New directions in Wilson Cycle concepts: Supercontinent and Tectonic Rock Cycles

Steven J. Whitmeyer*
Lynn S. Fichter
Eric J. Pyle
Department of Geology and Environmental Science, James Madison University, Harrisonburg, Virginia 22807, USA

ABSTRACT

Modern earth science pedagogy is increasingly based on an integrated systems framework, where all of the major earth systems, including lithospheric cycles, are interlinked and dependent on each other through feedback loops. Most secondary school and introductory college-level geology courses present the concepts of plate tectonics and rock classifications. However, many instructional approaches fail to integrate these topics within an earth systems viewpoint, where supercontinent cycles are viewed in both spatial and temporal dimensions, and the classification of rock types is intrinsically dependent on the tectonic, as well as the depositional environment in which they were formed. This contribution presents new tectonic animations and images that allow students to investigate supercontinent cycles (e.g., the assembly and breakup of Rodinia, and the Paleozoic interactions of Laurentia, Gondwana, and Baltica) and integrated Wilson Cycle and Tectonic Rock Cycles that equate rock genesis with tectonic and environmental settings. Central to these visualizations is the concept that processes of rock genesis have evolved, and will continue to evolve, through geologic time. We discuss the conceptual and historical background for each of these visualizations, and follow this with detailed descriptions of, and educational uses for, the images and animations.

To be of optimal instructional utility, the animations and images consider the visual domain as a primary, rather than secondary instructional tool. As such, they are designed to function optimally in an inquiry-driven educational setting. They take into account the complex cognitive interactions between visual and verbal representations in learning environments by providing rapid interchange between these two domains. Where factual information is of interest, e.g., when introducing a topic or relaying important background information, the typical verbal primacy is observed. But in instances where spatial and temporal relationships are of interest, such as in the Rodinia and Pangaea supercontinent cycles, and the "No Rock is Accidental" tectonic rock cycle, the visualizations assume the primary role, with text-based annotations or verbal discussion as secondary.

We conclude with discussions on the importance of inquiry-based educational approaches and effective ways of evaluating educational visualizations. We suggest that to best utilize the available media (digital and paper based), the level of cognitive engagement of the learning task should be closely tied to a taxonomy of visualizations that encompass detailed, integrated representations and animations. Inquiry-based interfaces, such as we present in this paper, promote more mindful articulations of the desired learning tasks and an increased retention of the subject material outside the bounds of the classroom. Teaching a systems-based understanding of the Earth and the concepts of evolving tectonic and rock cycles provides students with holistic foundations from which they can better evaluate, and make decisions about, their living environment.

Keywords: plate tectonics, Rodinia, Laurentia, Wilson Cycle, rock cycle

INTRODUCTION

Modern approaches to earth science education are increasingly focused on "systems thinking," wherein each component of the earth system (lithosphere, atmosphere, hydrosphere, and biosphere) is dependent on interactions with the other components, through positive and negative feedback loops (Assaraf and Orion, 2005). In contrast, a review of pre-college and undergraduate earth science curricula in the United States suggests that earth science instruction is still commonly organized into discrete bits of content. Generally speaking, learning objectives are arranged with elements such as landform development, plate tectonics, and rock genesis as separate, distinct topics, often with limited integrative connection (Hoffman and Barstow, 2007). The organization of these topics in a cause-effect fashion, or as a substantive part of an integrated system, is the exception, rather than the rule.

Not surprisingly, instructional materials reflect this same descriptive and reductive organization. While many introductory college geology textbooks present plate tectonic theory early in the text as an organizing and potentially unifying theme, most pre-college earth science texts provide information on plate tectonics in a manner that precludes connections with rock generation or landform development (Chambliss and Calfee, 1989). As a result, the generation of rocks and landforms are disconnected from the tectonic and environmental processes that generate them. Discussions of plate tectonics are limited to paleontological and geophysical evidence for the theory, such as *Glossoptera* fossils, volcano and earthquake occurrences, and paleomagnetic data. More importantly, students are commonly presented with a truncated depiction of global tectonic history that only encompasses the breakup of Pangaea (ca. 200 Ma) to the present, with prior supercontinent cycles represented, if at all, only in a discussion of geologic time (e.g., Tarbuck and Lutgens, 2005). The breakup of Pangaea is presented as an isolated system,

*whitmesj@jmu.edu

Geosphere; December 2007; v. 3; no. 6; p. 511–526; doi: 10.1130/GES00091.1; 8 figures; 3 animations.

and the dynamic nature of the Earth's evolutionary history is merely implied. In rock genesis, where the three rock "types" (igneous, sedimentary, and metamorphic) are unified through the ubiquitous "rock cycle" diagram, relationships are presented as a closed loop, with little regard for how the types and volumes of rocks on Earth have evolved through billions of years of the Earth's tectonic history.

Part of the handicap with presenting topics like the Earth's dynamic history and rock genesis as integrated systems is that textbooks and even PowerPoint illustrations are primarily descriptive rather than generative, wherein complex dynamic processes are reduced to static images. Comprehension is also made difficult by the range of scales of observation at which Earth processes function—from the microscopic to the global and from microseconds to hundreds of millions of years. Integration of these processes into an effective instructional approach is an ongoing challenge, and it is within this time-dependent, process-oriented framework that modern computer-aided visualizations can be effectively utilized.

The educational potential for visualizations has been recognized by the American Association for the Advancement of Science (AAAS), through the textbook analysis framework developed by Project 2061 (Kesidou and Roseman, 2002). Their framework includes, as a criterion, "relevant phenomena"—that is, real-world examples or illustrations of scientific concepts requiring, in part, a vicarious sense of observation of phenomena. Project 2061 showed that while scientific visualizations are common in most science textbooks, their connections to the text materials and the overall concepts do not provide the direct support for student learning that teachers, parents, and adoption committees envisioned, relative to the curricula for which the textbooks were intended. In the non-earth sciences, such visualizations are possible as demonstrations or laboratory experiments; we can observe in real time animal behavior, or a swinging pendulum, or the results of a chemical reaction. The same is not true for the generation of a granite body, the growth of a mountain, or the movement of continents, all of which occur within timeframes much longer than human observation.

The earth sciences are distinct from the classical sciences in other fundamental ways. Although earth scientists often conduct laboratory experiments in the classical framework of a single dependent variable, field examination of a rock outcrop yields data that incorporates the sum total of all generative processes that occurred at many scales of action, over many scales of time. Inevitably there are unknown variables operating. "Prediction" in this sense is not the same in the earth sciences as it is in classical science. In complex systems like the Earth, theories are less likely to predict a specific outcome but rather an explanation of the underlying mechanisms at work; e.g., under a particular set of conditions, a certain set of structures and rocks will form. Time is an essential component, because the slow rates of tectonic and evolutionary processes require millions or billions of years to accomplish the significant changes apparent in the rock record. This viewpoint is fundamental in the earth sciences, where time is used in a forward and backward manner—predictions as well as "retrodictions" (Frodeman, 1995).

Earth scientists are still a long way from fully explaining or integrating how the complex world works, i.e., how all the Earth's systems interact to produce the outcomes we observe. However, we now appreciate the necessity of viewing the Earth and teaching Earth's history in the context of interconnected and interdependent complex systems. This contribution presents spatial and temporal animations of plate tectonic processes and sequential diagrams of modern Wilson Cycles and Tectonic Rock Cycles that integrate tectonic processes and rock genesis in an evolutionary framework. We expect that these animations and models will help secondary through undergraduate educators teach rock cycle and tectonic concepts as an integrated, time- and space-dependent, evolutionary system. By animating complex continental movements over nearly a billion years of history, but in temporal and spatial frameworks humans can grasp, students can begin to appreciate not only the complexity of tectonic movements but also the continuity of a set of recurring processes, such as continental collisions and supercontinent assembly and breakup. From this appreciation, we hope to demonstrate predictability—not specific predictability, such as 500 million years from now two continents will collide in a certain way—but, rather, predictions such as when two tectonic blocks interact in a particular way, the same kinds of rocks and structures will be generated by the same kinds of processes. With each continental collision, uniquely different mountains are formed, but they are similar enough that we can deduce and predict common processes.

CONCEPTUAL BACKGROUND

It is not wise for teachers and textbook authors to chase after every new idea that comes along, because ideas and theories need to mature (i.e., be validated and accepted by the scientific community) before they are introduced into the introductory classroom. In addition, as scientific ideas evolve, they tend to become more complicated, and more difficult to teach. However, ideas and theories do progress in accuracy and complexity, and at some point teaching what is simple and familiar does both the discipline and the student a disservice. Decision making in these cases is not clean and simple; academia benefits from the dynamic tension between conservative foundations and new directions precipitated by modern research. In the following sections of this paper, we argue that theories about the Earth's tectonic processes have evolved to the point where we need to reevaluate what we teach and how we teach it. We begin with a brief summary of how rapidly changing scientific ideas have influenced the teaching of earth tectonics over the past half century and then discuss why existing depictions of tectonic cycles and rock cycles in educational materials need further refinement within a broader earth systems context.

Geosynclinal Theory to Modern Tectonic Models

Before the majority of American geoscientists accepted that continents moved, the governing tectonic theory from the last half of the nineteenth century into the late 1960s was geosynclinal theory. Emanating from the Appalachians-focused work of James Hall (1811–1898) and James Dana (who coined the term geosyncline in 1873), geosynclinal theory tried to explain mountain building in the context of a cooling and shrinking Earth from an originally molten state. Marshall Kay (1952) published the culminating synthesis of geosynclinal theory, and since Kay and most other American geologists at the time were working from a "fixidist" assumption (continents do not move), mountains were depicted as forming in place without laterally directed outside influence. This interpretation is apparent in a series of block diagrams from Brice (1962; Fig. 1) that provides a pre–plate tectonic interpretation of mountain building. However, it is important to recognize that, in general, European geoscientists were quicker to accept continental drift and early plate tectonic theory than their American counterparts (Oreskes, 1999). Arthur Holmes presented a remarkably accurate depiction of continental drift and mantle convection in his 1944 introductory geology text (Holmes, 1944), and by the mid-1950s, paleomagnetic data was causing European fixidist stalwarts, such as Keith Runcorn, to embrace drift theory (Runcorn, 1955, 1956).

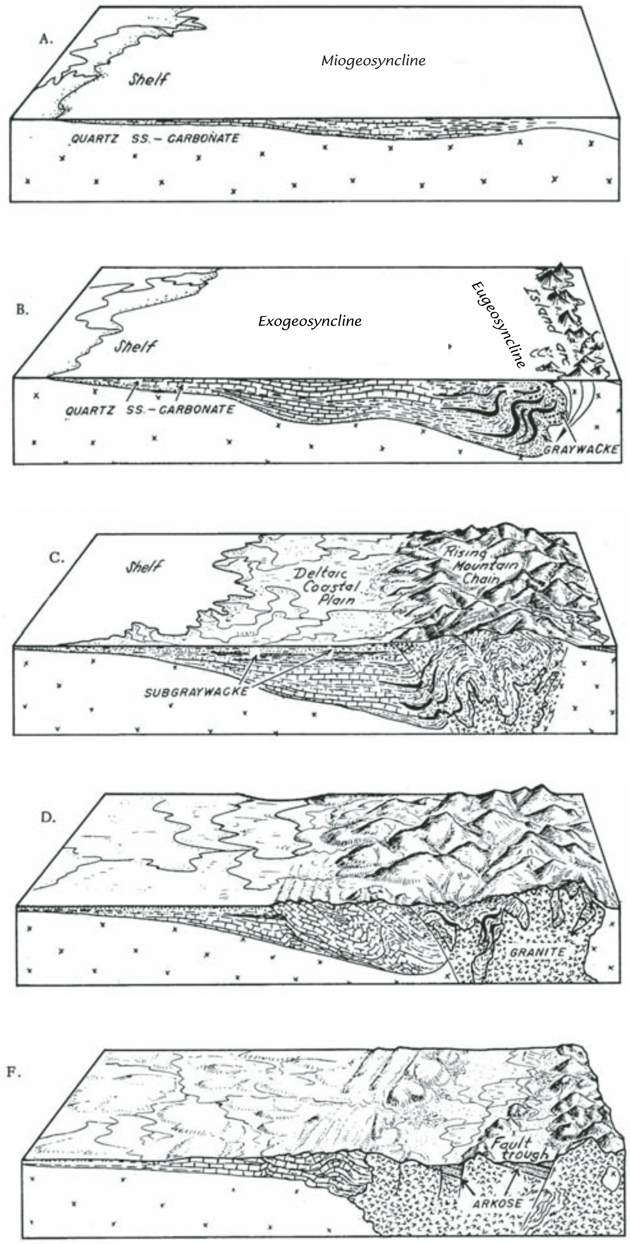


Figure 1. Block diagrams showing six stages in the development of geosynclinal mountain building; after Brice (1962). (A) Pre-orogenic miogeosyncline characterized by shallow-water carbonates, quartz-rich sandstones, no volcanics, and relative tectonic stability. Observe that on the eastern (right) side, the geosyncline seems to transition vaguely into something, but it is unspecified. (B) A volcanic arc rises up on the outside flank (ocean side, away from the craton) of the miogeosyncline, converting it into a deepwater eugeosyncline, while the miogeosyncline subsides into an exogeosyncline. The exogeosyncline fills with immature deepwater sediment ("graywacke," a.k.a. flysch) eroded from the volcanic arc/eugeosyncline lying beside it, interbedded with underwater lava flows. No magma source for the volcanic arc is indicated in the cross section, but since we find the remnants of the arcs in the Piedmont today, it is presumed they formed in place at those locations in the past. (C) Granites intrude the eugeosyncline, leading to widespread metamorphism, accompanied by compression leading to folding, faulting, and mountain uplift. Subgraywacke sediments (a.k.a. molasse) are deposited across the "delta coastal plain," mostly in rivers and shallow marine environments. (D) and (E) Mountain building has ended, and all that remains is for the mountains to be eroded down. (F) Graben formation, corresponding with the Triassic basins of the Atlantic coastal plain and Piedmont.

Geosynclinal concepts such as those in Figure 1 strongly influenced the generation of American geologists who contributed to the early development of plate tectonic theory in the 1960s and 1970s (Oreskes, 2001). During these formative years, many plate tectonic aspects of mountain building were explicitly described using geosynclinal terminology (e.g., Atwater, 1970; Bird and Dewey, 1970; Dewey and Bird, 1970; Dickinson, 1971; Gilluly, 1971), since that was the accepted language that addressed mountain divisions, structure, and formation. As plate tectonic theory came of age during the late 1970s and early 1980s, a whole new set of terminology developed, consistent with newly recognized divisions and mechanisms. In the interim, however, two sets of terminology were present in both the scientific literature and in textbooks (e.g., Verhoogen et al., 1970; Press and Siever, 1974).

An example of this transition period is seen in the cross sections of Dietz (1972; Fig. 2), where early plate tectonic and vestigial geosynclinal concepts are both in evidence: "The concept that the geosynclinal cycle is controlled by plate tectonics provides some new answers to old questions about geosynclines" (Dietz, 1972, p. 108). Dietz made extensive use of the terms miogeocline and eugeocline (taking the "syn" out since they are no longer synformal in his reconstructions), but placed them in a plate tectonic context. In addition, the Dietz model makes explicit the opening and closing of ocean basins, which is implicit in the geosynclinal diagrams of Brice (Fig. 1). Building on the paleogeographic maps of Dietz and Holden (1970), Dietz (1972) not only opens and closes the Paleozoic ocean basin, he extends it to include developing models of Pangaea. This model was important not just to the geoscience research community, but also because it proliferated in introductory geology textbooks (e.g., Press and Siever, 1978), inculcating a new generation of geoscientists and lay people alike in how plate tectonics influenced Atlantic geologic history.

A major problem with these early tectonic models (Dietz, 1972; Bird and Dewey, 1970) is that they depict Appalachian mountain belts as generated by west-dipping subduction of an oceanic plate. This assumption was implicit in geosynclinal theory where volcanic arcs were located in the eugeosyncline (Kay, 1952), and this geometry was adapted to early plate tectonic models to generate Appalachian volcanic arcs with west-dipping subduction zones. The assumption that volcanic arcs always formed in situ was challenged originally in studies of the Cordilleran region, where evidence pointed to the existence of suspect terranes (Hamilton, 1969; Irwin, 1972; Ernst, 1975). However, as

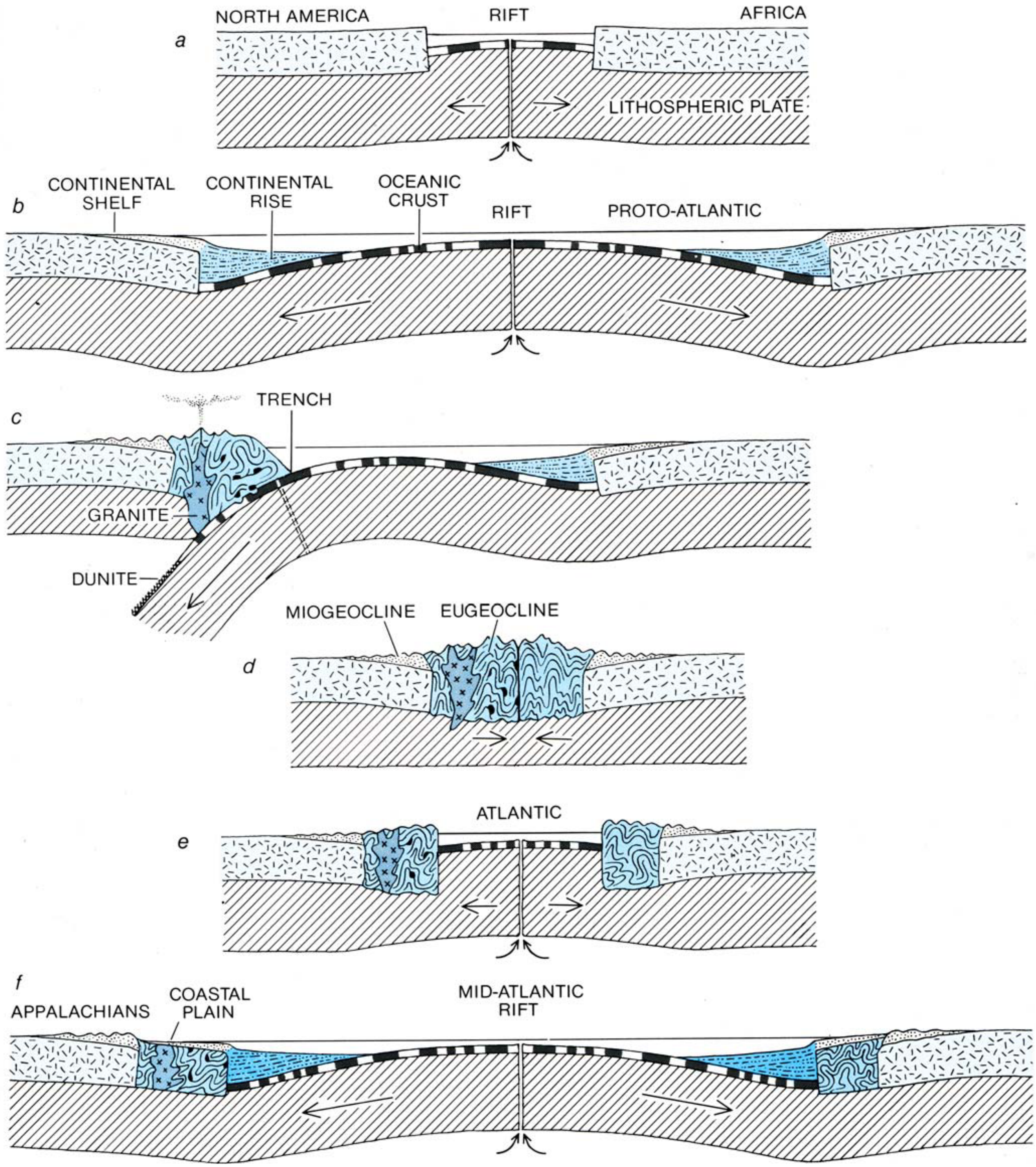


Figure 2. An early set of cross sections showing the Wilson Cycle. This model is a synthesis of geosynclinal concepts and plate tectonic concepts based on interpretations of Appalachian and European geology; after Dietz (1972).

the full consequences of the suspect terrane idea became appreciated in the Appalachian context, it led to a complete reversal of thinking about the closure of the Iapetus (proto-Atlantic) ocean (Hatcher, 1989, among others). Instead of subduction zones that dipped westward under North America, newer models showed them generally dipping eastward (Hatcher, 1972; Secor et al., 1983; Nance et al., 1991; Dennis and Wright, 1997). Today, the majority of Appalachian suspect terranes are no longer considered "suspect"; geologic, paleontologic, and geophysical studies confirm their exotic origins (Hatcher et al., 1989; Williams, 1995; Hatcher et al., 2004). For our purposes, the main point is that the models of Dietz (1972) and Bird and Dewey (1970), because they quickly infiltrated the teaching literature and the classroom, strongly influenced the thinking of many geologists. They were simple, slick, neat models; they were relatively easy to teach; but they don't represent our current understanding of earth processes, and we no longer teach them.

Geologic Systems Thinking

Terms like system, complex system, complex systems theory (a.k.a. chaos theory), earth system, and earth system science are used ever more frequently in the modern earth science lexicon. Part of our goal in this contribution is to develop visualizations that help students develop high-order systems thinking skills about the Earth. We frequently use the term "system," but unfortunately, system concepts are used differently in different disciplines and are evolving rapidly (Shufeldt, 2007). A common characteristic of systems across disciplines is that systems exist and function as a whole, while depending on the interactions of their parts through positive and negative feedback loops (Assaraf and Orion, 2005). Each component has a specific purpose, and therefore each component must be functioning for the whole system to perform ideally. A full exploration of systems theory is beyond the scope of this paper, but we need to briefly address two systems-oriented concepts that are relevant to the visualizations and educational approaches we propose:

(1) Students need to think about the Earth, not as isolated parts, but as a system wherein all components are interconnected through positive and negative feedback mechanisms. When talking about "earth systems science," this usually encompasses the relative influences of the lithosphere, atmosphere, hydrosphere, and biosphere on each other. In this paper, we focus on lithosphere processes, but with the same goal of inculcating thinking about how rock genesis and tectonics are inextricably intertwined.

(2) Student use of systems thinking about the Earth will aid in the development of higher order thinking skills (Kali et al., 2003; Assaraf and Orion, 2005). As phrased in a report by the American Association for the Advancement of Science (1993, p. 262): "One of the essential components of higher-order thinking is the ability to think about a whole in terms of its parts and, alternatively, about parts in terms of how they relate to one another and to the whole."

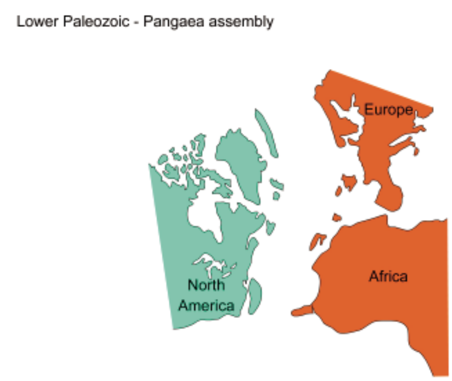
In addition to higher order thinking skills, systems thinking encourages the ability to analyze different parts of a system simultaneously, at scales ranging from the microscopic to the macroscopic (Hmelo et al., 2000; Kali et al., 2003), and "the ability to identify relationships among the system's components and organize the system's components and processes within a framework of relationships" (Assaraf and Orion, 2005, p. 523). Kali et al. (2003) focused on students' understanding of a traditional rock cycle. Their goal was an explanation that went beyond a static view of the system and contained "highly developed dynamic thinking of material transformation within the rock cycle, and a rich understanding of the interconnectedness between parts of the system" (p. 558). They concluded that students possessed "chunks" of process knowledge, e.g., material transformation in the rock cycle, that are initially specific and disconnected from each other (low-level systems thinking). Specifically, students exhibited problems with making full, dynamic connections between different parts of the rock cycle. To move beyond such limitations, a dynamic, systems thinking approach to instruction is required to associate initial "chunks" to broader ideas (high-order systems thinking).

The visualizations presented in this paper are driven by systems-oriented ideas, even if not explicitly stated. However, teaching from a systems perspective should not be approached lightly. Systems thinking about the Earth as a whole requires high-order and critical thinking skills that many students are not accustomed to, and many faculty are not used to teaching (at least at the pre-college and undergraduate levels). It is our intention that the accompanying visualizations will help to make this complex teaching task more comprehensive and intuitive.

Implications for Earth Science Teaching

New models of the Earth's evolution that incorporate integrated systems theory have radically changed our depiction of historical and present-day tectonics, but these concepts and their larger implications have not yet been adequately incorporated into classrooms and textbooks. These concepts include: (1) Earth originated with no, or at best, only small continental blocks, and the continents have grown with time (Windley, 1995; Condie, 1997; Whitmeyer and Karlstrom, 2007). (2) Today's continents are composed of many smaller crustal components and did not reach their present configuration until recently in Earth's history (Hoffman, 1988; Karlstrom et al., 1999; Whitmeyer and Karlstrom, 2007). (3) Within the past billion years, at least two major supercontinents, Rodinia and Pangaea, assembled and dispersed (McKerrow and Scotese, 1990; Moores, 1991; Li et al., 2007), and the associated history of continental movements is neither simple nor straightforward.

The implications of these ideas influence existing models that are, or have been, deeply imbedded in geoscience teaching, and that need rethinking. The problem is that many previous and existing models have been useful educational tools; however, they no longer represent modern understanding of the Earth. An example of this is the tectonic model of Wilson (1966), which is often termed the "Wilson Cycle." In the early days of plate tectonic theory, Wilson's (1966) original map-view model of the Atlantic closing and then reopening (see Animation 1[1]) and Dietz's (1972) cross sections (Fig. 2) that epitomize the Wilson Cycle concept were common in text books (Press and Siever, 1978) and classrooms. Today, however, we recognize that these early depictions of orthogonal collisions and symmetrical extensional collapse of North America with Africa and Europe are far too simplistic. Modern reconstructions depict the



Animation 1. QuickTime movie of Wilson's (1966) original Atlantic closing and then reopening "cycle." Note the basically orthogonal collision of Europe (orange) and Africa (orange) with North America (blue), with no depiction of rotational or latitudinal complications of 3D geometry. Breakup is along similar orthogonal lines, although some consideration of rotational motion of North America and Europe relative to Africa is inferred.

[1]If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00091.S1, http://dx.doi.org/10.1130/GES00091.S2, and http://dx.doi.org/10.1130/GES00091.S3 or the full-text article on www.gsajournals.org to view the animations.

Neoproterozoic-Early Cambrian opening of the Iapetus ocean with ancestral South America (the Rio de La Plata and Amazon cratons) rifting away from Laurentia (ancestral North America; Fig. 3), while the Late Paleozoic closing of the Rheic ocean culminates with the collision of Laurentia and the African part of Gondwana (Fig. 4). These modern plate reconstructions reveal important complexities, such as the rotational movement of plates (McKenzie and Parker, 1967; Morgan, 1968) and transform boundaries (Wilson, 1965), as required on a three-dimensional globe. However, these fundamental concepts are intricate and often difficult to teach effectively without the use of modern computer-aided animations.

A more serious implication of new tectonic theories is that the traditional, circular rock cycle universally presented in textbooks and taught in classrooms—and the Huttonian/Lyellian uniformitarian philosophical principle behind it—is no longer valid. A circular rock cycle is analogous to Carnot's (1824) model of an ideal heat engine, which has the rather tricky result of transferring heat between two sources at different temperatures without any contact between those sources. The circular rock cycle transforms one rock into another without acknowledging that these transformations take place in specific tectonic regimes, on a planet that has evolved substantially since its origin, and where the diversity and abundance of rocks has changed through time. Modern theories of the Earth and its processes suggest that we need integrated models that illustrate how rock genesis, rock transformations (e.g.,

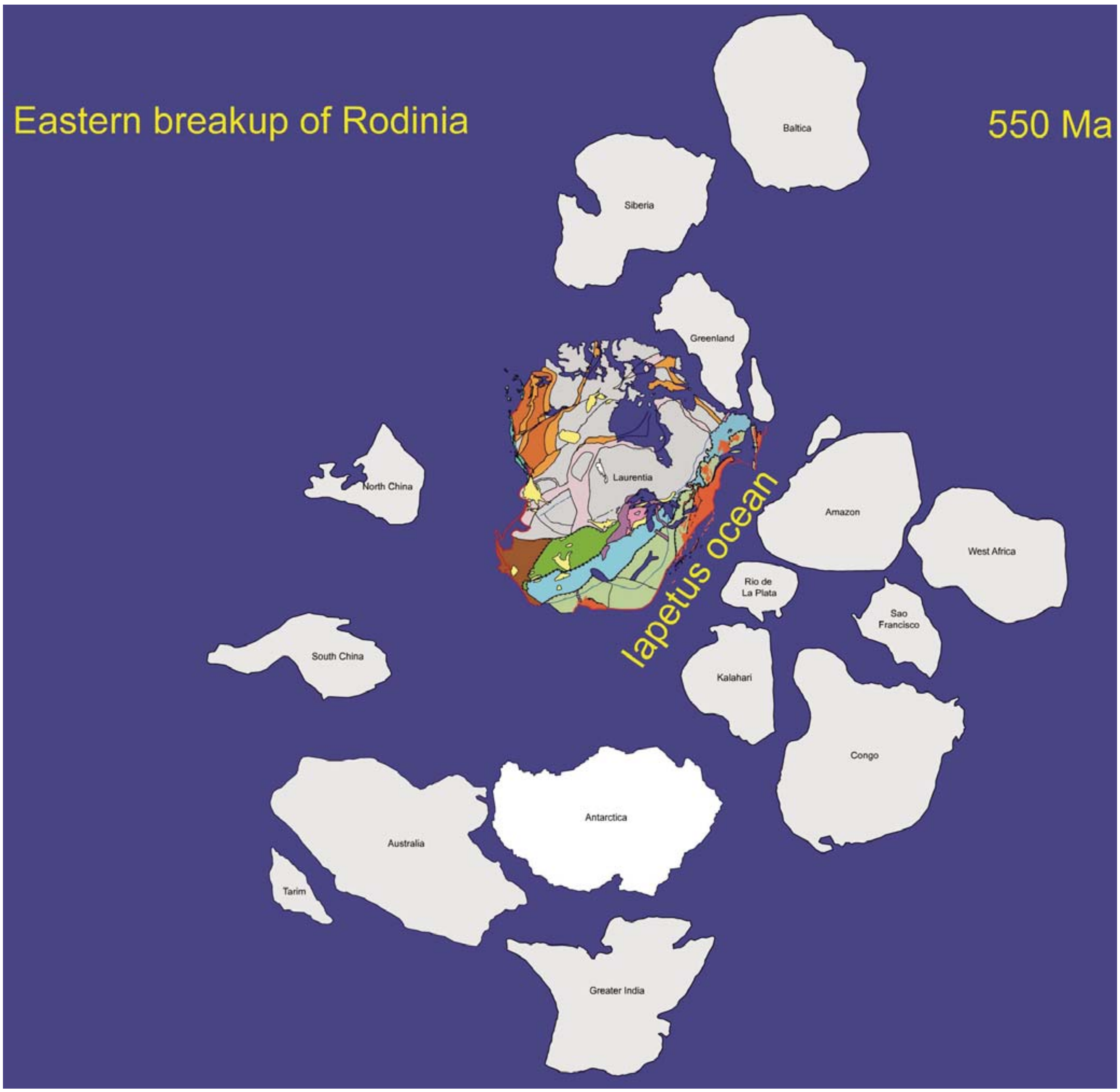


Figure 3. The Rio de La Plata and Amazon cratons rifting away from Laurentia (ancestral North America).

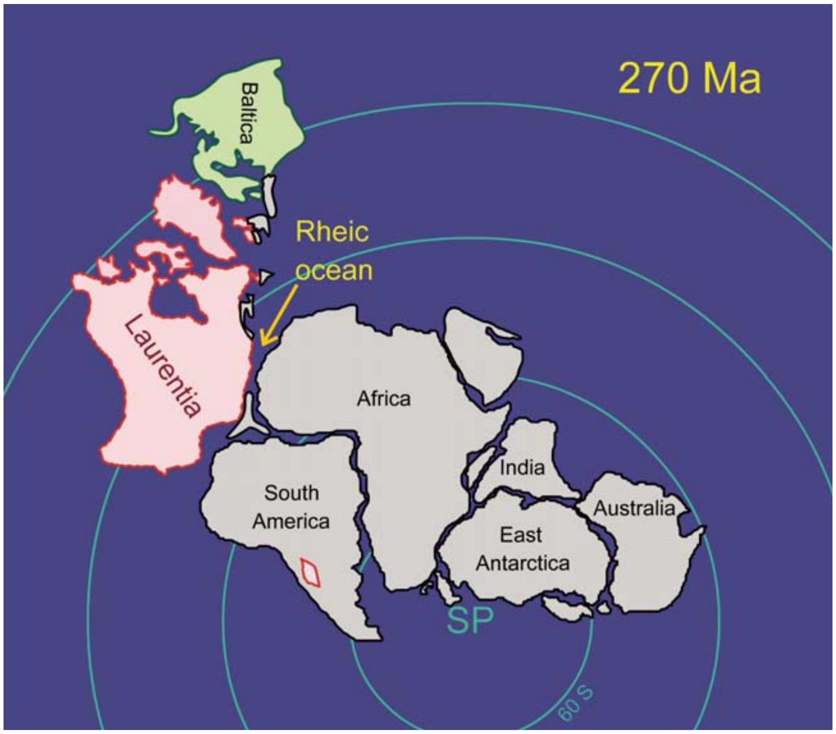


Figure 4. The closing of the Iapetus ocean culminates with the collision of Laurentia and the African part of Gondwana.

rock cycles), climate, and tectonic models work together (Dickinson and Sucek, 1979; Earth System Science Committee, 1986; Steffen et al., 2004). More importantly, these must be in a form that can be incorporated into college introductory geology classrooms and simplified for secondary school classrooms.

With this in mind, the text that follows presents visualizations and animations of supercontinent cycles, Wilson Cycles, and rock cycles based on our current understanding of the integrated earth system. These have been designed as teaching tools to be used in interactive classroom environments, but we recognize that these tools are just a subset of the materials necessary to effectively educate students in the amazingly complex earth system. We follow discussions of the individual visualization products with a section on the educational and cognitive implications for this relatively new systems-based approach to teaching integrated earth processes.

MODERN DEPICTIONS OF EARTH SYSTEM CYCLES

One of the main purposes of this contribution is to advocate the use of more advanced (and more accurate) earth system "cycles" as modern, up-to-date teaching devices. In the following sections, we focus on: (1) computer animations that depict modern concepts of "supercontinent cycles" as spatially correct depictions of the assembly and breakup of supercontinents within the past 1.1 billion years of Earth's history; (2) a heuristic Wilson Cycle developed as a series of cross sections that elucidate the plate tectonic conditions under which specific rock types and structures form; and (3) a Tectonic Rock Cycle that combines traditional circular rock cycle concepts with specific plate tectonic processes. The visualizations we present in this paper are not devoid of simplifications and distortions, however. The map-view animations are 2D representations of continental movements around a 3D globe. In an effort to minimize students' comprehensive difficulties with distorted landmasses, we have treated the globe as if it were a flat surface and removed projection-derived distortions of the continent's shapes. Each animation has a distinct focal point: the Rodinia animation (#3) shows the continents relative to Laurentia, and the Laurentia-Gondwana animation (#2) shows Paleozoic movements relative to the South Pole. These focal points magnify distortions at the boundaries of the images, but our goal was to maximize student comprehension of plate tectonic relationships during the highlighted time periods. Similarly, the Wilson Cycle cross sections are somewhat cartoon-like, with some vertical exaggeration and enlargement of critical tectonic and rock type associations. Our experience suggests that the benefit of increased comprehension from students outweighs the geometric approximations in these visualizations.

Supercontinent Cycles

One of the principal shortcomings of representations of plate tectonic cycles in many introductory geology texts is the restriction of historical plate movements to the period from the full assembly of Pangaea (ca. 250–200 Ma) to the present day (e.g., Holt, Rinehart, and Winston's *Modern Earth Science*, 2002). This is largely the result of historical precedent; the early Continental Drift concepts of Wegener (1912) began with a supercontinent that he called Gondwana (now termed Pangaea) and followed the movement (drift) of the continents to their present-day positions. Wilson (1966) recognized that this "breakup" of Pangaea was only part of the story: Pangaea must have assembled from existing continental fragments before it could later break apart (e.g., Animation 1). In some textbooks, the formation of ancient mountain ranges is depicted, but usually as an illustration of convergent margins (e.g., McGraw-Hill's *Earth Science*, 2002). The origin of the preexisting fragments is left somewhat open. Past plate positions are often depicted, but usually in the context of geologic time periods and not as a function of rock formation. A comprehensive model of supercontinent cycles is at best only implied.

In the 40 years since Wilson's seminal paper (1966), we have recognized that Paleozoic plate movements and continental interactions are far more complicated than Wilson originally described, although we suspect that Wilson had a good appreciation for these complexities back in the 1960s. The Neoproterozoic breakup of Rodinia quickly produced another smaller supercontinent, Gondwana, composed of the present-day continents of Africa, South America, Antarctica, and Australia, as well as continental fragments, such as India, Florida, and Avalonia (Hoffman, 1991; Dalziel, 1991, 1995). Other isolated Paleozoic continents included Baltica (present-day Scandinavia and northern Europe) and Laurentia (most of present-day North America). Gondwana spent much of the Paleozoic rotating around the South Pole; indeed Wegener (1912) used evidence of early Paleozoic glaciations to connect many of the continental components of Gondwana. During this period of time, Laurentia and Baltica rotated around Gondwana in a predominantly clockwise motion (Dalziel, 1995, 1997; Roberts, 2003) before colliding with Gondwana at the end of the Paleozoic to form Pangaea (Dietz and Holden, 1970; McKerrow and Scotese, 1990;

Lawver et al., 1998). The interactions between Laurentia and Gondwana during this period are highlighted by the transfer of two micro-continental terranes—the Laurentia-derived Precordillera and the Gondwana-derived Avalonia. Thomas and Astini (1996) determined that the Precordillera terrane rifted from the Texas embayment region of southeastern Laurentia in the early Cambrian, migrated across the Iapetus ocean, and collided with the western margin of Gondwana (present-day western Argentina) in the late Ordovician to early Devonian. In contrast, the microcontinent of Avalonia traveled from northern Gondwana to eastern Laurentia, the opposite direction across the Iapetus, in the late Ordovician-Silurian (Murphy et al., 2002; Keppie et al., 2003; among others). Baltica moved independently for most of the period, prior to joining the northern extent of Avalonia just before their Silurian-Devonian collision with eastern Laurentia during the Acadian orogeny (Roberts, 2003; among others).

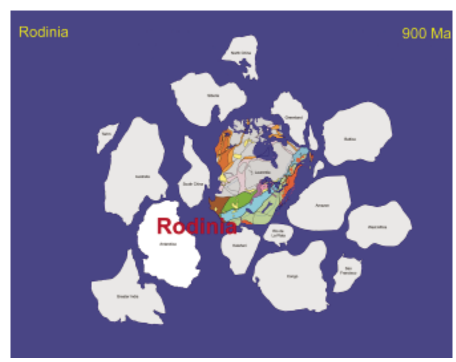
The simple diagrams of Wilson (1966) and Dietz (1972) barely hint at the Paleozoic tectonic complexities described above. However, simple tectonic illustrations that vary little from these 40-yr-old models persist in many modern textbooks, and thus do a poor job of illustrating plate tectonic history as we now understand it. This is likely because it is difficult, if not impossible, to fully comprehend the Paleozoic tectonic movements of the major continents and microcontinental fragments with verbal descriptions (demonstrated by the difficulty of keeping track of and visualizing continental movements solely from the descriptions in the last paragraph), or traditional, static map-view or cross-sectional images. However, interactive computer animations are an ideal medium to allow students to explore our modern understanding of Paleozoic plate interactions that led to the assembly of Pangaea. Animation 2 (see footnote 1) shows the movements of Laurentia, Gondwana, Baltica, and the Precordillera and Avalonia microcontinents from the Neoproterozoic breakup of eastern Rodinia (ca. 600 Ma) to the assembly of Pangaea (ca. 250 Ma). The QuickTime interface allows the user to view the images as a continuous movie, or to advance through the sequence step by step, either forward or backward. This puts students in control of an inquiry-based learning process, and teachers can propose "What if" questions to enhance the students' understanding of the complex tectonic scenarios.

Animation 2. QuickTime movie of the relative positions of Laurentia (pink), Gondwana (gray), and Baltica (green) from the Neoproterozoic to the Late Paleozoic, leading up to the assembly of Pangaea. Included are significant microcontinental movements—the Laurentia to Gondwana transfer of the Precordillera terrane and the Gondwana to Laurentia transfer of Avalonia. Movements are shown relative to the South Pole (SP). Laurentia and Gondwana movements are largely based on Dalziel's (1991, 1995, 1997) depictions of the "end run" clockwise movement of Laurentia around Gondwana during the Paleozoic. Locations of Baltica are largely based on Roberts (2003). Transfer of the Precordillera microcontinent (pink) from the Ouachita embayment region of southeast Laurentia to the western South America region of Gondwana is based on Thomas and Astini (1996). Transfer of Avalonia (gray) from the north African margin of Gondwana to eastern Laurentia based on Roberts (2003) and Keppie et al. (2003).

The Diachronous Assembly and Breakup of Supercontinents

After investigating Paleozoic tectonics leading up to the formation of the Pangaea supercontinent, students often recognize the next logical step and ask whether supercontinents, in addition to Gondwana, existed prior to Pangaea. Indeed we now recognize the possible existence of several early supercontinents, such as "United Plates of America" (Hoffman, 1988), "Nuna" (Hoffman, 1997), and "Columbia" (Rogers and Santosh, 2002), among others. The most robust reconstructions of a pre-Pangaea supercontinent depict an assembly of most existing continental fragments at ca. 1.1–0.9 Ga as the supercontinent Rodinia. Early proposals for a ca. 1.0-Ga supercontinent (Moores, 1991; Dalziel, 1991) showed part of the story with Australia and Antarctica attached to western North America (Laurentia). Subsequent reconstructions (Karlstrom et al., 1999; Sears and Price, 2000; Meert and Torsvik, 2003; among others) have modified these early depictions and added more pieces to the puzzle.

A recent multinational effort (the International Geoscience Programme [IGCP] 440 project) has produced the most detailed Rodinia reconstruction to date (Li et al., 2007) and, in the process, highlighted a critically underappreciated concept. Simply stated, the various continental components of supercontinents do not all assemble at the same time: supercontinent assembly is diachronous. Several continental blocks, such as South China and Siberia, were already accreted to northwestern Laurentia by 1100 Ma, followed by eastern components (Baltica, Amazon, and the African blocks) at ca. 1000 Ma. Full assembly of Rodinia culminated with the accretion of Australia and Antarctica (with India) to southwestern Laurentia at ca. 900 Ma (Karlstrom et al. 1999; Li et al., 2007). Thus, the assembly of the Rodinia supercontinent consisted of a protracted sequence of continental terranes that accreted to the Laurentian core over more than 200 million years. Animation 3 (see footnote 1) is a QuickTime movie that illustrates this diachronous assembly of Rodinia, and also demonstrates that, while Laurentia is close to the dimensions of present-day North America by 1.0 Ga, one is hard pressed to discern the shapes of present-day



Animation 3. QuickTime movie of the diachronous assembly and breakup of Rodinia from 1100 Ma to 530 Ma. Positions of continental fragments (white) relative to Laurentia (multi-colored) at key time slices (e.g., 1100 Ma, 1000 Ma, 900 Ma, 700 Ma, 550 Ma) based on the IGCP 440 reconstruction of the Rodinia supercontinent, as summarized in Li et al. (2007 and references therein). Development of Laurentia during this time period based on Whitmeyer and Karlstrom (2007). Early Cambrian rifting of the Precordillera micro-continent from Laurentia based on Thomas and Astini (1996). Neoproterozoic-Cambrian assembly of Gondwana following breakup of Rodinia largely based on Powell et al. (1993) and Dalziel (1997).

South America and Africa from the Proterozoic continental blocks of Rio de La Plata, Amazon, Kalahari, Congo, San Francisco, and West Africa. This evolutionary growth and assembly of smaller continental fragments into present-day continents is a critical earth systems concept and will be further addressed in the "heuristic Wilson Cycle" section below.

The breakup of supercontinents is also a diachronous process. Breakup of Rodinia began along the west coast of Laurentia (ca. 780–685 Ma), 200–150 million years prior to successful breakup of Rodinia along the east coast of Laurentia (ca. 600–535 Ma; Hatcher, 1989; Powell et al., 1993; Hatcher et al., 2004; Thomas, 2006), as shown in the closing frames of Animation 3. The same is true for the breakup of Pangaea: the rifting of North America and Africa/Eurasia opened the northern Atlantic Ocean ~60 million years before the rifting of South America and Africa opened the southern Atlantic (Dietz and Holden, 1970; Scotese and Sager, 1988). These "details" of global tectonics are more than just complications of existing simple models. The use of interactive animations allows students to appreciate the subtleties of global tectonic movements and finish with a better understanding of subcrustal convection and plate movement on the Earth's three-dimensional surface. In addition, the evolving and cycling supercontinent system helps reinforce the concept of the gradual evolution of earth systems at geologic (i.e., slow!) rates throughout 4.5 billion years.

Modern Heuristic Wilson Cycle

When Wilson (1966) asked "Did the Atlantic Close and then Re-Open" he provoked the idea that ocean basins have a life history—a recognizable beginning, ending, and rebirth. Initially, Wilson was mainly concerned with Appalachian mountain building (closing of the Iapetus ocean) followed by subsequent rifting (opening of the Atlantic Ocean; see Animation 1). This original presentation of the "Wilson Cycle" concept was out of phase with subsequent depictions of "Wilson Cycles" that began with the opening of an ocean basin. For example, Dietz (1972) illustrated one and one-half Wilson Cycles (opening and closing of the Iapetus, followed by opening of the Atlantic). These early models were revolutionary in their introduction of tectonic cycles and ultimately led to more recent models for the assembly and breakup of supercontinents like Pangaea (Scotese and Sager, 1988) and Rodinia (Li et al., 2007).

The models of Wilson (1966) and Dietz (1972) are location specific (eastern Laurentia/North America) and, in part, historically dated, but many of the intrinsic ideas are still relevant and can be effectively applied within a modern Earth systems context. We have modified and expanded on these original Wilson Cycle concepts to produce a generalized Wilson Cycle (Fig. 5) that can serve as a globally applicable heuristic model. Such a model should equate a recognizable sequence of major tectonic events that occur throughout the lifespan of an ocean basin to typical conditions under which igneous, sedimentary, and metamorphic rocks occur. For example, a heuristic Wilson Cycle should explain the variety of pressure/temperature (P/T) conditions under which metamorphic rocks form: low P/T, HP/LT, high P/T, etc., as well as the range of depositional environments for sedimentary rocks, and the sources for compositional differences of igneous rocks. An important corollary of this is that ambient P/T conditions recorded in metamorphic rocks are only preserved by rapid exhumation from tectonic and/or climatic processes.

The detailed, nine-stage Wilson Cycle depicted in Figure 5 (Fichter, 1999a; Fichter and Pyle, 2007) incorporates major tectonic events in the context of the lifespan of an ocean basin (full Wilson Cycle). It begins with one hypothetical supercontinent and ends with another and illustrates rifting processes, ophiolite formation, island arc orogenesis, arc-continent collisions, cordilleran-type orogenies, and continent-continent collisions. Climate-driven erosion of sediments, followed by deposition in grabens and passive margin environments and lithification as sedimentary rocks, is illustrated in the extensional stages (Figs. 5B–5D). Metamorphism of existing rocks is apparent in the collisional environments of Figures 5E–5G. The formation of igneous rocks is apparent in many of the stages as decompression melting (Figs. 5B–5D) and as melting induced by dewatering of subducting slabs (Figs. 5E–5G).

The heuristic Wilson Cycle also contains fundamental evolutionary components: continents enlarge and new juvenile crust (i.e., igneous rocks) is generated through accretionary events (Windley, 1995; Whitmeyer and Karlstrom, 2007). For example, as compared with the stage A continent (Fig. 5A), the stage I continent (Fig. 5I) is significantly larger and contains more intermediate to felsic igneous rock. This results from the formation of a volcanic arc that accretes to the Westcontinent during the first closing phase (Figs. 5E–5F), and Cordilleran plutonism and metamorphism that takes place on the margin of the Eastcontinent during the second closing phase of the model (Figs. 5G–5H). This sequence reflects our current understanding that new intermediate and felsic continental igneous rock is generated with each subduction zone, and continents thus grow with time.

The multistage Wilson Cycle equates time-dependent tectonic processes with characteristic rock-forming environments, and thus facilitates the integration of mineralogy, petrology, passive margin stratigraphy and deformation with tectonics in a full earth system. Through the use of these cross sections in an inquiry-based education setting, students should readily grasp the interconnectedness of tectonic environment with rock type. From this point, it is only a small step to the realization that if tectonic environments and continents evolve with (geologic) time, then rocks and rock types must also evolve. At this point, it becomes clear that the traditional, closed-loop rock cycle diagram is conceptually flawed—even for the beginning earth science student.

Tectonic Rock Cycle

The simplest model we have of earth processes is the circular rock cycle (Fig. 6). It summarizes a core concept of geology: all rocks are related to each other and can be transformed from one to the other. The cycle is the most theoretically abstract description of these rock relationships: it incorporates or is expandable to all rock processes, but does not necessarily specify or justify them. It also suggests the pathways by which one rock can transform into another, but does not explicate the necessary conditions under which these transformations take place. The simplicity of the circular rock cycle provides a framework for rock genesis that can be easily understood by most students. However, the traditional circular rock cycle fails to incorporate fundamental feedback relationships between tectonics, climate, and rock genesis.

The circular rock cycle also implies that rocks cycle endlessly from one to the other, with no evolutionary change through time. Thus, it reflects the nineteenth century uniformitarian school of thinking, captured best by James Hutton (1788), when he said the Earth has "no vestige of a beginning, and no prospect of an end." Contrast that with the heuristic Wilson Cycle described above, wherein continents grow with time, largely through the generation of intermediate and felsic igneous rocks. N.L. Bowen (1912) determined the fractionation process by which felsic igneous rocks were generated from a more mafic parent, and extrapolation of that process suggests that the composition of igneous rock suites must have evolved through geologic time. Igneous rock evolution is supported by less evolved igneous rock suites, such as Archean greenstone belts and TTG (tonolite, trondhjemite, and granodiorite) suites and Proterozoic AMCG (anorthosite, mangerite, charnokite, and granite)

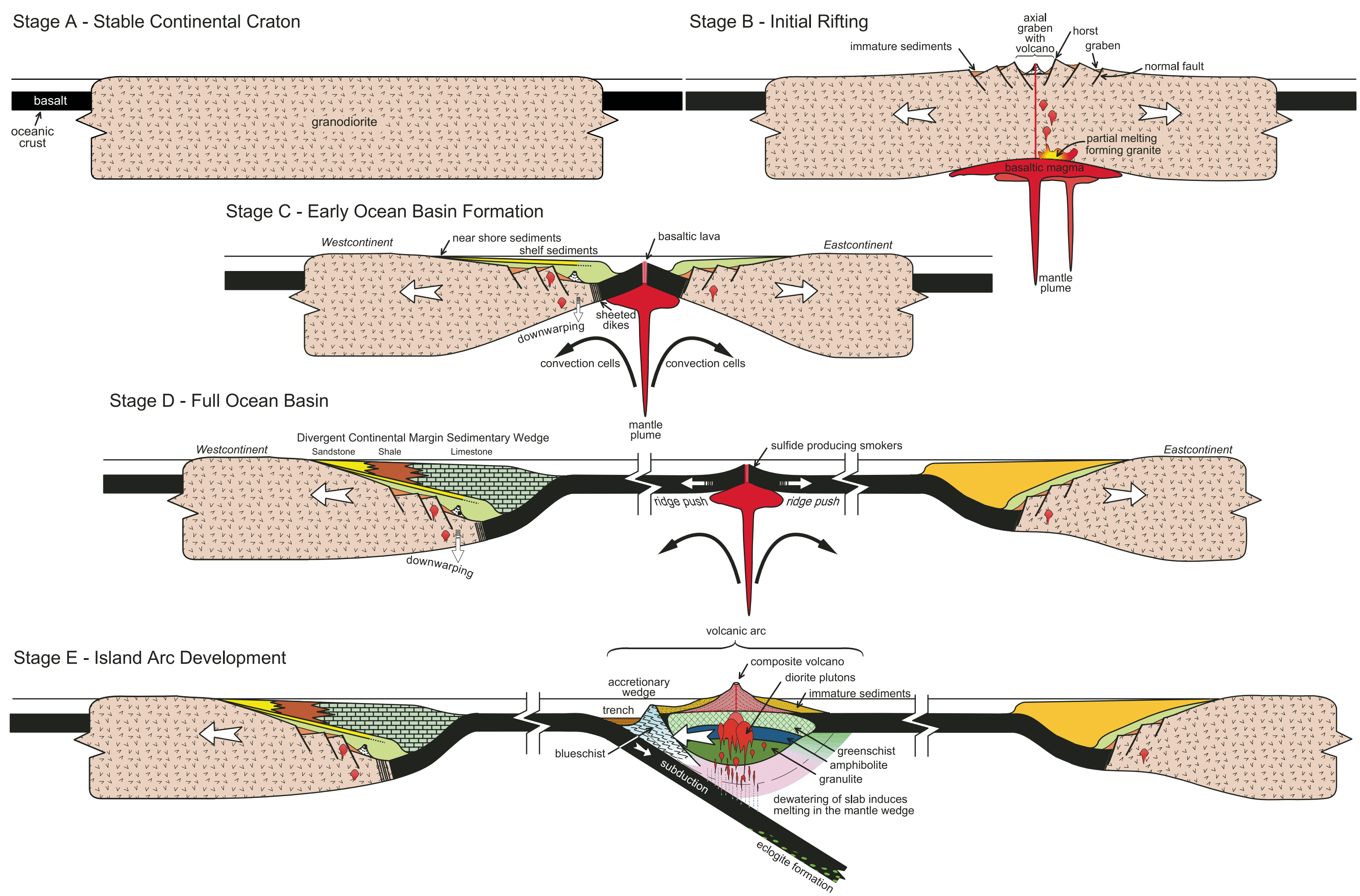


Figure 5 (*on this and following page*) **A nine-stage, heuristic Wilson Cycle, encompassing the life cycle of an ocean basin: Stage A—Stable Continental Craton starting point; Stage B—Initial Rifting phase of the continent from mantle plume(s); Stage C—Early Ocean Basin Formation, the rift to drift phase; Stage D—Full Ocean Basin, with divergent continental margins (DCM) on both continental fragments; Stage E—Island Arc Development, following initiation of a subduction zone, polarity could be either direction; Stage F—Arc-Continent Collision, first collisional event with shrinking of ocean basin; Stage G—Cordillera Mountain Building, continental arc develops above subduction zone under Eastcontinent; Stage H—Continent-Continent Collision, full closure of ocean basin; Stage I—Peneplained Continent, erosion of mountains to stable craton; after Fichter (1999a) and Fichter and Pyle (2007). Cross sections are reprinted with permission from Science Kit, LLC ©2007.**

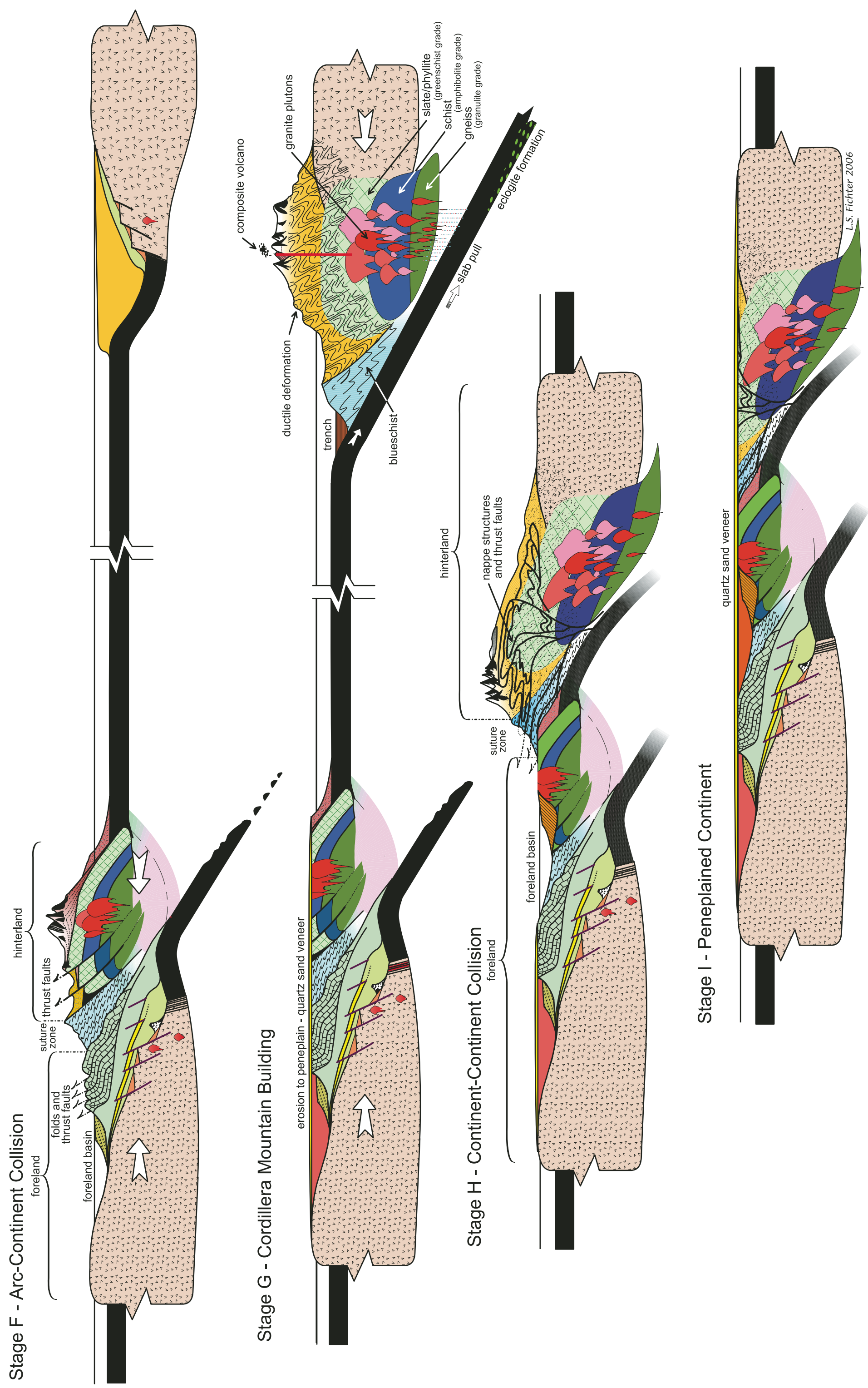


Figure 5 (*continued*).

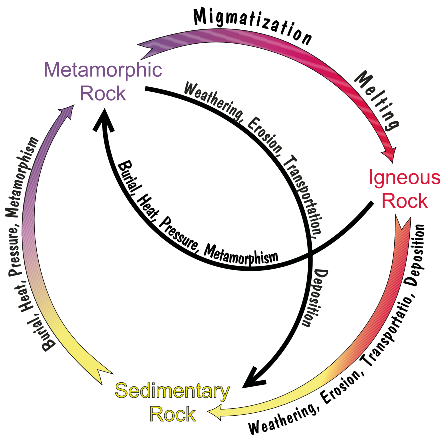


Figure 6. A simple, circular rock cycle, as presented in many introductory geology texts.

suites that are not produced in modern tectonic cycles (Barker, 1979; Windley, 1995; Frost et al., 2006). In contrast, S-type, highly-aluminous (and highly fractionated) granites are commonly produced today through melting of continental crust, but they are absent from Archean and most Proterozoic crust (Pitcher, 1979; Atherton and Tarney, 1979; Windley, 1995). Thus, field evidence suggests that igneous rock associations have evolved through time, an important concept that is missing in the closed loop of the circular rock cycle.

The Tectonic Rock Cycle is a more complex modification of the traditional, circular rock cycle that incorporates rock evolution through time (Fichter, 1996, 1999b; Fig. 7). In Figure 7, we see in one diagram a flow chart of most of the processes that lead to the evolution of the physical earth. The path forms a question-mark shape, and it does not cycle back on itself completely. Instead, beginning with a mafic/ultramafic parent rock, earth processes fractionate this material over and over, each time producing a rock whose composition gets ever lower on Bowen's Reaction Series (Bowen, 1912). Even sedimentary processes fractionate the rock's chemistry. Observe that the sedimentary rocks in the yellow box, when metamorphosed (heated) to the melting state, result in an igneous rock low on the reaction series. However, what is more important is that each stage of the Tectonic Rock Cycle relates directly with one or more stages in the heuristic Wilson Cycle (Fig. 5). Thus, we have two interconnected heuristic models, often left unconnected in introductory courses—a tectonic model (heuristic Wilson Cycle) linked stage for stage with the Tectonic Rock Cycle (Fig. 7).

Educational Applications and Inquiry

How does one systematically inquire about the Earth? Fundamentally, geology is the study of (a) *materials* (such as rocks, minerals, water, etc.), (b) *space* (i.e., where the materials are found or how they are distributed), and (c) *time* (i.e., how materials and their distributions have changed and evolved). An important consideration in earth inquiries is that students should create "by [their] own effort an independent assemblage of truth," a point made by one of the fathers of American geology, T.C. Chamberlin (1897, p. 848). What becomes apparent early in any earth inquiry is that questions are often based on incomplete information about complex, interactive, and (ultimately) uncontrollable events, and thus, these questions defy explanation through any single pathway of inquiry (Ault, 1998; Frodeman, 1995). Inquiries in the earth sciences are not necessarily about making generalizable statements that go beyond a setting. They can, instead, consist of describing an event that represents a setting and then comparing descriptions for different settings (Ault, 1998). The challenge is to frame these questions in terms of material, space, and time, and then facilitate larger and longer term understandings by promoting a broader significance. Geology as a science is dependent on time and place (Toulmin, 1990), and earth inquiries are fundamentally place bound. Only when considered as components of an interdependent system can one integrate inquiries into topics, such as tectonic cycles and rock genesis, across locations and time (Kitts, 1977).

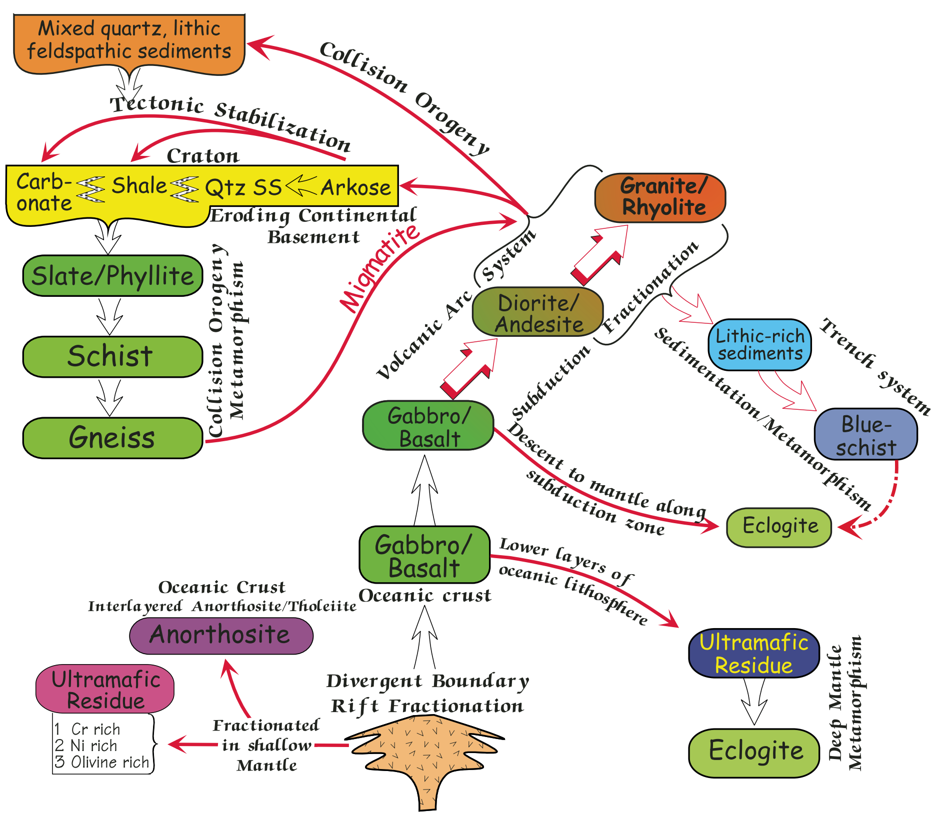


Figure 7. Tectonic Rock Cycle (after Fichter, 1996, 1999b), which illustrates the interconnected pathways between rock types related to their genesis in a particular tectonic setting. A divergent boundary (Fig. 5, stages B–D) produces basalt and gabbro, leaving behind ultramafic residue in the mantle. Initiation of a volcanic arc system produces diorite/andesite in island arc settings (Fig. 5, stage E) and granite/rhyolite in continental arc settings (Fig. 5, stage G). Subduction and metamorphism of oceanic crust and lithic-rich sediments produce blueschists and eclogites (Fig. 5, stages E and G). Mountain building along continental margins thickens the crust and produces Barrovian-style metamorphism of felsic sedimentary rocks, yielding slates, schists, and gneisses (Fig. 5, stages G–H). Tectonic stabilization enables extensive erosion of mountains that produces arkose, quartz sandstone, and shales and carbonates in shallow seas (Fig. 5, stage I).

Supercontinent Cycles and Diachroneity as Focal Points for Inquiry

We highlight two important concepts that are lacking from many depictions of plate tectonics in introductory earth science texts: (1) the cyclical, recurring nature of supercontinent assembly and breakup (e.g., there are more supercontinents than just Pangaea), and (2) the diachronous assembly of continental blocks into a supercontinent. Our approach is to address these instructional deficiencies with animations of historical and modern supercontinent cycle concepts. A simple animation of Wilson's (1966) original map view of closing and reopening the Atlantic Ocean (Animation 1) can be compared with a modern interpretation of the relative movements of major continents (Laurentia, Gondwana, and Baltica) and microcontinents (Avalonia and Precordillera) throughout the Paleozoic that preceded the assembly of Pangaea (Animation 2). By comparing and contrasting these two animations, we find that students intuitively get a feel for the limitations of simple models of plate tectonics, as compared with modern tectonic cycles that consider geometrical implications and constraints of 3D plate motion.

The incorporation of the assembly and breakup of the ca. 900-Ma Rodinia supercontinent (Animation 3) into the standard plate tectonics curriculum encourages students to appreciate that there were predecessor supercontinents to Pangaea. Students should logically deduce that supercontinent assembly is cyclic and make the connection that we are currently within a transitional period between Pangaea and some future supercontinent. The Rodinia animation also demonstrates that supercontinents assemble and break apart in stages. This can be further reinforced by a comparison with the Paleozoic Laurentia-Gondwana animation (Animation 2), where the smaller supercontinent of Gondwana forms in the early Paleozoic and is separated from Laurentia by the Iapetus ocean throughout the Paleozoic. Closure of the Iapetus ocean and final assembly of Pangaea occurs at the end of the Paleozoic, at least 200 million years after early assembly of Africa, South America, Antarctica, and India as Gondwana. Thus, the early Paleozoic assembly of Gondwana can be considered the first phase in the assembly of Pangaea, followed in the later Paleozoic by the accretion of Laurentia and Baltica to the Gondwanan core.

Another important feature of supercontinent cycles is that ancient rocks and crustal components are reused (and often reworked) in a variety of tectonic settings through geologic time. Rocks that formed in Archean island arcs (e.g., TTG suites) later assembled into small protocontinents as early continental crust (Windley, 1995). In the late Archean to early Proterozoic, many of these protocontinents assembled to form the cores (shield regions) of larger continents (such as Laurentia; Whitmeyer and Karlstrom, 2007). In turn, these larger continents collided to form Rodinia (Li et al., 2007), and later Pangaea (Scotese and Sager, 1988), while continually enlarging and modifying their margins. Thus, rocks created as juvenile, igneous arc material ultimately become ancient, stable metamorphic rocks in the centers of present-day continents. Through this process, rocks can spend millions of years at any of the stages of the heuristic Wilson Cycle (Fig. 5) or at any location on the Tectonic Rock Cycle (Fig. 7). By focusing on the evolution of rocks in a variety of tectonic settings through time, the concepts of slow rates of geologic change through billions of years of the Earth's history are reinforced in an integrated systems context.

No Rock Is Accidental

No rock is accidental, and every rock has a geologic story to tell. However, typically the rocks we use as teaching examples, especially in primary and middle schools, are the ones that are readily available in teaching collections. These collections commonly leave out rocks that are abundant on Earth but not easily accessible. For example, ocean lithospheric rocks (including pillow basalts, peridotites, and serpentinites) cover ~70% of the Earth's surface but are often ignored because of their relative inaccessibility. However, they are abundant and important for a holistic understanding of how the earth system works.

Part of our goal in this paper is to find a rational basis for deciding what should be taught, and what should be let go. As earth scientists, we work toward simple, ideal models, as is the case in classical physics, where principles can be clearly laid out and explored with mathematical precision, independent of the messiness of the real world. The problem is, the Earth is not simple, or neat, and our job as teachers is to help students grasp the world as it really is, with all its complexity. Geology does have its simple, ideal models—the circular rock cycle, for example, where rocks are transformed one into the other. However, the circular rock cycle is rarely related to generative tectonic conditions. This is not surprising, since plate tectonics is a subject with its own history, specialized techniques (e.g., gravity, magnetic, seismic studies), and vocabulary that largely arose out of oceanography and geophysics, not out of geology. The integrated Wilson Cycles (Fig. 5) and Tectonic Rock Cycles (Fig. 7) we present provide a rationale for choosing which rocks are important to teach by placing them in an earth systems framework where the relationships are more important than the rocks themselves.

The models are heuristic; we use the term "heuristic" to mean a simplification that reduces or limits inherently complex situations to their basic components and explicates the basic ways those components relate to each other. Once the students come to understand how the components relate to each other, they can move on to more real and likely more complex situations and analyze them with the heuristic tool kit they have developed. Through an understanding of how these systems work, students can move beyond memorization to actually thinking about how the concepts can be applied to new situations. Thus, study of the Earth becomes deductive and predictive, not just inductive. Students can deductively predict what kinds of rocks will be generated under specific tectonic situations and, more importantly, use rocks to determine ancient tectonic environments and processes. Students not only learn about the Earth, they develop a scientific strategy for investigating the Earth.

Visualization-Focused Inquiry

Our use of animations to address the spatial and temporal aspects of tectonic systems prompts the question: what design features should be incorporated to ensure that the intended learning task is, in fact, accomplished? Visualizations come in many forms—graphics, illustrations, charts, and photographs. They contain a complexity that derives from fidelity to the reality or concepts that they attempt to represent, with a level of abstraction associated with their intended purpose. Holliday (1995) described a range of visualization types, including those tied directly to textbooks, that (1) have affective value to students (spark interest, general appeal to students, promote relevance), (2) promote positive learning behaviors (focusing attention, facilitating remembering, rehearsal, and reinforcement), or (3) have specific cognitive functions (summarization, compare/contrast, portrayal of spatial relationships, and understanding of scientific conventions). This approach equates specific features of visualizations with appropriate classroom applications, indicating that images and animations need to be tailored to a specific educational objective.

Further framing the categorization of visualizations, Winn (1989) defined graphics used in instruction by the (a) *methods*, or those strategies that activate specific cognitive processes, (b) *outcomes*, or the tasks that are expected of learners, and (c) the *conditions*, or the context and circumstances under which the instruction utilizing the graphics is to take place, inclusive of learning modalities and aptitudes of the learners. Within the range of *methods*, Winn describes grouping of concepts, labels and symbols, convention-based graphs, sequential representations, hierarchies, and comparisons as the means to make the abstract more concrete. For our purposes, we wish to move learning away from traditional representations of the rock cycle, which are descriptive but abstract, and use the Wilson Cycle to tie rock-forming processes to particular places and times, adding predictive value based on plate tectonic theory. In relation to the *outcomes*, or task expected of learners, one needs to distinguish between the identification of concepts, classification of relevant attributes of objects, sequences and patterns of elements, problem-solving information, and mental modeling inputs. We desire for learners to understand that continents grow over time and that an evolutionary perspective on rock formation provides more learning value than abstract descriptions alone can provide. With respect to the *conditions*, Winn describes the use of graphics in the supplantation of learners' prior or preexisting conceptual frameworks, the activation and enhancement of learners' skills, and the formal modeling of implicit and explicit relationships. Considering the predictive value of the Wilson Cycle, desired skill activations and enhancements include the generation of relevant questions, such as inquiring whether plates always separate, or must they sometimes converge. Collectively, these elements help to frame classification taxonomies for both the description and application of science visualizations as a function of instruction.

Recent research on basic characteristics of illustrations in biology textbooks (Bowen and Roth, 2002; Pozzier and Roth, 2003) classified visualizations on a scale reflective of their concrete or abstract natures. These classifications lead to taxonomies of visualizations, such as those in information design (Hansen, 1999; Wileman, 1980), which provide information not only on concrete-abstract levels of representation, but also on specific indicators of audience response, perceptions of informativeness of specific types of visualizations, and evaluative frameworks for determining the impact of visualizations on learning. Through their descriptions and use of visual analogies, Issing et al. (1989) established the basis for the independence of visualizations apart from text materials in mediating the learning process, such that visualizations can have a direct path to learning tasks in a context in which the text becomes adjunct to the visualization. Animations employed in this context do not readily support, nor are they intended to support, dense verbal components or explanations—the animation is the intended voice. As such, the tectonic animations and Wilson Cycle and Tectonic Rock Cycle diagrams presented in this paper can be most effectively applied within an inquiry-driven educational environment. Following minimal introduction, students explore the animations and diagrams and their implications prior to verbal discussion. Thus, the visualizations are primary, and the verbal component is secondary.

The Effectiveness of Visualizations in Education

In considering the relative quality of visualizations in instructional settings, Weidenmann (1989) offered a cognitive model of evaluating visualizations in their own right, rather than strictly in support of text materials, considering both text and visual materials in light of the expectations on learners as well as the learners' perceptions of the task to which the materials (text or visual) are related. He defines four key elements—the Learner, the Task, the Text material (Mt), and the Picture material (Mp)—as context-defining instructional variables in which both text and visualizations are considered simultaneously and independently. Weidenmann argues that most people assume that since visualizations are a simple medium, then the picture processing should only require (falsely) minimal cognitive effort. Thus, pictures tend to receive only superficial processing. To gauge the level of processing, one must consider not only how the picture is to be used by the learner, but also the learner's perception of the task to which the picture material has been assigned. Three positive interactions are required for a visualization to have a desired effect (Fig. 8):

(a) M_p/T—the function and relevance of the picture to the task must be clear and relevant, such that the picture can define the task;
(b) M_p/M_t—the text and picture materials must exhibit a mutual support and relevance for interpretation, clarification, and explanation; and
(c) M_p/L—there must be a facilitative role for the picture in terms of attending, understanding, and remembering by the learner.

When both text and pictures are used in the context of engaging student tasks, however, the effect is decidedly positive on student learning (Pyle and Akins-Moffatt, 1999). Our approach uses visualizations to focus on the learning task of grasping three variables simultaneously (X-Y, position, and time), ultimately adding a fourth dimension—lithology. Thus, the task (T) presented to students using these visualizations is to understand the multidimensional reality of both the rock cycle and plate tectonics, as opposed to the more typical disconnected presentation of these topics. In addition, the general mode by which a learner (L) is exposed to such content is through text (M_t), supported by static visuals (i.e., reference pictures and maps).

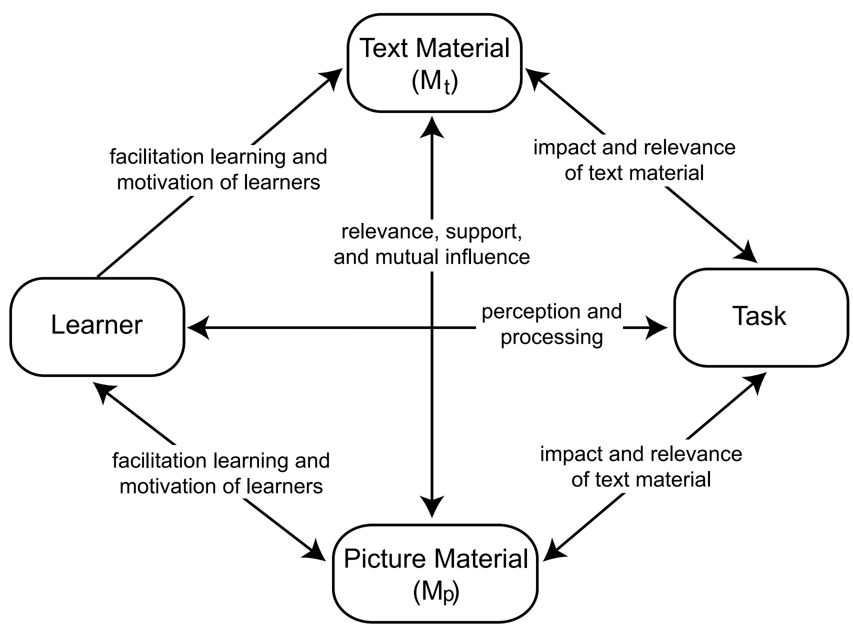


Figure 8. Conceptual diagram of the relationships between learners, pictures, text, and the learning task.

To best represent reality, we focus on visualizations (as M_p) to drive learning, with text serving in an adjunct role. In doing so, it is our belief that the visualizations perform a stronger facilitative role, showing space, time, and lithology in a manner that captures learner attention and encourages investigation beyond just "what" or "where," to include "why" particular rocks form in a particular place and time.

The task that we set for learners is to apply plate tectonic theory as a useful device in understanding the natural world. It is our contention that the standard representations of tectonics and rock cycles in both texts and instruction, particularly in pre-college settings, provides only limited capacity for students to see plate tectonic theory in the same light as biological evolution, with at least predictive value or precision. Students are typically presented with self-limiting maps showing plate positions that provide only two-dimensional information in X-Y frames. These representations are interesting, but they sacrifice the demonstration of interdependent relationships across time. The animations presented in this work provide a three-dimensional framework (X, Y, and time) in a context that yields both predictive and "retrodictive" value as part of the instructional process. Interconnected Wilson Cycle and Tectonic Rock Cycle diagrams make explicit lithologic evolution with time, thus linking petrogenesis to tectonics in a broader Earth system. It is in this manner that supercontinent, Wilson Cycle, and Tectonic Rock Cycles, as presented in this paper, can fully satisfy the requirements of a scientific theory that has staying power with learners.

SUMMARY

If we expect students to understand the relationships between tectonics and petrogenesis over geologic time, we need to employ tools that effectively express these relationship**s**. We suggest that time and effort spent on developing and incorporating tools such as spatial-temporal animations and integrated tectonic rock cycles into earth science curricula should lead to a substantial increase in student understanding of complex earth systems. Ultimately, we as educators must strive for student retention of material beyond a class or semester and subsequent application of the material to outside affairs. It is only when we embrace an integrated systems framework as an educational goal that we should expect to see curricula and instructional materials change. The instructional tools presented in this paper are only the tip of an iceberg that has the potential to give earth science students the encouragement and motivation to discover the intriguing, interconnected pathways of earth systems. The realization that rocks and continents, not just organic life forms, evolve over time can provoke a powerful leap of cognition in a student toward an understanding of the Earth, its history, and its possible futures. The realization that supercontinent cycles have evolved over the past two billion years, and are an integral part of plate tectonic theory, should provoke students to ask the questions: "What will the crust of our planet look like in the future?" and "What are the implications?" It is this level of student-initiated inquiry that we hope to reach as modern, geologically accurate visualizations are developed for the integrated and realistically complex earth system and are used within systems-focused curricula.

ACKNOWLEDGMENTS

This contribution benefited from comments by Tim Wawrzyniec and two anonymous reviewers. Cross sections in Figure 5 are reprinted with permission from Science Kit, LLC ©2007.

REFERENCES CITED

American Association for the Advancement of Science (AAAS), 1993, Benchmarks for science literacy: http://www.project2061.org/publications/bs/online/bolintro.htm.

Assaraf, O., and Orion, N., 2005, Development of system thinking skills in the context of Earth system education: Journal of Research in Science Teaching, v. 42, p. 518–560, doi: 10.1002/tea.20061.

Atherton, M.P., and Tarney, J., 1979, Origin of granite batholiths: Geochemical evidence: Kent, Shiva Publications, 148 p.

Atwater, T.M., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536, doi: 10.1130/0016-7606(1970)81[3513:IOPTFT]2.0.CO;2.

Ault, C.R., Jr., 1998, Criteria of excellence for geological inquiry: The necessity of ambiguity: Journal of Research in Science Teaching, v. 35, p. 189–212, doi: 10.1002/(SICI)1098-2736(199802)35:2<189::AID-TEA8>3.0.CO;2-O.

Barker, F., 1979, Trondhjemites, dacites, and related rocks: Amsterdam, Elsevier, 414 p.

Bird, J.M., and Dewey, J.F., 1970, Lithosphere plate: Continental margin tectonics and the evolution of the Appalachian orogen: Geological Society of America Bulletin, v. 81, p. 1031–1060, doi: 10.1130/0016-7606(1970)81[1031:LPMTAT]2.0.CO;2.

Bowen, G.M., and Roth, W.-M., 2002, Why students may not learn to interpret scientific inscriptions: Research in Science Education, v. 32, p. 303–327, doi: 10.1023/A:1020833231966.

Bowen, N.L., 1912, The order of crystallization in igneous rocks: The Journal of Geology, v. 20, p. 457–468.

Brice, J., 1962, Workbook in Historical Geology: William C. Brown Company Publishers, 174 p.

Carnot, S., 1824, Réflexions sur la puissance motrice du feu et sur les machines propres a developper cette puissance: Paris, Bachelier, 118 p.

Chamberlin, T.C., 1897, The method of multiple working hypotheses: The Journal of Geology, v. 5, p. 837–848.

Chambliss, M.J., and Calfee, R.C., 1989, Designing science textbooks to enhance student understanding: Educational Psychologist, v. 24, p. 307–322, doi: 10.1207/s15326985ep2403_5.

Condie, K.C., 1997, Plate tectonics and crustal evolution: Oxford, Butterworth Heinemann, 282 p.

Dalziel, I.W.D., 1991, Pacific margins of Laurentia and East Antarctica-Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent: Geology, v. 19, p. 598–601, doi: 10.1130/0091-7613(1991)019<0598:PMOLAE>2.3.CO;2.

Dalziel, I.W.D., 1995, Earth before Pangea: Scientific American, v. 280, p. 58–63.

Dalziel, I.W.D., 1997, Overview: Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculations: Geological Society of America Bulletin, v. 109, p. 16–42, doi: 10.1130/0016-7606(1997)109<0016:ONPGAT>2.3.CO;2.

Dennis, A.J., and Wright, J.E., 1997, The Carolina terrane in northwestern South Carolina, U.S.A.: Late Precambrian-Cambrian deformation and metamorphism in a peri-Gondwanan oceanic arc: Tectonics, v. 16, p. 460–473, doi: 10.1029/97TC00449.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the new global tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dickinson, W.R., 1971, Plate tectonic models of geosynclines: Earth and Planetary Science Letters, v. 10, p. 165–174, doi: 10.1016/0012-821X(71)90002-1.

Dickinson, W.R., and Sucek, C.A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin, v. 63, p. 2164–2182.

Dietz, R.S., 1972, Geosynclines, mountains, and continent-building, *in* Wilson, J.T., Continents adrift and continents aground: Readings from Scientific American: W.H. Freeman and Company, p. 103–111.

Dietz, R.S., and Holden, J.C., 1970, Reconstruction of Pangaea: Breakup and dispersion of continents, Permian to present: Journal of Geophysical Research, v. 75, p. 295–312.

Earth System Science Committee, 1986, Earth system science: A program for global change: Washington, D.C., National Aeronautics and Space Administration.

Ernst, W.G., 1975, Systematics of large-scale tectonics and age progression in Alpine and circum-Pacific blueschist belts: Tectonophysics, v. 17, p. 255–272.

Fichter, L.S., 1996, Tectonic rock cycles: Journal of Geoscience Education, v. 44, p. 134–148.

Fichter, L.S., 1999a, The Wilson cycle: http://csmres.jmu.edu/geollab/Fichter/Wilson/Wilson.html

Fichter, L.S., 1999b, Tectonic rock cycles: http://csmres.jmu.edu/geollab/Fichter/Wilson/PTRC.html

Fichter, L.S., and Pyle, E.J., (2007). Wilson Cycle poster: Tonowanda, New York, Science Kit and Boreal Laboratories.

Frodeman, R., 1995, Geological reasoning: Geology as an interpretive and historical science: Geological Society of America Bulletin, v. 107, p. 960–968, doi: 10.1130/0016-7606(1995)107<0960:GRGAAI>2.3.CO;2.

Frost, C.D., Frost, B.R., Kirkwood, R., and Chamberlain, K.R., 2006, The tonalite-trondhjemite-granodiorite (TTG) to granodiorite-granite (GG) transition in the late Archean plutonic rocks of the central Wyoming Province: Canadian Journal of Earth Sciences, v. 43, p. 1419–1444, doi: 10.1139/E06-082.

Gilluly, J., 1971, Plate tectonics and magmatic evolution: Geological Society of America Bulletin, v. 82, p. 2383–2396, doi: 10.1130/0016-7606(1971)82[2383:PTAME]2.0.CO;2.

Hamilton, W.B., 1969, Mesozoic California and underflow of the Pacific mantle: Geological Society of America Bulletin, v. 80, p. 2409–2430, doi: 10.1130/0016-7606(1969)80[2409:MCATUO]2.0.CO;2.

Hansen, Y.M., 1999, Visualization for thinking, planning, and problem solving, *in* Jacobson, R., ed., Information design: Cambridge, Massachusetts Institute of Technology Press.

Hatcher, R.D. Jr., 1972, Developmental model for the Southern Appalachians: Geological Society of America Bulletin, v. 83, p. 2735–2760, doi: 10.1130/0016-7606(1972)83[2735:DMFTSA]2.0.CO;2.

Hatcher, R.D. Jr., 1989, Tectonic synthesis of the US Appalachians, *in* Hatcher, R.D. Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 511–535.

Hatcher, R.D. Jr., Thomas, W.A., and Viele, G.W., 1989, The geology of North America: The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, 767 p.

Hatcher, R.D., Jr., Bream, B.R., Miller, C.F., Eckert, J.O., Jr., Fullagar, P.D., and Carrigan, C.W., 2004. Paleozoic structure of internal basement massifs, southern Appalachian Blue Ridge, incorporating new geochronologic, Nd and Sr isotopic, and geochemical data, *in* Tollo, R.P., Corriveau, L., McLelland, J., and Bartholomew, M.J., eds., Proterozoic tectonic evolution of the Grenville orogen in North America: Boulder, Colorado, Geological Society of America Memoir 197, p. 525–547.

Hmelo, C.E., Holton, D.L., and Kolodner, J.L., 2000, Designing learning about complex systems: The Journal of the Learning Science, v. 9, p. 247–298, doi: 10.1207/S15327809JLS0903_2.

Hoffman, M., and Barstow, D., 2007, Revolutionizing Earth system science education for the 21st century, report and recommendations from a 50-state analysis of Earth science education standards: Cambridge, Massachusetts, TERC.

Hoffman, P.F., 1988, United plates of America, the birth of a craton; early Proterozoic assembly and growth of Laurentia: Annual Review of Earth and Planetary Sciences, v. 16, p. 543–603, doi: 10.1146/annurev.ea.16.050188.002551.

Hoffman, P.F., 1991, Did the breakout of Laurentia turn Gondwanaland inside-out?: Science, v. 252, p. 1409–1411, doi: 10.1126/science.252.5011.1409.

Hoffman, P.F., 1997, Tectonic genealogy of North America, *in* Van der Pluijm, B.A., and Marhak, S., eds., Earth structure, and introduction to structural geology and tectonics: New York, McGraw Hill, p. 459–464.

Holliday, W., 1995, A guide to assessing, selecting, and using science textbook visuals: Research Matters—To the science teacher: National Science Teachers Association.

Holmes, A., 1944, The machinery of continental drift: The search for a mechanism, *in* Holmes, A., Principles of physical geology: London, p. 505–509.

Holt, Rinehart, and Winston, 2002, Modern Earth Science, Austin, Texas.

Hutton, J., 1788, Theory of the Earth or an Investigation of the Laws observable in the Composition, Dissolution, and Restoration of Land upon the Globe): Royal Society of Edinburgh Transactions, v. 1.

Irwin, W.P., 1972, Terranes of the western Paleozoic and Triassic belt in the southern Klamath Mountains, California: U.S. Geological Survey Professional Paper 800-C, p. C103–C111.

Issing, L.J., Hanneman, J., and Haack, J., 1989, Visualization by pictorial analogies in understanding expository text, *in* Mandl, H., and Levin, J., eds., Knowledge acquisition from text and pictures: Elsevier Science, p. 195–214.

Kali, Y., Orion, N., and Elon, B., 2003, The effect of knowledge integration activities on students' perception of the Earth's crust as a cyclic system: Journal of Research in Science Teaching, v. 40, p. 545–565, doi: 10.1002/tea.10096.

Karlstrom, K.E., Harlan, S.S., Williams, M.L., McLelland, J., Geissman, J.W., and Ahall, K.I., 1999, Refining Rodinia: Geologic evidence for the Australia-western U.S. connection for the Proterozoic: GSA Today, v. 9, no. 10, p. 1–7.

Kay, M., 1952, North American geosynclines: Geological Society of America Memoir 48, 143 p.

Keppie, J.D., Nance, R.D., Murphy, J.B., and Dostal, J., 2003, Tethyan, Mediterrannean, and Pacific analogues for the Neoproterozoic-Paleozoic birth and development of peri-Gondwanan terranes and their transfer to Laurentia and Laurussia: Tectonophysics, v. 365, p. 195–219, doi: 10.1016/S0040-1951(03)00037-4.

Kesidou, S., and Roseman, J.E., 2002, How well do middle school science programs measure up? Findings from Project 2061's curriculum review: Journal of Research Teaching, v. 39, p. 522–549, doi: 10.1002/tea.10035.

Kitts, D.B., 1977, The structure of geology: Dallas, Texas, Southern Methodist University.

Lawver, L.A., Gahagan, L.M., and Dalziel, I.W.D., 1998, A tight fit—Early Mesozoic Gondwana, A plate reconstruction perspective, *in* Motoyoshi, Y., and Shiraishi, K., eds., Origin and evolution of continents: Proceedings of the International Symposium "Origin and Evolution of Continents": Tokyo, National Institute of Polar Research Memoirs, p. 214–229.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub, D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., and Thrane, K., 2007, Assembly, configuration, and break-up history of Rodinia: A synthesis: Precambrian Research, doi: 10.1016/j.precamres.2007.04.021.

McGraw-Hill, 2002, Earth Science, Columbus, Ohio.

McKenzie, D.P., and Parker, R.L., 1967, The north Pacific: An example of tectonics on a sphere: Nature, v. 216, p. 1276–1280, doi: 10.1038/2161276a0.

McKerrow, W.S., and Scotese, C.R., 1990, Palaeozoic biogeography and paleogeography: Geological Society of London, Memoir 12, 435 p.

Meert, J.G., and Torsvik, T.H., 2003, The making and unmaking of a supercontinent: Rodinia revisited: Tectonophysics, v. 375, p. 261–288, doi: 10.1016/S0040-1951(03)00342-1.

Moores, E.M., 1991, The Southwest U.S.-East Antarctica (SWEAT) connection: A hypothesis: Geology, v. 19, p. 425–428, doi: 10.1130/0091-7613(1991)019<0425:SUSEAS>2.3.CO;2.

Morgan, W.J., 1968, Rises, trenches, great faults, and crustal blocks: Journal of Geophysical Research, v. 73, p. 1959–1982.

Murphy, J.B., Equiluz, L., and Zulauf, G., 2002, Cadomian orogens, peri-Gondwanan correlatives and Laurentia-Baltica connections: Tectonophysics, v. 352, p. 1–9, doi: 10.1016/S0040-1951(02)00186-5.

Nance, N.D., Murphy, J.B., Strachan, R.A., D'Lemos, R.S., and Taylor, G.K., 1991, Late Proterozoic tectonostratigraphic evolution of the Avalonian and Cadomian terranes: Precambrian Geology, v. 53, p. 41–78, doi: 10.1016/0301-9268(91)90005-U.

Oreskes, N., 1999. The rejection of continental drift: Theory and method in American Earth science: New York, Oxford University Press, 432 p.

Oreskes, N., 2001, From continental drift to plate tectonics, *in* Oreskes, N., ed., Plate tectonics: An insider's history of the modern theory of the earth: Boulder, Colorado, Westview Press, p. 3–27.

Pitcher, W.S., 1979, The nature, ascent and emplacement of granitic magmas: Journal of the Geological Society of London, v. 136, p. 627–662.

Powell, C.McA., Li, Z.X., McElhinny, M.W., Meert, J.G., and Park, J.K., 1993, Paleomagnetic constraints on the timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana: Geology, v. 21, p. 889–892, doi: 10.1130/0091-7613(1993)021<0889:PCOTOT>2.3.CO;2.

Pozzier, L.L., and Roth, W.-M., 2003, Prevalence, function, and structure of photographs in high school biology textbooks: Journal of Research in Science Teaching, v. 40, p. 1089–1114, doi: 10.1002/tea.10122.

Press, F., and Siever, R., 1974, Earth: San Francisco, California, W.H. Freeman, 649 p.

Press, F., and Siever, R., 1978, Earth, 2nd edition: San Francisco, California, W.H. Freeman, 649 p.

Pyle, E.J., and Akins-Moffatt, J., 1999, The effects of visually-enhanced instructional environments on students' conceptual development: Electronic Journal of Science Education, v. 3, http://unr.edu/homepage/crowther/ejse/pyle.html.

Roberts, D., 2003, The Scandinavian Caledonides: Event chronology, paleogeographic settings and likely modern analogues: Tectonophysics, v. 365, p. 283–299, doi: 10.1016/S0040-1951(03)00026-X.

Rogers, J.J.W., and Santosh, M., 2002, Configuration of Columbia, a Mesoproterozoic supercontinent: Gondwana Research, v. 5, p. 5–22, doi: 10.1016/S1342-937X(05)70883-2.

Runcorn, S.K., 1955, Paleomagnetism of sediments from the Colorado Plateau: Nature, v. 176, p. 505–506, doi: 10.1038/176505a0.

Runcorn, S.K., 1956, Palaeomagnetic comparisons between Europe and North America: Proceedings of the Geological Association of Canada, v. 8, p. 77–85.

Scotese, C.R., and Sager, W.W., 1988, Mesozoic and Cenozoic plate tectonic reconstructions: Tectonophysics, v. 155, p. 27–48, doi: 10.1016/0040-1951(88)90259-4.

Sears, J.W., and Price, R.A., 2000, New look at the Siberian connection: No SWEAT: Geology, v. 28, p. 423–426, doi: 10.1130/0091-7613(2000)28<423:NLATSC>2.0.CO;2.

Secor, D.T., Samson, S.L., Snoke, A.W., and Palmer, A.R., 1983, Confirmation of the Carolina slate belt as an exotic terrane: Science, v. 221, p. 649–851, doi: 10.1126/science.221.4611.649.

Shufeldt, O.P., 2007, Interactive scientific modeling of an island arc system: Expanding geoscience education [B.S. thesis]: James Madison University, 82 p.

Steffen, W., Sanderson, A., Tyson, P.D., Jager, J., Matson, P.A., Moore, B., III, Oldfield, F., Richardson, K., Schellnhuber, H.J., Turner, B.L., II, and Wasson, R.J., 2004, Global change and the Earth system: A planet under pressure: Springer, 332 p.

Tarbuck, E.J., and Lutgens, F.K., 2005, Earth science: Eleventh edition: Prentice Hall, 752 p.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, p. 4–11, doi: 10.1130/1052-5173(2006)016[4:TIAACM]2.0.CO;2.

Thomas, W.A., and Astini, R.A., 1996, The Argentine Precordillera: A traveler from the Ouachita embayment of North American Laurentia: Science, v. 273, no. 5276, p. 752–756, doi: 10.1126/science.273.5276.752.

Verhoogen, J., Turner, F.J., Weiss, L.E., and Wahrhaftig, C., 1970, The Earth: New York, Holt, Rinehart, and Winston, 694 p.

Wegener, A., 1912, Die Entstehung der Kontinente: Geologische Rundschau, v. 3, p. 276–292, doi: 10.1007/BF02202896.

Weidenmann, B., 1989, When good pictures fail: An information-processing approach to the effect of illustrations, *in* Mandl, H., and Levin, J., eds., Knowledge acquisition from text and pictures: Elsevier Science, p. 157–170.

Whitmeyer, S.J., and Karlstrom, K.E., 2007, Tectonic model for the Proterozoic growth of North America: Geosphere, v. 3, p. 220–259, doi: 10.1130/GES00055.1.

Wileman, R.E., 1980, Visual thinking: New York, Hastings House Publishers.

Williams, H., 1995, Geology of the Appalachian-Caledonian orogen in Canada and Greenland: Ottawa, Geological Survey of Canada, Geology of North America, v. F1, 944 p.

Wilson, J.T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, p. 343–347, doi: 10.1038/207343a0.

Wilson, J.T., 1966, Did the Atlantic Close and Then Re-Open?: Nature, v. 211, p. 676–681, doi: 10.1038/211676a0.

Windley, B.F., 1995, The evolving continents, 3rd edition: Chichester, Wiley, 544 p.

Winn, W., 1989, The design and use of instructional graphics, *in* Mandl, H., and Levin, J., eds., Knowledge acquisition from text and pictures: Elsevier Science, p. 125–144.

Manuscript Received 6 February 2007
Revised Manuscript Received 2 September 2007
Manuscript Accepted 4 September 2007