the 1926 AAPG symposium on continental drift, edited by W.A.J.M. van Waterschoot van der Gracht and published in 1928 under the equally lengthy title *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 OK: American Association of Petroleum Geologists is a remarkable collection of papers, anecdotes, and discussions that were held. It is perhaps one of the most revealing treatments of Wegener and his ideas from a sociological point of view. It all took place during a single evening in November.

12. Later on, in 1944, Bailey Willis – one of America's most influential writers in geology – penned the now classic paper that appeared in *The American Journal of Science,* "Continental Drift – ein Märchen (a fairy tale)". This, essentially, was such a vitriolic devastation of Wegener's ideas, his credentials, and even his nationality, there was in its wake no conceivable rehabilitation of the notions of drift among the American geological establishment.

13. Many eminent physicists, including Pascual Jordan (1966, 1971), R.H. Dicke (1957, 1959) and P.A.M. Dirac (1937, 1938) have, at times, offered some treatment of the expansion hypothesis through consideration of a decrease in the value of 'G' (that is, 'G' varies inversely as the age of the Earth). A number of geophysicists have written papers on the possibility of earth expansion, including Dearnley (1966), Egyed (1957), Schmidt and Embleton (1981), Ward (1963), Weijermars (1986), and J.Tuzo Wilson (1960).

14. Among S. Warren Carey's works, the following are significant in tracking his early mobilist thinking to an eventual commitment to continental displacement due to the expansion of the Earth:

Carey, S. Warren (1958). A Tectonic Approach to Continental Drift; in *Continental Drift, a Symposium;* Hobart: University of Tasmania p. 177-355.

Carey, S. Warren (1975). The Expanding Earth – an Essay Review; *Earth Science Reviews, vol. 11, p.* 105-143.

Carey, S. Warren (1976). *The Expanding Earth; Developments in Geotectonics 10, Amsterdam: Elsevier*

Carey, S. Warren (1983). The Necessity for Earth Expansion; in S.W. Carey (ed.) *Expanding Earth Symposium,* Sydney: University of Tasmania. p. 375-393.

Carey, S. Warren (1988). *Theories of the Earth and Universe: a History of Dogma in the Earth Sciences.* Stanford Univ. Press. 413 p.

Carey, S. Warren (2000). *Earth, Universe, Cosmos.* Hobart : University of Tasmania Press

15. Details of Beloussov's geology, and his well-known opposition to mobilism and plate tectonics can be found in can be found in a variety of sources, including some of his own publications such as: Beloussov, Vladimir V. (1968). "An open letter to J. Tuzo Wilson". *Geotimes (December),* vol. 13, p. 17-19; (1970). Against the hypothesis of ocean-floor spreading. *Tectonophysics,* vol. 9, p. 489-511; (1974). Sea-floor spreading and tectonic reality. In C. Kahle (ed.) *Plate Tectonics: Assessments and Reassessments – AAPG Memoir 23.* Tulsa OK: AAPG, p. 155-166; (1979). "Why I do not accept plate tectonics". *EOS: Transactions of the American Geophysical Union,* April 24 1979, p. 207-211.

For other aspects of this "Russian rift", see the historical anecdotes contained in Robert Muir Wood (1985), H. William Menard (1986), John Arden Stewart (1979, 1990), and Oreskes (2001).

16. See, for instance, the exchange between Beloussov (1968) and Wilson (1968b) and a similarly acrimonious one featuring a paragraph-by-paragraph debate among Beloussov (1979), and Sengör and Burke (1979).

17. Beloussov looked to the Ural Mountains for support, claiming that identifying them as evidence of an old "suture zone" where an ancient ocean closed up "was contradictory to all studies that he and others had conducted in that area" (quoted in Stewart, 1979). Sengör and Burke suggested that Beloussov's conceptions rested upon the fossil evidence and, therefore, could not be justified within Uniformitarianism, which holds that only processes seen in operation today can be used to explain past events and their resulting histories. Since plate tectonics *is* based on directly observed phenomena on the sea-floor and at continental margins, it is by definition a uniformitarian theory. It is interesting to note, then, that in the 1930's the opponents of drift theory argued that it was *counter* to uniformitarian principles, and was an appeal to catastrophism.

One other point can be raised here in the Popperian falsificationist realm. When Beloussov challenged the proponents of plate tectonics to explain why very ancient rocks had been found near the mid-Atlantic Ridge (a seeming impossibility in the sea-floor spreading hypothesis), Sengör and Burke (1979: p. 208) rejoined that these rocks "need to be studied further, but we are not prepared to abandon a theory that explains so many aspects of Atlantic geology for one curious observation." Beloussov was in agreement that some version of Popperian methodology was healthy, and then asks " but why then do plate tectonicians stubbornly disregard things that are wrong in plate tectonics theory, and why are they so aggressive toward those who try to point out the wrong sides of their theory? Is this attitude evidence of the strength of the theory, or of its weakness?" (Beloussov, 1979; p. 209).

18. When formed, continental igneous rocks become permanent magnets with a weak field. Upon cooling from the molten state, ferromagnetic minerals will become magnetized in the direction of the prevailing dipole field of the Earth as these fall below the Curie temperature. In essence, this thermo-remanent magnetism (TRM) locks in the paleolatitude of the rock, and provides a permanent record of the original location of emplacement (provided no thermal effects have "re-set" the magnetization, or the rock has undergone no major deformations).

19. The process is now known by the word *subduction*, which is a term borrowed from physiology, meaning "to turn down" (as for eyelids being turned down).

4.0 COLLIDING PARADIGMS – A MODEL FOR TEACHING THE NEW GLOBAL TECTONICS

4.1 Developing an Approach to Teaching the Geoscience Revolution to Students

> Historical science is still widely misunderstood, under-appreciated, or denigrated. Most children first meet science in their formal education by learning about a powerful mode of reasoning called *"the scientific method"* (italics in original). Beyond a few platitudes about objectivity and willingness to change one's mind, students learn a restricted stereotype about observation, simplification to tease apart controlling variables, crucial experiment, and prediction with repetition as a test. These classic 'billiard ball' modes of simple physical systems grant no uniqueness to time and object – indeed, they remove any special character as a confusing variable – lest repeatability under common conditions be compromised. Thus, when students later confront history, where complex events occur but once in detailed glory, they can only conclude that such a subject must be less than science. And when they approach taxonomic diversity, or phylogenetic history, or biogeography, or geology – where experiment and repetition have limited application to systems *in toto* – they can only conclude that something beneath science, something merely "descriptive", lies before them. (Stephen Jay Gould, 1986; quoted in Mayer *et al.*, 1992: p. 68).

In outlining a model for the teaching of global tectonics through the complimentary lenses of the history and philosophy of science, it is useful to be reminded of the two key components that are considered important in the theoretical model of Monk and Osborne (1997). First, they point out that HPS perspectives *must have* a rationale that is integral to, and consistent with, the overall goals of the teacher. This aspect fosters *inclusion* of the historical context in the first place. Secondly, the inclusion of HPS perspectives must *directly contribute* to the students' learning of the science concepts themselves. Their efforts were in developing a model that, in their view, offers the potential for students to both learn the concepts themselves and more *about* science at the same time.

The characteristics of the six phases discussed in the model of Monk and Osborne can be adapted, together with the relevant Kuhnian phases, into a new teaching and learning foundation that addresses *both* the historical and the key philosophical perspectives together. These factors can then find expression in examining the geological revolution from the point of view of rivalry or, perhaps more appropriate to geology, through *controversy.* The connections among these are summarized in Figure 4.1 and in Table 4.1 (succeeding pages), and each will be treated in some detail in the section that follows.

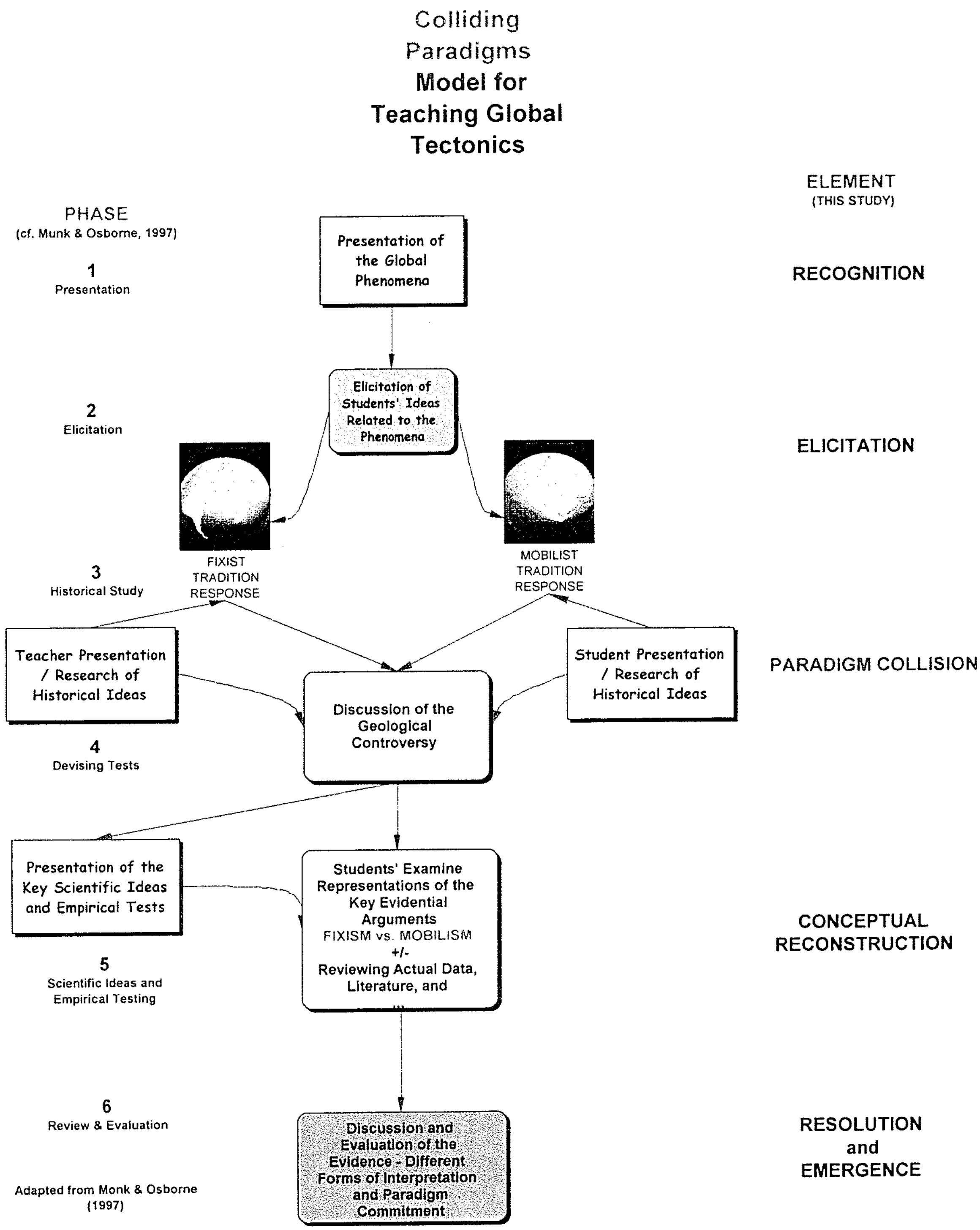

Figure 4.1 Concept map outline of the features of the teaching-learning model (present study) and those developed in the model of Monk and Osborne (1997)

Table 4.1: Relationships among the elements in the present model (this study), that of Monk and Osborne (1997), and their associated Kuhnian phases, with details from 20th century geology.

ELEMENT (this study)	PHASE (Monk & Osborne, 1997)	KUHNIAN GEOLOGICAL PHASE
RECOGNITION Identification of the "big questions" – what are continents made of? Is the 'fit' of continents real or imagined? What is the nature of volcanism, mountains? Are the Earth's dimensions constant? Enhancing student interest in the historical context	1 – Presentation	**"Pre-Paradigmatic" Science in Geology** Geoscientists work on multiple problems based on "Multiple Working Hypotheses (Chamberlin, 1890); Issues of faunal distribution, permanence of ocean basins and continents, isostasy.
ELICITATION How do students' thoughts explain the existence of mountains; the 'fit' of continents? Awareness of the importance of their own explanations	2 – Elicitation	**The Road to "Normal" Science in Geology – The Emergence of Two Schools of Physics and Geology** Geology begins to address early versions of "global" theories; first emergence of ideas related to mountain-building and origin of continents and oceans; The Continental Drift Debate (1915-1930)
PARADIGM COLLISION Importance of social and cultural aspects of scientific debate; evaluate the meaning of and implications of alternative points of view such as those of Wegener and Jeffreys; personal and institutional rivalries in geology are to be found almost everywhere	3 – Historical Study	**Quasi-Dogmatic "Normal Science" of Fixism and its Mobilist Rival** The Continental Drift Debate (1930-1965); the struggle between the MOBILISTS and the FIXISTS; isolation of the mobilists after the 'first collision'; 'second collision' (1958-1965) questions the fixist hegemony
CONCEPTUAL RECONSTRUCTION Assessing the evidence in support of both fixist and mobilist traditions; exposure to the dynamics of the scientific community during an exciting phase of rapid change	4 – Devising Tests 5 – Scientific Ideas and Empirical Tests	**Anomalies and Crisis – Working with "Extraordinary" Science in Geology** The new Oceanography; sea-floor spreading; magnetic anomalies; unanticipated applications of the mobilists' ideas (1965 – 1968)
RESOLUTION and EMERGENCE Modification of students' views on the nature of scientific inquiry; "Why do I accept Plate Tectonics?"	6 – Review and Evaluation	**Paradigm Acceptance - The "New Orthodoxy" of Plate Tectonics** Geology's "conversion experience"; widespread acclaim for the new global tectonics (1968 – 1975)

4.1.1 Elements of the Model

ELEMENT 1 – RECOGNITION

KUHNIAN CONTEXT : "PRE-PARADIGMATIC" SCIENCE IN GEOLOGY

The first element, or phase, in the proposed model is termed *recognition* – that is, offering students the basis for why the examination of global theories of the Earth are worthwhile, relevant, and fruitful. In essence, this is a *recognition* of a selection of the "big ideas" that have concerned geologists for some time now (and ones, conceivably, that could capture the imaginations of students) including:

- What are continents made of ? The ocean floors – are they of the same material?;
- Is the puzzle-like 'fit' of continents real or imagined?;
- What does the distribution of fossil assemblages tell us about the configuration of the continents over geologic time?;
- What is the nature of volcanism, and its geographic connection to mountains?;
- Why do "volcanic" island chains have an arcuate shape when they are located near a continent, but tend to be more linear when in the centre of an ocean basin?;
- Why are mountains generally found in long, arcuate chains that run north-south (predominantly) or east-west (across the largest continental land mass, Eurasia)?;
- Are the Earth's dimensions constant over geological time?;
- Why is the vast majority of the world's continental land mass located in the northern hemisphere?; and

- All major north-south elongated continents have a "vermiform tail" that is directed toward the east. Why is this so predictable a feature?

In the period prior to 1910, geology could be interpreted as working within its "pre-paradigmatic" phase, insofar as it was indifferent to the analysis of large-scale tectonic problems. The science of geology was dominated by paleontology and mineralogy as subdisciplines, for these were seen as its "roots" in the traditions of James Hutton and Charles Lyell. Nevertheless, there was more than a passing interest in some of the global-scale features of the Earth, with many of these listed above which should act to capture the intrigue of students. At this time, due in part to the influence and encouragement of Thomas Chrowder Chamberlin and his "multiple working hypotheses" edict (Chamberlin, 1890), geology was a loose association of unrelated problems and an equally disparate mosaic of field pursuits. The need or desire for a unifying framework to organize geology into a working relationship among the specialties was not viewed as an expedient. This aspect continued well into the 1960's as the plate tectonics model was being developed. Witness the following exchange at the 1974 Penrose Conference when asked if the assumption of fixed continents was widely accepted (Stewart, 1979, p. 431):

> H. W. Menard: I think in the United States, it [fixed continents] was widely accepted. Continental drift was a non-subject. As far as mountain-building goes, the general model of Vening Meinesz and Griggs about convection in the mantle causing mountains by pushing things together was one that was popular, but it was clear that there wasn't any way that you could prove anything. If it wasn't clear, it should have been.
>
> Kevin Burke: I think it is also difficult to think about how little most people worried about major issues like this, because there was no immediate access to a model that would work. People tended to take far more interest in more detailed sorts of things, and did not attempt to fit them into a general framework. That's one of the big changes I have noticed [lately].

H.W. Menard: It's exactly as [Burke] says it is. Right now, 90 percent of the papers correlate whatever a man is doing with plate tectonics, but at that [former] time, nobody cared…a man could become a world expert by writing one mediocre paper about how mountains were formed, because there was not much on it at that time.

ELEMENT 2 – ELICITATION

KUHNIAN CONTEXT: The Road To "Normal" Science In Geology – The Emergence Of Two Schools, Physics And Geology

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In this second element, students' initial conceptualizations of the answers to questions such as those generated in the recognition element are of more than superficial interest. In the same way that generations of observers have speculated systematically (or even wildly irrationally) on issues such as the figure of the earth, the origin of mountains (orogenesis) [1], the symmetries of continental coastlines, the constitution of the continents and ocean floors, and the distribution of fossil assemblages, it is important to *elicit* student generalizations about these phenomena. According to Driver and Oldham (1985), exploring these conceptions of students serves to define why the topic(s) under study is (are) important to them, and draw out students' awareness of their own thinking.

An example of this could be the coastline symmetry issue, which has tantalized observers since the first pan-Atlantic maps were made available. A student group discussion, for instance, could be generated from two simple observations:

- South America and Africa seem to fit together very well; and
- South America and Africa are apart now, separated by an expanse of the Atlantic Ocean.

In the period 1910 – 1930 (coincident with the untimely death of Alfred Wegener on a Greenland icecap), geologists had begun to entertain the earliest notions of a set "drift" hypotheses, with Wegener's model the most visible and contested. Over the same period, serious *geophysical* objections to the viability of any lateral displacement emerged from the mathematical physics community – particularly at the hands of Harold Jeffreys at Cambridge.[2] With the first (and only) serious airing of Wegener's drift hypothesis (see Section 3.2) having taken place at the 1926 AAPG symposium, the attributes of the two rival worldviews – a fixist interpretation that was defended largely on geophysical grounds, and the mobilist interpretation that utilized unique geological evidence in support of the *necessity* for mobility of continents. The two views can be adequately summarized with conceptual organizers as follows:

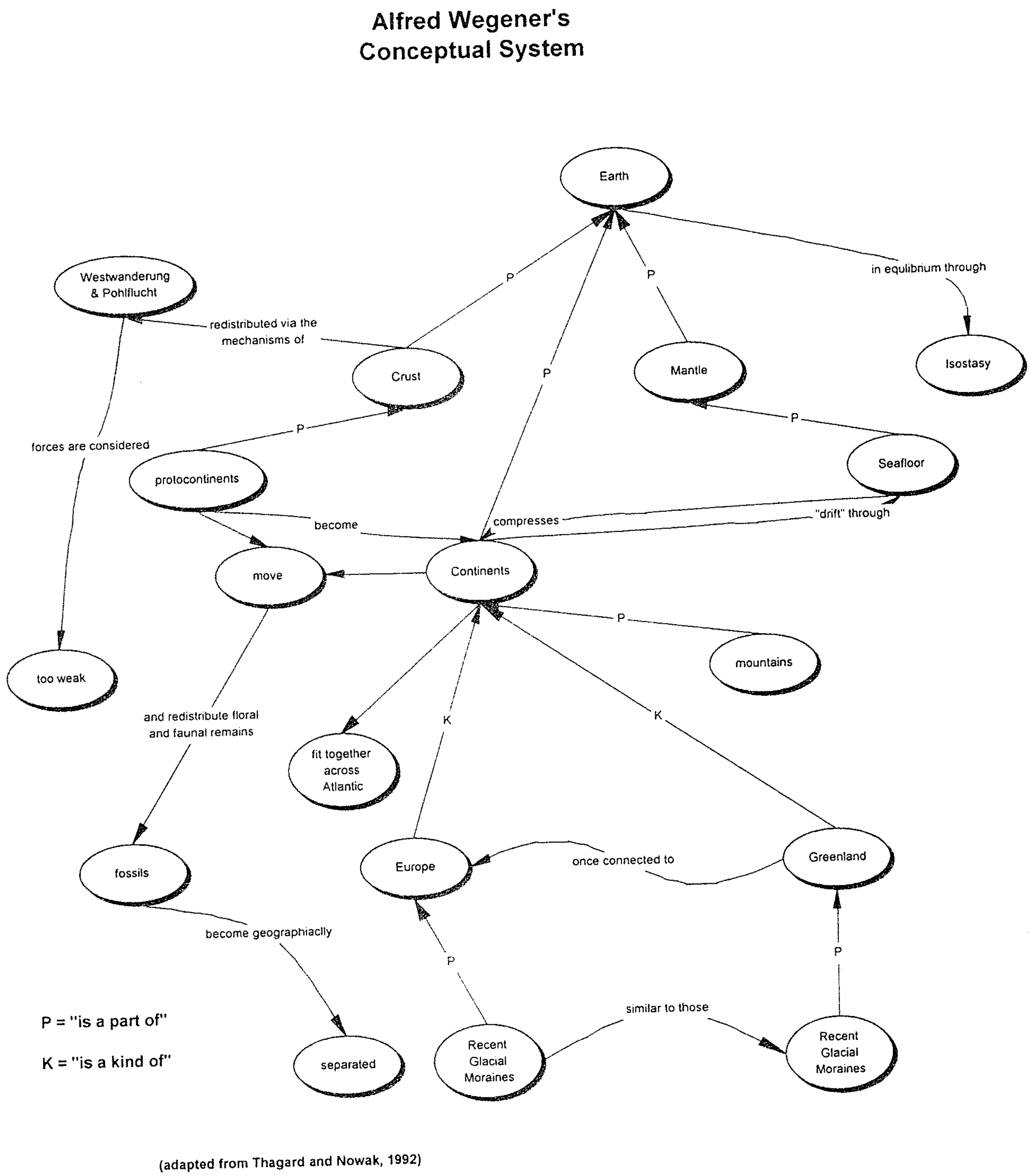

Figure 4.2: Diagram of the conceptual system of Alfred Wegener and his supporters in the wake of the publication of his 4th German edition of *Die Enstehung* in 1929. This system is based primarily on *geological* evidence, with drift deduced from it (adapted from Thagard and Nowak, 1992).

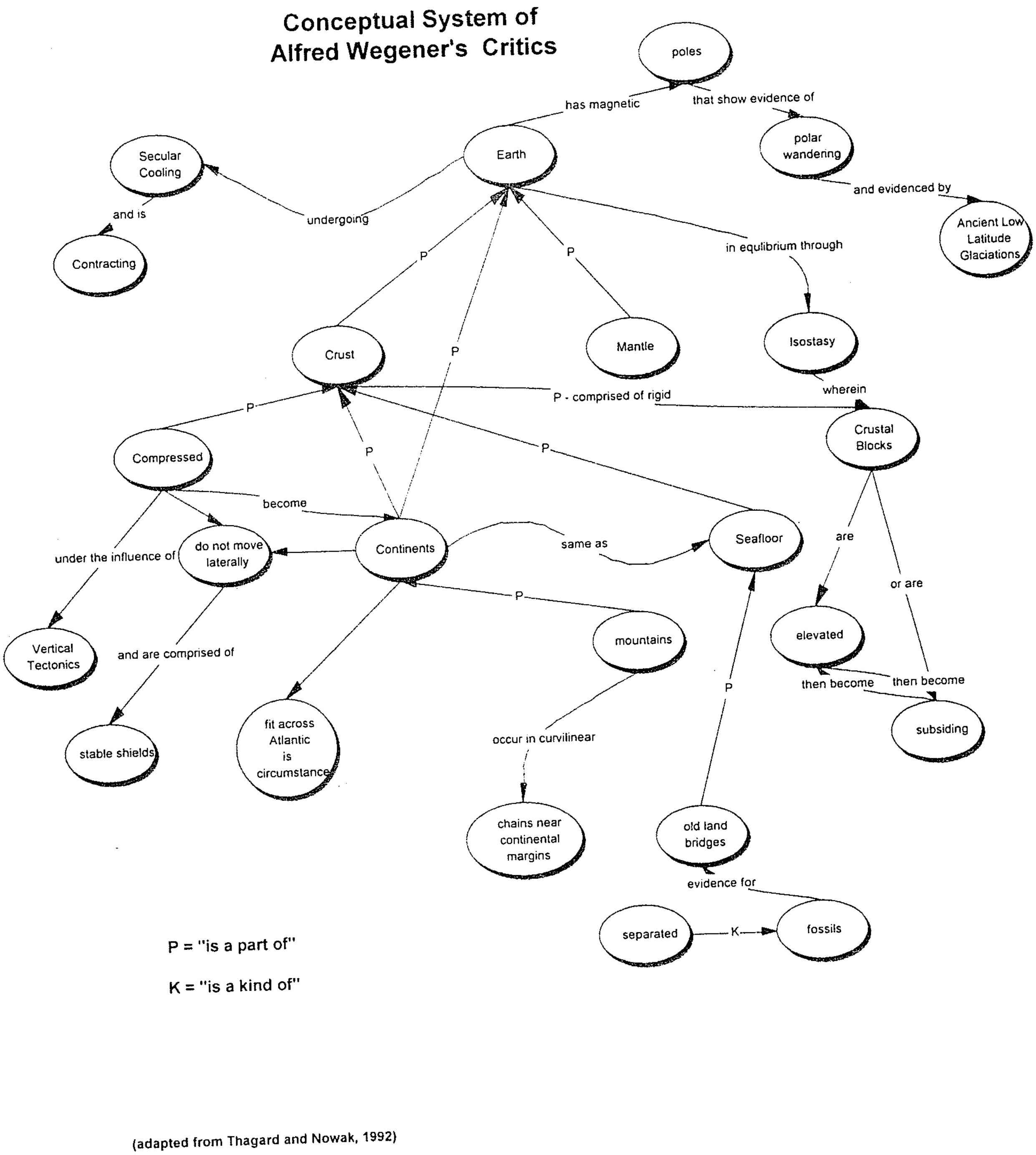

Figure 4.3: The conceptual system of Wegener's fixist (primarily contractionist) opponents in the period 1920 – 1930; a largely *geophysical* counterpoint to Wegener (adapted from Thagard and Nowak, 1992).

ELEMENT 3 – PARADIGM COLLISION

KUHNIAN CONTEXT: Quasi-Dogmatic "Normal Science" of Fixism Meets its Mobilist Rival

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This, the third element of the model, is certainly the one that is to be a particular focus of attention – for both the teacher and the students. Viewing 20th century geological thought through an historical context naturally highlights the following characteristics of scientific change:

- The importance of sociological, geographic, institutional, and cultural aspects of scientific behaviour among communities of workers;
- The implications of radically opposing views in geology;
- The influence wielded by the icons of popular (and sometimes unpopular) models, and the personal rivalries that, at times, are of equal importance with the ideas themselves that are competing
- How entrenched communities of geo-scientists, during a "collision phase", often mimic geology itself (i.e., creating a literature "landscape" with separate islands, gulfs that separate incommensurable ideas, the "subduction" of the former models

The components of paradigm collision that are considered here are two historically significant events that can assist in a deeper conceptual understanding of the new global tectonics, namely:

The First Collision: The continental drift debate in the wake of Wegener's publication, and translation into English, of his *Die Enstehung der Continente und Ozeane*; and

The Second Collision: The renewal of the "drift" debates with the emergence of the new oceanographic data, seismology studies, and the geomagnetic chronologies in the years 1958 – 1968.

ELEMENT 4 – CONCEPTUAL RECONSTRUCTION

KUHNIAN CONTEXT: Anomalies and Crisis – Working with "Extraordinary" Science in Geology

The fourth element – *conceptual reconstruction* – involves the students in a detailed examination of how the new evidence (i.e., novel facts, etc.) was variously interpreted by the fixist and the mobilist traditions. By linking this element to the Kuhnian contexts of *anomalies and crisis,* and the doing of *extraordinary science,* students gain explicit exposure to the dynamics of the scientific community – particularly the fluid behaviour of certain of the personality icons (e.g., J. Tuzo Wilson of Canada). Moreover, by setting this within the context of a period of rapid theoretical advancement and exchange of allegiances, the student is invited into an "insider" point of view of a field that is rapidly seeing its most cherished models questioned and dismantled over a very brief period in history.

One attempt at encouraging this form of conceptual change in students – that of Thompson *et al.* (2000) – was intended to swing students over to the mobilist point of view, beginning early on historically with Wegener. There are many unfortunate results that derive from such an *anti-misconception* approach, including:

- Convincing students, on authoritarian grounds, to abandon their "naïve" fixist beliefs about how the planet behaves (this is particularly problematic if what the teacher views as a misconception in students is actually an underdeveloped theoretical view, or is not a misconception at all based on recent evidence that is not known to the teacher);

- Students have become convinced mobilists prior to the "second collision" phase that occurred well after Wegerner and his contemporaries had left the scene; the net result is that artificial dismissal of fixists' ideas occurs in the majority of students, without having gone through the struggle that the geologists experienced in the critical period 1958 – 1975 or so;

- Students become, then, staunchly opposed to fixist alternatives, without having examined the evidence contemporaneously with the mobilist ideas, which is what did happen historically, but in very defined locations and venues.

ELEMENT 5 – RESOLUTION and EMERGENCE

KUHNIAN CONTEXT: Paradigm Acceptance – The "New Orthodoxy" of Plate Tectonics

The final element in the teaching and learning model is that of *resolution and emergence*, wherein the students assess the respective attributes of the paradigms that have "collided", and reach a level of commitment that permits them to answer the following questions:

- Have I been convinced that allegiance to either the fixist or mobilist (or neither, if that were possible!) view of global tectonics is one that *I* have achieved in a more personalized manner;

- The decision has been arrived at through a careful examination of the available evidence, rhetoric of scientists, arguments in the debate, and is rationalized upon some or all of Kuhn's stated characteristics of a "good theory" (simplicity, internal and external coherence, scope, etc.);

- Was it an epiphany? A "conversion experience" for you? Have you sensed the "herd mentality" that some observers have claimed existed with the acceptance of plate tectonics (see Nitecki *et al.*, 1978); and

- Why do I now accept plate tectonics as the new orthodoxy in global tectonics? Are there any other mobilist (or fixist) models that were competitors with classical plate tectonics that were appealing to you as alternatives (e.g., plate tectonics on an expanding Earth; fixed, deep-rooted continents with mobile, young ocean floors; Carey's vision of continental displacement on an expanding Earth)?

The next section will outline in detail the ***elements*** of this five-step approach, organizing around the controversy between the fixists and the mobilists, and mirroring the learning cycle.

4.2 Relationships Among the Five Elements in the Model – an Example for Teachers and Curriculum Developers Using HPS Perspectives in the New Global Tectonics

The following sequence of charts (Tables 4.2 to 4.6) are intended to outline in greater detail how the five elements – *recognition, elicitation, paradigm collision, conceptual reconstruction,* and *resolution and emergence* - in this model could develop more fully the geological content, historical perspectives, and the Kuhnian connections related to this episode of scientific change. It is the model put into action. Teacher educators and curriculum developers will note that significant content can be addressed coincidentally with these two HPS perspectives, with significantly richer detail afforded to the students. As best as possible, an attempt has been made to link the Kuhnian with the historical sequence of events as these unfolded in 20th century geology in a complimentary manner. Though the connection between the "Kuhnian Geological Phase" and each of the five elements noted above is at times a tenuous one, the overall fit is reasonably good.

"The depreciation of historical fact is deeply, and probably functionally, ingrained in the ideology of the scientific profession, the same profession that places the highest of all values upon factual details of other sorts."

(T.S. Kuhn, *The Structure of Scientific Revolutions*, p.138)

4.2.1 EXAMPLE DEVELOPMENT USING THE MODEL

Table 4.2: Details of **ELEMENT 1 – RECOGNITION** of students' prior understandings large-scale Tectonic problems similar to those discussed in geological circles in the period prior to 1910.

ELEMENT 1 RECOGNITION	THE FIXIST VIEW	THE MOBILIST VIEW
THE ICONS	James Dwight Dana (the "drying, shrinking apple model"); Sir Charles Lyell and his *Principles of Geology*.	French geologist Antonio Snider-Pellegrini (1858) and the American Frank Bursley Taylor (1910)
THE GEOLOGY	All of geology is governed by the principles of Uniformitarianism; isostasy dictated that continents and ocean basins may exchange positions through elevation changes, but this was contrary to American thinking that the continents and oceans are permanent features. The CONTRACTION THEORY was the most widely acceptable model, particularly for explaining the origin of mountains through geosynclinal theory.	Snider-Pellegrini argues that the continents were once united, but driven apart by the Noachian Deluge (see Marvin, 1973; Stewart, 1979, 1990) This was a period where there existed few alternatives to the fixist view of the globe's features
HPS PERSPECTIVES	In a Kuhnian sense, geology was in its "pre-paradigmatic" period, where there was lacking a stimulus to consider the larger-scale global tectonic problems. The commitment to the Uniformitarian view of slow, cyclic, gradual change was favoured by geology, particularly as an antidote to biblical support for geologic change at the Earth's surface	Thoughts of continental mobility raised the prospect of a *new catastrophism* that would take geology too close again to biblical sources for an explanation of natural phenomena.
SUGGESTED STUDENT ACTIVITIES	Examine the large-scale features of the Earth, and speculate on the reasons for the following within a model of a contracting Earth: Origins of linear and curvilinear mountain chains; what could the continents and ocean floors be comprised of?; Is the "puzzle-like" fit of the continents across the Atlantic a coincidence or a phenomenon that demands an explanation? What does the distribution of earthquakes and volcanism have to say about the positions of continents and oceans over time? Did land bridges once exist, connecting continents?	Examine the large-scale features of the Earth, and speculate on the reasons for the following within a model of drifting continents: Origins of linear and curvilinear mountain chains; what could the continents and ocean floors be comprised of?; Is the "puzzle-like" fit of the continents across the Atlantic a coincidence or a phenomenon that demands an explanation? What does the distribution of earthquakes and volcanism have to say about the positions of continents and oceans over time?

KUHNIAN GEOLOGICAL PHASE

"PRE-PARADIGMATIC" SCIENCE IN GEOLOGY

GEOSCIENTISTS WORK ON MULTIPLE PROBLEMS BASED ON "MULTIPLE WORKING HYPOTHESES (CHAMBERLIN, 1890); ISSUES OF FAUNAL DISTRIBUTION, PERMANENCE OF OCEAN BASINS AND CONTINENTS, ISOSTASY.

Timeline: Prior to 1910

STUDENT ASSESSMENT	Determine the degree to which the students' conceptions are close approximations to those that were established by the geologists themselves.	Determine the degree to which the students' conceptions are close approximations to those that were established by the geologists themselves who were in possession of alternative ideas to the fixist hegemony.

Table 4.3: Details of **ELEMENT 2 – ELICITATION** of students' points of view during the period when the mobilist ideas of Wegener were first being circulated, ca. 1915 – 1930.

ELEMENT 2 ELICITATION	THE FIXIST VIEW	THE MOBILIST VIEW
THE ICONS	Harold Jeffreys, mathematical physicist at Cambridge, who is a staunch "anti-drifter" ostensibly on geophysical grounds; his first edition of *The Earth: Its Origin, History and Physical Constitution* (1924) became the new standard of the soon to emerge discipline of geophysics.	Alfred Lowthar Wegener (1915, 1924, 1929, 1966), an astrophysicist and meteorologist by training, publishes his opus *Die Enstehung der Continente und Ozeane;* In 1937, working out of South Africa, Alexander DuToit publishes his own version of drift in *Our Wandering Continents,* where he coins the terms "Laurasia" and "Gondwanaland" for the northern and southern super-continents, respectively.
THE GEOLOGY	At this time, convection in the mantle was thought to be next to impossible due to its finite strength and essentially solid state; The CONTRACTION THEORY was still the most widely shared model, particularly for explaining the origin of mountains. With the quantitative support of Jeffreys' calculations, there was no *conceivable* mechanism that could be responsible for drift. Among the evidence that was considered explainable within the fixist tradition, the following stand out against Wegener's mobilism: Large, ancient continental shields are flat, and stable; there are mountain chains in the interior of the continents which are quite old; continents which were originally north of the equator should be equatorial by now (an answer to Wegener's *pohlfluchtkraft*; geodetic measurements made in 1926 showed no movement of Greenland	Wegener outlined an impressive variety of evidence for drift, including results (both solid and weak) from a diversity of fields, including: paleoclimatology, glaciology, paleontoogy, structural geology, and geodetic measurements. Among his propositions, the following are important for students: The shape of the Atlantic coastlines is a close match; there are several north-south trending mountain chains; continental blocks that taper toward the south (e.g., North America, South America, SE Asia) have curves to the east; during the Cretaceous (~65 Ma ago), Spitzbergen was tropical and central Africa was polar; the continents were once all connected; tidal forces pull apart the continents and move them westward

KUHNIAN GEOLOGICAL PHASE

PERIOD OF "PRE-NORMAL" SCIENCE IN GEOLOGY – THE EMERGENCE OF TWO SCHOOLS OF PHYSICS AND GEOLOGY

GEOLOGY BEGINS TO ADDRESS EARLY VERSIONS OF "GLOBAL" THEORIES; FIRST EMERGENCE OF IDEAS RELATED TO MOUNTAIN-BUILDING AND ORIGIN OF CONTINENTS AND OCEANS; THE CONTINENTAL DRIFT DEBATE (1915-1930);

TIMELINE: 1910 - 1930

HPS PERSPECTIVES	In a Kuhnian sense, geology was in its "pre-normal" science period, where there were the beginnings of a stimulus to consider the larger-scale global tectonic problems. With the advent of the "Wegener heresy", there was now a reason to entrench the contractionist orthodoxy, and to defend it against the upstart mobilists who were now emerging.	Wegener was met with rather hostile treatment by the American geological establishment. They objected to his "doing violence" to the cherished underpinnings of Uniformitarianism; accused of somewhat wild speculation, the geophysicists were particularly opposed to his offering no conceivable physical mechanism that could be adequate to move continents, and be quantifiable.
SUGGESTED STUDENT ACTIVITIES	Identify where the youngest mountain ranges are on Earth today, and compare with the location of any identifiable, older mountain ranges; check for parallelism, for instance Access the published proceedings of the 1926 AAPG Symposium on Continental Drift (van der Gracht, 1928a;b), and chronicle the contributions of the fixist opponents of Wegener, including Harold Jeffreys, Chester Longwell, Bailey Willis, R.T. Chamberlin, and Charles Schuchert as laid out in the same publication	Access the published proceedings of the 1926 AAPG Symposium on Continental Drift (van der Gracht, 1928), and chronicle the contributions of the more sympathetic voices giving tacit support to Wegener, including John Joly of Trinity College in Dublin, and G.A.F. Mollengraaf, a Dutch supporter of drift.
STUDENT ASSESSMENT	Develop a re-creation of the evening of November 26, 1926 in New York City, and assume the roles of the key protagonists; this would be particularly appropriate to hold as a "mock trial" or as regional representatives at an international "tectonic development" organization meeting; Summarize the evidence that is persuasive within the fixist paradigm...from a student perspective; Debate the nature of certain key episodes in the debate among the fixists and the "drifters" by role playing, case studies, or simulation games. Construct, and discuss in group dynamic, a CONCEPTUAL MAP of Wegener's opponents' system (see Appendix for sample student-generated map)	Develop a re-creation of the evening of November 26, 1926 in New York City, and assume the role of the key protagonist, Alfred Wegener; this would be particularly appropriate to hold as a "mock trial" or as an instance of defending his arguments at an international "tectonic development" organization meeting; Summarize the evidence that is persuasive within the mobilist paradigm...from a student perspective; Debate the nature of certain key episodes in the debate among the fixists and the "drifters" by role playing, case studies, or simulation games; Construct, and discuss in group dynamic, a CONCEPTUAL MAP of Wegener's system as it opposes that of the fixists (see Appendix for sample student-generated map)

Table 4.4: Details of **ELEMENT 3 – PARADIGM COLLISION** - where students examine the importance of the social and cultural aspects of scientific debate during a time of "revolutionary change". In this element, students are invited to evaluate the meaning of, and implications of, alternative points of view as defintions change, and scientific communities are on an inevitable course toward conflict and controversy.

ELEMENT 3 PARADIGM COLLISION	THE FIXIST VIEW	THE MOBILIST VIEW
THE ICONS	Soviet geologist Vladimir Beloussov retains his influential commitment to "continentalist" interpretations; Canadian geophysicist J. Tuzo Wilson writes a series of contractionist papers dealing with the growth and evolution of continents during the 1950's; as President of the IUGG and coordinator of the International Geophysical Year (in 1957), Wilson travels extensively on all four continents; Maurice Ewing and his core of students at Lamont (of Columbia University) hold most of the key new ocean floor evidence under contract from the US Office of Naval Research (most data confidential) Sir Harold Jeffreys still casts a long geophysical "shadow" in favour of the permanence of continents and ocean basins; Gordon J. F. MacDonald (1963) publishes his thesis on the *deep structure of continents,* which is strongly negative on the prospect of mobility in the mantle, and is viewed as "a barrier to progress" by the growing influence of the "drift" community in the UK	S. Warren Carey of Tasmania convenes the first international symposium on continental drift (Sydney, 1956) since Wegener's death in 1930; the southern continent "Gondwanalanders" Lester King, Carey, and DuToit are still on the fringe with "the drifters"; Arthur Holmes (1944; 1965) continues to offer his insightful *convection-driven* model; Tuzo Wilson of Toronto, likely under the influence of Carey, seriously entertains the conceptual model of an expanding earth, and publishes a tantalizingly cautious paper in *Nature* (Wilson, 1961) The symposium on continental drift, convened at Cambridge in 1964 by P.M.S. Blackett (a Nobel laureate), Edward "Teddy" Bullard and Keith Runcorn (Newcastle-on-Tyne) produces a powerful set of figures who are now committed "drifters"; the so-called computer-generated "Bullard Fit" of the continents across the Atlantic is very influential; Following a sabbatical at Cambridge, Wilson now abandons his commitment to contractionism, is circumspect of being associated with the expansionists and Warren Carey, and falls in with the core of the "drifters" by 1963;
THE GEOLOGY	Most American and British geo-scientists are still committed to Permanentism or a form of Contractionism in the 1950's; The post WW II research by American oceanographic institutes such as Scripps in	Carey, influenced by the earlier work of the German expansionist school of Hilgenberg and the Hungarian Laszlo Egyed (1956; 1957), offers a significant new drift synthesis with his *"The Tectonic Approach to Continental Drift"* (Carey, 1958) which argues for exponential expansion of the Earth since the break-

KUHNIAN GEOLOGICAL PHASE

QUASI-DOGMATIC "NORMAL SCIENCE" OF FIXISM AND ITS MOBILIST RIVAL

THE STRUGGLE BETWEEN THE **MOBILISTS** AND THE **FIXISTS**; ISOLATION OF THE MOBILISTS AFTER THE 'FIRST COLLISION'; 'SECOND COLLISION' **(1958-1965)** QUESTIONS THE FIXIST HEGEMONY

	California and Lamont reveals a completely unexpected topography of the world's ocean floors – it is still too early to explain through a mobilist model; Rock magnetic evidence of "polar wandering" is interpreted by the fixists as "true polar wander" – that is, the geomagnetic pole is inconstant over geological time scales, and deviates at times significantly from the geographic poles;	up of Pangaea; Harry H. Hess (1960; 1962) of Princeton, and contemporaneously, Robert S. Dietz (1961) publish astounding papers on the prospect of *sea-floor spreading;* not very many notice them. Fred Vine and Drummond Matthews (1963) announce their magnetic evidence that aligns with Hess' sea-floor spreading hypothesis; in the same year, Canadian Lawrence Morley (1964) arrives at a similar view that paleomagnetics could be used as a means of dating geological events; Rock magnetic evidence of "polar wandering" is interpreted by the mobilsts as "apparent polar wander" – that is, the geomagnetic pole is inconstant over geological time scales, and deviates at times significantly from the geographic poles due to the drifting of the continents over time;
HPS PERSPECTIVES	A sophisticated contractionist model appears in the influential textbook *Physics and Geology* (Jacobs, Russell and Wilson, 1959); New technologies (e.g. sonar, magnetometer) developed during WW II permit access to "novel facts" about the ocean floors; The FIXISTS (primarliy geologists and mathematicians) begin to lose contact with the more aggressive "drifters" (the geophysicists), and the beginnings of a Kuhnian *incommensurability* develop; The Lamont group, under the leadership of Ewing (and his staunch fixist proclivities), begins to face the crossroads of internal friction; Highlight the growing confrontation with the mobilists;	Bruce Heezen (a student at Lamont) comes out in 1960 as favouring an *expansion* explanation of the new oceanographic data; he becomes locked in a bitter struggle with director Maurice Ewing at Lamont, who was still a contractionist defender; Lawrence Morley has his paper rejected *twice* by leading journals as too speculative – six months later, Vine and Matthews get their similar model published in *Nature*; Morley retreats in disgust, and never again returns to solid Earth geophysics in his career; Institutional rivalries related to mobilism are primarily internal debates among a very few, select institutions who had access to the relevant data; Highlight the growing confrontation with the fixists;
SUGGESTED STUDENT ACTIVITIES	Examine the convection-current model of Arthur Holmes (1944), which was developed within the fixist paradigm, but invoked a "conveyor-belt" analogy of lateral motions (see Appendix); Discuss the significance to Canada of having one of the authors of an influential contractionist textbook	Examine the model of convection current-driven motions beneath the sea-floor according to Hess (ca. 1960's), and note the similarities to Holmes' earlier attempts (see Appendix); Outline the controversy between Hess and Dietz about the issue of priority in establishing the sea-floor

	at the University of Toronto (Wilson); Gather depth and geographic location data on shallow-focus and deep-focus earthquake activity, and plot the location of these quakes using the "fault-plane" cross-section from Wilson's contractionist model (Wilson, 1959) Explain, from the fixists' viewpoint, the phenomenon of "polar wandering"	spreading hypothesis; Gather depth and geographic location data on shallow-focus and deep-focus earthquake activity, and plot the location of these quakes using the modern plate tectonics block diagram; compare to the plot for Wilson's model (ca. 1959 – 1963); Explain, from the mobilists' viewpoint, the phenomenon of "polar wandering" as it relates to an hypothesis of continental drift
STUDENT ASSESSMENT	Demonstrate evidence of the acquisition of a sense of the dynamical workings that occur within a scientific community driven by influential, almost iconic, individuals (include the chronological element in scientific careers..)	Demonstrate evidence of the acquisition of a sense of the dynamical workings that occur within a scientific community driven by influential, almost iconic, individuals (include the chronological element in scientific careers..)

Table 4.5: Details of ELEMENT 4 – **CONCEPTUAL RECONSTRUCTION** - where students examine the evidence that acts in support of both the fixist and mobilist traditions, but during a crucial phase of rapid exchange in global tectonic views.

ELEMENT 4 CONCEPTUAL RECONSTRUCTION	THE FIXIST VIEW	THE MOBILIST VIEW
THE ICONS	Soviet geologist Vladimir Beloussov publicizes his influential commitment to "continentalist" interpretations with a memorable exchange with Tuzo Wilson; Canadian geophysicist J. Tuzo Wilson has, by this time, formally abandoned his contractionist allegiances; Maurice Ewing and his core of students at Lamont (of Columbia University) still hold most of the key new ocean floor evidence under contract from the US Office of Naval Research (most data confidential) Sir Harold Jeffreys still casts a long geophysical "shadow" in favour of the permanence of continents and ocean basins; Gordon J. F. MacDonald and his thesis on the *deep structure of continents,* which is strongly negative on the prospect of mobility in the mantle, is viewed as a regressive " barrier to progress" at the Goddard Symposium of 1966	S. Warren Carey of Tasmania is strangely quiescent and "off the scene" in the mainstream of geological circles – he has been rejected as a "bombast", and sent into a sort of oblivion of ignominy. He still lectures on the concept of a rapidly expanding Earth, but is no longer taken seriously in most circles; In 1965, Wilson coins the term "plates", referring to rigid, thin blocks of crust that are in rotational motion about an Euler pole of rotation; Tuzo Wilson of Toronto writes and lectures extensively on what he describes as a "revolution in the earth sciences" (Wilson, 1968), and comes out as the most vigorous and visible proponent of the new mobilist tectonic paradigm; The symposium on *The History of the Earth's Crust,* convened in 1966 at the Goddard centre of NASA, invites all the influential "drifters" to put an end to the fixist "holdouts" – Wilson cannot attend (or was not invited?); Young graduate students, such as Dan MacKenzie (1967) at Scripps, Xavier LePichon (1968) at Lamont, and W. Jason Morgan (1968) at Princeton publish the first early syntheses that would come to be known as *plate tectonics*
THE GEOLOGY	Most American and British geo-scientists are still committed to Permanentism or a form of Contractionism in the 1960's, and will be in need of "conversion" to mobilism; Very little of the new oceanographic data can be	Fred Vine (1966) publishes compelling new evidence that favours the sea-floor spreading hypothesis "almost without question"; Evidence from seismology virtually "cements" the notion of earthquakes as the operational definition of

KUHNIAN GEOLOGICAL PHASE

ANOMALIES AND CRISIS – WORKING WITH "EXTRAORDINARY" SCIENCE IN GEOLOGY

THE NEW OCEANOGRAPHY; SEA-FLOOR SPREADING; MAGNETIC ANOMALIES; UNANTICIPATED APPLICATIONS OF THE MOBILISTS' IDEAS (1965 – 1968)

	explained within the contexts of fixism (and its corollary, contractionism); The fixist community is stunned by the evidence that all the world's ocean floors are geologically "young" (< 200Ma), while the continents are more than an order of magnitude older (> 3.8 Ga);	a "plate boundary" (but this is a tautology); Walter Pitman III and James Heirtzler (1966) publish the now famous *Eltanin 19* seismic profile that links a theoretical magnetic anomaly profile with an almost prefectly-matching actual profile revealed via a shipboard deep-tow magnetometer in the Indian Ocean; The mobilists concentrate of the geological significance of the ocean floors, but cannot readily apply the new theoretical structure to the evolution of the ancient continents;
HPS PERSPECTIVES	The FIXISTS (primarliy geologists and mathematicians) begin to lose contact with the more aggressive "drifters" (the geophysicists), and the beginnings of a Kuhnian *incommensurability* develop; This group rapidly loses its influence, and must retreat into a sort of anachronistic caucus (led by Jeffreys, among others)	Bruce Heezen (formerly a student at Lamont under Maurice Ewing) has lost his security clearance to conduct research under the auspices of the Office of Naval Research – in 1968, Heezen dies aboard ship in the Atlantic while on "the fringe" at Lamont; Late one night at Lamont early in 1966, Pitman and Heirtzler look at the *Eltanin 19* magnetic profile, and then make to leave for the night...then Pitman says "Wait a minute, Jim..." – the two look at it carefully again, then at one another, and say "Oh my God !!"; The spring 1967 meeting of the American Geophysical Union becomes the "watershed experience" for many North American geologists; as one observer describes it, "you could see it on their faces...it was as though scales fell from their eyes and they saw everything in a new light....and for some, it was an agonizing couple of days with a great deal of colourful language in the hallways.." W. Jason Morgan, at the podium as a young, inarticulate and confusing graduate student, changes his abstract in a surprise move, and begins to enunciate the principles of plate tectonics to a now half-full conference room of baffled listeners; As Menard (1986) recalls the event, some in the hallways shout out "Morgan is dropping a bomb on everyone !!...he has changed his talk and is spouting some gibberish about moving crustal blocks and seismicity and such...you have got to hear this!!"; some recount that Ph.D.'s were running down the hall to crowd back into the room, but no one knew what

		Morgan was talking about...;
SUGGESTED STUDENT ACTIVITIES	Be an audience participant in the re-creation of the 1967 or 1968 American Geophysical Union meetings, listening for the first time to the details of this "new heresy"	Research, represent visually and orally, the new evidence for sea-floor mobilism as revealed from oceanographic research, and particularly outline the inescapable influences of the new technologies that allowed geophysicists to "see deeper and farther" than before
STUDENT ASSESSMENT	Students are identifiably taking note of, and attempting to reveal in themselves, a sense of *confrontation* as a result of taking on the role of defending the fixist model in the face of mounting evidence for mobilism and the new oceanographic data; What was my reaction to hearing the details of the "new global tectonics? On whose authority will I find it an acceptable model?	Students can identify with the social aspects of knowledge construction in the sciences, particularly the aspect of the "theory-ladenness" of observation from Kuhn's analysis; Resolve the question: "To what degree is scientific knowledge an advancing frontier preceeded by new technologies?"

Table 4.6: Details of **ELEMENT 5 – RESOLUTION and EMERGENCE** - where students begin to entertain the modification of their own views in the light of a "revolutionary experience". We now seek to answer the question, *"Why do I accept plate tectonics?"*

ELEMENT 5 RESOLUTION & EMERGENCE	THE FIXIST VIEW	THE MOBILIST VIEW
THE ICONS	Sir Harold Jeffreys (1974) is still resolute in his belief that continental drift simply "is impossible" on rheological grounds – he now focusses less on geophysics, and more on arcane physics such as Lomnitz's Law of viscosity; The Russians, still led by Beloussov (and perhaps with some measure of Cold War opposition according to Wood (1985)) are still in the anti-plate tectonics group of skeptics in the 1970's; The American father-son duo of Howard and Arthur Meyerhoff (petroleum geologists) become the dominant opponents of plate tectonics; All of the above publish detailed attacks on the veracity of plate tectonics in the volume *Plate Tectonics: Assessments and Reassessments* published in 1974 by the AAPG; Carey is certainly not a fixist, but he denies as irrelevant (and unnecessary) the plate tectonics *ad hoc* hypothesis of *subduction* of crust at the ocean trenches	S. Warren Carey of Tasmania is still strangely quiescent and "off the scene" in the mainstream of geological circles – he has been rejected as a "bombast", and sent into a sort of oblivion of ignominy. He publishes on the expansionist theory of global tectonics (Carey, 1975; 1976), but little attention is paid to these lengthy treatises; New workers, who are among the first to apply the new principles of plate tectonics (e.g., J.F. Dewey and J.M. Bird (1970); Kevin Burke and J.T. Wilson (1972)), see opportunity in "getting in early" in the explosion of plate tectonics literature; J. Tuzo Wilson, over the seemingly "brief" period of 1958 – 1968, has passed through commitment to contractionism, a casual flirtation with expansionism, to early acceptance of sea-floor spreading, and then to very public defense of the "new, revolutionary geology" – and all this, without loss of esteem and stature within the community of earth scientists Hugh Gwyn Owen (1976, 1981, 1983a, 1983b, 1992) argues persuasively for a renewed look at the expansionist model, and publishes a remarkable series of detailed maps supporting limited earth expansion
THE GEOLOGY	Most American and British geo-scientists have abandoned their commitment to Permanentism or a form of Contractionism in the 1970's, and some have experienced true "conversion" to mobilism;	Almost all new research is conducted within the "new paradigm" of plate tectonics; the earth sciences are unified as never before, and there is an exponential growth in the literature related to the new synthesis as it impacts other disciplines;

KUHNIAN GEOLOGICAL PHASE

PARADIGM ACCEPTANCE - THE "NEW ORTHODOXY" OF PLATE TECTONICS

GEOLOGY'S "CONVERSION EXPERIENCE"; WIDESPREAD ACCLAIM FOR THE NEW GLOBAL TECTONICS (1968 – 1975)

	The fixists "rejoice" at the discovery of ancient rocks near the Mid-Atlantic Ridge, which is a glaring anomaly that cannot be accounted for according to the sea-floor spreading model critical to plate tectonic theory; The Meyerhoffs, along with R. Briggs, publish a new contractionist model as an alternative to plate tectonics in 1972;	The mobilists discount this anomalous ancient ocean floor as being any sort of a "crucial test" of sea-floor spreading, and begin to focus on applications of the theory rather than justifications of it; Hugh Gwyn Owen (1976) of the British Museum publishes a significant cartographic treatment of the new sea-floor data in the *Philosophical Transactions of the Royal Society*. His conclusion – only expansion of the Earth along with the principles of plate tectonics can account for the constraints imposed by geography and cartography.
HPS PERSPECTIVES	The FIXISTS (primarliy Soviet – and a few notable American and British - geologists and mathematicians) begin to lose all contact with the more aggressive "drifters" (the geophysicists), and the Kuhnian *incommensurability* is almost complete and irreversible; The arguments of the "anti-drifters" are emphasizing evidence that the other side trivializes, or interprets the common evidence in a notably different manner; This group rapidly loses its influence, is seen as a "complaining minority opinion", and must retreat as a sort of anachronistic caucus (led by Jeffreys, among others); Beloussov, at this time, is still admonishing the American geological community for abandoning their own legacy of the *method of multiple working hypotheses;* Some of the traditionally staunch adherents of fixism grudgingly accept the new global tectonics, but only as a "working hypothesis" that could be significantly revised;	Plate tectonics has now become accepted by the vast majority of earth scientists (Nitecki *et al.*, 1978), but each has a particular set of reasons for "believing"; Textbooks are now being re-written, and are strongly in favour of the new global tectonics and drift theory; there is virtually no trace of the prior contractionists' ideas; geology now embraces T.S. Kuhn's two essential paradigm characteristics – the achievement was an "unprecedented conceptual leap that attracted an enduring group of adherents away from competing modes of scientific activity", and; it was "sufficiently open-ended to leave all sorts of problems for the redefined group of practitioners to resolve" (Kuhn, 1996; p. 10) Some workers, notably Isacks, Oliver and Sykes (1968) in their landmark paper *Seismology and the New Global Tectonics*, attempt a sort of Popperian falsificationism, but in the end, comment "...we report an earnest effort to uncover reliable information from the field of seismology that might provide a case against the new global tectonics. There appears to be no such evidence" (p. 5862); The clear emergence of a Kuhnian "normal science" in geology under the umbrella of the new paradigm is observable; Wilson stands as an "icon of radical change", and his personal influence does not wane, even under the glare of having altered his position by 180 degrees (or more) in recent years. As a sexagenarian, this is even more remarkable from the point of view of Planck's Principle;

SUGGESTED STUDENT ACTIVITIES	Summarize the available evidence, as of the mid-1970's, that can still be interpreted within the fixist (particularly the contractionist) paradigm (see Appendix 'E' for a summary of that evidence) Identify the key roles played by persuasive icons such as Gordon MacDonald and Sir Harold Jeffreys, and connect these efforts to a deeper understanding of the nature of scientific inquiry, and how these icons handled (or mishandled through obstinacy) problematic areas of a new, emerging theoretical model; There are still fixists operating within the geological community, though their ability to publish is severely impaired; students should identify the *New Concepts in Global Tectonics* working group, comprised primarily of Australian, Chinese, and American workers, and assess the nature of their research programme.	Summarize the available evidence, as of the mid-1970's, that can *only* be interpreted within the new global tectonics of the mobilist (particularly the plate tectonics version) paradigm (see Appendix 'E' for a summary of that evidence); Detail the evidence, provided by student research, of the "anomalies" that still perplex geologists within the modern plate tectonics paradigm; Explore the important details of the expansionist models developed by S. Warren Carey and Hugh Gwyn Owen – repeat the reconstruction of the continents prior to the present on increasingly smaller spheres, and compare the 'fit' with similar reconstructions on constant dimensions spheres; Attempt to answer, as completely as possible, the question "why did the new global tectonics abandon the concept of expansion of the Earth?"; Is it a model with some merit? Identify the key roles played by persuasive icons such as J. Tuzo Wilson, and connect these efforts to a deeper understanding of the nature of scientific inquiry, and how the icons handle problematic areas of a new, emerging theoretical model
STUDENT ASSESSMENT	Identify, as a competing explanatory model, Kuhn's five characteristics of a "good theory" (accuracy, scope, consistency, simplicity, fruitfulness) as these are demonstrated by maintaining a commitment to a FIXIST view of the planet's crust.	Evaluate students' efforts to answer the question "Why do I accept plate tectonics" as the way the Earth's surface works? Refrain from inviting students to justify the validity of continental drift on the basis of their "improper puzzle-fitting of the continents" – an exercise that, in itself, lacks validity. Many of the "best fits" are purely coincidences of geometry, and have no basis in geological (or other) relationships; this is, however, an opportunity to assess students' desires to "get the right fit" according to the teacher or Teddy Bullard… Identify, as a successful and accepted explanatory model, Kuhn's five characteristics of a "good theory" (accuracy, scope, consistency, simplicity, fruitfulness) as these are demonstrated by maintaining a commitment to a MOBILIST view of the planet's crust.

Notes, Chapter 4

1. Orogenesis derives from the Greek "οροσ" (*"oros"*), meaning "mountain".

2. Perhaps the most widely read historical analysis (and one not without its inherent bias toward the triumph of geophysics over geology) of the physics versus geology debate is Robert Muir Wood's 1985 volume *The Dark Side of the Earth: The Battle for the Earth Sciences.* Wood attempts to convince the reader that the real "revolution" in geology was the veritable loss of the discipline to physics in the wake of the development of plate tectonics. The *earth sciences,* for Wood, becomes the new synthesis of the remains of physics and geology.

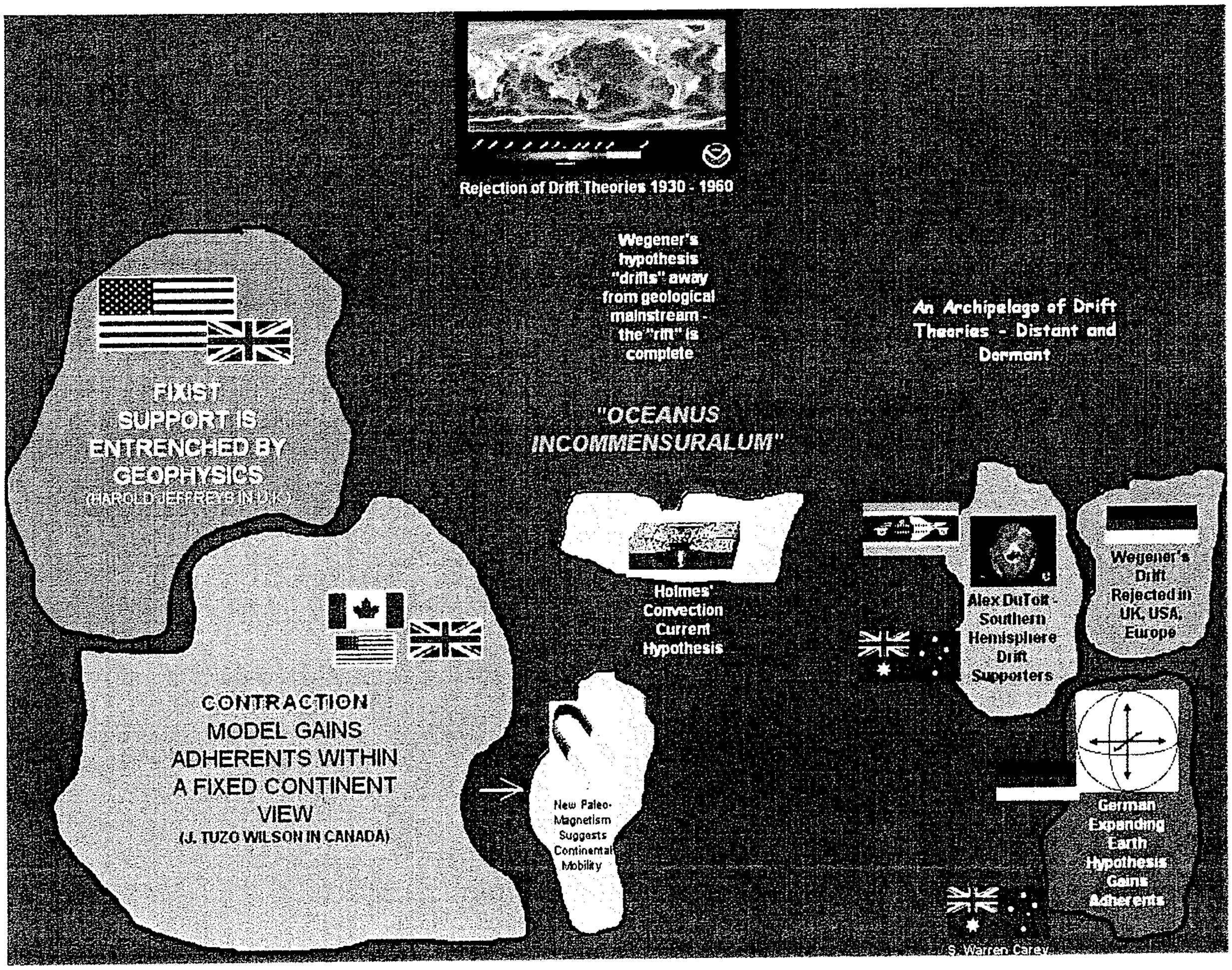

Plate 3: In the period 1930 – 1960, the fixist position was solidified through the work of Harold Jeffreys at Cambridge, who presented seemingly impenetrable geophysical arguments precluding mantle convection and continental mobility. At the same time, particularly in Canada – with J. T. Wilson and others – the contractionist version within the fixist tradition was gaining credence among those with an interest in global theories. The "drifters" were now geographically and theoretically out of the mainstream of thought, most of them being in the southern hemisphere or pre- or post-war Gerrnany. A possible new "land bridge" between these opposing camps was the new convection-current hypothesis of Arthur Holmes, a creative and influential British geologist.

5.0 Summary and Implications

5.1 Discussion

It was about a quarter century ago when Ruse (1978) pointed out that philosophers of science and historians had arrived at an analysis of the occurrences in late 20th century geology somewhat late – well after the significant change was over. This indictment was perhaps premature, for well into the 1970's, the field of tectonics was still very much in a state of flux. It would seem, in retrospect, that their timing was very good in capturing the essence of the "geological revolution". In the intervening period up to the present, one disappointment has been the inability of earth science curriculum developers to capture that same "essence" for students in the science classroom. My intent to outline a model for teaching the acceptance of the new global tectonics in a more humanistic fashion, shaped by historical and philosophical perspectives, serves to recapture some of that exciting time.

There have been, in the last decade, some rare efforts to implement teaching and learning materials that are aimed at giving students a closer look at the historical development of continental drift and plate tectonics (e.g., Kiddell, 1996; Marques, 1994; Thompson *et al.*, 2000). These efforts, generally, have taken one of two forms: 1) presenting the historical context in a fashion that is remarkably similar to what appears in the standard textbook teaching approach, though the claim is to the contrary (i.e., that the development of a new global synthesis was an inevitable end result of the availability of new technologies from geophysics), or; 2) make use of one version of a constructivist approach that is strongly biased toward ensuring that students reject their personalized "neo-fixist" beliefs and concur with the mobilists' perpectives. This is to be accomplished as early in the teaching and learning process as possible.

The model developed here is unique in two key respects: 1) it encourages students to recognize that the transition from a fixist mentality to a mobilist point of view has a lengthy history of *parallelism* – that is, the two traditions appeared early on in 20th century geological thinking and both remained viable alternatives – and opponents - for well over seventy years, and; 2) Students are given an initiation into the HPS by identifying the Kuhnian aspects of the "revolution in the earth sciences" and utlilizing this context for passing some degree of rational judgement on why *they* are accepting of the new global tectonics. The emphasis here, then, is not on inculcating in students that Wegenerian continental drift or plate tectonics are *correct,* but that they are *presently accepted* (and at one point were vehemently opposed) for many of the reasons outlined in Kuhn's analysis of scientific change.

This thesis has taken considerable effort to outline some of the "benchmark" moments contained in the historical development of this unique scientific controversy. The reasoning behind this is three-fold:

- To enhance the treatment of the historical perspective through the primary literature of the protagonists themselves, or the cogent analyses of leading historians of geology, and not standard textbook treatments;

- Highlight, for those who would make use of the model, some of the interesting moments along the way that are not found in *any* identifiable curriculum materials that have been developed to date
- To discourage some of the standard practices that occur in earth science classrooms that are of a "verificationist" type, such as attempting to reproduce puzzle-like refits of the world's continental landmasses in order to vindicate Wegener's *pangaea*; plotting the locations of world seismicity in order to confirm the existence of *plates*, when in fact this distribution has been known since the early 1950's and fitted quite well into the contractionists' "fault plane" model; and projecting as naïve the notion of the acceptance of a contractionist (i.e. fixist) paradigm (many of these faults have been treated within other science disciplines by Hodson, 1996)

A key reason for focussing on the significance of the historical struggle between the fixist and the mobilist ideas in geology is to offer a window into the nature of science for students within the context of change and controversy. It can serve to assist students in appreciating how scientific communities (or research traditions within a science) act and react in times of radical, epistemic change. Moreover, some of this community behaviour is of a highly personal nature, and can involve the attack on credentials (cf. Wegener's struggle with the American establishment), accusations of holding up progress (cf. treatment of Gordon MacDonald by the "drifters"), and publication priority (cf. Lawrence Morley's "Canadiana" rejection; Dietz's scoop of Hess in getting to sea-floor spreading first in the literature; little deference to Arthur Holmes' [by later adoptees of the] convection model, the actual precursor to a mechanism for opening up ocean basins).

In a memorable moment at the 1966 Goddard Symposium[1], the following exchange took place among some of the proponents of drift and their more reluctant contemporaries (Phinney, 1968, p. 226-228):

Dr. Anderson: "You don't seem particularly impressed by the fact that when you shove South America into Africa, the lithofacies [rock assemblages] patterns match."

Dr. Boucot: "Naturally, I'm impressed. I loaded the dice that way myself. On the other hand, I am realistic enough to understand that there may be an alternate explanation of this seeming good fit. I feel it is much wiser to be conservative in these matters than to stick your neck way out and prejudge things. I would rather say the data we have are consistent with continental drift, but certainly don't prove it. It is also consistent with a *lack* of continental drift."

Dr. Bullard: "Why is it more conservative to *not* believe in continental drift?"

(laughter erupts)

Dr. Boucot: " Possibly it is because I am afraid I might be wrong. I am not sure which side to come out for."

Dr. Dewey: " There are many places in your diagram where major structures are striking right into the edges of continents. What does it suggest to you?"

Dr. Boucot: " It suggests to me that either pieces of the continents have been oceanized [according to Beloussov] or that continental drift has occurred."

Dr. Dewey: " Can you think of a process in connection with that?"

Dr. Boucot: " That's another man's job."

Dr. Fairbridge: " Dr. Boucot deserves our commendation for pointing out the dangers of the misuse of paleontological data, which has been indulged in to a very large degree over the last 50 years. There are one or two rules which you can apply – one you mentioned yourself – that you can't take a major land mammal across a large body of water. In other words, the fossil elephants of the Celebes Islands have to have got there on foot, because even a living elephant doesn't swim very far. Only the major organisms are involved in such rules. Most of the smaller organisms can go as passengers in some way – spores are blown in the wind, seeds are carried in mud, feces, stick to branches and can float.."

Dr. Bullard: " They can take a ride on the backs of elephants, too!"

(laughter)

Anonymous Voice: " I did read that an elephant was once seen swimming in the middle of the Bay of Bengal, 50 miles from land, which rather shook me. Maybe that will change some of these ideas.

(laughter)

Dr. Imbrie: " Was it pregnant?"

Dr. Fairbridge: "That is a point....I understand that in the rutting season, the major mammals do travel in very peculiar ways."

Vignettes such as these have been shown, in the author's classroom, to be memorable and invaluable to students toward appreciating the importance of symposia, fora, and other opportunities for public discourse around emerging research and ideas (see the examples of fictitious exchanges written by Senior 1 level students in Appendix 'B'). According to some recollections of the geologists themselves, it is the one rare opportunity where a scientist can "let down the guard" and engage in some very vigorous conversation without the pressure to live up to those notions in print later on. For instance, at the 1974 Penrose Conference of the Geological Society of America, we hear of the more relaxed style of scientific discourse from one of the founders of this series, Allan Cox, then a specialist in paleomagnetism:

> ...people are much less defensive at that kind of meeting. They are more willing to express their doubts, and they see one another for a couple of days. We structured the Penrose so that there are no published reports....we debated about that when we set the thing up, and decided that they should be small, restrictive, somewhat snobbish – they are open to all members, but the chair decides who comes, except that he must include a number of students. It's also conducive to people bringing their data, showing it, and not defending a position they know they will have to write up. They are free to change their views while they are there...you are much more honest with people that way [discussing data limitations and one's doubts] than you are in your publications...only then can you try to comminicate how uncertain you are (Cox, quoted in Stewart 1979, p. 390-391).

Students too can derive benefit from having their own similar opportunity to discuss the historic events that have led to periods of upheaval within a science discipline, but it should be done with care, not over-used, and pursue a reasonably achievable scientific literacy related to the nature of scientific inquiry (Rudolph, 2000).

I have attempted, in the main, to link the students' exploration path toward the ideas contained in the new global tectonics with five design elements of *recognition, elicitation, paradigm collision, conceptual reconstruction, and resolution/emergence.* These design elements constitute not only an embeddedness in the historical narrative (the great "science story") as it unfolds chronologically, but are linked corroboratively with five *Kuhnian geological phases* taken and adapted from *Structure.* In turn, these interconnected elements and phases provide the details of an HPS approach to the teaching and learning of the new global tectonics that maintains a common thread throughout – the controversy between the fixist view of the crust and that of their mobilist rivals[2]. This is the over-arching theme, these two titanic "conceptual supercontinents" – one conservative and establishment, and the other heretical, brash, and liberal in its outlook on the globe.

5.2 Implications for Future Practices in Geological Education

In an important first step, Kiddell (1996) maintained that her "first goal of [incorporating] history, was to take the students away from the idea of "final form" science as conventionally presented in science textbooks that students tend to memorize. I wanted to show the students a more dynamic, on-going science by emphasizing the historical development of the theory of plate tectonics" (p. 61). In addition to this, Kiddell focussed on two other components – co-operative learning in teams as analogy with a research community, and then examining real-world connections from regions in the world that are greatly affected by crustal movements today. The work of Marques (1994) that was followed up by his collaboration with the group at the University of Keele (Thompson *et al.*, 2000) took the step of (hopefully) securing epistemic change in students through a decided effort to alter their earlier "naïve misconceptions" about the behaviour of the crust.

My goal in developing the present model is not so much to undermine the previous efforts within geological education that identify with the widespread attractiveness of the plate tectonics paradigm. Nor was it to critique the conceptual confinement that arises from those efforts, but to seriously consider the consensus that gave rise to the adoption of the present orthodoxy (see Kim, 1996). At the 1996 Geological Society of America annual meeting, I spoke to Robert H. Dott, Jr., an historian (and practitioner) of geology, as we were finishing up co-chairing a symposium session on *A History of Approaches to Tectonics in North American Geology* (Murray, 1996a, 1996b). In response to a question I put to him on that day, "Do you have any concern that dogmatic allegiance to plate tectonics could well one day be seen as a repitition of a Jeffreys'- like attachment to fixism?", Dott confided that "plate tectonics is *already* a dogma… and there isn't a damn thing we can do about it!"

(personal communication, 1996). At the same conference two years later, in 1998, a leading Pre-Cambrian tectonician (who had noted that a few expansionist papers were being delivered at the conference) noted "for a moment, I thought that Sam Carey had come back to raise the spectre of his hucksterism again…" These are the experiences that students need to become partner to on an almost daily basis as they struggle with the content and processes related to continental drift and plate tectonics. The content gains a presence from adding such historical components that cannot otherwise be gleaned, and this does not do violence to geological integrity. I look forward with anticipation to the possibility that HPS, in this case, stands ready to be the *only* manner in which plate tectonics can be taught with fullness and truly "real-world connections".

Geological science education today, as do other disciplines, gives significant stature to the textbook beyond what is necessary and desirable. Thomas Kuhn, who clearly recognised the vitality of the textbook for the initiation of students into "normal science", had these observations about texts:

> Given the slightest reason for doing so, the man [sic] who reads a science text can easily take the applications to be evidence for the theory, the reasons why it ought to be believed. But science students accept theories on the authority of teacher or text, not because of evidence…what alternatives have they, or what competence? The applications given in texts are not there as evidence, but because learning them is part of learning the paradigm at the base of current practice (1996, p. 80)

and further on:

> …more than any single aspect of science, that pedagogic form [the textbook] has determined our image of the nature of science and the role of discovery and invention in its advance (*ibid.,* 1996, p. 143)

Perusal of any currently adopted textbook in introductory geology indicates that much of what Kuhn had in mind about the role of textbooks is borne out – and it is, admittedly, a predictable and necessary rite of passage into a paradigm. In a similar manner, though, we do not see significant treatment of the *way* in which the paradigm achieved its current acceptability or consensus. The rival models, particularly those that were the most serious rivals, are systematically silenced from further discussion. Students, then, are not offered the glimmer of an *opportunity* to weigh the merits of alternatives, and this can be extremely rewarding for future problem-solvers. The implication here is to ensure that provision is made by curriculum developers to expose students to as many alternative points of view as possible when examining the development of large-scale theories in science. It is consistent with my aims that the geological revolution be viewed through an informative, stimulating, and above all well-balanced treatment involving both of the serious rival views. What remains to be taken as a next step is for this model to be developed into a complete teaching and learning experience and brought to the classroom. This challenge is left to the future.

5.3 Possible Barriers - Teacher Development

It is readily apparent that in order to achieve more modest and tangible gains in the science classroom through the contexts created by the HPS, students will inevitably be called upon to provide a more active voice in the classroom environment. There will be a commensurate effect on teachers in this, and I propose that it be in the form of preparing the science classroom to express itself more often through *argument.* Despite curriculum impetus to the contrary over the last quarter century, current practices in science teaching still depend largely on promoting an image of science as "ideas and facts which can be derived in an unproblematic way from observation and experiments (Erduran *et al.,* 2002; Driver *et al.,* 1994). It is clear that the exchange of ideas in geology discussed at length here argue for a vision of science that has argumentation playing a central, defining role in understanding the how the current content of the new global tectonics was itself fostered through intense debate, community consensus-building, and the defeat of rivals. I claim that *doing* and *talking* about globalist ideas is far superior to passive acceptance or authoritarian (read, teacher) inculcation of the ideas.

Earlier on, the case was presented to offer both the *context of development/discovery* and the *context of justification* together in a balanced treatment. One of these contexts is not to dominate the other, but together the two offer the prospect of having the historical development of ideas (discovery) merging with the ahistorical analysis provided by the justification of beliefs (justification). Recently, a case has been put forward where argument and discussion are to be placed at the very *core* of science education in the classroom (Erduran *et. al.,* 2002). Among the reasons for claiming this argumentation aspect when implementing the model proposed here, the following points made by these authors are notable:

- science education, of itself, naturally offers a range of opportunities for argumentation;
- the consideration of different theoretical explanations of given phenomena can be fostered directly;
- student deliberations about methods, technologies used, and the evaluation of possible interpretations of data become core activities;
- the discussion of alternative decisions relating to the controversial socio-scientific contexts that occur is very engaging for students, and delivers a more humanistic science education;
- how scientific ideas are presented, evaluated, and disseminated (for instance, by publication in journals, peer review by fellow scientists, or even through mimeograph when publications are rejected);
- how scientific controversies can arise from different ways of interpreting empirical evidence (for instance, the present controversy); and
- the manner in which scientific inquiry may be affected by the contexts in which it is taking place (for instance, social, geographical, institutional, governmental, and moral/ethical considerations).

Such an approach is consistent with one advocated about a decade ago by Elizabeth Finkel (1992) in a paper outlining, among other aspects, how the theory of continental drift came to be accepted by geologists. In her recommendations, she proposed an activity wherein many of the issues raised by my controversy model could be exercised in the classroom (such as guiding assumptions of rivals, basis for theory choice, and NOS). Finkel advocated a climactic debate between the "stabilists" and the "drifters" to settle the issue among students. Recent work in the author's classroom (see Appendix 'B') bears out that these debates can lead to fruitful, student-generated scripts of real historical merit and accuracy (with, of course, the attendant emotions that derive from secondary-level students).

As early as 1964, Rutherford identified some of the key classroom-based difficulties related to teachers' lack of knowledge about the history and nature of science:

> Science teachers must come to understand just how inquiry is in fact conducted in the sciences. Until science teachers have acquired a rather thorough grounding in the history and philosophy of the sciences they teach, this kind of understanding will elude them, in which event not much progress toward the teaching of science as inquiry can be expected (Rutherford, 1964, p. 84).

This situation, as outlined decades ago, has certainly changed – but only incrementally by most accounts. We still have a long road ahead in terms of ongoing teacher development. In order for teachers of science, though, to effectively present the major ideas of their disciplines, the attendent historical contexts in which these ideas originated, and their development, appropriate pre- and in-service teacher development must take place. Opportunity to be more effective at teaching science as inquiry is at least as important as the end itself. One first step, then, is to continually concentrate on the development – and field validation – of *curriculum materials* that specifically highlight these components of what is now considered desireable practices. One of those first steps has been taken here, and there are similar initiatives taking root among student teachers, their mentors, and among faculties of education.

5.4 Suggestions For Further Research

The basis for this thesis was the pursuit of a model for teaching and learning that would address two key questions:

- Can teaching and learning experiences drawn from the significant historical struggle between FIXIST and MOBILIST ideas in geology be considered an exemplary experience of the nature of science for students?; and
- Can the historical context generated by the two dominant paradigms in 20th-century geology become, for students, an exploration of Thomas S. Kuhn's ideas of revolutionary scientific change in the science classroom?

The two questions are not considered here to be mutually independent, but have served in the recent past as the gulf that has existed between the work of historians of geology, philosophers of geology, and geological education and practices. The challenge I wish to leave with prospective curriculum developers and science teachers, is that the gulf has been narrowed somewhat with the development of a teaching model firmly grounded in historical narrative and the philosophy of science as outlined by Thomas S. Kuhn. The single most influential episode in modern geological thought is one that *can* be shared intimately with students, and it has a "freshness" that places it among our times. Due to the disconnections in textbook-treatment of global tectonics mentioned, their teacher-adherents miss the mark on the character of how the new global tectonics came into being by presenting only the tenets of the theory as established models. I suggest that the next crucial step is to take the treatment of the new global tectonics to the senior-secondary level, using the model outlined here, where students are well-positioned for a first steps into some of the NOS and HPS perspectives that are contained in it. Words such as *anomaly, crisis, plurality, paradigm, controversy* lie at the heart of the treatment I am proposing for the classroom, and the task is a challenging one when students' are selecting an increasingly parsimonious vision of what to glean from their science education.

In geology, opting for the less establishment-oriented hypothesis usually meant certain oblivion (S. Warren Carey describes it as "lethal"; 1988). If we wish to encourage the traditional, the comfortable, and the more familiar in our science classrooms, then the "one-paradigm" approach is a necessity. However, if we choose to support a more dynamic response, then the probable impasse can be avoided – students will remain open to the notion that there still exist some key problems to be solved. Indeed, some of those key problems have yet to be unveiled in the earth sciences. Owen (1981) described the geoscience revolution as "probably just beginning", and Kiddell (1996) identified the need to have students engaging in "on-going scientific developments". This is borne out by some recent significant findings relating to the dynamics of the mantle, which seems to be displaying a tempting simplicity that Rumford would be attracted to (Reed, 2002). Additionally, a recent review of progress over the last thirty years indicates that much potential exists for refining – or *redefining* – certains aspects of current theory. Richards *et al.* (2000) offer the following state of our knowledge:

> It is plate tectonics on Earth that is hardest to explain in terms of dynamical models – to date none can be considered very successful. Moreover, no convection theory accounts satisfactorily for the coexistence of mantle plumes (hotspots such as Hawaii) and plate motions. Simple and attractive thermal convection models, with or without plates, overpredict Earth's observed dynamic topography by at least a factor of two, and fail to account for isotopic and trace element signatures observed in mantle-derived lavas. Have the geodynamicists failed, or are these processes in Earth's interior so well concealed that

> they cannot be discerned from surface observations? We believe the answer is "no" on both counts (Richards, Gordon, and van der Hilst, 2000, p. 2)

It would seem, then, that there exists plenty of opportunity for students to see unsolved problems within global tectonics, and so the "science story" is prepared to write new chapters, not produce the epilogue.

I can offer science educators the following avenues for further development and description of the model presented in this study:

- Curriculum needs to be presented clearly and simply. Scientific knowledge can best be presented in the curriculum as a number of key 'explanatory stories'. The curriculum, then, should introduce young people to a number of important ideas *about* science (cf. Millar and Osborne, 1998). This implies that the global tectonics "science story" be offered to students in a manner more closely resembling the model outlined in this work;
- The case-study approach, where historical and current issues-oriented curriculum delivery can be delivered, requires continued field validation. In particular, the role of *assessing student learning* through experiencing 'explanatory stories'. Such field work will not only match student efforts with the needs and interests of the learners and their teachers, but assist in solving the "it will never give you gains in student achievement" counterinstance mentioned earlier;
- Assessment of this model depends on alternative, differentiated methods of determining students' performance. The focus here may be on developing techniques of assessment (and devices) that focus primarily on students' abilities to contemplate, interpret, and articulate scientific information. This, in addition to the knowledge base of science and understanding of scientific ideas;

- Assessment based on student ability to recognize the *role of scientific evidence* in the resolution of competing arguments or differing theoretical accounts from the same data. This, to place an emphasis on commitment to evidence, while asking only for a broad commitment and familiarity with the fundamentals of science and its historical development. This realm of assessment can only be fully realized through the sort of validation that comes from student *opportunity* to read in-depth with a topic, conduct an achievable level of independent research, and view, write and represent ideas that emerge without the pressure of time constraints so typical of summative assessments;

- establish some formal procedures by which innovative approaches to science education can be trialled in representative school situations. Since innovations are not really such until field evidence offers some evidence of effectiveness, this model should not be considered for widespread adoption until such time as extensive pilot-phase activity has been accomplished, and;

- since we are now in times of curriculum transition in various jurisdictions in Canada, perhaps the time is here to field test the model; and I invite teacher educators to consider this option in the shorter term

Global tectonics has a simplicity that makes it attractive to teachers, but it also has the problems of multiple anomalies and action over immense (and humanly), incomprehensible time scales. We have a crust that, when compared to the bulk volume of the planet, is *membranously* thin (Turcotte, 1974). One cannot discount how cautious that must make all of us when we consider how the surface of Earth can be so noticeably re-worked by powerful geological forces. Chaotic and non-linear behaviour may offer us some *geological lepidopterology* ("the butterflies" of MacPherson, 1995) that may stir the imaginations of students when properly attuned to their influence. The transition to the new global tectonics is every bit as dramatic as that of the *gestalt* switch from Ptolemaic to Copernican astronomy. What remains for teachers and their students is to affirm that this is a door that has been opened slightly, and there is more than just "hope" remaining among Pandora's treasures.

Pax Sam...and Stephen...

> Revolutions close with a total victory for one of the two opposing camps. Will that group ever say that the result of its victory has been something less than progress? To them, at least, the outcome of revolution must be progress, and they are in an excellent position to make certain that future members of their community will see past history in just the same way (T.S. Kuhn, 1996, p.166)

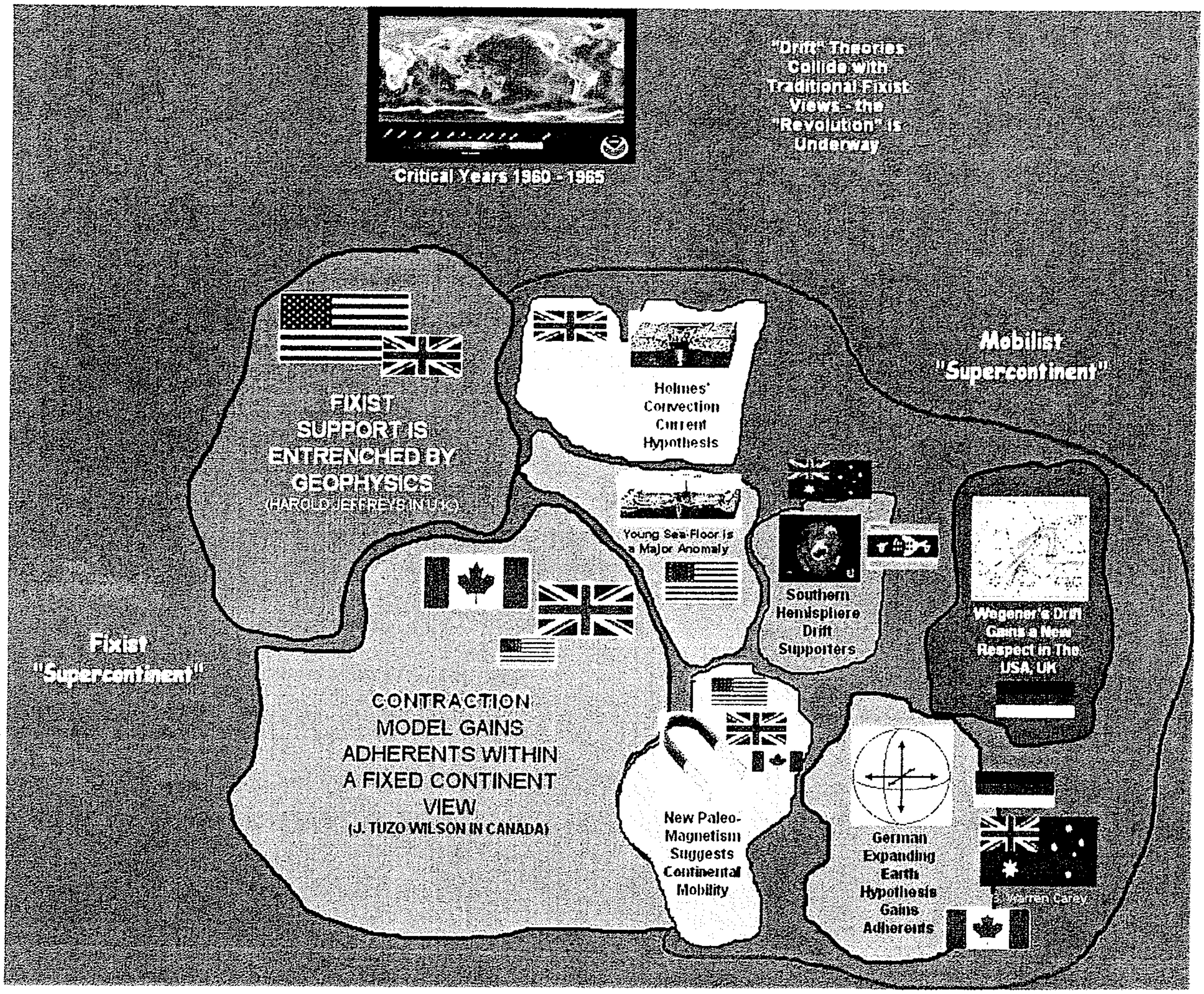

Plate 4: In the period 1960 – 1965, with the renewed ascendancy of the mobilist theories, and movement of some workers within the fixist paradigm toward that of the rivals, all "drifter" and mobilist theories squared off in a remarkable debate period where a plenitude of models were openly discussed. Interests were in collision, and leaders in global tectonics moved to solidify their positions on one side of the debate or the other. The mobilists described themselves as progressive, and labelled the fixists as stalwart "hold-outs" whose ideas would soon be moribund. Results from paleomagnetic studies were demonstrating that "polar wandering" had not occurred, but was an *apparent* effect of continental mobility.

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Appendix 'A' : Definition of Key Terms

Anthropic: Conditions that exist in the universe must allow for a human observer to be present in order to observe and ponder them (this version is generally known as the '*weak' anthropic principle*)

Conceptual change: Learning that involves the modification of previously held ideas. this can occur through the processes of radical restructuring and accommodation of novel conceptions

Conceptual 'Continent': A large-scale, first-order model of the earth's evolution, particularly its surface features, as developed within communities of earth scientists. Each 'continent' is comprised of its own guiding assumptions, defenders, iconography, lexicon, neologisms (new terminologies) and particular view of global tectonics. Term was first used as a means of "mapping" citations in the geological literature during the plate tectonics "revolution" (Stewart, 1979,1980,1981,1990)

Constructivism: Philosophy of learning in which knowledge is viewed as personally constructed meaning that results from interaction between existing knowledge and new experience

Constructivist learning: Learning that takes place as a result of interaction between existing knowledge and new experiences

Constructivist teaching: Teaching that takes into account the fundamental role of interaction between existing knowledge and new experience in its attempts to facilitate learning

Context of development: A context within which the teaching of science may be approached that emphasizes the development of an understanding of the manner in which earlier theories have impacted current scientific understanding (Duschl, Hamilton, and Grandy, 1992)

Context of discovery: Historically, the use of imaginative ideas and unconventional techniques toward the achievement of novel – and heretofore unthought of – conclusions. (Monk and Dillon, 2000)

Context of justification: An "ahistorical" context within which the teaching of science may be approached. it emphasizes the development of an understanding of the evidence used to support current scientific theories "without regard to predecessor theories" (Duschl *et al.*, 1992, p. 28). or, the combination of evidence, logic, communications skills, rhetoric, and personal connections important to the success and acceptance of one's ideas. (Monk and Dillon, 2000)

Contractionism: The dominant geophysical paradigm of the pre-plate tectonics period. Hypothesized that the Earth's surface features could be best explained via contraction from an initial, hotter primordial planet. Chief supporters early on were J.J. Thomson (Lord Kelvin), Edouard Suess, and Sir Harold Jeffreys

Expanding Earth Theory (EET): Geophysical model, first developed in the 1930's German geological school, that explains the earth's surface features and tectonic behaviour through an exponential increase in the Earth's radius since Permian time (ca. 255 Ma). Prior to the expansion phase, the entire Earth was covered by continental crust, and oceans were 'epieric' (shallow, epi-continental bodies of water). The present ocean basins emerged as radial expansion fragmented and displaced continental material as large blocks having deep roots in the crust. Most notable supporters have been geologists Samuel Warren Carey of the University of Tasmania and Bruce Heezen of Columbia University, and the German physicist Pascual Jordan.

Fixism: The favoured model of the Earth throughout most of the history of ideas in geology. Basic tenet is that the continents and ocean basins are permanent features of the Earth's surface, and are immovable (cf. Mobilism).

Geonomy: New term for the science of geology, first coined by Canadian geophysicist J. Tuzo Wilson, to indicate that the earth sciences had matured to the level of being governed by immutable geophysical laws not likely to be overturned (Wilson, 1968)

Geosemiosis: The post-modern philosophy of geology referring to the hermeneutic of signs, symbols, and reasoning about planet earth and its past

Global Expansion Tectonics (GET): A recent adaptation (1990's) of the earlier expanding earth hypothesis, but incorporating the modern datasets from sea-floor research. The model uses the sea-floor chronologies to reconstruct past continental configurations on an Earth that is radially expanding over geological time. Primary exponents are James Maxlow of Australia and Prof. Karl Luckert of the United Sates.

Gondwanaland: Hypothetical land area believed to have once connected the Indian subcontinent and the landmasses of the southern hemisphere (after DuToit, 1937). Also a term used pejoratively to indicate the location of geologists who are physically separated from the mainstream of thought ("Gondwanalanders")

Guiding Assumptions: Substantive assumptions about the world, and guidelines for theory construction ands modification in science. Commensurate with the 'paradigm' concept of Kuhn, Lakatos' 'research programmes', and Laudan's 'research tradition', but with a broader context than the more narrow definition of a 'theory' in science (after Laudan *et al.*, 1986. 1988)

Island arc: A linear, but more significantly an arcuate chain of volcanic islands formed in the environment of a *convergent plate boundary*. The volcanism is thought to derive from partially melting the descending slab of oceanic crust at a subduction zone. (e.g., Japan islands)

Membrane Tectonics: A set of hypotheses, related to plate motions on a sphere, but modelled on the principle that the Earth's crust, relative to the entire planet, is vanishingly thin (i.e. membranous) and may behave plastically in a manner analogous to our understanding of other membrane structures. Principal author of the model was Donald Turcotte of Harvard (Turcotte, 1974)

Misconception: An idea that is at odds with currently accepted scientific knowledge claims

Mobilism: Geophysical model supporting the movement of continents about the surface of the Earth through the semi-rigid oceanic crust (e.g., Wegenerian 'drift') (cf. Fixism).

Neo-Fixism: A modern (1980's and 90's) adaptation of the former fixist paradigm, which claims that modern geophysical datasets support a model of continental fixity based on the deep mantle roots of the continents – not continental mobilism as is the most common interpretation. In this view, only the ocean basins demonstrate the principles and behaviour of a mobilist perspective through the confirmation of sea-floor spreading by paleomagnetism. Supporters of this model include Paul D. Lowman of the NASA Goddard Spaceflight Center and Peter James of the UK

Normal science: Scientific activity characterized by its dependence on "one or more past scientific achievements, achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice" (Kuhn, 1970, p. 10)

Oceanization: Geophysical model favoured by the Russian (former USSR) geological community to explain the surface features of the Earth. The continents are fixed features, and the ocean basins are the subsided ("oceanized") and metamorphosed materials that were once continental. Chief supporter was the Russian geophysicist Vladimir V. Beloussov, one of the few Soviet geologists who regularly communicated with and published among English-speaking geoscientists.

Plate Tectonics: The geological paradigm involving the study of the kinematic movements and deformation of the crust on a large scale, including orogeny (mountain building, metamorphism, folding, faulting). Basic assumption is that the earth's crust consists of a number of quasi-rigid "plates", whose motions can be described as Euler rotations about poles on a spherical body (the Earth)

Pulsation Tectonics: A late 20^{th} century (ca. 1980's) geotectonic model supportive of the view that the Earth's surface expression can only be explained through a cyclic sequence of global expansions and contractions over geologic time, perhaps couple to an astrophysical mechanism as yet indeterminate. For instance, the opening of oceanic basins would be characteristic of a radial expansive phase, and collisional orogenic events (island arcs, curved mountain chains (oroclines), etc.) would take place during a phase of contraction. This geotectonic model has modern advocates in the Russian and Chinese geological establishments (e.g. Smirnoff, 1992)

Pre-paradigmatic science: Scientific activity generated in the absence of the guiding set of rules and understandings that characterizes normal science. it is "marked by frequent and deep debates over legitimate methods, problems, and standards of solution, though these serve rather to define schools than to produce agreement." (Kuhn, 1970, p. 47-48)

Revolutionary science: Science characterized by the rejection of the ideas upon which normal science in a given field of study is based. it involves the fundamental reorganization and re-evaluation of existing ideas (Kuhn, 1970)

Real science: Methods of science employed by practicing scientists

School science: Methods of science defined by school curricula and employed by practicing teachers

Theory evaluation: Various means by which the accuracy of a given theory is judged. In this thesis, the term will make use of the characteristics of a "good theory" according to the analysis of Thomas S. Kuhn

Thought experiment: Mental manipulation of objects in a manner that allows the experimenter to explore the implications of a particular theory as an abstraction

Uniformitarianism: The traditional geological axiom that past processes acting to shape the surface of the earth can be understood in terms of their present-day equivalent processes. Usually summed up by the phrase "the present is the key to the past"

Wegenerian Drift: The hypothesis, originally proposed by Alfred Wegener, German meteorologist and aeronomist, of continental displacement. In this model from the early 20th century, paleo-biogeographical, lithologic (rock types), and paleo-climatological arguments were presented to support a model wherein the earth's continents had moved about the surface of the earth over geologic time periods

Whig historiography: Used to define history of science writing that regards history as essentially progressive, culminating in present knowledge that is correct, and makes judgements about past science by comparison with modern knowledge. It is associated, then, with historiographical anachronism.

Appendix 'B': Samples for Assessment - Student-Generated Responses to the Pluralist Model Approach in the Classroom

Author's Note: The pieces of student work presented here comprise a sample collection of an unedited essay and brief, one-act dramatizations that were generated in the author's classroom by grade nine students (primarily 15-16 year-olds). These were a component of student assessment in order to gauge the effectiveness of teaching global tectonic models through the lens of *scientific controversy.* The contexts are drawn from the content cluster "The Earth's Dynamic Crust" which, at the time in 1999, was one of four major units in the Manitoba Grade Nine (Senior 1) science program. The student names given in the *dramatis personae* are pseudonyms; those of the geo-scientists are actual historical figures.

"The Wonderful World of Geological Science"

Act 1

Cast of Characters (in order of appearance)

The Science Teacher
Janus (a student)
Jean-Luc (a student)
The Narrator
The Librarian
The Old Man, James D. Dana (American geologist)
S. Warren Carey (Tasmanian geologist)
Frank Bursley Taylor (American geologist)
Alfred Wegener (meteorologist)
Gaia (the Creator)

The Setting: A Grade 9 Science Class

The Science Teacher: " Hello!! Welcome to the wonderful world of science...."

Class: << Groan....!!>>

The Science Teacher: " Hey, science is exciting !! Today, I am going to introduce you to *geology* – and the origins of the Earth.....Does anyone know what the Earth looked like at the beginning of time?"

Janus:" Umm, well – did it start as one giant supercontinent, Pangea?"

The Science Teacher: " Well, there's a lot of evidence pointing us in that general direction. But, do you know the name of the theory that gave rise to this idea? – anyone?"

Jean-Luc: "Yeah, I know.....continental drift !"

The Science Teacher: " RIGHT ON !! Well, there are three more theories worth considering here. The fixed earth theory, the contracting earth theory and the earth expansion theory. " <fade out>

The Narrator: The lesson continued, and the class was assigned an oral report project that would present each student's views on the three theories plus Wegener's ideas about continental drift. I guess that means four theories now. They were to examine each one closely, and then choose which one they felt was the "right" one.

Jean-Luc: " Umm.... Can we work in pairs?"

The Science Teacher: " Certainly !! I don't see why not...."

Janus:" OK, Jean-Luc....I'll go with you!"

Jean-Luc: " Alright....so....Janus, which theory attracts you?"

Janus:" Well, I don't feel that I know enough to decide which one is "right". How 'bout you?"

Jean-Luc: " Umm....I don't know enough either!"

Janus:" Well, I guess we should go and research some at the library....maybe then we'll be able to decide."

Jean-Luc: "Okay, let's go."

SETTING: The Local Library

Janus:<<scrounging through books>> "Man, I can't find anything!!"

Jean-Luc: " Oh, don't worry....the librarian will help us find something."

Janus:" Umm, <ahem> excuse me, but we're doing a project on the Earth's origin, and we're wondering if you have any information about the continental drift theory, the expanding earth theory, or the fixed / contracting earth theories..."

The Librarian: " Well, I think I have something of use to you....follow me."

The Narrator: The librarian directed the two to a strange room, which seemed to be hidden behind a large bookcase. She told them to wait while she found some items for them....

SETTING: The Strange Room

Janus:" Uh, that woman's kinda... weird, don't you think"

Jean-Luc: " Yeah – too much reading, I guess."

The Narrator: Suddenly, in the blink of the eye, the strange room was transformed into a large and elegant conference hall, and the two companions were surrounded by people who seemed very old fashioned......kind of like from another century....

Janus:" Woah !! What's goin' on ?! Am I imagining this? Or is this real?"

Jean-Luc: " Well, I can see it too...so I guess it *is* real !"

Janus:" Woah – PSYCHO!! Who *are* all these people?"

The Old Man: " Umm, excuse me miss – you're in my chair...."

Janus:" Oh, I'm sorry.... Sir, may I ask where we are and who all these str-......people are?"

The Old Man: " Allow me to introduce myself. I am Professor James Dwight Dana, minerologist.....welcome to both of you to our annual "Hot Topics" session...today we'll be talking about the origin of the earth..."

Janus:" Nice to meet you, sir. Are you sure you don't mind if my friend and I stay to listen?"

Dana: " No!! Not at all ! We love it when others show an interest in our ideas..."

Janus:" I'm so sorry, we haven't introduced ourselves to you yet....my name is Janus and this is my very best friend, Jean-Luc."

Jean-Luc: " Allo.....*excuse moi, comment t'appelle-tu?"*

Dana: " Ah, from France, young man?....and perhaps a student of that outlandish set of ideas from Emile Argand....or, perhaps Snider-Pellegrini who has us believe that the continents can be ripped apart by the tides ?!!" <<after he stares intently at Jean-Luc for a moment>> " Alors, let me introduce you to the speakers for tonight.....this is Frank Bursley Taylor – he specializes in geology like myself. And this is hier Alfred Lowthar Wegener – he studies the geophysics of Greenland in his spare time....although we all wish he had stuck with his meteorology rather than dabbling in outrageous geological ideas!!"

Jean-Luc: <whispering to Janus> " Hey, Janus...I recognize this man's name....our science teacher was talking about him in class."

Janus:" You mean.....he's *that* famous ?!"

Jean-Luc: " Yeah, you could say that.....he's been famous for, like, eighty years or so !!"

Janus:" Wow !! He looks young for his age...even if he smokes a pipe!"

Jean-Luc: <with some sarcasm> " Yeah...funny.....whatever!"

Dana: "Alright, everyone, take your places! Let the annual hot topic session begin! So ...where do we start ...um, Good Afternoon. .. today's session will be focussing on the origin ofthe Earth...I would like to start with my view. Imagine a dried apple.. . picture it shrinking and shriveling up into a ball of wrinkles. Now-picture that the apple is the earth. The wrinkles, in this case, would represent the mountains and the low areas between the wrinkles would be the ocean basins and lakes. I call my theory the GEOSYNCLINAL-CONTRACTIONTHEORY. I have found evidence and physical information from the studies of G.H. Darwin. Also, I have conducted geologic surveys in the Western United States, and in the European Alps."

Taylor: "Um, excuse me, James, but I don't agree with your theory... the earth's surface varies from flat, rolling areas, to high mountain ranges. If the earth contracts like in your theory, the mountains would be evenly distributed over the planet, not arranged in certain mountain belts called fold mountains. . . I would like to share with all of you my theory ...I believe the earth's continents `drifted' apart by means of tidal forces, resulting from the Earth's capture ofthe moon. My ideas are similar to Wegener's, but I feel mine differ greatly in many respects."

Wegener: "Well excuse me, Mr. Taylor. .. but my theory of continental displacement has excessive amounts of evidence. My climatological evidence is shown through the age similarities of the different coal beds within the various parts of the world. Also, the mountain ranges in Scotland and Labrador have the same structure and fault traces. That's geological *evidence,* not to mention the fossil evidence of that little reptile, *Lystrosaurus*, found both in South Africa and Brazil, and the earthworms found on both sides of the Atlantic...they are unable to swim, and cannot withstand cold temperatures. There's some real biological *evidence* for you. Now, imagine the earth's continents, each acting like an iceberg. Now picture each slowly drifting away ...I think, once, a giant supercontinent existed ...Pangea! As you can see, were we to refit the torn pieces of a newspaper by matching their edges, and then checking whether the lines of print run across, you would indeed find a good fit."

Janus: Excuse me sir, but I have a comment - I've heard and been taught that a certain mountain range - the Himalayas to be precise - were formed by a collision between India and Asia some 35 million years ago."

Wegener: "Yes, my child!!! I also feel that the western mountains of North and South America are just `wrinkles' acquired as the continents sailed through the crust at the bottom of the oceans."

Samuel Warren Carey (an Earth Expansionist): "Excuse me, Hier Wegener... you're hypothesis is an intriguing one and very well laid out, and I agree with much of what you offer as evidence to support this notion of `drift'. And yet, just what *mechanism* , or force, operates to separate your landmasses? The calculations of the esteemed British physicist Sir Harold Jeffreys seem to indicate that any known forces are inadequate to achieve this sort of lateral motion in the solid state ....perhaps allow me to speculate with a radical new notion - that of Earth Expansion over geological time. If the Earth were to expand radially outward at, say, a few centimetres per year, that would be enough to drive the continents apart from one another and open up new ocean basins. There would be no need for *subduction* of old ocean crust - this is simply a geological myth necessarily invented to save plate tectonics!! A colleague of mine at the British Museum - Hugh Gwyn Owen - has painstakingly drawn cartographically sound maps (without distortions) that demonstrate a remarkable set of facts . . . .if the Earth's volume were only 80% of its current value, you can completely reassemble *Pangea* without any gaps or special considerations. If the Earth were of constant radius, there exist unexplainable gaps in the seafloor rock record that simply cannot be dismissed as unimportant anomalies. I owe a great debt to Prof. Owen, and his expertise as a mapmaker and computer cartographer. And yet, as with Galileo before us, no one will look through our telescope long enough to evaluate the facts . . . .this is very bad for science, to not have one's own work read and discussed honestly."

The Narrator: The meeting of these esteemed geological minds was soon to degenerate into a colossal uproar, and the two uninitiated students were appearing bothered by the need to choose from among these minds of geological science. Perhaps they were sucked in by the outdated notion that science is driven by the acceptance of the "right" theory by the largest number of people possible. These guys behave more like political figures than scientists !!

Janus: "They're becoming so agitated they might destroy one another's ideas right here and now ...!!

Jean-Luc: "Now what are we supposed to do?! Either way, we'll still be confused and the "right" answers will elude us !!"

The Narrator: Then ....suddenly...the scientists fell silent in awe at the great light that had appeared in their midst.

Gaea (the Creator): "Be calm my children ...why do you argue so over such trivial matters? As I had asked my servant Job so many centuries ago... ' Where were you when I laid down the foundations of the Earth? Upon what are its bases grounded? Where is the hiding place of darkness? Out of whose womb came the icy masses? Speak to the Earth, and it shall teach Thee...' You must respect and admire one another's opinions ....and wonder at the diversity of it all. And if everyone is wrong...who is right?"

Janus: "Dear Lord Gaea and Creator, what are we to do? All of these luminaries want us to accept their notions and opinions - even our own science teacher has his biases, and wishes us to fall in line with his own preconceived ideas. What can a poor student of science do anyway?"

The Creator: "Fear not my little ones...all will find its place in your hearts and thoughts - the only decision you need make now is to remain broad-minded and universal in your evaluation of these great minds and their ideas. But be wary of their cunning, for many are self-interested, and attract students with their charisma to further their own works. Take each step with caution, but with a sense of peace that all is not known at this time in human history."

The Narrator: Just then, the dazzling light left them, and a report was seen laying on a small, inelegant table between the two students. All of the scientists had disappeared now, and the stately room has lost its conference elegance. Jean-Luc and Janus handed in their report to the science teacher, with the confidence that the "right" theory was simply a myth to be believed in - some sort of science discipleship.

The Science Teacher: "Excellent paper by the two of you!! It was the most creative science story I have yet read this year! You deserve all the credit that will be coming to you. We can't wait until you present it tomorrow in class..."

The Narrator: No one came to know of these miraculous events that Janus and Jean-Luc had experienced. It remained their secret. As for the mysterious librarian - she was to never be seen again until she was spotted in an old issue of *National Geographic* magazine (perhaps November of 1994). There, on those glossy pages was Dr. Rachel Haymon of the Scripps Institute of Oceanography at La Jolla, California. She was the one who had dove to the volcanic vents on the seafloor at 10°N in the eastern Pacific Ocean..and a heroine to so many aspiring young women marine geologists ....but that, my friends, is a piece of "geopoetry" for another issue. Until next time....

"In Praise of Older Gaians...a Geo-documentary Debate"

Cast of Characters

Diana

Jeshua Christo

James D. Dana

Frank B. Taylor

Tammy Tellus

Alfred Wegener

Samuel Warren Carey

Hugh G. Owen

Rachel Haymon

Diana: "Hello, everyone! It's so nice to see you all here today...."

Jeshua: "Well thank-you very much for inviting us all over. Would it be alright if I began with a short prayer - it is a tradition among my people?

Diana: "Oh Yes! Please do!

Jeshua: "Dear Father Sky, who is so good to us, please help us see the beauty of everything that you've created, and please help us to see each other's points of view. Amen.

Everyone: "Amen....."

Diana: "Well thank you, Jeshua Christo. I've invited you all over here today to discuss all the possibilities of how the earth came to be as we now know it. Would anyone like to begin?

Dana: "If you don't mind, I would like to start things off. I am a firm believer in the fixed continent model. I don't think that anyone here today is going to change my opinion about that. I mean, doesn't it make more sense than lands actually moving!? That's a ridiculous and fantastic notion to any sane man!!"

Taylor: "Why do you think that's so ridiculous? It makes perfect sense, for instance, that the Moon would have had something to do with the way mountains have been formed! Why, look at what great tides it can muster each day ...is it absurd to speculate that the Earth's surface features could be drawn up by such a force over the millenia? How could you even think of comparing something as complex as the earth to something as simple as a dried up apple?"

Dana: "And, you think that the Moon's gravity pulls the continents away from each other the same way that it creates tides in the ocean? That makes no sense... you would need something way more forceful to happen to create mountains."

Tellus: "I see your point of view, and I agree with what you're saying. If the moon's gravitational pull creates tides in the oceans, I don't think that it would be likely that it could create mountains, because it wouldn't have enough force to put such immensities in motion about the Earth's plan."

Dana: "Thank you. At least someone has the sense to agree with me."

Tammy: "Oh, I agree with your argument against Mr. Taylor's theory, but I don't know if I agree with your theory. I'm more interested in hearing what Hier Wegener has to say about his Continental Displacement hypothesis..."

Diana: So am I, would you like to share some of your ideas with us Mr. Wegener?"

Wegener: "I'd be more than happy to! I'm always so glad when young people get excited about science. It makes me feel like I've really done something with my life!..... Cool!"

Taylor: <exasperated> "Get on with it, please!"

Wegener: "I'm sorry, I'm sorry. Well, I believe that the continents have also drifted apart, but I believe that they had once been joined together in one large land mass that I have called, "Pangea".

Dana: "Why would you call it "Pangea"? What does that mean?"

Wegener: "I'm glad you asked..... *"pangea"* is the Greek word for "all land", so you see how the term is fitting? Well, to get on with it, I hypothesized that if continents could move up and down, then they should be able to move from side to side, too.

Taylor: "What do you mean, "continents can move up and down" ?"

Wegener: "Oh! I'm surprised someone of your high position in science doesn't know what I'm talking about. Well..... I shall explain for you poor souls. At one time in North America, glaciers covered the land. When these glaciers melted, the continents seemed to rise, slowly, and we have, in the past, called that *isostasy.*"

Dana: "Oh, my! I don't know how any of us didn't discover this sooner, it all makes so much sense!"

Wegener: "Another thing that proves my theory is correct is that a mountain range in South Africa is the same age as the sierra mountains in Argentina."

Taylor: "That doesn't prove a thing.....a mere geological coincidence!"

Wegener: "Oh, but it does! These places also contain similar fossils and have the similar type of geological structures. As well, there is biological evidence.. an example is that there are fossil remains of the same reptile in Brazil as are found in South Africa. The animal's name was *Lystrosourus....*"

Dana: "Now he's going to try and tell us there's no such thing as a land bridge for these creatures to lumber across on their tiny little legs!"

Wegener: "Actually, at one time I was favouring the *isthmythian land links* idea, but my displacement hypothesis eliminates the need for such structures."

Dana: "What?! Of course there is.....!"

Wegener: "No, there cannot be ....I have demonstrated it convincingly here!!"

Dana: "That's a crock!"

Wegener: "As I was saying, land bridges do not exist. The animals who apparently crossed over them could never have crossed such great distances over such a narrow piece of land. Also, why would land bridges sink? There is no explanation for this since continents, as we know, are more buoyant than the sea floor basalts."

Taylor: "What proof of this do you have?"

Wegener: "Well, a land bridge would be made out of the same material as the continent would be. Therefore, if the land bridge sinks, then wouldn't the continents around them sink as well.....they are so much larger than the land bridges?"

Dana: "Is there any more evidence of this having taken place?"

Wegener: "Well,compare it to an iceberg. They often breakup and some pieces drift away. These pieces will eventually melt, but since they're less dense than water, they'll never sink. I think land bridges should behave the same way.

Diana: "I think that that's a very well thought-out theory. It makes a lot of sense to me."

Tellus: "This theory seems very convincing to me, too."

Carey: "What are your views on the hypothesis of an expanding earth? Doesn't that make more sense than purely continental drift alone, since it provides for both displacement of continents and a better physical fit of these continents on the surface of the Earth?

Owen: "I'm a strong supporter of the expanding earth model. To me, it makes more sense, and is a better 'fit' than any of the other theories we've heard from today, and this is due to the cartographic work I have done, making use of the latest seafloor age dating data sets."

Diana: "Can you "expand" on the theory?....(pardoning the pun) What is it all about?"

Owen: "Well, I think that over time, we're talking millions of year here, the earth has been expanding at a slow rate, and as it expands the continents broke free and began to drift apart to look as the world around us does right now."

Tellus: "So you're saying the earth has been growing in volume over the past hundreds of millions of years?"

Carey: "Yes, that's what we are trying to argue here. Over time, the earth has been growing, therefore breaking apart the continents and creating ocean basins in their wake."

Diana: "Well, we've heard some pretty convincing theories here today. The last one we have in from Dr. Rachel Haymon of the University of California at San Diego."

Rachel: "Well, I don't really know what I think anymore. I've heard so many good theories here that I'm not sure what to believe in. What do you girls think?"

Tellus: "I think that what most convinced me was Mr. Wegener's idea. Continental drift seems the best way for me to go. It makes the most sense to me. What about you?"

Diana: "I think that Profs. Owen and Carey convinced me. I believe in their theory because there's a lot more evidence to verify this theory than to prove any other of the theories we've heard today. What's your opinion, Jeshua? You've been awfully quiet throughout this whole debate session..."

Jeshua: "Well, my children, only the Creator knows the Truth, and so do I. Someday you will, too. For now I will not say a word and let science run its course. You will someday come to the conclusion you've been awaiting."

Diana: "Well, thank you all for coming here today and for expressing your opinions, they were very much appreciated. 1 hope all of you come again soon. Goodbye, and enjoy your geofantasies gentlemen and ladies....."

The End

"A Brief History of the Geological Revolutions in Science" – an Essay Review

by Ashley

Author's Note: *This student chose to prepare a brief essay on theories of the Earth as a component of the final examination in a Senior 1 science course in a Winnipeg area independent school.*

For the remaining part of my exam, I have chosen to do option "B". The reason that 1 have chosen this option is because I really enjoyed learning about all the different theories of the earth.

From the point form notes on my outline sheets, here is what I have learned.

In 1873, a man by the name of James D. Dana began his research on theories about the Contracting Earth Model, as well as the Fixed Continent Model. In this time, many people believed that the continents were in the same place ever since the earth was formed. The continents were fixed in place, and they did not move.

Dana's idea suggested that the Earth was cooling, and getting smaller. He thought that as the earth was shrinking, it was because the earth was cooling, and the core would shrink. This shrinking caused wrinkles on the Earth's surface. He compared his theory to a drying apple. As the apple cooled (the Earth), the interior shrank, causing wrinkles on the apple's surface. Although this was a good idea, it was not a good comparison. The wrinkles on an apple's surface are usually evenly distributed. The "wrinkles" on the Earth are not. Most high mountain ranges are near the edges of continents, and not random all over its surface.

Long before these ideas, in about 1620, the first maps of the world, were developed. A man by the name of Sir Francis Bacon noticed that some of the continents appeared as if they could fit together at the coastlines - like the pieces of a puzzle.

In about 1756, a man by the name of Theodor Christoph Lilienthal of Germany, saw to that it appeared like the coastlines of many continents could possibly fit together. He believed that this meant that at one time, all of the continents fit together to form one big land mass. He also believed that the reason the continents are separated now was because of the massive floods much like the ones that were described in the Bible.

In 1857, a man from Paris by the name of Antonio Sinder-Pellegrini noticed that there were rocks and fossils that were very similar to one another on opposite sides of the ocean! Antonio believed that molten rock flowing out of the Earth's core, during the time of the Biblical flood, forced landmasses apart. So it was that the oceans were formed.

Early scientists were now saying that continents could have moved long distances.

In 1908, earth scientist Frank B. Taylor thought that mountains were formed when large forces between two land masses would push up the mountains when collisions occurred. This was a pushing up of rocks and the whole earth upward.
He said that movement of land could have been caused by the Moon's gravitational pull on the earth, moving continents with tremendous tide forces. These were thought to be similar to how the Moon helps move the ocean's tides.

Very few scientists believed the early theories of Continental Drift. Most believed in the Fixed Continent Model. Supporters of the fixed model believed land bridges allowed animals and plants to move from continent to continent. The land bridges would only appear when sea level was low. Otherwise most of the time they were under water. Many scientists began to outwardly accept the land bridge theory over continental drift, mostly because it was the idea most favoured by prominent American geologists. They couldn't even imagine a force that was strong enough to cause whole landmasses to move. In the early 1900's many people believed that the continents did not move for this reason.

A man by the name of Alfred Wegener had his own ideas about continental drift. He made up a new map of the world, where all continents were joined as one. He called this super continent, "Pangea". He thought that if continents could move up and down by the weight of glaciers on top of them, then they could move side to side, drifting like icebergs. Wegener said that land bridges were impossible according to the Principle of Isostasy (I am still not too sure what this means, though). There was no way that plants and animals could cross the ocean on narrow strips of land, since these land bridges were not necessary. There was no explanation as to why land bridges would sink or float either.

Scientists have yet to find the information that demonstrates that there are forces strong enough to move whole continents, and very large land masses, but like Wegener, time and timeliness will prove important ....

The End

"Through The Eyes of A Student" – a One Act Play

by Shelly

Time: December 13, 2001

Location : A Washington D.C. courtroom

<The doors swung open with a large BOOM coming out. It scared my friend and I deeply. Professor Wegener came in, walking slowly, with the chains clinging behind him. He sits down. This was not fair, I thought. His attorney, Frank Bursley Taylor, the esteemed American geologist, came along with him. The prosecutor, Dr James D. Dana also sat down. The judge came in and we all rose.>

"You may be seated", the judge spoke, "Mr. Dana, your first witness please." Mr. Dana called Professor Wegener up to the bench. Prof Wegener took his seat.

"Do you know why you are here today?," Mr. Dana asked grimly.

"Actually, not really," Wegener said impatiently.

"Well, Mr.... oh, excuse me, Professor Wegener, you are here today, because of some illegal actions allegedly taking place in the university of late – continents jostling about, tremendous forces moving them about the face of the globe, and related heresies."

"Yes, I know, but I don't think it is right for my radical ideas to be considered illegal..." Wegener offered.

"Well, Professor Wegener, it is illegal to teach or profit in universities by supporting other, dangerously alternative ideas about the Earth. You must know that, in this jurisdiction, a law was passed that people are not allowed to speak beyond the accepted notios of fixed continents and their aqssociated, acceptable ideas?" Dana said wisely.

"I have *evidence* that it isn't just an idea, but factually true, Mr. Dana!"

"By all means, sir, demonstrate this to us – and to me," Mr. Dana said impatiently.

"Well, there is evidence, that I just found out from my sources, that Brazil and Africa have the same fossil forms. Not only that , but also in Australia, and in North and South America, there are the remains of the same marsupials... !!" Alfred Wegener said proudly.

(My friend and I almost wanted to get up and start cheering, but we knew our behaviors had to be well-intentioned and dignified in the courtroom)

"Yes, I know all this but, it could have happened with land bridges. They had to have been used by the fauna, Professor Wegener, so that evidence is not sufficient to carry the day. You may step down now", Mr. Dana said happily.

The judge called Professor Taylor up. Frank Bursley Taylor spoke with Professor Wegener, and asked him questions that we already knew. It was taught to us about a month ago. About the Moon being the likely mechanism that pulled the continents. F.B. Taylor is credited with having popularized that particular theory.

Then the judge called Mr. Dana for his next witnesses, Samuel Warren Carey & Hugh Gwyn Owen to the stand.

"Professor Carey, you teach at Professor Wegener's university, don't you?" asked Mr. Dana.

"Why, yes I have visited him a few times, and now I have been working there for two years now. So has my co-worker, Hugh Gwyn Owen who is on leave from the British Museum in London, England. We teach that the best model to explain continental displacement and the geological fit of the Earth's continents and ocean basins is *earth expansion*."

"That is a crime..!! Don't you know that the expanding earth is totally preposterous, and has been banned from civil society and civil geology meetings?!!".

"No, you don't understand.... it is not just an idea. Why don't you just open your mind a little, instead of steadfastly clinging to that outmoded "fixed continent theory." "How do you know for sure?" Prof. Carey said angrily.

"That's a joke, Professors Carey and Hugh Owen. For hundreds of years, people and other scientists have accepted that *fixed* is the answer to the nature of the Earth's surface plan!"

(Mr. Dana was now getting on my friend's nerves - and mine too!!)

"Your next witness, Mr. Dana..., we have limited time. Don't you know I have a golf game?" the judge said expeditiously.

"Yes, I call Rachel Haymon to the stand."

Dr. Haymon rose up from her seat in front of us and went to the bench.

"Dr. Haymon, you also teach at Wegener's institution..., am I correct?" asked Mr. Dana.

"Why, yes I do, I've just started working with Mr. Wegener. He is such a brilliant man!"

"Yes, enough of that!! What do you have to say about the *fixed continents model* that is being advocated here, or these ridiculous and unproven notions of *continental drift*?" he asked sadly.

"Well, Mr. Dana, it is not a fact. I worked in different places in the world, leaming about the power of the new plate tectonics model, and its ability to predict the nature and behaviour of the ocean floors particularly near the ocean ridges where I do most of my work. I have found some very interesting facts. The continents did, in fact, actually move ...and still are today, for our satellites are close to confirming this!"

"Dr. Haymon, there is no mechanism in the world that could push or pull those continents around the face of the globe. You people don't get it!"

Mr. Dana was now at the point of apoplexy, and I could see it in his eyes.

"There is this suggestion, it is called *subduction*, and with this we can explain the budget of the Earth's crust. See, the ocean floors are spreading away from mid-ocean ridges, at one point, where new oceanic crust was forming. The continents could have moved with the crust along extremely long time scales. It is really happening in the oceans, not on the continents, don't you see? And this is why all of the continental geologists are going nuts over our mobilist thinking"

Mr. Dana stood quietly for a second or two, and then looked at Prof Haymon carefully. Then he spoke.

"Are you meaning to tell me that the ocean basins carry the continents and move them on some great conveyor belt?"

"Yes", she said.

"That is the stupidest thing I ever heard in my life! Either you are really on to something, or simply losing sight of your geological integrity!! You should be sentenced to banishment, ostricization from
the community of believers for being a crazy mind on the loose!"

Dr. Haymon was in shock. I wanted to get up and just slap him very hard. Prof Haymon was one of the most talented and ambitious women I have ever met. My friend nudged me on the shoulder and gave me a dirty look... she could see in my eyes that I wanted to get back at that James D. Dana so hard.

"You may take your seat, Prof Haymon" the judge spoke softly.

Mr. Frank Bursley Taylor stood up and said, "I object to any more insults hurled at my defendants, please."

"Sustained", the judge ruled.

"I want to call, Mr. Owen please," said Mr. Dana. Mr. Owen walked up to the bench, slowly and steadily.

"Mr. Owen, I have to ask you one more question, about this expanding earth thing. To clarify for the jury and me, can you explain it?"

"Yes I can…." Went on Dr. Owen. "Well, it was as if the earth was once smaller and it underwent expansion, making the continents move and spread across the earth, opening up ocean basins as they did so. That is about it." Mr. Owen spoke kindly.

"Well yes, but that does not make sense," said Mr. Dana.

"But, then how can your theory work about the earth shrinking. That is really out there, too ...real fringe stuff!!"

Mr. Dana looked shocked, like somebody called him the most obnoxious person in the world.

"That is not true! It has been proven by the sound notion of land bridges," Dana shot back.

"How could land bridges have been there? By listening to Hier Wegener and Prof Haymon, they could of not just melted away - they would have to be floating still. Because they're just like icebergs in a way."

Mr. Owen was now getting red-faced and somewhat out of control.

"That is enough, you may take your seat!!" the judge spoke.

"Hier Wegener, may you please take your place on the stand ...." Dana asked carefully.

"Mr. Wegener, for the last time, will you stop teaching your nonsense at our universities, or I will be forced to close it down and send you and your colleagues to the *archipelago*, if the jury agrees with me... "

"No, I will not!!", Wegener spoke impatiently by now.

"You are wasting my time and the government, so let's stop this and get on with things." Mr. Dana was shouting at him now.

Everything was in chaos. People were yelling, and I even found my friend yelling. Then suddenly came a beam of light hitting down upon us. It was Gaea – the Greek goddess of the Earth. We were all shocked that he stopped everything and looked at her with all our mouths open.

"Why, do you fight, my people?" Gaea asked.

"God said, let the waters below the sky come together in one place, so that the land will appear. He then named the land Earth and he was pleased." Gaea spoke with passion in his voice...

"The Creator made this earth for you, not to fight over and make people pay heavy personal prices for the rejection of their ideas - are you not as pleased as the Creator was so many years ago?", Gaea asked. "I will have to go now, but remember, it is not right to make an innocent person pay a fine, or face imprisonment for simply holding onto alternative ideas. Justice is perverse when good people are punished and have their reputations destroyed in this manner." Then a light hit us, and the mysterious goddess went away.

Everybody was in awe. Even Mr. Dana.

The judge then spoke...."Um, order please, everyone take your seats."

The verdict came in with surprising swiftness.

"Please rise..., we the government and jury, find Mr. Wegener and his co-workers not guilty of all charges, you are all dismissed."

Everybody stood up and yelled and cheered and
hugged. We ran up to Professor Wegener and hugged him. He looked at us and said five words:

"Did you finish your homework... ! ?"

"Aw, Professor Wegener, it was really long and . . . ."

Then we all walked out of the room happy as ever, for our old professor was finally back.

End of Story

Appendix 'C': *The Geotectonic Credo*

" I believe in plate tectonics, the Almighty, Unifier of the Earth Sciences, and explanation of all things geological and geophysical; and in our Xavier – Le Pichon, revealer of relative crustal motions deduced from sea-floor spreading rates about all the ocean ridges;
Hypothesis of Hypotheses, Theory of Theories, Fact of Veritable Facts; deduced, not assumed; Continents being of One with the Oceans, from which all Plates spread laterally; which, when they encounter another plate, are Subducted, descend along the Benioff Zone, are resorbed into the Aesthenosphere, and are made Mantle;

(all genuflect)

And these cause Earthquake Foci under Island Arcs; the plates then soften, and can flow; and at the Ridges, magma rises again according to the Vine-Matthews-Morley Hypothesis; it ascends into the Crust, and thereby maketh symmetrical Magnetic Anomalies; and the Sea-Floor spreadeth again, together with the Continents, to create both Mountains and Great Faults; and whose continual evolution as the Wilson Cycle will have no prospect of an end in accordance with the prophets Hutton and Lyell.

And I believe in Continental Drift, the Controller of the evolution of Life, which proceeds from Plate Tectonics and Sea-Floor Spreading; and which with Plate Tectonics and Sea-Floor Spreading is worshipped and glorified; which was spoken of through the prophet Wegener;

And I believe in only One model of crustal evolution; I acknowledge only One Cause for the deformation of all rocks; and I patiently await the emplacement of new ocean ridges, the demise of the Expanding Earth Hypothesis and the heretical adherents of Contractionism, the continual Subduction of the Plates, and the formation of Supercontinents to come… "

Amen

(adapted from Scharnberger and Kerr, 1972; with apologies to the Council of Nicaea (325 AD))