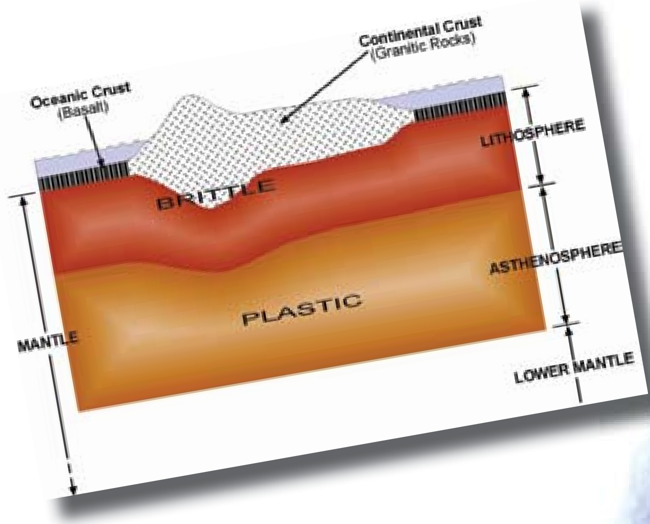
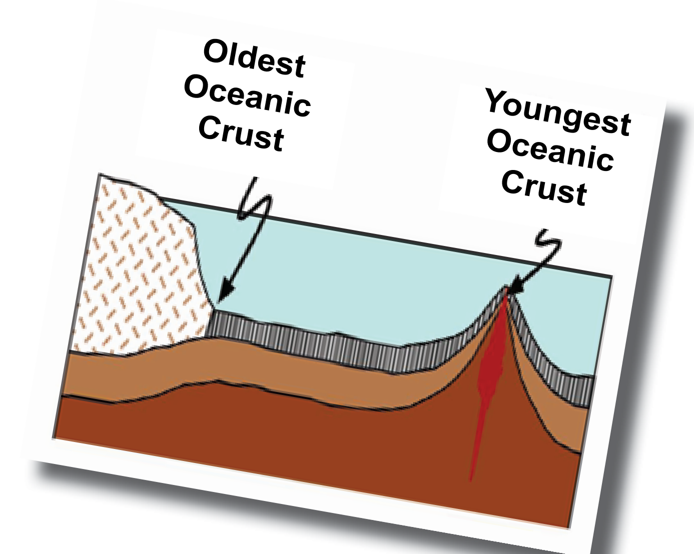
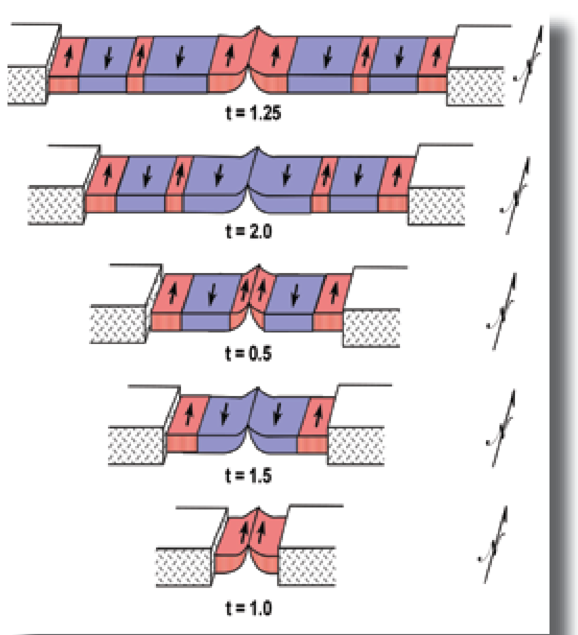
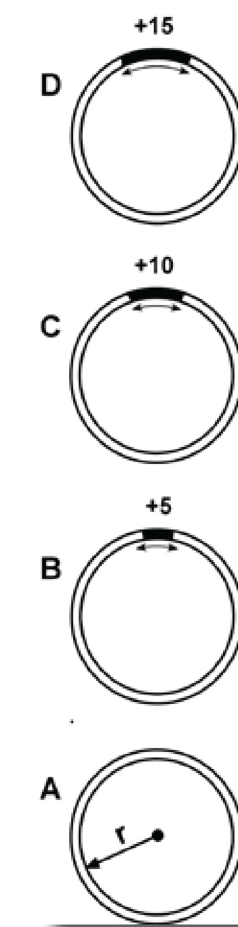
Conceptual Understanding Series for West Virginia Teachers

Plate Tectonics









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Foreword

It is important to acknowledge this work as introductory in nature. It is not, and was never meant to be, an exhaustive examination of the subject. It is intended to be a concise (as concise as a PhD can make anything!) presentation that helps you develop a better understanding of plate tectonics. Why? As a teacher you truly comprehend the importance of knowing more about a subject than the learner. Therefore, it is designed to provide you with what we consider to be the absolute minimal content knowledge required to correctly teach plate tectonics. This does not imply that you must present your students everything you read in this text. It does mean that you will be able to better teach them what you deem and/or the content standards deem important because you will have a richer background than they do.

The first thing you will encounter is the writing style. It is not that of the formal third-person language textbook. Instead, I hope you will become immersed in a first-person narrative constructed from numerous written passages and conversations between myself and Dr. Jack Renton, professor of geology at West Virginia University. You will be served best if you accept the text as an edited transcript that preserves style and tone above formal grammar. For example, embedded movements from present to past to future tense are, in many cases, retained because they are reflective of our discussions. Comments such as "In our opinion..." are intended to clearly inform you that other interpretations may exist. Educationally, such a simple admission should not be overlooked as it pointedly demonstrates that the nature of science remains rooted in scientific argument and debate. Furthermore, comments such as "We don't know..." expose the dynamic nature of the scientific pursuit and a forthright admission that the lack of answers or explanations does not always imply failure. Indeed, such comments may demonstrative clear opportunities for the next generation. Finally, if you are a teacher of science, consider this; if the geology professor doesn't know the answer I think you are on safe grounds telling your students you do not know the answer. Finally, the right hand "side bar" column on each page serves as an opportunistic location for small illustrations, asking and/or answering questions, factoids, and a "running headline" of major ideas.

Every discipline has an issue with terminology and, more often than not, burdens the beginner with excessive nomenclature. This diminishes the will to want to know. The simple and common practice of bolding encourages rote learning by misdirecting the reader away from their responsibility to build conceptual knowledge. We all know that scientists use exact words to concisely and precisely convey ideas. There is nothing wrong with this. In stark contrast, years of experience serving those possessing no, or limited, prior geologic knowledge has shown they "read over" terminology, become confused by its rampant use, manufacture or reinforce misconceptions, and worst of all, abandon the effort. For these reasons, there are places in the text were I have replaced a term with a series of words or even an entire sentence. While some categorize this as "dumbing down," I contend the novice must first be given the chance to understand before they can build meaning. This discussion employs facts, illustrations, statements, and opinions used in his classroom. If this process has embedded minor technical irregularities within the content they are my fault, not Jack's. You will no doubt find other geologists, or internet sources, with different methods of presenting the same material or claiming you need to know more before you can teach it. Do not dwell on it. Instead, recognize and appreciate the relative positions occupied by the expert, you, and your students along the road to learning.

Two overarching metaphors organize the discussion. "Setting the Stage" explores the fundamental laws of geology, the idea of continental drift, and the evolution of scientific ideas required for any meaningful appreciation of plate tectonics as a working and viable scientific theory. The "Road to Plate Tectonics" discusses plate tectonics mechanisms and how the idea was developed from seemingly unrelated discoveries and ideas.

This work has been reviewed by the following West Virginia science educators: Michele Adams, Berkeley County Schools; James Giles, Nicholas County Schools; Robin Anglin, WV State Science Coordinator; Dr. Deb Hemler, Fairmont State University; Ed Berry, Wood County Schools; Sheba Kendig, Braxton County Schools; Mary Sue Burns, Pocahontas County Schools; Kathleen Prusa, Barbour County Schools; Pam Casto, Mason County Schools; Paula Waggy, Pendleton County Schools (retired); and Todd Ensign, NASA IV&V Educator Resource Center. Much to his chagrin, Dr. Renton learned that this group takes their editing very seriously! Thanks for a job well done. I would also like to thank Mike Hohn, Jim Britton, Barnes Nugent, and Jeanne Sutton for their comments and suggestions. Betty Schleger is responsible for the actual production of this work. Artwork, page layout, reviewing, and making suggestions that result in concrete improvements all exist within her formidable skill set. Her demonstrated patience in dealing with my numerous requests for changes, new ideas, and re-edits of previously made edits has been nothing short of remarkable. Most appreciated is her ability to occasional re-focus others to the task at hand. Thanks, Betty.

If you have comments on this product, please contact me.

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Introduction *by Jack Renton*

For more than a decade, I have been involved in a K-12 professional development program called RockCamp that provides basic geological education for West Virginia teachers of earth science. Within the program, my responsibility is to introduce basic geological concepts. This task is compounded by the fact that a significant majority of the enrolled teachers have little-to-no prior geologic knowledge. Needless to say, the needs of this population vary greatly. I am also a university geology professor with more than four decades of classroom teaching experience. As is the case with my own university classes, I am most thrilled to help those with limited understanding but a strong desire to learn.

To teach introductory geology at the university level, I have written my own textbook and drawn my own illustrations. The book has been published and is widely used. However, my work with teachers has required me to reexamine such text. As I look at them and their accompanying materials it has become obvious to me that they are presentations reflective of the traditional scientific writing style—formal and jargon laden. My own textbook is a prime example. This is not a bad thing but over the years I have repeatedly heard students claim these kinds of textbooks were too difficult to follow and there were too many terms to learn. More importantly, they couldn't see how any of what they had to read could be relevant to their everyday background. But when I talk to them in my office about plate tectonics, minerals, volcanoes, etc. the most common response is "Now I understand."

What was the difference between the two presentation methods; the book and the discussion? It was so clear. The explanation I presented in my office was a CONVERSATION. One-on-one conversation with a student is the utopian dream of teachers. But, as any instructor knows, this is not going to happen in the real world of a time-constrained educational system. What I needed to develop was, for me, a new publication. One that would require a radically different writing style. In essence, a transcription of a conversation onto pieces of paper.

For someone who has written as a science professional for his entire life the transition has not been easy. To write in the first person, to shy away from jargon, to leave out some information, to explain things in common terms, to ask lots of questions (some of which I do not answer but evoke for your own consideration), and to suggest activities that teachers could use was all so very different. But that is what I have attempted to do. In this new style, I try to introduce basic geologic concepts as if you and I were engaged in a conversation in my office or at an outcrop in the field. During conversations I have noticed that the "fear of science" that possesses many learners vanishes (or at least diminishes the intimidation). Also, once I explain that I don't really memorize chemical formulas or mathematical equations but only use them as shorthand, the mutual exchange of ideas increases significantly.

In this written conversation, I would like you, the reader, to enjoy what you are reading rather than becoming bogged down in terms and terse professional prose. I hope that a relaxed mind will be a more porous one that will permit greater absorption of conceptual ideas without worrying about numerous details. And, for you the teacher, I would hope that this material will both enhance your ability to teach the content while also providing you with the deeper geologic background knowledge required to deal with interested students and their sometimes probing questions. I would also like to provide some sense of the nature of science. For example, after forty years as a geologist I continue to learn more about the basic concepts I will discuss. Like you, I am asked questions for which I have no answers and sometimes my assertions are rejected by colleagues. I would like you to begin to look at the geology that surrounds you and begin to wonder how it all came about. To accomplish this we must start somewhere. So, for those with no geologic background, consider the narrative that follows as your first foray into the BIG STORIES OF GEOLOGY. For those with more prior knowledge, consider it a review, better yet, a refinement of what you know and what you teach. In any case, I want to help you know more about the geology I find so fascinating.

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CONTENTS

Visit http://www.wvgs.wvnet.edu/www/geoeduc/geresources.htm to access printable digital version or to download individual .jpg file of each illustration.

SETTING THE STAGE

SCENE 1: EXPLORING FUNDAMENTAL GEOLOGIC PRINCIPLES

Look at Figure 1. This is a photograph of sedimentary rocks taken along a road in southern West Virginia. Roadcuts ("exposures" to a geologist) such as this one are commonplace statewide. The thickness of the various rock layers can be estimated using the preserved 300 million year old tree stump for scale. Five rock samples have been taken at the site. The location of each sample has been indicated. Before reading further try to answer these questions:

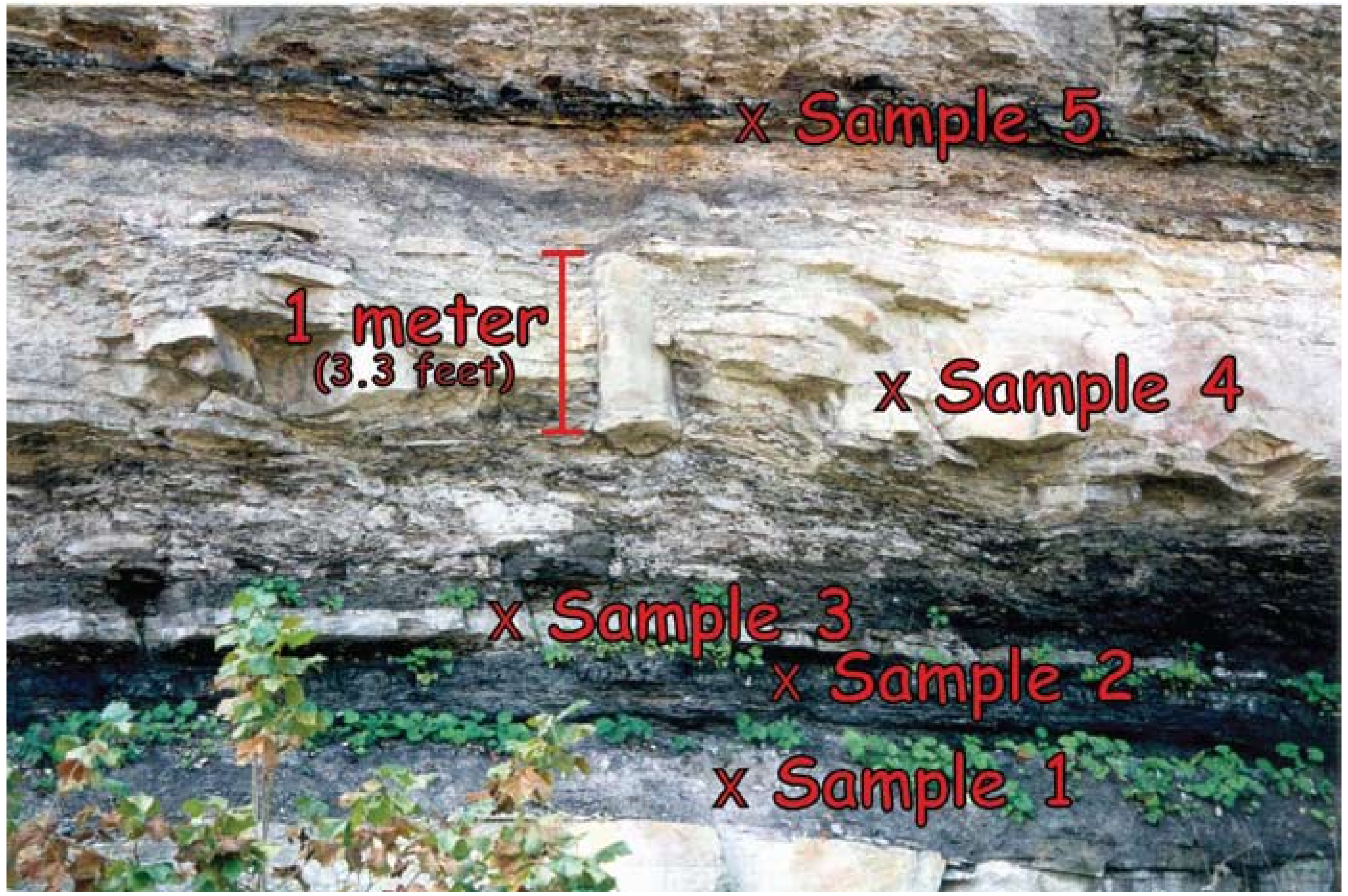


Figure 1

A. How would you describe the orientation of the sedimentary rock layers?

B. Is Sample 1 older or younger than Sample 5?

C. Defend your answer to the previous question.

Do your responses concur with the answers found in the right hand margin? What previous scientific training provided you with the knowledge to even attempt to answer these questions? Were the answers obvious?

In our simple opening exploration you uncovered several of geology's fundamental principles. More importantly, we hope you see that a modicum of common sense is an important component of the geologic sciences. As you read the next few pages you may occasionally think to yourself "That's obvious." In fact, you may have muttered the same sentiment during at least some portion of the opening exercise. For some, the following paragraphs may accomplish nothing more than adding descriptive terminology to intuitive knowledge. On the other hand, this may be the first time you have encountered such thoughts. It is our opinion that understanding even introductory plate tectonics requires a grasp of the basic geologic laws. Therefore, we will introduce five fundamental geologic principles. Without them, the science of geology and the development of plate tectonic theory would not have been possible. Finally, we ask you to keep the historical perspective at the forefront. After all, this is a journey through time.

Setting the Stage
Scene 1: Exploring Fundamental Geologic Principles
Scene 2: Continental Drift and Wegener
Scene 3: From Myth to Science

Let's begin by exploring what you already know!

A. *Horizontal*

B. *Sample 1 is older than Sample 5*

C. *Sample 1 is older than Sample 5 because Sample 1 is underneath Sample 5. Sample 1 had to form before Sample 5 or even before Sample 2, 3, or 4.*

Fundamental Geologic Principle #1: Law of Original Horizontality

As early as the 17th century, Nicolas Steno (1638-1686) first proposed two concepts that field geologists use every day. The first concept stated that regardless of how intricately the sedimentary rocks exposed in an outcrop are folded or tilted, when the sediments from which they formed were first laid down they were originally laid down horizontally. Think about the sediments as they are deposited on the ocean bottom, a stream channel, a flood plain, on a coastal plain, or on someone's front lawn after a flood. This concept became known as the Law of Original Horizontality. This principle is demonstrated by the horizontal layers of sedimentary rock in Figure 2.

Fundamental Geologic Principle #2: Law of Superposition

Steno was not done. He went on to state that in a sequence of sedimentary rocks the oldest layer is on the bottom and the youngest is on the top. Let's look at Figure 1 again. You more than likely suggested that Sample 1 is older than Sample 5. Unless the layers of rock have been deformed, overturned, or faulted, the layer on the bottom must be older than the layer on top. In the classroom, this simple, but monumental principle, can be demonstrated by both physical and mental exercises. For example, ask your students to think of the trash in the classroom garbage can. If you were hunting for the oldest document in the can, where would you look? At the bottom of the can! At this point the important question is "Why on the bottom?" Explaining the "WHY" of the sequencing of the trash is your students first step towards understanding the geology of sedimentary rocks.

Remember our earlier introductory admonishment about perspective? You must remember that during Steno's time most scientists were totally unaware of the nature of sedimentary rocks. Today, his ideas seem so simple. But, at the time, the whole idea of layering in rocks was not understood. Called the Law of Superposition, Steno's idea is posed today every time a geologist asks the question, "Which way is up?". If you think about it metaphorically the layers of sedimentary rocks are pages in a book entitled "The History of Earth." If you fail to establish the proper sequence order you may end up reading the book backwards!

Fundamental Geologic Principle #3: Law of Cross-cutting Relations

To compliment and expand upon Steno's work, Charles Lyell (1797-1875) proposed the Law of Cross-cutting Relations. With his work, Lyell explained how to determined the relative (older/younger) age of two geologic features. By the middle 1800s a good set of tools was available to help scientists evaluate the relative age, and by extension the nature and origin, of different but associated rocks.

Common sense tells you that the vertical crack in Figure 2 must be younger than the horizontal layers of sedimentary rocks it cuts across. Now, let's apply this concept to a sketch of a sequence of sedimentary rocks (Figure 3). The layers are cut through by a fault and a dike. (A dike is an igneous body of rock that forces its way through sedimentary rocks at an angle to the rock layers.) Now we would like you to think like a geologist. What is the relative age of the layers of sedimentary rocks, the dike, and the fault? In other words, which is oldest? Which came second? And, what event was the youngest?

The dike and fault must be younger than the sedimentary rocks. Why? The sedimentary layers had to have been there first in order for the fault and dike to cut across them. Which is older, the dike or the fault? Notice that the dike is offest by the fault. This means that the faulting occurred after the dike.Thus, our relative age sequence for Figure 3 is, oldest to youngest: sedimentary rock, dike, and then the fault.

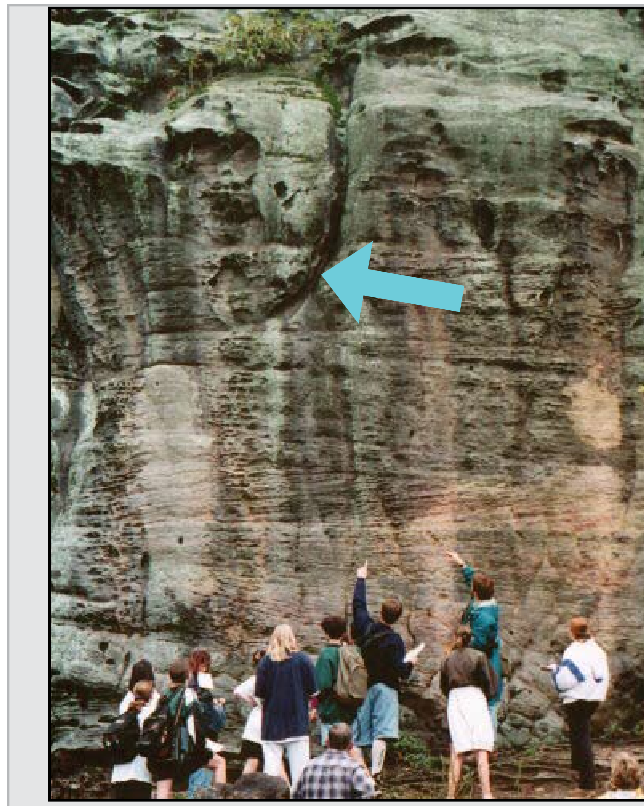


Figure 2

Is the age of the large crack (blue arrow) in Figure 2 older or younger than the age of the sedimentary rocks?

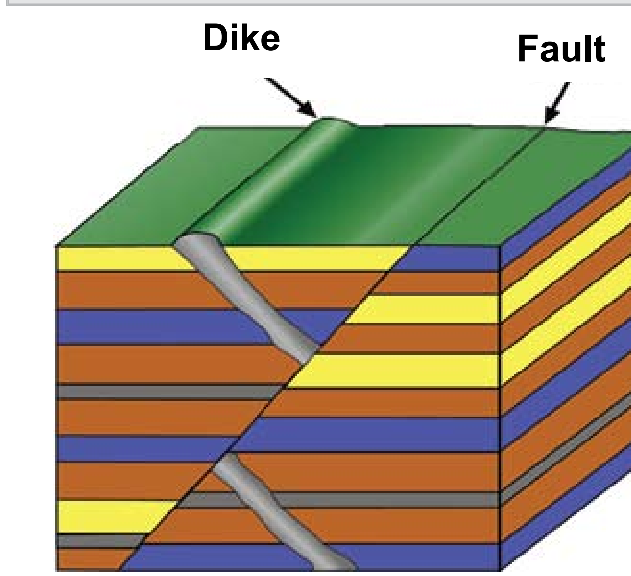


Figure 3

Fundamental Geologic Principle #4: Law of Faunal Succession

Let's try another exercise to get your mind working. Figure 4 shows side-by-side sketches of two hypothetical sedimentary rock outcrops. Let's assume outcrop 1 is located 30 kilometers (18 miles) from outcrop 2. The blue color signifies limestone, the yellow means sandstone, and the gray and purple are shale. Try answering the following questions:

A. Which layers represent the same rock in both outcrops?
B. Layer E is not found in outcrop 1. Explain.

Congratulations, you just did geology! The basic question being asked in this exercise is "How can I be reasonably certain that I am seeing the same layer of rock at two different locations? The fossils are the key. Geologists use the word "correlate" as a verb when they use fossils to connect sedimentary rocks of the same age between exposures both near and far. The important component of the fossils is their exactness–the gastropod must be the exact same species of gastropod to be used as a correlative tool. It is important to note that not all fossils will work. Some are so ubiquitous through the geologic rock record as to be useless.

Fossil secession and the principle of correlating rocks over distance was developed by William Smith (1769-1839) from observations made when supervising the digging of canals across Southern England. As the canals cut into the horizontal sedimentary rocks, Smith noted that some of the layers were especially rich in fossils. At first, the fossils were only curiosities. However, Smith soon came to realize that wherever he encountered a certain layer of rock the assemblage of fossils within the layer was always the same. It wasn't long before he observed that within a vertical sequence of sedimentary rocks the fossil assemblage changed in a predictable way. Further work on this idea eventually produced the concept of using fossils to correlate seemingly unrelated rock units. In 1915, the application of this simple idea would have a profound effect when used by the German meteorologist Alfred Wegener.

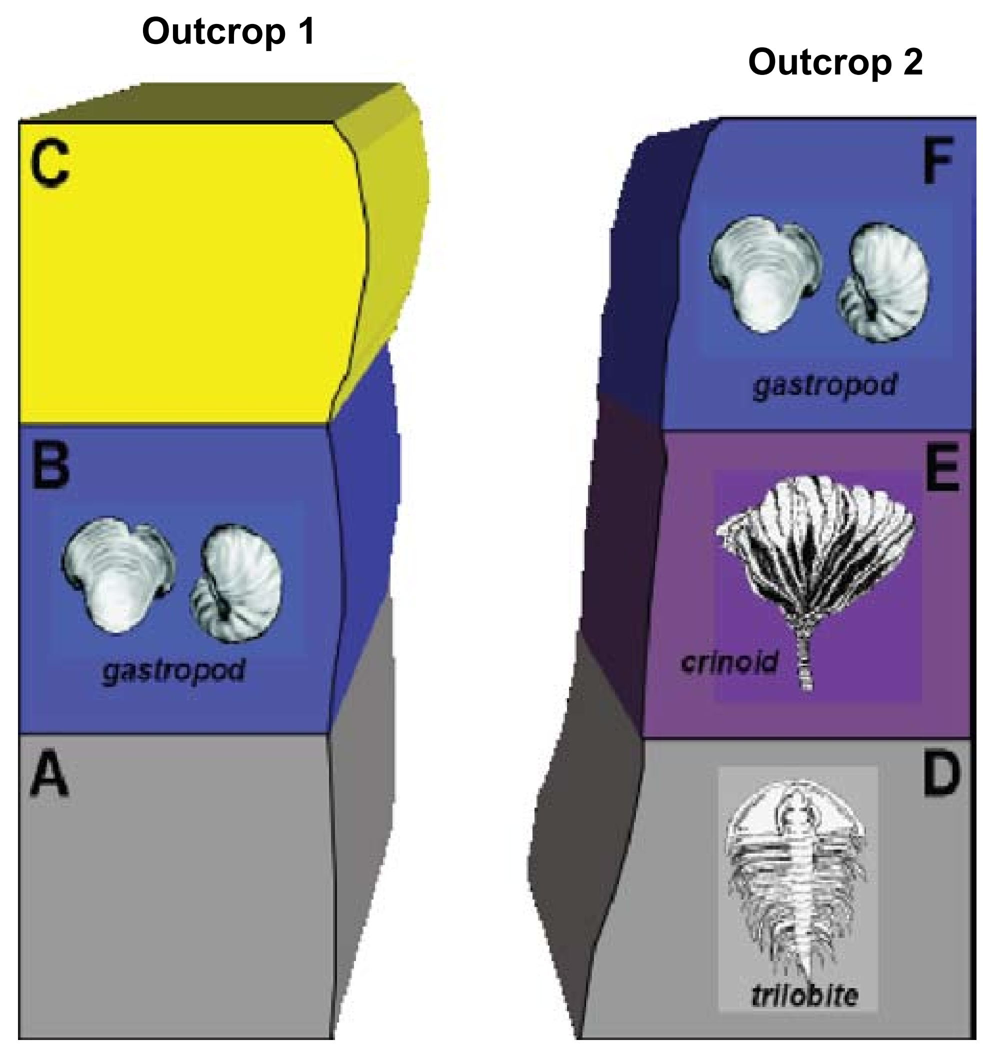


Figure 4

Why fossils are important.

A. *Layers B and F are the same layer because they share the same fossil.*

B. *Two options exist: (1) it never formed, or (2) it was present but was removed by weathering and erosion.*

Do you know what it means to "correlate rocks"?

Fundamental Geologic Principle #5: Uniformitarianism

Plate tectonics completely revolutionized the existing science of geology but in 1785 uniformitarianism actually established the science of geology. The concept of uniformitarianism, set forth by James Hutton, is defined by the *Glossary of Geology* as "the geologic processes and natural laws now operating to modify Earth's crust have acted in the same regular manner and with essentially the same intensity throughout geologic time". Uniformitarianism is commonly summarized in the statement "the present is the key to the past". In the mid-1700s, such an idea was in direct conflict with the existing concept of catastrophism which proposed that sudden, violent, short-lived, more or less worldwide events outside our present experience or knowledge of nature have greatly modified Earth's crust. Why did the earth scientists of the day feel that Earth features were formed by catastrophic events? The main reason was because a footnote in the King James version of the Bible stated that Earth was created in the year 4004 BC. When one considers that this provided only 6,000 years to create everything we see, catastrophism was probably a reasonable explanation as to how Earth's surface changed. However, Hutton had methodically observed the slow weathering and erosion of the rocks in his beloved Scottish Highlands. He also watched the products of weathering being carried to the sea where the sediments were deposited. From these simple observations he postulated that Earth's surface was being changed by very slow processes. More importantly, these processes were too slow to allow the sculpting and changing of Earth's surface within a short 6,000 years. The outcome of all of his work culminated in the concept of uniformitarianism.

However, is Hutton's idea the only explanation for changes to Earth? Can you suggest events that might violate the principle of slow and steady change supported by uniformitarianism? Of course you can—hurricanes, floods, volcanos, and earthquakes can drastically modify the areas they impact. During these events the rate of geologic processes change. Some geologists consider such events examples of what is referred to as catastrophic-uniformitarianism. Similar events have been suggested in the evolution of organisms as indications of what some biologists call punctuated evolution. In other words, the concept of uniformitarianism does not preclude the occurrence of catastrophic events. It simply eliminates catastrophism as a major mechanism of long-term change.

The present is the key to the past.

Uniformitarianism turned purely observational geology into science.

Uniformitarianism limits long-term change caused by catastrophic events.

SETTING THE STAGE

SCENE 2: CONTINENTAL DRIFT AND WEGENER

In our minds, the Theory of Plate Tectonics is the most important concept set forth in the science of geology since Hutton's founding of the science in the mid-1700s. Jack tells his students that plate tectonics is to geology what Darwin's Origin of Species was to biology or what Newton's laws of motion were to physics. All three cases are symptomatic of paradigm shifts in thinking. In geology there are processes and features that we have observed for centuries but never really understood until the advent of plate tectonics; the similarity of the geographic distributions of volcanism and earthquakes and the creation of mountains such as the Rockies, Appalachians, and Himalayas to name just three. So, what was the origin of plate tectonics?

Throughout the early years of earth science it was believed that the sizes, shapes, and locations of the continents as we see them today was determined when Earth's crust was first created. This idea seemed to be perfectly reasonable and all was well until the 15th and 16th century when Portuguese and Spanish mariners began to discover distant lands. Based on their findings, cartographers had to revise existing world maps. Although the precision of their maps was nowhere near that of modern maps, some were good enough to portray the general outline of the major continents. These maps provided the basis for one particular, and to some, unsettling, observation. You can have your students recreate this moment by asking them to record a list of observations about land masses on a world map. Sooner or later one of them will note, as did the historical scientists, what is shown in Figure 5–the similarity of the Atlantic coastline of South America and Africa.

To scientists before 1960, the implications of the perceived "fit" of the western part of Africa and the eastern part of South America were astounding and breathtaking. Could continents actually move? Were the two continents at some time in the past joined together? And, if so, how did the larger landmass break apart into two pieces that moved away from each other? Early observers were exhilarated by the possibilities. They were also frustrated because no one could disprove any offered idea. It was all conjecture and speculation lacking scientific fact.

The similarity of coastal outlines was noted by Sir Francis Bacon (1561-1626). Benjamin Franklin (1706-1790) wrote: "The crust of Earth must be a shell floating on a fluid interior. Thus the surface of the globe would be capable of being broken and disordered by the violent movement of the fluids on which it rested." When the earth scientists of the day were confronted by inquiring minds asking whether the two continents could once have been joined, they answered with a resounding "No!" It would not be until the 1960s that the scientists were proven to be wrong.

Why did it take two hundred years? We think the basic problem that confronted the proponents of what would become known as continental drift was the fact that they could not answer two important questions:

A. Where are you going to get the energy to rip a continent apart?
B. What mechanism can generate the tensional forces needed to literally pull a continent apart?

Remember, these inquiries began before the advent of uniformitarianism. We have always been surprised that the early proponents of continental drift didn't call on some catastrophic process to answer both questions. After all, they called on catastrophic events to explain everything else from the creation of mountains to chasms such as the Grand Canyon. The story of

Examples of scientific paradigm shifts: Newtonian physics, evolution, plate tectonics.

Early maps suggested the "fit" of South America and African coastlines.

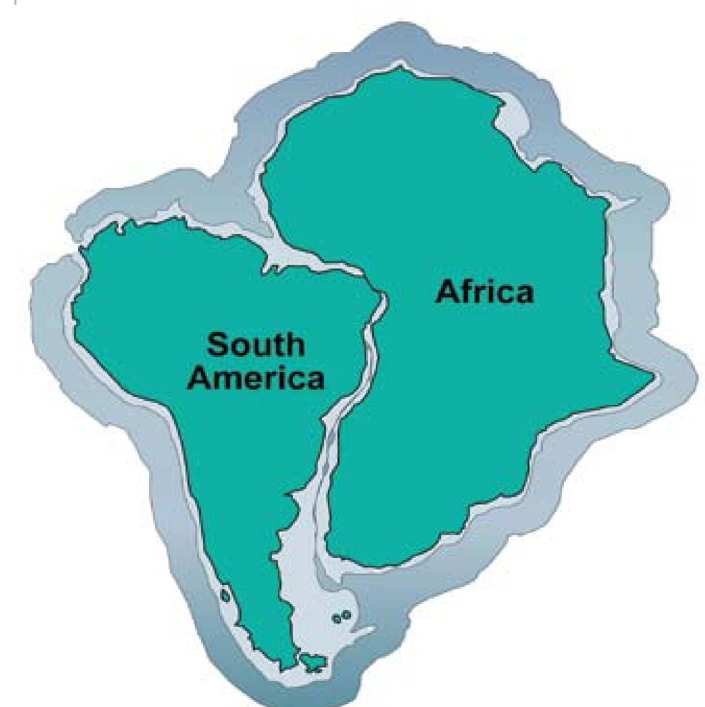


Figure 5

plate tectonics distinguishes itself from continental drift because it is really an account of the science required to answer the energy and mechanism questions. But, prior to 1960 scientists were still wrestling with the idea of continental drift and the person central to the hypothesis of continental drift was Alfred Wegener.

Alfred Wegener (1880-1930) was a German geographer who, like many before him, had compared the Atlantic coastlines of Africa and South America. The difference was that he was unwilling to accept the geologist's denial that the two continents were ever joined. Using common sense, he set out to prove them wrong. Figure 6 presents only some of the evidence that Wegener used to "prove" that Africa and South America were once joined. By applying the basic geologic laws I presented earlier, he showed that South American and African fossilized bones of the reptile Cynognathus were of the same age, even though the rocks were separated by thousands of miles of ocean. Wegener asked a simple question: "Would these reptiles, when alive, have dog paddled their way across the South Atlantic?" He presented the fossilized seed of Glossopteris that was found on both continents. Since this seed was fairly large, was it plausible, Wegener asked, for the seed to have been transported by the wind from one continent to another? Science usually works towards the most simple answer. So, Wegener concluded that the bone and seed fossils were found where they had lived—on a larger continent.

Note that this evidence consists of real data, not just speculative assertions. Wegener also showed that there are rock structures in the "nose" of South America that match rocks found in the "armpit" of Africa. Wegener's data are impossible to explain unless the continents were once linked. In summary, Wegener presented what, today, would have been accepted as definitive proof. Although a few geologists agreed with his findings, most geologists did not. Why? Think about this for a minute as we continue.

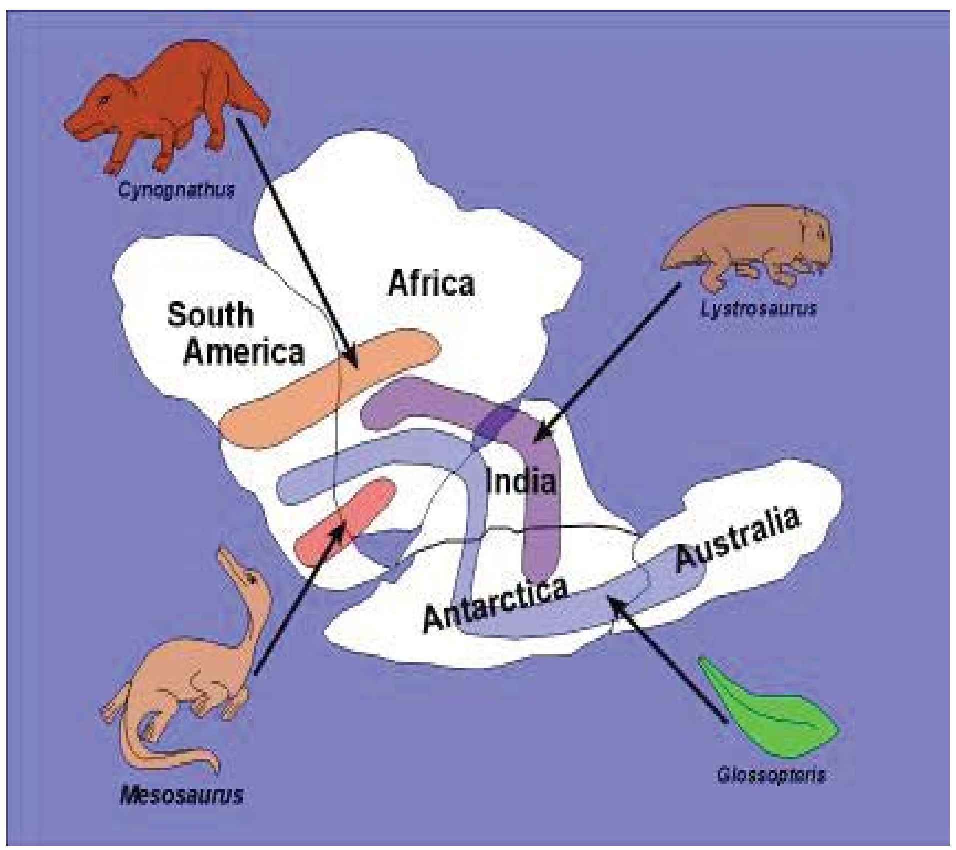


Figure 6

Undetered by rejection, Wegener proceeded to show how all of the present continents could have been joined into a single super-continent called Pangea (Figure 7). Accordingly, the location of our present day continents has been dictated by the "drifting" that occurred during the past 200 million years. Wegener explained his ideas in a 1915 publication titled "*The Origin of Continents and Oceans*". [Note the similarity to Darwin's *Origin of Species*!] His hypothesis was soundly rejected, repeatedly, by the geologists of the day. Can you suggest why his ideas were scorned? You guessed it—energy and mechanism! Like all of his predecessors, Wegener could not come up with a scientifically sound source for the required energy or with a mechanism that could drive Earth's continents through Earth's crust to their present locales.

An idea was required to explain energy and mechanism of continent movement.

Wegener provided evidence that South America and Africa were once joined.

Geologists who more willing accepted Wegener's idea were more likely to live in the southern hemisphere while those who outright denied his premise were from the northern hemisphere. Reason? Numerous regionally published studies by southern hemisphere earth scientists had revealed strong similarities between 150 to 300 million year old fossils and rocks of South America, Africa, India, Australia, and Antarctica. However, before Wegener's idea they had assumed the continents were linked by land bridges.

Figure 7. The northern part of super-continent of Pangea is called Laurasia and the southern part is called Gondwana. The red star shows the approximate location of West Virginia.

SCENE 3: FROM MYTH TO SCIENCE

We think it is interesting to note that throughout history, many major scientific concepts were, for the most part, synthesized by a single individual. Others preceded and provided important contributions but we commonly acknowledge Copernicus for the Sun-centered solar system, Newton for the theories of gravity and laws of motion, and Einstein for his vision of space-time. Such has not been the case with the theory of plate tectonics. The data that eventually led to the formulation of the theory came from teams of scientists working in a number of different research areas. Their only common factor was that they were all exploring some aspect of the ocean floor. Furthermore, although their work had nothing to do with what Wegener had first described as "continental drift", their combined efforts would eventually allow us to come to a better understanding of Earth.

Before going further this is an appropriate time to make a short statement about the nature of science. In addition to Jack's teaching, he did research on coal for more than 30 years. Never in that time did he employ the hierarchical procedure which textbooks routinely peddle as the scientific method. He did what most scientists do: He explored questions and used observations to provide support for answers. Sometimes he found a new and better way to explain the natural world. Sometimes he did not. The operative condition in science is maturation. Looking at the growth of theory from an historical perspective what you will see is how ideas, data, research, methods, thinking, comprehension of links between seemingly disparate concepts, and finally, understanding, mature. Deductive and inductive reasoning are two methods of logic used to arrive at a conclusion based on assumed truth, or factual, information/data. The origins of plate tectonic theory is the product of "if-then" deductive reasoning in the sense that ideas are developed based upon observations and consequences without knowing their cause. For example, Iceland was known to be an active volcano and an island. However, the nature of its association with the Mid-Atlantic Ridge was unknown until a better understanding of the sea floor was acquired. In contrast, understanding the sea floor was built using inductive reasoning involving the synthesis of data-based facts into generalizations. For example, defining the volcanoes around the rim of the Pacific Ocean as the Ring of Fire is an example of inductive thinking if you define the process as creating general principles by starting with many specific instances. As you read our discussion of the maturation of plate tectonic theory you will note that the scientific process often wavers between these two lines of thinking. The point we are trying to make here is that science is dynamic. It proceeds as an outcome of the human condition of exploration and curiosity. As such, it is not linear, clean, and orderly. It is messy, confusing, and convoluted. If you can come to appreciate science as tentative but durable you are more likely to correctly understand that as a "work in progress" the scientist's goal is not to prove theories but search for and present evidence to disprove them. Falsification is the only method science has for discarding theories. This simple nature of science explains why controversial theories can persist and thrive.

Finally, as you read, try to maintain the relationship between the questions being asked, the development of plate tectonic theory, and its historical foundation. Science is often taught as static fact. We are here to tell you that it is not. In Jack's lifetime, he has lived through the dynamic process of scientific change. Given the current speed with which science and technology grows, we are sure many of you will have a similar experience.

Development of plate tectonic theory required integration of scientific disciplines.

Nature of science

"Proving theories" is a misconception

Importance of historical development of plate tectonics

DEVELOPMENT OF A NEW SCIENTIFIC THEORY: ROAD TO PLATE TECTONICS THEORY

My First Contact With Plate Tectonics *by Jack Renton*

I first heard of plate tectonics, or more accurately, continental drift, in the Spring of 1956 during the last semester of my senior year at college. I was a chemistry major. I had signed up for a course in physical geology because a few of my friends were taking the course and had told me that the class was scheduled to take a field trip to upstate New York over Easter break. Having never been further than 50 miles from home I thought it a great opportunity to expand my horizons. Sometime during the semester I read an article one of my friends had about continental drift. I was absolutely amazed! Nothing that I had ever read in any of my chemistry courses had ever been so wild—continents moving around on the surface of the globe! Compared to that, the rules and equations and laws that dominated my chemistry life looked pretty humdrum. At the first opportunity, I asked my geology instructor about what I had read. He nearly went into coronary arrest! His response was "It's a stupid idea and I'm not going to waste my time answering such a question!!!" My reaction was "OK, I just asked but are the continents still drifting apart?"

When I came to West Virginia University to interview for chemistry graduate school, I thought I might as well interview for the geology department. The chair for geology at the time thought that a combination of a B.S. in chemistry and an M.S. in geology would be a great idea. He told me to seriously consider geology for my graduate work. When I arrived on registration day I still hadn't made up my mind. I enjoyed chemistry and even though it would take me an extra year to make up all my geology deficiencies, I kept thinking about that article on continental drift. When I went to registration (no on-line registration back then) the line in front of the chemistry table stretched across the floor. Three tables away, three students stood in the geology line. Absolutely certain that it was a sign from above, I got into the geology line. The rest is history. Only later did I find out that the long chemistry line were freshmen signing up for chemistry labs. In my classes I use this last incident to point out that, more often than not, science is more than a planned event. By incorporating discussion on the serendipitous nature of science I find that I can more fully develop my students appreciation of the history of geology and the advancements made by earth scientists.

How Jack became fascinated by geology.

The serendipitous nature of science.

ROAD TO PLATE TECTONICS THEORY
STEP 1: NATURE OF THE OCEAN FLOOR

Until the 1940s, most scientists pictured the deep ocean floor as being a perfectly flat surface that extended from continent to continent. Why would they have such an image? Mainly, we think, because of their data. At that time, the nature of the deep ocean bottom was built upon an insignificant number of soundings. Depth measurements made by dropping a weighted line overboard and measuring the length of line played out when the weight hit bottom. We think you can see lots of problems using such a technique. For example, do you think the weight dropped directly down to the ocean bottom so that the length of the line was an accurate depth measurement? If there were no ocean currents, we suppose it could. However, there are currents within the ocean that would most likely divert the weighted line. Were the mathematical implications of a sounding line played out behind a moving ship ever explored by the measurers? We do not know but it seems like a good practical use for geometry. Nevertheless, it was the only data available and seemed to suggest that the abyssal ocean bottom was essentially a flat plain 3,000-3,500 meters (10,000 to 12,000 feet) below sealevel. Admittedly, there were some soundings that showed shallower water. And, of course, there were numerous volcanic islands (Hawaii, Iceland, etc.) in the middle of each ocean. Adequate reasons for none of this existed when the U.S. Navy began using sonar.

Sonar was invented just after World War I and became a useful tool in World War II. It is a device that allows the depth of water to be determined by measuring the time it takes for a shock (sound) wave to go from the surface to the bottom and return (Figure 8). If the water is shallow the sound wave can be generated by some device in the bow of the ship, such as a hammer hitting an anvil. If the water is deep, the sound wave is generated by detonating an explosive charge or by releasing a burst of compressed air just behind the ship. In either case, the returning (reflected) sound wave, or echo, is picked up by a microphone (geophone) towed behind the ship. Knowing the speed of sound in water allows the use of mathematics to calculate the distance (depth) of the sea floor. By sailing a sonar-equipped ship across an ocean, the Navy investigators were able to construct an ocean floor profile. What they discovered was quite shocking. Rather than the expected billiard-table flat surface they found a sea floor mountain range or ridge that ran the length of every ocean basin. The dimensions of the mountain ranges was also unexpected. Terrestrial mountain ranges (Appalachians, Rockies, Andes, etc.) are typically quite narrow relative to their length. In contrast, the newly discovered oceanic ridges were very broad relative to their length. In Figure 9 for example, the base of the Mid-Atlantic oceanic ridge averages about 2,400 km (1,500 miles) across. This is about half the width of the entire ocean basin. It would be like the Appalachian Mountains extending from West Virginia to Kansas! As more data was

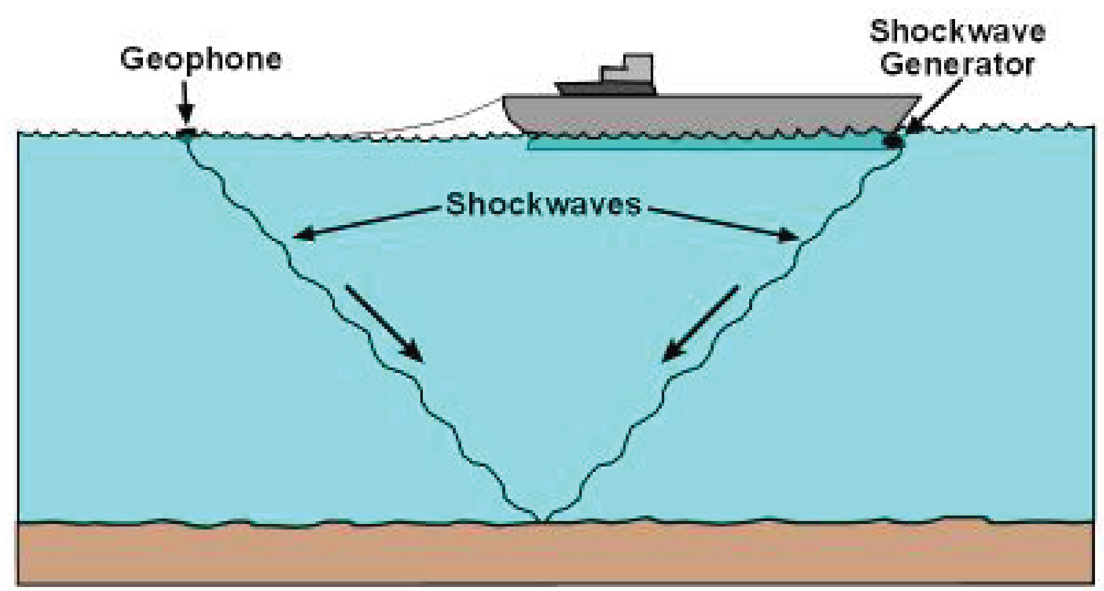


Figure 8

Here’s a great bit of trivia for you. What does sonar stand for? SOund NAvigation Ranging. I don’t know what that means in Navy-talk, but it still makes a great bit of trivia. Most individuals will recognize sonar as the ping-ping noise heard in submarine movies. Fishing enthusiasts will commonly have a smaller version on board to locate the lake bottom and schools of fish.

Sea-floor profiles reveal previously unknown mid-ocean ridges prompting questions on how they formed.

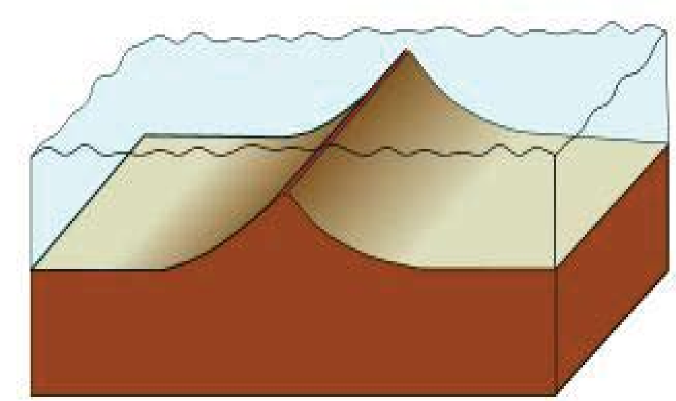


Figure 9

acquired, it was soon discovered that all of the oceanic ridges were interconnected. We now know that this single underwater chain extends for 64,000 km (40,000 miles).

Iceland turned out to be an important geological key when it was recognized, in reality, as just an exposed high point along the Mid-Atlantic Oceanic Ridge. Since Iceland was a volcano, geologists surmised, correctly so, that the oceanic ridges were volcanic in nature. Questions immediately arose. How did these ridges form? What geologic significance did they have? Why were they volcanically active? Why were they all interconnected? The early investigators had no answers to these questions. At the time, the presence of the oceanic ridges was simply an observation made by curious oceanographers. Before we leave the topic of the oceanic ridges consider this. The experts, whoever they are, claim that if the water was removed from the ocean basins and Earth was approached from space, the first physical feature that would be seen would be Earth's oceanic ridge system!

In addition to an oceanic ridge, depth profiles made in the Pacific Ocean revealed long, relatively narrow, deep trenches in the ocean floor (Figure 10 and 11). The deepest of these discoveries was the Mariana Trench located just east of the island of Guam and about 2,100 km (1,300 miles) east of the Philippine Islands. The trench plunges nearly 7,300 meters (24,000 feet) below the ocean floor. Consider this, if you placed Mount Everest at the bottom of the trench it would have more than 2,000 meters (6,600 feet) of water above it.

When the oceanic ridge and trench data was mapped, it was found that the deep sea trenches always paralleled the margin of the nearest continent. Since many of the continental margins have a curved shaped, geologists termed these locations "arcs ". Further work lead to the discovery of two different deep sea trench scenarios. When the trench was located within a few miles or tens of miles of the continental margin, volcanoes were always present along the margin of the continent (Figure 10). These became known as continental arc volcanoes. An excellent example of a continental arc volcano range is the Andes Mountains. A smaller example is provided by the Cascade Mountains of our Pacific Northwest.

If, on the other hand, the trench was located a hundred or more miles offshore, the mountain range consisted of a series of volcanoes that rose from the ocean floor. This scenario produced a chain of volcanic islands between the trench and the continental margin (Figure 11). These became known as island arc volcanoes. Good examples of these structures are the Aleutian Islands and the string of volcanic islands that extend from the volcanically active Kamchatka Peninsula southward through the Japanese Islands and the Philippine Islands to the northern island of New Zealand.

Approximate average depths of all of the earth's oceans is about 3,600 meters (12,000 feet).

Deepest places:

- Indian Ocean's Java Trench at 7,725 meters (25,344 feet) deep.
- Atlantic Ocean's Puerto Rico Trench at 8,648 meters (28,374 feet) deep.
- Pacific Ocean's Mariana Trench at 11,033 meters (36,201 feet) deep. Bottom was reached in 1960. It is 2, 542 km (1,580 miles) long and 69 km (43 miles) wide. The Pressure at the deepest part of the Mariana Trench is over 1,124 kg/cm^2 (8 tons/in^2).

Scientists eventually associated the trench locations with the Ring of Fire, a known belt of major volcanic activity surrounding the Pacific Ocean basin.

Discovery of deep-sea trenches generated many more questions, such as: How did these trenches form? Why do the trenches occur parallel to continental margins? Why are some trenches located close to the continental margin while others are quite far away from the continental margin? Why are some trenches in the middle of seemingly nowhere? Why are volcanic mountains always associated with the trenches? Is there any relationship between the deep sea trenches with their chains of volcanoes and the volcanically active oceanic ridges?

Once again, the scientists of the day had no answers.

Continental arcs vs. island arcs improve understanding of volcano distribution.

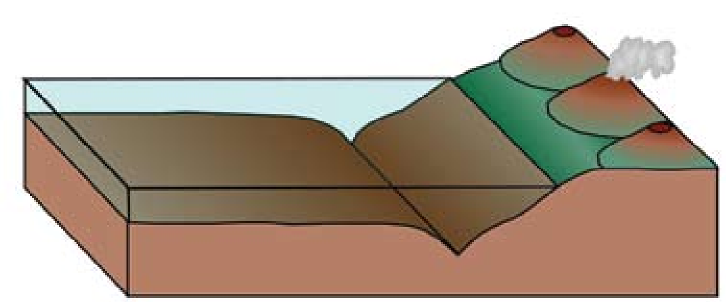


Figure 10

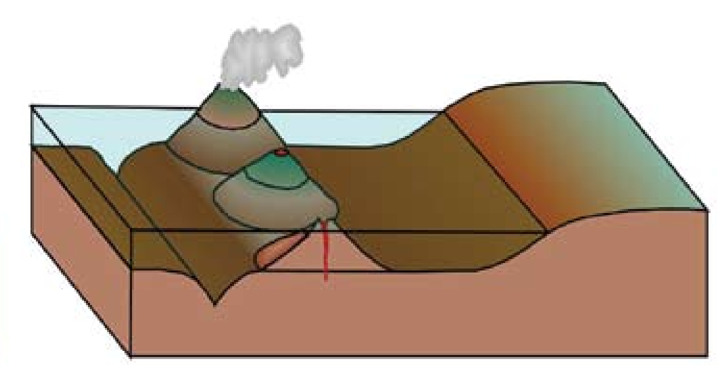


Figure 11

The deep sea trenches and their associated volcanic activity were simply observations made by oceanographers studying the topography of the ocean bottom. The discovery of deep-sea trenches forced scientists to ask new questions, to inquire so to speak.

THE ROAD TO PLATE TECTONICS
STEP 2: PALEOMAGNETISM

Not long after uncovering the true nature of the sea floor earth scientists discovered another, even more remarkable, fact about Earth's geologically old magnetic field. The geologic shorthand for this is paleomagnetism ("paleo" means old). We have all used a compass to determine the direction to the north magnetic pole. But, scientists figured out a way to determine which way was north millions, even hundreds of millions, of years ago. To explain what they did, you need to know something about the study of magnetism in rocks. As you read this part it will be necessary for you to distinguish between two very similar words. These are magnetism and magnetite. Magnetite (Fe_3O_4) is a mineral found in rocks.

About 1955 research was being conducted on the paleomagnetism of lava flows covering 520,000 sq. km (200,000 square miles) of the Columbia Plateau of eastern Washington and Oregon. (Figure 12). Beginning about 20 million years ago multiple lava flows occurred in this area. Each flow covered the one that came before it. This process resulted in a cumulative thickness of more than 1,800 meters (6,000 feet) of stacked lavaflows. Using the Law of Superposition the oldest to youngest ages of the numerous stacked flows could be determined.

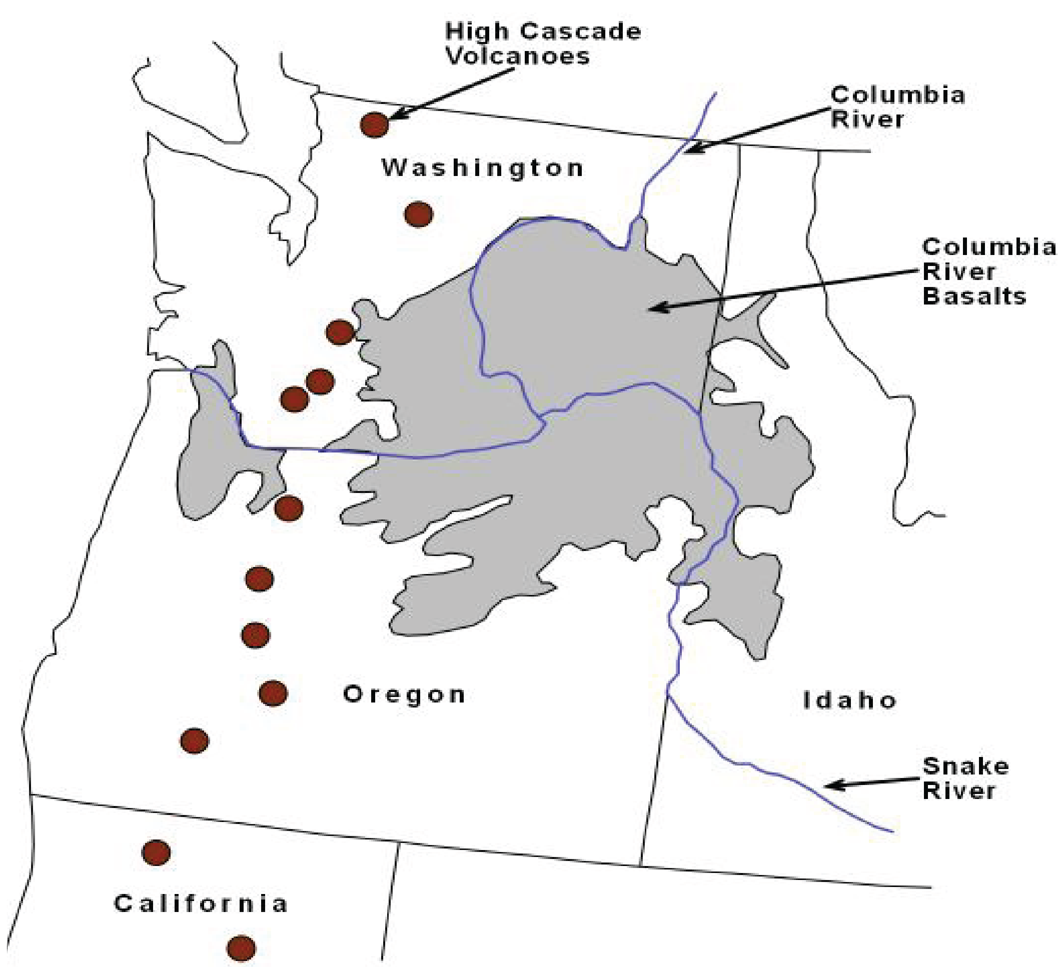


Figure 12

How was paleomagnetic data of the basalt in the Columbia Plateau acquired? A drill was used to take a small cylindrical core from the magnetite-rich basalt. This is an "oriented sample" because its three-dimensional position was carefully recorded. (Think of this as GPSing the sample.) Back at the laboratory a magnetometer was used to determine the direction of the sample's magnetic orientation. This provided data on the direction of the north pole of the basalt's magnetite. By collecting oriented samples from different lava flows, and applying superposition, the sequence of changes in Earth's magnetic field was uncovered. Worldwide application of this process to basalts of different ages confirmed multiple reversals of Earth's magnetic field through geologic time.

Why were these rocks being studied in the first place? First, start with the lava. When it cooled it became the igneous rock called basalt (Figure 13). Basalt can have natural magnetic properties if it contains the mineral magnetite. As the name implies each crystal of magnetite is a tiny magnet like the one in your compass. So, the reason for the study was based on the facts that the relative ages of the individual flows could be determined (superposition) and that the Columbia Plateau basalt contained magnetite. What happened to the basalt-rich lava as it cooled? Your instinctive response is to say it "cooled down." True enough. But, can you provide a more in-depth explanation?

Figure 13. Basalt (left) is the dominate rock of the sea floor portion of Earth's lithospheric crust. Granite (right) is the dominate rock of the continental portion of Earth lithospheric crust. The magnet indicates the presence of the mineral magnetite within this sample of basalt.

The lava began to solidify and, most critically, the scientists recognized that it was cooling within Earth's existing magnetic field. Magnetite crystals began to form early in the cooling process, but the high level of existing thermal energy (heat) prevented a magnetic field from developing within each magnetite crystal. Eventually, as the lava cooled, it reached a temperature, called the Curie Point, where the amount of energy was too low to inhibit the formation of a magnetic field. Therefore, at the Curie Point magnetic fields began to form for each magnetite crystal. Each of these fields were

A few students demand more about the magnetism of rocks. According to a physicist friend of Jack's "...magnetism of the magnetite crystals is due to the parallel alignment of the rotational momentum of the electrons surrounding the iron atoms within the structure of the magnetite crystals." What does that really mean? Picture an iron atom with electrons revolving around its nucleus. In addition to this orbiting motion each electron also is rotating about its own axis. (Helpful analogy - a planet both revolves and rotates.) Now, we want you to picture an iron atom contained in lava at or near its Curie Point. In this scenario, the rotational axis of all of the atom's electrons line up parallel to each other. This multiple alignment produces a magnetic field around the atomic nucleus. As long as the temperature remains below its Curie Point, the magnetic field around the iron atom is locked in, that is, it remains a permanent magnet! Now, imagine all of the electrons around all of the iron atoms of all of the magnetite crystals doing the same thing. This cumulative effect produces a permanent magnet with the same orientation as Earth's existing magnetic field. As in the case of any permanent magnet, as long as the temperature remains below the Curie Point the magnetic field is locked into the rock. Here's a question that we will allow you to contemplate on your own. Can you think of any situation where the magnetic record incorporated into a rock could be erased by having it subjected to temperatures above the Curie Point?

The Curie Point for the Columbia River Basalts was about 500° celsius.

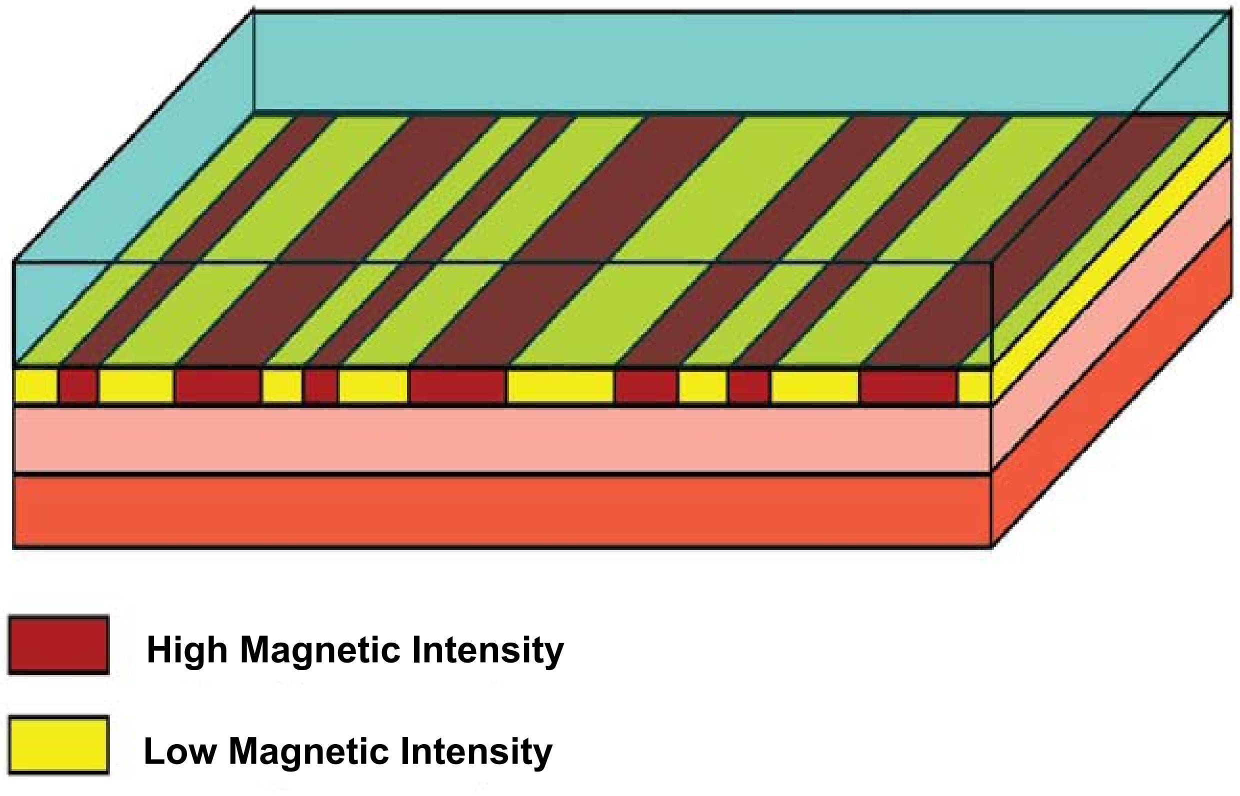


Figure 14

aligned with Earth's existing magnetic field. As a result, each magnetite crystal within the solid lava (now basalt) provides data on the orientation of the Earth's magnetic field at the time the lava cooled and solidified including the location of Earth's north and south poles.

Why was the paleomagnetism of basalt of such interest? The quick answer is that nearly all lava flows, young or old, are made of basalt. The scientists reasoned that, if understood, these rocks could provide a continuous geologic record of Earth's magnetic field. The investigative work produced a result which no one had predicted. The magnetic data for each of the individual lava flows in the Columbia Plateau implied that Earth's magnetic field was not static. Magnetic alignment, as indicated by the magnetite in the basalt, reversed multiple times as stacks of lava flows were studied. In other words, Earth's north pole became the south pole and visa versa! Magnetic reversal on a global scale had been uncovered. To date, we know of no explanation as to why or how this happens. Because no magnetic reversal has occurred in recorded history there is no way of knowing how we, people, would react to such an event.

The scientists had found a way to measure magnetic reversals in terrestrial basalt. How were they going to measure the magnetic fields in the deep ocean balsaltic crust? Remember the sonar geophone used to determine the depth to the ocean floor? A similar towed device called a magnetometer was used to measure magnetic fields. Here is a brief idea of how it worked. Consider that the magnetometer was calibrated to recognize what we consider to be Earth's existing magnetic field. Consider also that this signal would be recorded as normal background data. As the magnetometer was towed through the water it constantly recorded the intensity of the magnetic field of the ocean floor. If the magnetometer measured an increased field of the same orientation the response would be recorded as an increase in the signal strength. If the variation was a magnetic field of differing orientation the response would be recorded as a decrease in signal strength. Using this process, scientists discovered the presence of alternating fields of magnetic intensity in the ocean floor basalt. When mapped, this data became alternating bands (Figure 14). Please remember you can't see these magnetic bands. Many students turn this concept into a gross misconception when they create a mental image of visible bands covering the sea floor. In reality, the magnetic bands do exist but only as artifacts of the plotted data. This is an example of why interpretation of collected data is so important to science.

Another question that students ask is: "Does the magnetic direction align itself with the physical alignment of the crystals within the lava?". This is a common misconception. The physical alignment of individual crystals has nothing to do with the magnetic field. The alignment of the rotational spin is the important part.

Reversal of Earth's magnetic field was revealed by applying superposition and magnetometer data.

No explanation for magnetic reversals.

Sonar uses geophones to record sound/ shock waves. Magnetometers record changes in magnetic field.

Magnetic data reveals pattern only when plotted on maps.

As an ever increasing amount of magnetic data was plotted an even more astonishing and wholly unexpected pattern began to emerge–the bands paralleled the trend of the mid-oceanic ridges and a magnetic band on one side of the ridge seemed to have a twin on the other side of the ridge. Let's use Figure 15 to visualize the plotted data. In Event 1, a mid-ocean ridge is surrounded by a linear band shown in red. This is band A. It represents newly formed ocean floor basalt. Note that the ridge bisects the band creating two mirrored halves–one on the right of the ridge and the other on the left of the ridge. Now, note the arrows on band A. These indicate the direction of the band's magnetic field. Remember, this field is locked into the basalt-rich lava once it cooled. Moving to Event 2 moves us forward in time at the same location. Band B in Event 2 is identifiable because its magnetic field is reversed (arrows) from band A. Now can you see how band A must have been moved aside to make room for band B and that the magnetic orientation of band B is reversed. If you continue on to the younger and younger events, you will see additional bands of basalt forming along and paralleling the oceanic ridge. The older bands seem to be moved out of the way to accommodate newer bands. Correspondingly, this movement requires that the right and left halves of band A must get further and further apart from each other. Of course, these observations created still more questions such as: How did parallel magnetic bands form and why are the bands mirror images on each side of the ridge? Once again, back then, there were no answers. For the moment, we will leave these questions unanswered until we can provide more background information. But, rest assured, they will be answered.

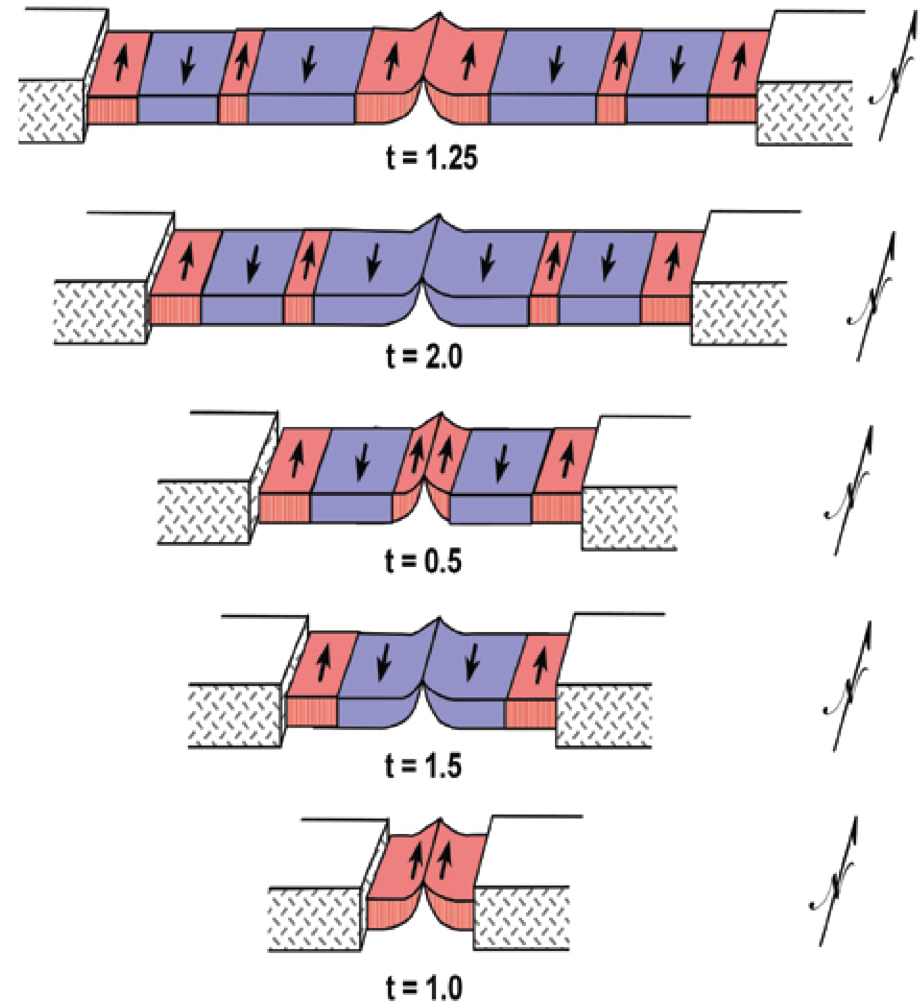


Figure 15

ROAD TO PLATE TECTONIC THEORY

STEP 3: Absolute Age of Earth's Crust

In the previous section we made several references to the Law of Superposition. And, if you remember back to the beginning of this discussion, we briefly discussed the Law of Cross-Cutting Relationships. Both of these laws provide a tool for determining the relative age of rocks–that is which rock is older or younger. This was, and remains, a powerful geologic investigative device. However, for many hundreds of years earth scientists had wrestled with Earth's actual, or absolute, age in years. From a modern perspective, while some of these historical age-dating techniques are suggestive of pseudo-science, a closer examination supports the dynamic nature of scientific argument. Lest our revisionist look be too critical, we must also remember that these ideas were based on knowledge available at that time. Let's start by looking at three early hypothesis used to determine Earth's absolute age.

Magnetic bands occur as twins on opposite sides of mid-ocean ridge summit.

What do we know about global magnetic reversal periodicity and cyclicity? The cycle of reversals can be very short. The Columbia Plateau data demonstrated reversals occurring from one lava flow to the next younger one above it. To a geologist this means magnetic reversals are essentially instantaneous. We also know that the normal length of time that a single orientation exists is variable. There are cases where multiple stacked lava flows (basalt) all show the same orientation. This means that Earth's magnetic field was stable for a very long period of time. On the other hand there is data demonstrating that a reversal occurred between two adjacent lava flows.

Absolute age is age in years. Relative age is younger/older comparison.

Sedimentary rock thickness hypothesis: This early seventeenth century idea was based on measuring the total thickness of sedimentary rocks that had accumulated since the creation of Earth's crust. This thickness was then divided by the annual rate at which sediments accumulate. Can you and/or your students find some problems with this line of thinking? We bet you can! First, weathering and erosion are essential processes involved in the formation of sedimentary rocks. Given this fact, there may have been previously existing sedimentary rocks that had been formed and destroyed by weathering and erosion. So, no record of the thickness of these rocks would exist. Which means there is no possibility of calculating the required "total thickness of sedimentary rocks." Second, there is not a single rate of accumulation. Consider a flood. As the water rises and then falls its velocity will change, and hence its ability to carry sediment. Therefore, even for a particular accumulation event (the flood) the rate of sediment accumulation will be variable. But having said all this, we must admit that, with the level of understanding that existed at the time, it was a logical suggestion.

Salt content of oceans hypothesis: In 1899, an Irish chemist and geologist named John Joly (1857-1933) suggested that Earth's age could be calculated by dividing the total salt content of the oceans by the annual rate at which salt was being deposited into the oceans by all of Earth's streams. Once again, we will ask you to suggest problems with this technique. First, an average figure for the concentration of salt in the ocean needed to be determined. This would require calculating the total amount of salt in the oceans. To do this correctly, the exact volume of all of the oceans would be needed. Do you see the problem here? The ocean's volume is not constant. For example, it changes with the presence or absence of ice ages. Second, even if all of that is ignored, what do you think of Joly's accuracy in determining the total amount of salt being contributed to the oceans? We wouldn't want the job. Third, to make things worse, Jolly would have had to assume that once the salt got into the ocean it stayed there. Does it? We don't think so. If it did, we wouldn't have all of the thick layers of salt being mined in places like northern Ohio, upstate New York and in Nova Scotia.

Earth cooling rate hypothesis: About the same time Lord Kelvin (1824-1907) entered the age-dating arena. Kelvin was the world's expert in heat and heat flow. According to him the solution was obviously simple. Begin by assuming Earth started out as a completely molten sphere. Then measure the rate at which heat passes through solid rock. Use these data to calculate how long it would take for a molten sphere the size of Earth to cool. Using these concepts Kelvin calculated that the absolute age of Earth was seventy million years. When the geologists of the day expressed their feeling that the age was far too short, Kelvin intimidated them with mathematics. At the time mathematics was not an integral component of geology so the geologists backed off. But, they still thought the age was much too short. Actually, one significant problem existed with Kelvin's calculations. And, to be fair, the problem was not even known to exist for several more decades. Can you make a guess? Kelvin assumed that all of the heat came from the Earth's core. Kelvin did not know about the heat given off by the breakdown of radioactive elements in Earth's crust.

Early attempts to calculate Earth's absolute age:

1. Cumulative thickness of sedimentary rock.
2. Salt content of ocean water.
3. Cooling rate of molten rock.

Note the problems involved with the basic assumptions made by each of these attempts.

In 1903, Maria Sklodowski Curie (1867-1934) and her husband Pierre (1859-1906) discovered radioactivity. Radioactive elements are those with nuclei that are unstable and begin to break apart from the moment they form by releasing protons, alpha particles (the combination of two protons and two neutrons), beta particles (electrons), and various kinds of radiation. The radioactive breakdown continues until a lower atomic numbered element is created whose nucleus is stable. For example, uranium (U^{238}) breaks down to eventually form lead (Pb^{206}). In this transition, the radioactive element is referred to the parent (U^{238}) while the final stable atom is called the daughter (Pb^{206}). The rate at which a radioactive element disintegrates is measured by the element's half-life which is the number of years required for any number of parent atoms to be reduced by half. In 1905, Lord Rutherford used the half-life concept to determine the absolute age of an igneous rock.

Why do we need a selection of radioactive isotopes with different half-lives? When used for radioactive dating, elements with long half-lives are used to date very old specimens while elements with short half-lives are used to date relatively young specimens. Radioactive elements such as U^{238} have very long half-lives (4.5 billion years) while others such as C^{14} have short half lives (5,730 years). Therefore U^{238} is used to date igneous rocks that may be hundreds of millions of years old and C^{14} is commonly used to date carbon-rich materials younger than about 60,000 years. The particular isotope used to date a rock depends on the assumed age of the rock. In otherwords, the older a rock sample is thought to be the longer the half life of the isotope needed to accurately date it. If you used an isotope with a short half-life (a relatively high rate of conversion of parent to daughter isotopes) to date a rock that is billions of years old, the number of atoms of the parent isotope may have decreased to the point where the analysis results in a concentration of zero. If the concentration of the parent isotope goes to zero, the parent isotope/daughter isotope drops to zero and can therefore not be used. For example, you couldn't use C^{14} to date something one million years old.

Before the advent of plate tectonics students were taught that Earth's crust (both continents and ocean floor) was formed at the same time about 4.1 billion years ago. The scientists at the time who were beginning to study the basalt recovered from the ocean floor assumed it would be the same age as the continental crust. Oops! As is often the case, assumptions turned out to be wrong. When samples of Pacific Ocean crust were analyzed using radiometric dating techniques their absolute age turned out only 250 million years old. Even more unsettling, the oldest Atlantic Ocean crustal basalt were found to be even younger—only 200 million years old. You will recall that we mentioned that Wegener postulated, by reasoning alone, that the Atlantic Ocean began to open 200 million years ago. Mere coincidence? Geology quickly moved on to a more pressing question: "What happened to all of the oceanic crust that formed between 4 billion and 250 million years ago?". If it did exist, where did it go?

Looking back in time for ideas and help the scientists remembered James Hutton. He had suggested that all rocks are eventually consumed by weathering. Could the oceanic crustal rocks have succumbed to the process of weathering? Unfortunately, weathering only involves rocks exposed to the atmosphere; it does not operate on the ocean bottom. Since weathering was not the answer some yet-unknown process must have been responsible for eliminating all of the oceanic crust older than 250 million years of age! But what kind of process could be responsible for such a feat? We're talking about rocks that at any one time cover 70% of Earth's surface. With no known geologic process capable of accomplishing the task, the search was on for answers.

Modern dating of Earth possible by discovery of radiometric dating using half-life principle.

Can you think of any reason why the age of sedimentary and metamorphic rocks can not be determined by radiometric dating techniques? What is a sedimentary rock? Do you remember the rock cycle? A sedimentary rock is formed from weathered and eroded fragments of older igneous, metamorphic, and sedimentary rocks. As you have probably surmised, sedimentary rocks might contain minerals that come from sources of vastly different ages. As a result, no one age would apply. Can you think of a possible exception? How about volcanic ash? This technique has been used to show that the absolute age of preserved ash fall in southern West Virginia is 310 million years. As for metamorphic rocks...well they can be very, very messy! You'll simply have to take our word that metamorphic rocks are not dated because the metamorphic process "resets" the time clock in each of the affected minerals. As a result, any radiometric age determination would not provide the age of the original rock but rather the date of the most recent episode of metamorphism.

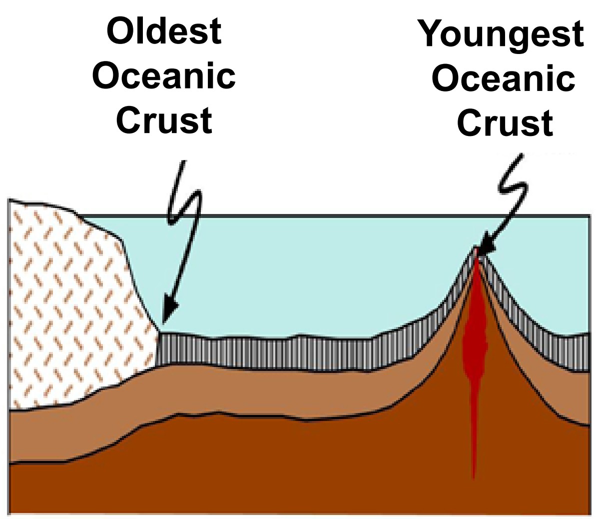


Figure 16

The next logical step was to plot absolute age data on a map. These maps first revealed that the oldest basaltic ocean floor always adjoined granitic rocks found at the continental margins. The mapped data also demonstrated that the ocean floor became progressively younger toward the mid-oceanic ridge (Figure 16). What was the significance of such an age distribution? Concurrently with this work, sampling had convinced most investigators that the presence of basalt was linked to eruptions occurring along the summit of the mid-ocean ridges. These facts suggested that new basalt-rich crust (ocean floor) was being created on a daily basis! If you will remember, we earlier mentioned that the paleomagnetic data seemed to suggest that the lava/rock along the summit of mid ocean ridges had to be moved aside to make space for the addition of a newer band of magnetically-oriented rock. Could the sea floor actually be spreading apart along the ocean ridges? Could this provide the energy and mechanism required to move continents? Looking for a global explanation, the scientists developed the following sequence that we now recognize as seafloor spreading:

A. New ocean crust (sea floor) was being created at the summit of oceanic ridges as basalt-rich magma was turned into the igneous rock basalt.
B. As new oceanic crust formed along the ridge summit the older oceanic crust had to be constantly moved away from the ridge summit to make way for the new material.
C. This action had to occur along both sides of the ridge summit. The observed twinning now had a mechanism and explanation.
D. As this process continued the ocean floor must widen. Consequently, continents on either side of the ridge summit must move away from each other.

Now think back to Wegener. But, picture the outcome if the sea floor spreading process worked in reverse. As rocks of the oceanic crust move toward the mid-ocean ridge, the continents adjoining the basin would be drawn along. The ocean floor would become progressively narrower. As the two continents move toward each other the oceanic crust is “squeezed” downward and into the oceanic ridge where it once again becomes nothing more than underlying molten material. What eventually must happen to the ocean basin? If the process continues to conclusion, the ocean basin itself must be eliminated when a single larger continent (super-continent) is created out of two smaller continents! If this had happened once upon a time in the Atlantic Ocean, the Americas must have been joined to Europe and Africa! That’s Pangea! Wegener also claimed that Pangea broke up 200 million years ago with newly-formed continents “drifting” away from each other (Figure 17). Furthermore, this motion created the Atlantic Ocean! Here was an explanation for the geologically young age of the oceanic rocks; the oceanic crust had only begun to form 200 million years ago!

As you can see, the diverse nature of the scientific work that occurred during the 1950’s and 1960’s resulted in a better understanding of Earth when scientists began to construct new ideas based on new and reasoned connections. In the late-1960s some of this work was just starting to appear in university textbooks. Although many questions remained unanswered, the pieces of the puzzle were beginning to fall into place.

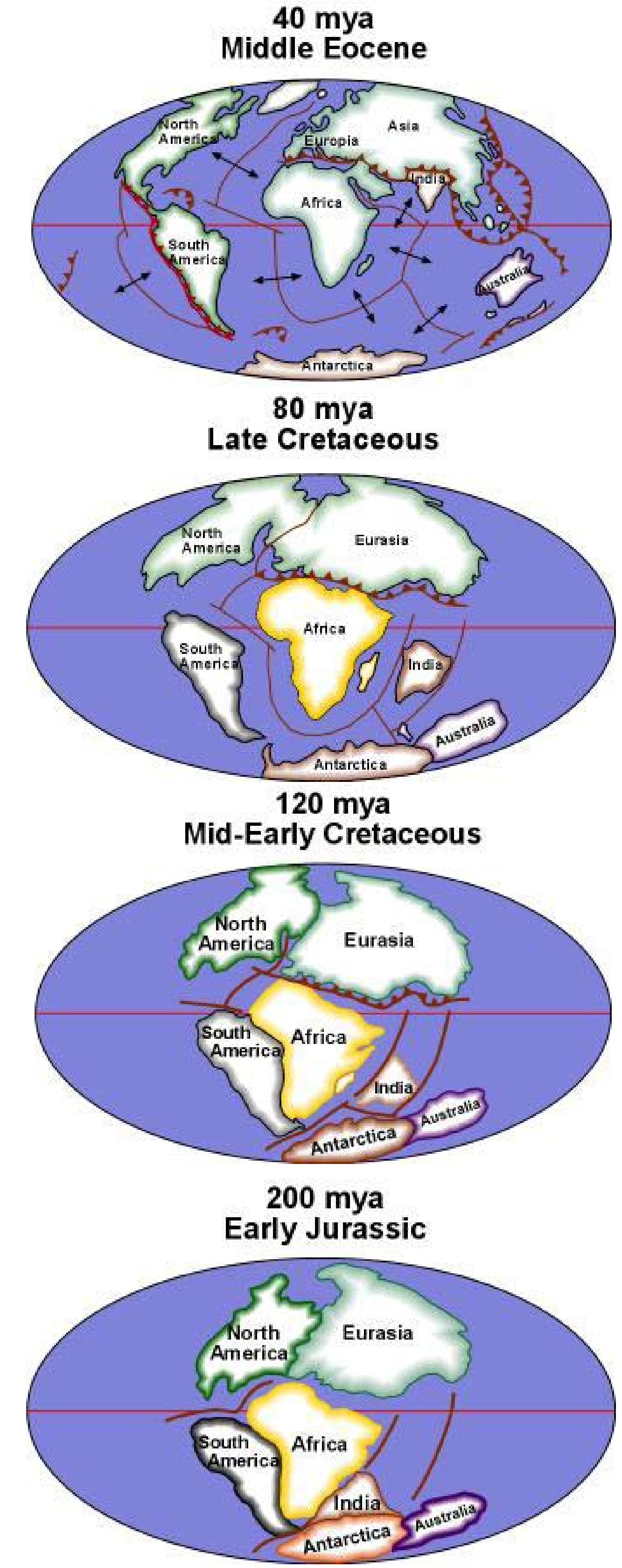


Figure 17

If you have been keeping track, we have yet to address some questions. However, you should be able to answer the following questions by now (Answers to the right!)

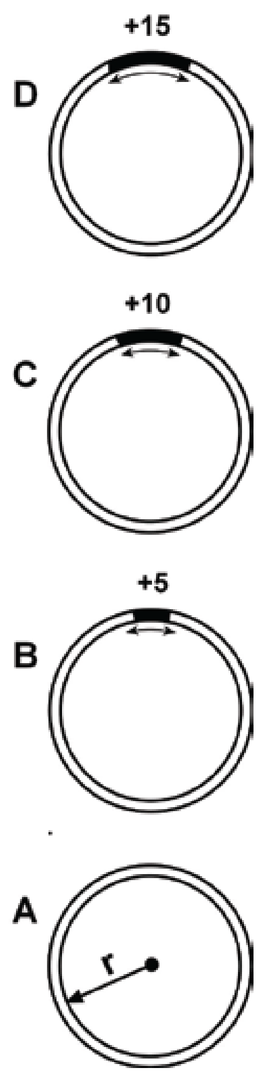


Figure 18

A. What is the significance of the oceanic ridge?
B. Why are the oldest crustal rocks in the Atlantic Ocean only 200 million years old?
C. What is the location of the oldest crustal rocks in the Atlantic Ocean basin?

The process of sea floor spreading was scientifically huge! It explained the systematic variation in the age of the oceanic crust. It explained the symmetry of the magnetic banding of the oceanic crust on opposite sides of the oceanic ridge. In short, magnetic reversals and sea floor spreading had to happen concurrently. However, now that investigators understood new oceanic crust was created at oceanic ridges they were faced with a dilemma. A surprisingly simple but profound one at that! Its answer led to a significant growth in realizing the true dynamic nature of Earth. By modeling Earth's circumference as a simple circle (Figure 18) and working through the following exercise your students can come to understand both the problem faced by the geoscientists and their revolutionary solution.

Earth is an oblate spheroid. Some use the term "egg-shaped". It is flatter at the poles and wider at the equator. For now I'd like you to think of Earth as a spheroid. Some baseline data is required. Assume Earth's equatorial radius ("r" in Figure 18A) is 6,378 kilometers (3,963 miles). What is its circumference? Notice that we are not supplying the answer! Use the provided equation to calculate the number.

In the previous paragraphs we discussed the discovery of newly formed oceanic crust along mid-ocean ridges. Figure 18B illustrates this using the diverging arrows to show that 5 kilometers (83 miles) of new crust have been added to the existing ocean floor along an oceanic ridge. Figures 18C and 18D show the continued formation of oceanic crust that eventually builds up 10 kilometers (6 miles) and then 15 kilometers (9 miles) of new crust along an oceanic ridge. Once again, have your students practice their math skills by calculating the circumference of Earth for each of these new crustal increases. By the way, Figure 18 is not to scale. Showing 5, 10, and 15 kilometers on any figure of Earth drawn to this size would be impractical. Make sure students understand this scale issue.

Now ask this question: "What does the mathematics of Figure 18B, C, and D require Earth to do?" Put another way, what must be happening to Earth as new oceanic crust is added along an oceanic ridge?" The simple answer is extremely problematic and outlandish! As new oceanic crust is added, the circumference of Earth must increase! Are you beginning to see the dilemma?

A. *The oceanic ridge is the birth scar of the ocean. It is were new crust is being formed and placed. The ridge also marks the location (suture) where two continents were once joined.*
B. *Because the first oceanic rocks could only form when Pangea began to split apart 200 million years ago.*
C. *Adjacent to the continental margins.*

Circumference = $2\prod r$

Applied Math—Do the math that scientists had to do to solve a riddle.

Measurement of Earth's size had been going on for a long time so the true nature of the dilemma quickly became apparent. [Modern satellite systems confirm that Earth's circumference is not increasing.] Geoscientists had convincingly shown that new oceanic crust was being added along oceanic ridges but the size of Earth was not increasing. What gives? What processes could negate the seemingly required growth in Earth's size? Before reading the next paragraph can you or your students suggest a meaningful resolution that addresses this dilemma?

The answer is provided in Figure 19. Can you see it? In reality the solution is nothing more than an application of mass balance principles. The fact that Earth's diameter is not increasing must mean that as the volume of new oceanic rocks are being created at an oceanic ridge, an equal amount of old oceanic rocks must be consumed elsewhere. Thus was the idea of crustal subduction born. Geologists explain subduction in these terms–for every volume of new oceanic crust created along an oceanic ridge an equal volume of older oceanic crust must be consumed within a zone of subduction. With this mechanism ridges are the birth place of crustal rock and subduction zones are their graveyard. In addition to all of this, subduction provided an easy explanation for deep sea trenches. Having established what is needed to prevent Earth from expanding and already understanding the process by which new oceanic crust forms as well as understanding where the process takes place, the obvious questions are: "What kind of process would consume old oceanic rocks?" and "Where was this consumption taking place?". Unfortunately two major questions remained unanswered. In fact, they were the very same two questions which had hounded proponents of continental drift for two centuries: (1) Energy: Where is the source of energy to drive the entire process?: (2) Mechanism: What mechanism can be applied to generate the required tensional and compressional forces? The answers had to await new discoveries made by seismologists studying Earth's interior.

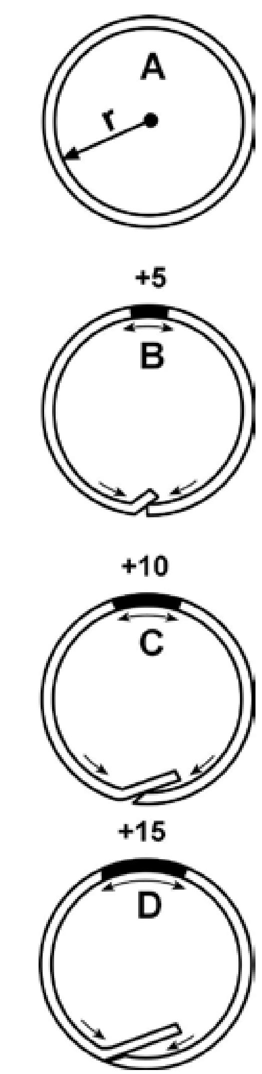


Figure 19

Balancing the creation and consumption of oceanic crust requires an understanding of the forces involved. Along the oceanic ridges there are tensional forces, implying forces that diverge or move away from each other. Now think about this: if a portion of a layer of rock (crust) is being subjected to tensional forces, there must be some offsetting compressional force someplace else. The question is: "Where within Earth's crust are the compressional forces most likely to be found?". A simple demonstration may help you explore the question. Hold your hands horizontally with your palms down and fingertips together. Slowly increase the pressure between your fingertips. Sooner or later, your fingers will begin to "downwarp" under the compressive forces. (OK, some of you contrarians will allow your fingers to upwarp but make them downwarp!) If you keep pushing, eventually one set of finger tips must "dive" beneath the other. What does this simple activity model? The downwarping fingertips simulate the creation of deep sea trenches. One hand diving under the other models a subduction zone. You have also demonstrated that a subduction zone is nothing more than a place where oceanic crust breaks along the margin of a continent and is then forced to dive beneath the continent.

Figure 20 geologically illustrates the formation of a deep sea trench and a subduction zone. Remember that the ocean floor is basalt and the continent is granite. As compressive forces drive the crust and the continent towards each other, the ocean floor, being much thinner and more dense, begins to buckle against the continental granite. First, a trench forms (Figure 20A). At some point the ocean crust will break. The broken oceanic crust continues to be compressed against the continental crust. What are the possible outcomes to this interaction? At first glance, it is common to state that there are three possibilities: (1) the basaltic crust can either be driven straight into, (2) go over, or (3) go under the continental crust. Density tells us which of the three possibilities will occur. (Have you noticed the importance of density to geology and earth science?) The average density of the oceanic crust is about 3.0 g/cm^3. The average density of granitic continental crust is 2.9 g/cm^3. A small but important difference. Can you now see which of the three outcomes is most likely? More dense materials must dive below less dense materials. Geologically, this is why oceanic crust (basalt) is subducted under relatively less dense continental crust (granite) (Figure 20B). An oft-asked student question is: "Why can't continental crust be subducted below oceanic crust?". Density, density, density! Can't happen. A little information can help you more authoritatively respond to student inquires!

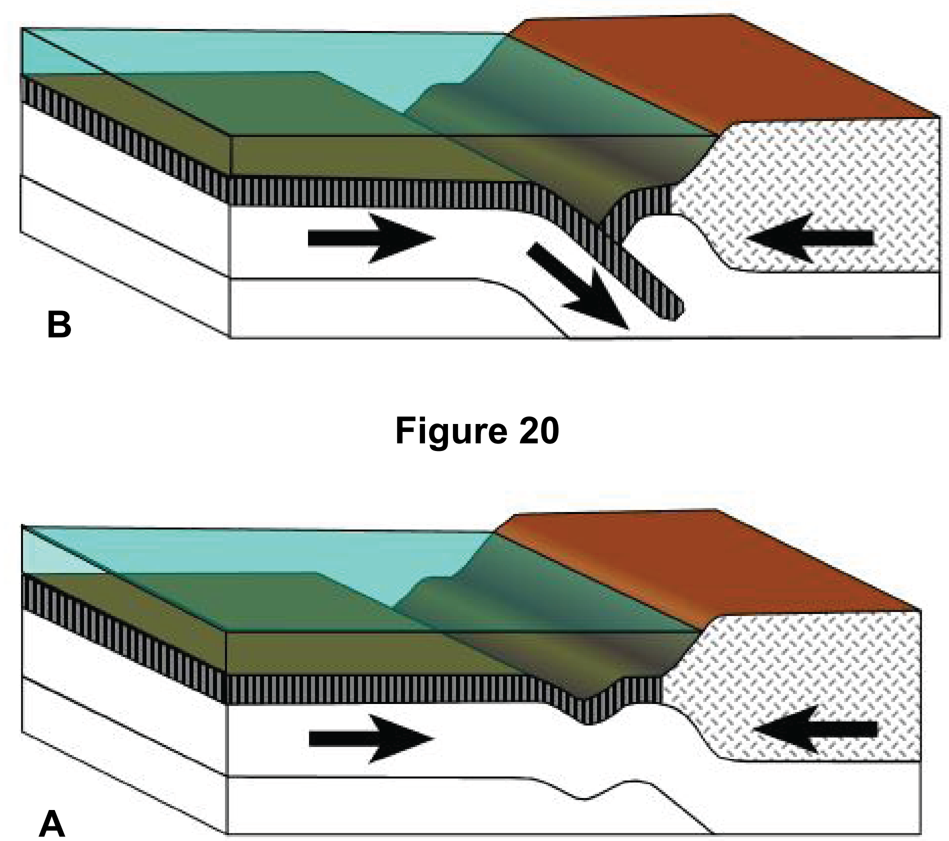


Figure 20

Compressive force pushes.
Tensional force pulls.

Continental crust is granite with average density of 2.9 g/cm^3.

Oceanic crust is basalt with average density of 3.0 g/cm^3.

Density rules their interaction!

Density and heat (energy) are related.

ROAD TO PLATE TECTONICS

STEP 5: SEISMOLOGICAL RESEARCH

Crustal rocks are brittle. Just from common usage, you would expect brittle materials (including rock) to break when subjected to some external compressional or extensional force. You can demonstrate the brittle nature of crustal rocks very easily with a hammer! This brittle material is called the lithosphere and includes both continental crust and oceanic crust and the top most part of the mantle (Figure 21).

Seismologists study Earth's interior by measuring the velocities with which shockwaves travel through the Earth. These earth scientists first identified the threefold internal structure (core, mantle, crust) of Earth you learned in elementary school (Figure 22). During the ten years of 1955-1965, scientists also discovered that the mantle was not brittle. It is plastic. They named this plastic layer the asthenosphere (Figure 21). What does plastic mean? First of all, it does not mean what you think it means. In today's vernacular usage the term "plastic" is a noun used to describe a material used to make something. Daily we use plastic wrap, we drink from plastic cups, and most of our cars are now made from plastic. To a geoscientist plastic is a adjective. It refers to the property that allows a solid material to act like a liquid. What do liquids do that most solids do not? They flow without breaking.

Let us apply the most simple of explanations to the complexity of what the seismologists accomplished. Scientists knew that waves travel through objects of differing density and rigidity at different speeds. For example, they knew that some types of waves travel through solids and liquids at different rates. Seismologists applied this knowledge to use seismic waves generated by earthquakes and atomic bomb testing to examine Earth. They used the premise that as the rigidity of a rock decreases (it becomes more fluid like) the velocity with which the seismic waves travel through it slows. Thus, differences in the rigidity of rocks should be reflected by their ability to conduct seismic waves through Earth's interior. It was the slowing of observed seismic waves travel times through this previously unknown part of the mantle that allowed seismologists to identify its presence. Basically, the rocks within the asthenosphere are solids acting like liquids.

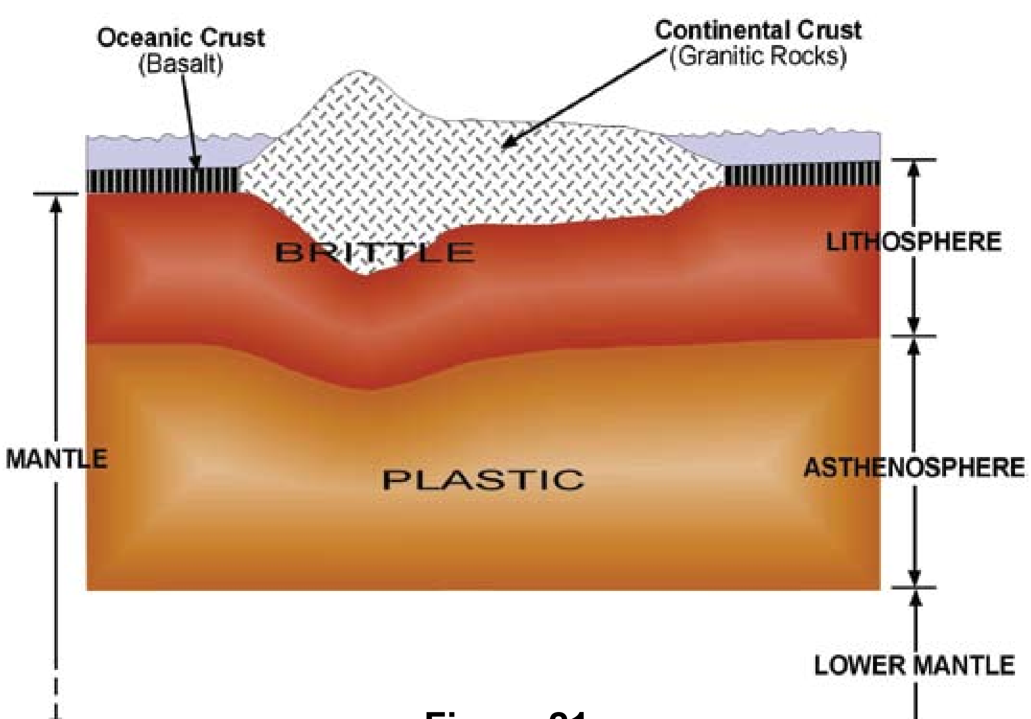


Figure 21

When geologists learned there was a layer beneath the crust that could flow, they resurrected and began modifying a more simplistic idea (Figure 23) set forth by a disciple of Wegener. In 1924, a geologist named Holmes was still promoting continental drift. Holmes suggested that heat derived from Earth's interior could be the elusive energy source for which everyone was hunting. He then took this idea one step further by suggesting that the rising magma of a heat-driven convection cell located under a continent would spread out laterally under the continent. The tensional forces involved and produced by the convective motion would stretch and tear the overlying continent apart.

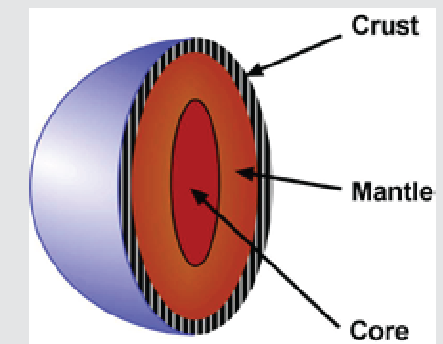


Figure 22

Actually it is rigidity that determines wave velocity because rock rigidity and density increase with depth.

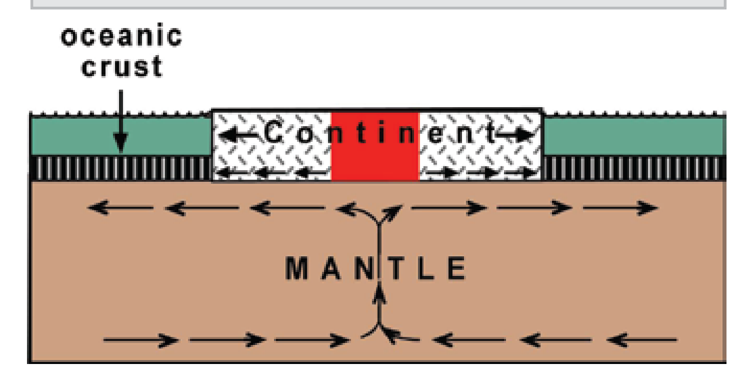
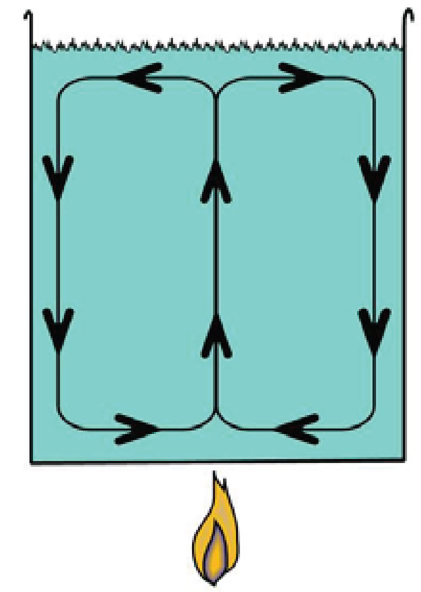


Figure 23

Holmes was using a well known phenomena which can be easily modeled using a beaker of water. When heat (energy) is applied to a beaker of water (Figure 24), the temperature of the water over the heat source increases. This mass of water becomes more buoyant than the surrounding water because its density decreases as its temperature increases. Increased buoyancy drives the hot mass of water to the surface where it encounters the water-air interface. Here it can only move outward. As the warm water moves outward it begins to cool. With cooling comes an increase in density and a loss of buoyancy. As a result, the water now begins to sink. At the bottom of the beaker the sinking water encounters the heat source. As it warms it begins to once again ascend, completing the loop. The completed cycle of movement is called a convection cell. Holmes extrapolated the basic direct relationship of temperature-to-density of heated water to explain the movement of a continent. It all seemed so simple. But, Holmes' proposal was soundly rejected by almost everyone. Why? Because in 1924 everyone thought that the mantle was made of brittle rocks and that brittle materials cannot possibly flow.

But with new ideas and new discoveries came acceptance. In the 1960s, geologists had a thick layer of rocks that could flow because the rocks were plastic! Could heat from within Earth's interior be the source of energy that had been sought for centuries? Could heat-driven convection cells within the asthenosphere be the mechanism that allows the energy source to be applied to do the job of rifting the continents? The answer to both questions was a resounding "yes".



Single Heat Source—Single Convection Cell

Figure 24

Why is the plastic molten material of the asthenosphere rising and falling? We know that its temperature is a function of Earth's internal heat. We also know that heat and density are related. As the molten material gains heat it is also gaining energy. This energy gain increases molecular motion within the molten material. Increased movement translates into increased volume of occupied space. Because the same mass of material is now a larger volume it is now less dense. As it becomes less dense relative to its surrounding it must rise to establish equilibrium either by losing heat as it rises and cools or by reaching a zone of compatible temperature. If the magma cools it must become more dense as its volume shrinks. At some point it will become dense enough to begin sinking. This process creates the continuous loop of the convection cell. You will find many different opinions about these features because geologists have yet to pin down the actual mechanisms and locations of plate tectonics convection cells. Remember, plate tectonics is a theory and theories are always ripe for improvement as more data leads to better understanding.

Road to Plate Tectonic Theory
Step 1: Nature of the Ocean Floor
Step 2: Paleomagnetism
Step 3: Absolute Age of Earth's Crust
Step 4: Theory Development
Step 5: Seismological Research
Step 6: Study of Earth is Changed

ROAD TO PLATE TECTONICS
STEP 6: STUDY OF EARTH IS CHANGED

The journey along our road to the theory of plate tectonics is nearly complete. We hope the discussion and thoughts will provide new ideas on how to introduce plate tectonics to new learners or encourage you to want to know more about it. We have shown that the discoveries and observations of different scientific disciplines were integrated to develop an encompassing plate tectonic theory. If you are a science teacher it should be apparent to you that density is one of the most important integrating concepts used by all Earth investigators.

Before we go any further, how about a quiz of sorts? Could you create a sequential illustration demonstrating what would happen to brittle lithospheric rock sitting on top of the relatively warmer and plastic material associated with an asthenospheric convection cell? Does your image look something like Figure 25 Now for the hard part; can you explain your illustration? Hopefully it will read something like this:

> The hotter asthenospheric material is forced to move laterally under the continental lithosphere (Figure 25A) within a convection cell. This motion provides the mechanism and energy required to split the overlying brittle continental lithosphere which is composed of granite. The location of the split is preserved as a mid-oceanic ridge (Figure 25B). With time, the continental masses move away from each other as new lithospheric rock (basalt) is emplaced along both sides of the mid-ocean ridge. As the oceanic basalt moves away from the ridge it begins to cool and become more dense causing it to begin sinking. This sinking motion, located near the continental margin, initiates the down-going portion of the convection cell (Figure 25B). A deep sea trench is formed and a zone of subduction will begin to consume the old descending oceanic floor. Once the descending material reaches the bottom of the asthenosphere, it will once again begin to warm from energy supplied by Earth's internal heat. With warming, the plastic material will begin to rise. A complete asthensopheric convection cell and the motion of tectonic plates and continents is realized using the related principles of density and heat.

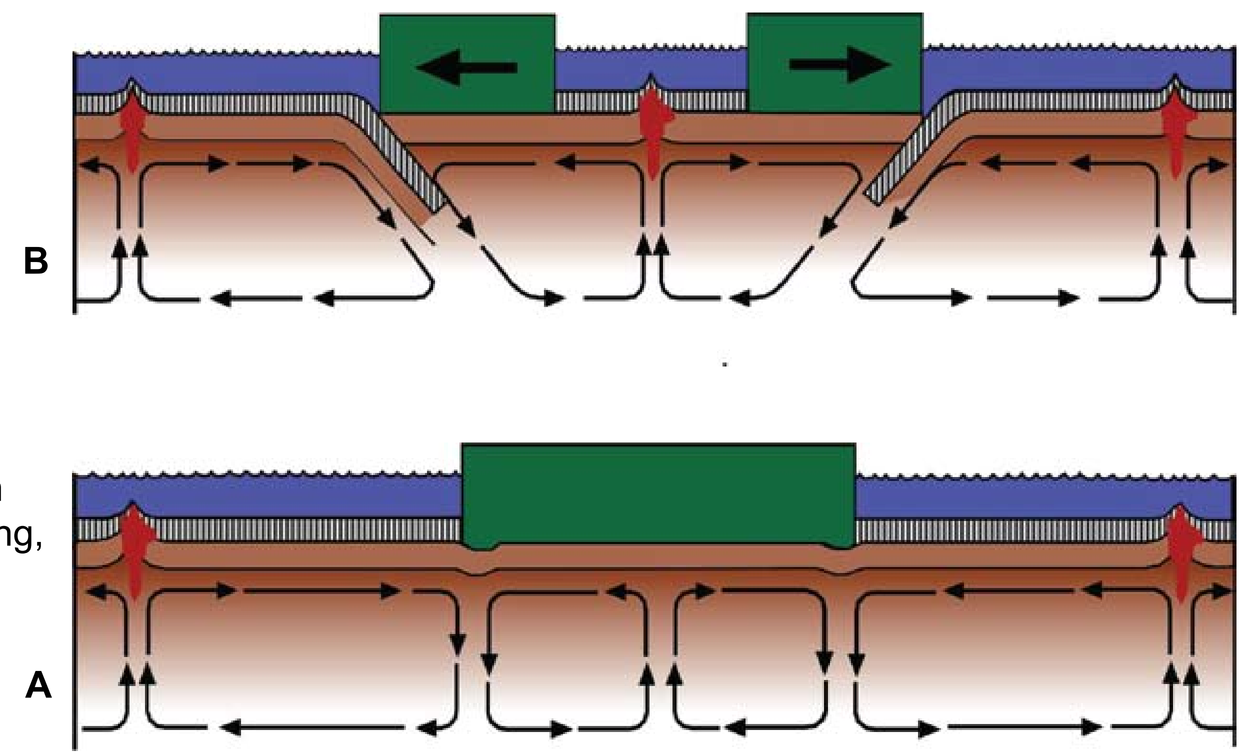


Figure 25

Heat was prominently mentioned in the previous paragraph because the transfer of heat is an important component of a convection cell. Heat moves from hot to cold. Obvious, you might say. However, can you provide even a rudimentary scientific explanation for why and how? Consider a cup of coffee that is too hot to drink. What do you do? You wait until it "cools off". Why does it cool? Because the concentrated heat energy within the hot coffee dispersed into an environment of lesser heat energy seeking equilibrium. The heat moved from hot to cold. Now consider a glass of your favorite cold beverage. Why do you drink your cold beverage relatively fast? Because it will warm up! Why will it become warm? Because heat from the hotter room air moved into the cold beverage. Note that in both cases, heat flows from hot to cold. Now let's apply density and heat flow to a brief discussion of plate tectonics.

Can you explain what you have been reading?

Part of the Second Law of Thermodynamics requires energy systems to increase their entropy through heat flow from a higher-temperature region to a lower-temperature region, but not the other way around. In other words, heat can flow from cold to hot only when energy is provided to the system. For example, you can use a stove to add energy to water to make it boil.

Let's look at Figure 26. Can you tell us what is the meaning of the "T's" and "C's"? Where would temperature and density changes to molten rock occur? Can you isolate the motion of a single convection cell? Finally, can you relate the movement of numerous tectonic plates, the creation and destruction of continents and oceans, and location of older versus younger lithospheric basalt to this diagram?

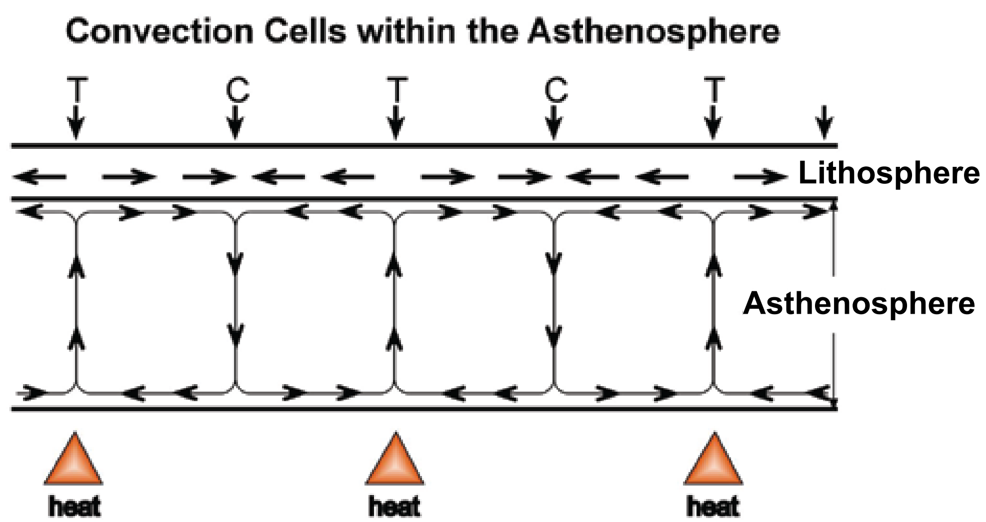


Figure 26

According to the theory of plate tectonics, the mechanism that drives tectonic plates is the presence of heat-driven convection cells within the plastic asthenosphere. These cells create both tensional and compressional forces that physically act upon the overlying, and brittle, lithosphere. Tensional (T) forces develop in those areas were the plastic material of the asthenosphere is forced to travel in opposite directions. This would occur, as you can see, where upward molten magma impacts the base of the lithosphere. The next question is: "What actually creates the forces that pull apart (rift) the overlying lithosphere?" The energy required to rift a continent, or drive two continents together to make a single larger one, is generated by a zone of friction located at the interface between the flowing asthenospheric magma and the base of the lithosphere. When exposed to such forces, the brittle rock of the lithosphere has only one option–to rift. Frictional forces also play an important role where the downward components of two convection cells meet. Here, as cooling plastic material is forced together in preparation for descent back into the asthenosphere, friction generates compressional (C) forces. It is at such locations that continents can be driven together to form super-continents.

This is a good time to look back and see why the pre-plate tectonic theory scientists were having problems with continental drift. The basic problem was that everyone at the time thought that the movement of continents only involved crustal rocks. Even back then they knew the crust was brittle. As such, they could not provide a mechanism by which brittle continental crust could move through brittle oceanic crust. Wegener, for example, used a ship analogy. He visualized the oceanic crust parting like the water in front of the bow of a ship as the continental crust plowed forward with the oceanic crust closing up behind the moving continent. Obviously, he was never able to find any proof for his idea because that's not what happened.

In the middle to late 1970's plate tectonics began to appear in textbooks as a workable theory by providing answers to the lingering problems of mechanism and energy. To this day, the theory is being refined and improved as we learn more. However, one troublesome problem persists. Namely, how do the rising portions of the asthenospheric convection cells become located beneath a continent? We don't know. Furthermore, nobody yet knows exactly what is going on within Earth's interior. Having provided that caveat, let us propose a plausible idea. We know that heat is constantly rising from Earth's interior. We know that some of this heat energy, upon reaching the surface, is radiated into space. We can accept the idea that the insulating properties of the continental crust would reduce the rate at which heat would pass through the continental crust. In fact, this rate would be significantly less than the rate at which it passes through the thinner oceanic crust. (Think of the heat conducted through a well insulated house attic versus an attic with much less insulation.) This would allow heat energy to accumulate within the asthenosphere located below a continent. In turn, this would produce a localized increase in temperature and a required decrease in density. This could explain the relationship between rising portions of a convection cell and the overlying continent. It might also

Relationship between density and heat flow can explain flow of plastic rock in astheno-spheric convection cell.

Tensional force vs. compressive force in convection cell.

How to split a continent!

How to build a super-continent!

Original problem with continental drift—energy and mechanism—solved.

Why is convection cell under a continent?

explain how convection cells are initiated within the asthenosphere. We must remind you that, at this point in time, these ideas are mere speculation. The exciting aspect of the development of plate tectonics is the fact that a workable model can now be applied to explain data and observations and that these data and observations can be applied to the development of a workable model. An inductive approach can now work in concert with deductive science. Now, before we end, let us provide a summarized explanation of plate tectonics. Much of this is repetitious but it is a good review and may help place organized component ideas within their conceptual framework.

Brief summary of plate tectonics.

How to make an ocean.

Earth requires balance of mass and volume.

Plate tectonics runs on heat energy derived from within Earth. The plates are being driven by forces generated by friction produced when plastic asthenospheric rock moves against brittle lithospheric rock. Tensional forces are generated when the convection cell generates oppositely-directed components of motion. This energy is used to initiate the rifting of the granitic continental lithosphere and any associated continent (Figure 27A). With time, as the continent is broken apart, the intervening rift area grows ever larger and becomes a rift valley (Figure 27B). In time one end of the rift valley could reach the sea and become flooded (Figure 27C). This would form a long, narrow linear ocean connected to the open sea at one end but still land-locked at the other, like the Red Sea (Figure 28). Would this linear sea exist for geologic time? Not as long as the underlying convection cell remained active! If rifting continued, the land-locked end would be breached signaling the opening of a new ocean. Where the split had originally begun would now be underwater. Since it is now underwater, it would be a mid-ocean ridge marking the location of newly created basalt-rich oceanic crust. This simple model provides explanations for ocean basins and mid-ocean ridges. Simultaneously, different events are taking place on the other side of the plate. Compressive forces caused by the descending portion of the convection cell produce a deep sea trench. Ultimately a zone of subduction forms where old oceanic crust descends into the asthenosphere and is consumed. This transfer maintains the balance between the volumes of asthenospheric material and lithospheric rocks.

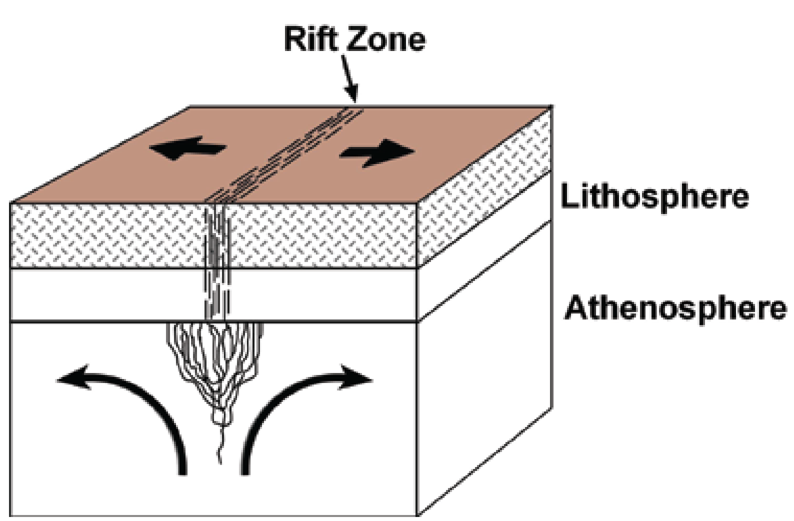


Figure 27A

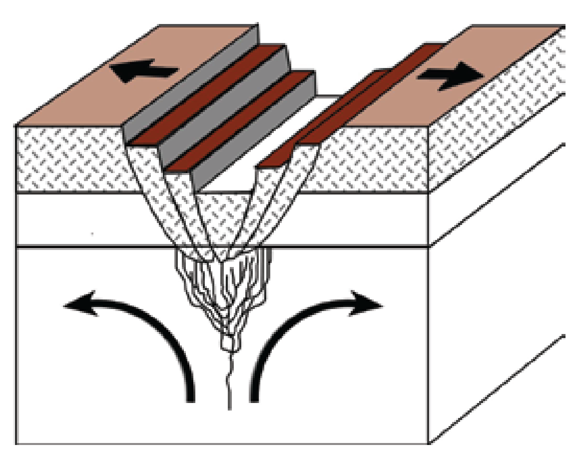


Figure 27B

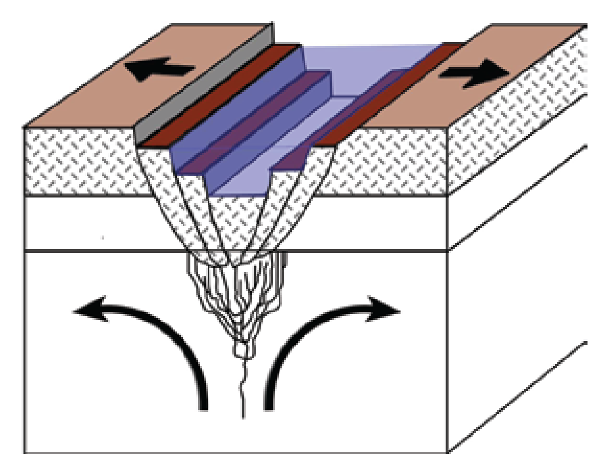


Figure 27C

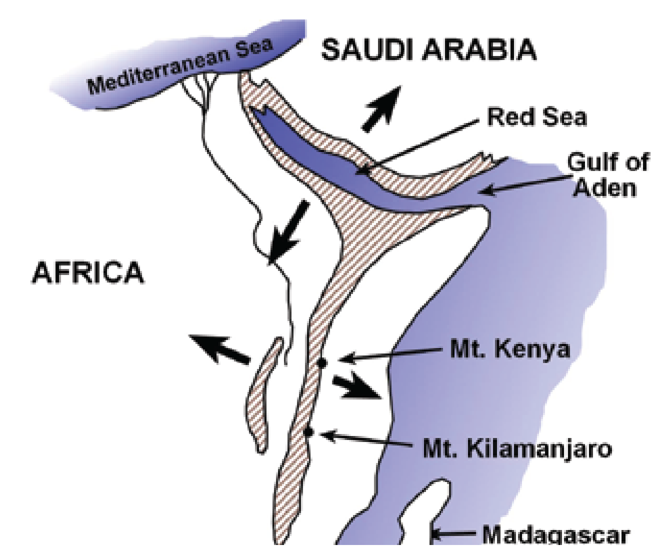


Figure 28

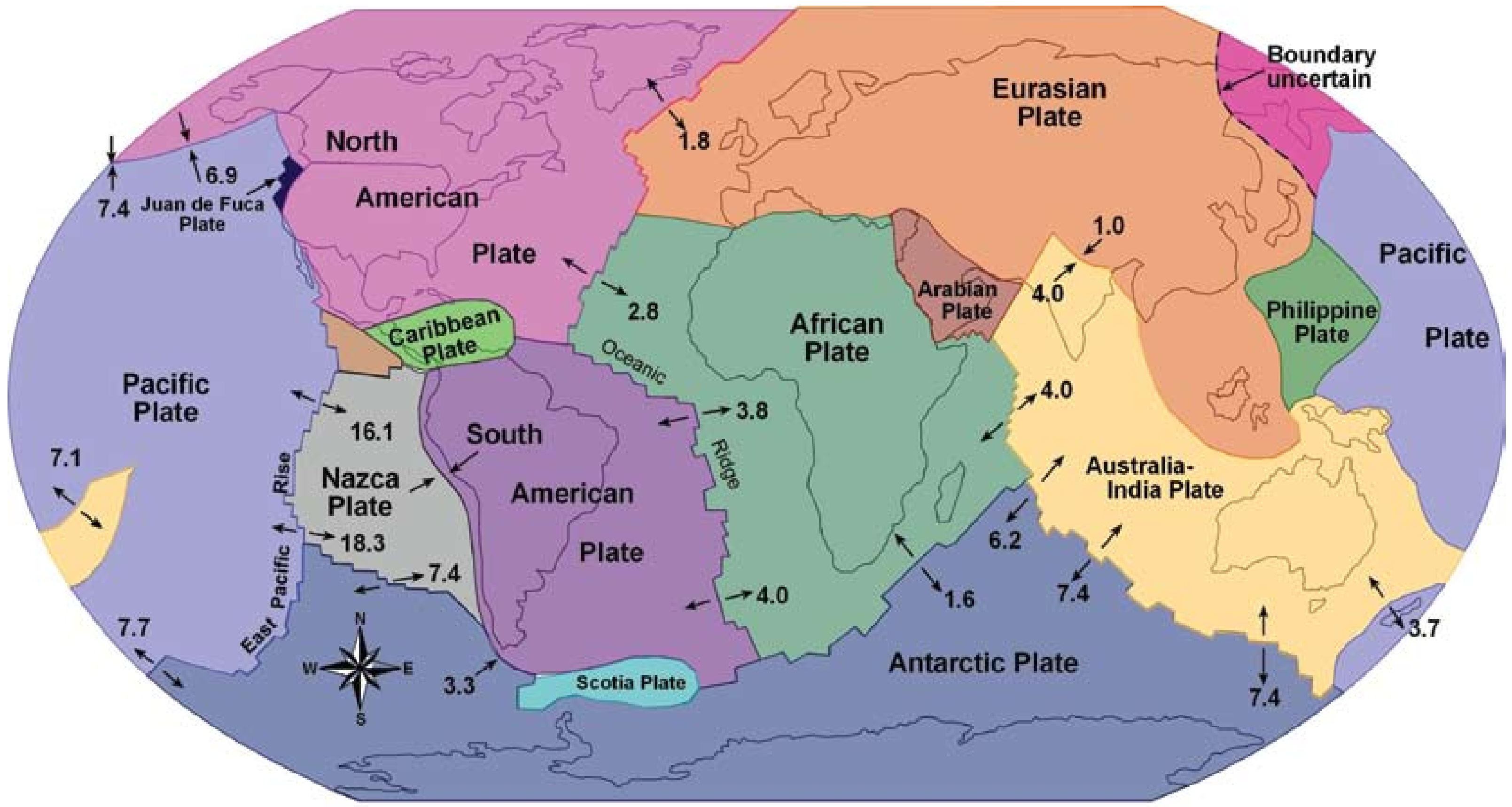


Figure 29

The combined result of the just described processes has broken the lithosphere into approximately a dozen plates (Figure 29). Some of the plates, such as the African and the North American plates are quite large. Others, such as the Carribean plate or the Juan de Fuca plate off the coast of Washington and Oregon are quite small. The boundaries between adjacent plates mark the location of geologic processes such as geologic events ranging from earthquakes to mountain building. The plate motions occurring at these boundaries explain the why, how, and where of geologic processes such as earthquakes and mountain building.

Two plates being pushed apart because of the underlying convection cell create a divergent plate boundary or margin. Can you find divergent margins in Figure 29? Hint: Use the arrows. On the other hand, convergent plate margins reveal locations where plates are being forced toward each other in response to the downward moving portion of an underlying convection cell. Can you find the convergent margins in Figure 29. Convergence can cause one plate to "dive" under the edge of another plate, creating a zone of subduction. In turn, the subduction zone is where lithospheric rock is forced downward into the asthenosphere where it melts and is recycled by the upward moving portion of the convection cell. Understanding this process allows you to respond to a lingering unanswered question: Do we now understand what happened to all of the oceanic crust that formed prior to 250 million years ago? Yes, all of it was consumed in zones of subduction!

The arrows on Figure 29 provide some idea of individual plate velocity. Remember that velocity is a vector term providing both speed and direction. The number associated with each arrow indicates the plates average annual motion in centimeters at that location. A good classroom exercise is to ask your students to average all of the plate movement data presented in Figure 29. Their calculations should indicate an overall average movement of 2.5 centimeters per year; about the same speed at which their fingernails grow. Using this average figure, calculate how long it has been since Europe and America were joined. In other words, calculate the age of the Atlantic Ocean!

Reason why no ocean crust older than 250 million years—it has been consumed by subduction zone.

divergent = tensional forces
convergent = compressive forces

Students often ask if the tectonic plates are being pushed or pulled by the convection cell. Earth scientists have been debating this ever since convective cell induced motion was accepted. Remembering that the collective scientific "we" (including us) really don't know exactly what goes on deep within Earth. Figure 30 illustrates three different possibilities:

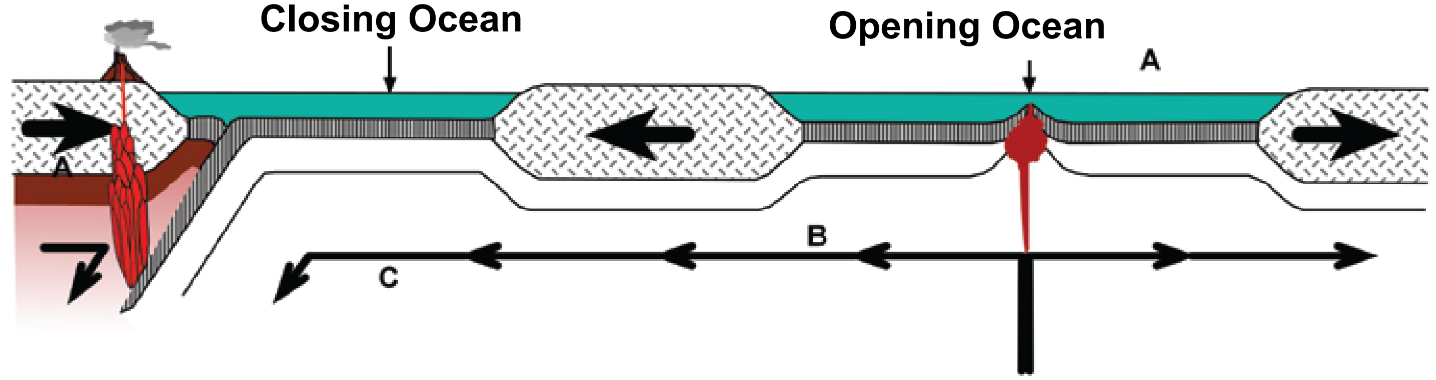


Figure 30

A. PUSH: caused by the combined upwelling of magma and subsequent formation of new oceanic lithosphere along the summit of the oceanic ridge.
B. FRICTIONAL DRAG: imposed on the base of the plate by the lateral movement of the underlying asthenospheric rocks.
C. PULL: exerted on the subducting portion of the plate as the underlying asthenosphere cools, increases in density, and sinks under the increased effect of gravity.

Of the three, which is most important? We do not know exactly. But most scientists agree that all three are probably involved although our gut feeling is that drag is perhaps the most important of the three.

We would like to make one last point. Actually, we would like to put to rest a surviving misconception. When Wegener introduced the term "continental drift" he envisioned continents actually moving through the ocean crust. But you can now see that Wegener could not come up with a mechanism by which such an event could happen. Now we understand why–the continents are not moving. It is the plates that are moving! Continents are simply being carried along as passive passengers as the lithosphere moves from the oceanic ridge to the subduction zone. To illustrate this point ask your students to mentally picture the moving sidewalks now common in airports. The sidewalk is simply a conveyor belt that rises out of the floor, moves down the hallway, and disappears back under the surface of the floor only to re-appear at the other end. As you step onto the conveyor belt you are carried from one end to the other. But are you walking? No you're not! You're just standing there. Through no action of your own you are carried along. Another example is the belt at your local supermarket. Is your bag of cookies walking away from you? No, it is just riding along on the moving belt.

One of the major discoveries of the theory of plate tectonics was the fact that the continents were not plowing through the oceanic crust. Rather, they were being carried along as part of the lithosphere as it moved from the oceanic ridge where it was being created to the zone of subduction where it was being consumed. In essence, a global moving sidewalk! What does all of this mean? It means that there is no such thing as continental drift!

If you want to demonstrate the role time plays in moving plates, have your students calculate the distance a continent can move if it is riding atop a plate moving 2 cm per year for one million years, 10 million years, and 100 million years.

Continental drift is not a theory.

Look at Figure 31A. An ocean containing a zone of subduction is a closing ocean. In other words, as two continental pieces approach each other the ocean shrinks as its crust is consumed by the subduction zone (Figure 31B). Pause for a moment to consider what would happen if the ocean between two continents completely closed? How would the passively riding continental masses interact once they collide? To a geologist this is a collision even though the movement is slow enough to be measured in centimeters per year. The most important aspect of the motion is its time duration. A little movement over millions, or even hundreds of millions of years, adds up to a lot of distance covered. Once again, what might be formed by a continent-to-continent collision? We have presented all of the evidence you need to suggest a plausible outcome. Can you do so? Or, is this a time for review?

The key to responding to the situation posed in the previous paragraph is, once again, the effects of force and density. By now, you should know that continents are predominately composed of granite. As a result, the average density of Earth's major continents is the about 2.9 g/cm^3. Using this tiny piece of data, what would happen if two continents were driven together by the convectional motion applied to their respective plates? First, the force being applied would be compressional. Second, if two masses of equal density are compressed together subduction is usually not an option. This leaves us with the best alternative explanation–the buckling, breaking, and upheaval of the continental edges where the continents are being compressed together (Figure 31C). Guess what, you just unveiled a simple, but elegant, explanation for mountain building!

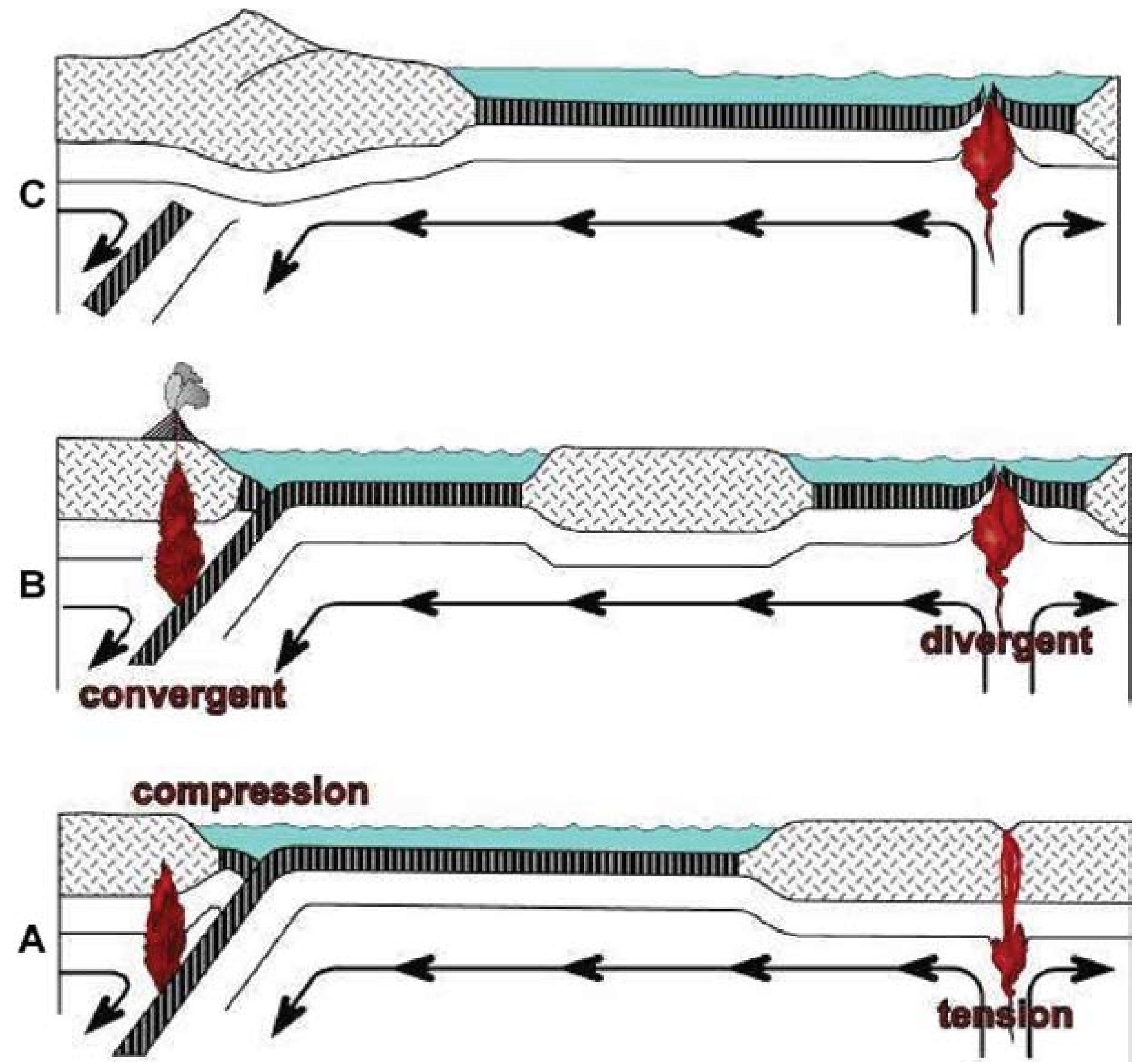


Figure 31

Can you explain how two continents could collide? What would be the result?

Tensional forces produce divergening plates. Divergence is responsible for splitting continents, producing relatively young ocean floor, and creating new ocean.

Compressive forces produce convergen-ing plates. Compression is responsible for closing ocean, consuming relatively old ocean floor, and colliding continents.

How to build a mountain.

Final Thoughts

Do continents drift? Are you now more confident in answering the question posed in the title of this book? Do you feel more comfortable explaining continental movement within its proper perspective relative to continental drift? Can you explain why continental drift is not a theory and why plate tectonics is a theory?

Until plate tectonics came onto the scene, I never understood how the Rocky Mountains or the Appalachian Mountains formed. For that matter, where ocean basins came from was also a mystery. Looking back at pre-plate tectonic textbooks I am entertained by the ambiguous ideas and descriptions used to explain mountain building. But, I did not know any better back then! Now we geoscientists know the Appalachian Mountains are nothing more than a by-product of a continent-to-continent collision. What is even more interesting is the fact that plate motion and mountain building is dynamic and continuous. As inhabitants of Earth, we live with it. For example, the Alps of Europe are rising right now in response to the approach of Africa. As grand as they are now, they will be even more spectacular when continental Africa physically collides with continental Europe. And then there are the Himalaya Mountains, in my opinion the best dynamic example of plate tectonics.

Amazing change in my lifetime as a scientist.

At this point allow me to challenge you to find ways in which physics, chemistry, physical science, and mathematics lessons can incorporate asthenospheric convection cells, lithospheric brittleness, and plate tectonics mechanics. By now you should have come to understand the ways in which density and heat flow can be used to draw together aspects of different disciplines. These simple concepts can provide the structure your integrated science unit requires.

In this presentation our goal was to help you become familiar with the foundational knowledge required to teach plate tectonic theory to your students. Much as you would do in your own classroom, repetition has been used to drive home important ideas, concepts, and principles and we have glossed over details and omitted many ideas because we value a conceptual understanding more highly than an overwhelming presentation of disparate facts.

Geology integrates all sciences and math to explain Earth.

Additional Materials

Visit the Geoscience Education page of the West Virginia Geological and Economic Survey's website at *http://www.wvgs.wvnet.edu/www/geoeduc/geoeduc.htm* to review or download the following free material:

Future editions.

1. Pangea Redux. Located within the Published Activity Ideas section.

2. Plate Tectonics and Plate Tectonics for Beginners in the Plate Tectonics, Geologic History, and Depositional Environments (PowerPoint Presentations) section.

3. Relative Age Dating #1 and Relative Age Dating #2 in the Animations and Videos Section.