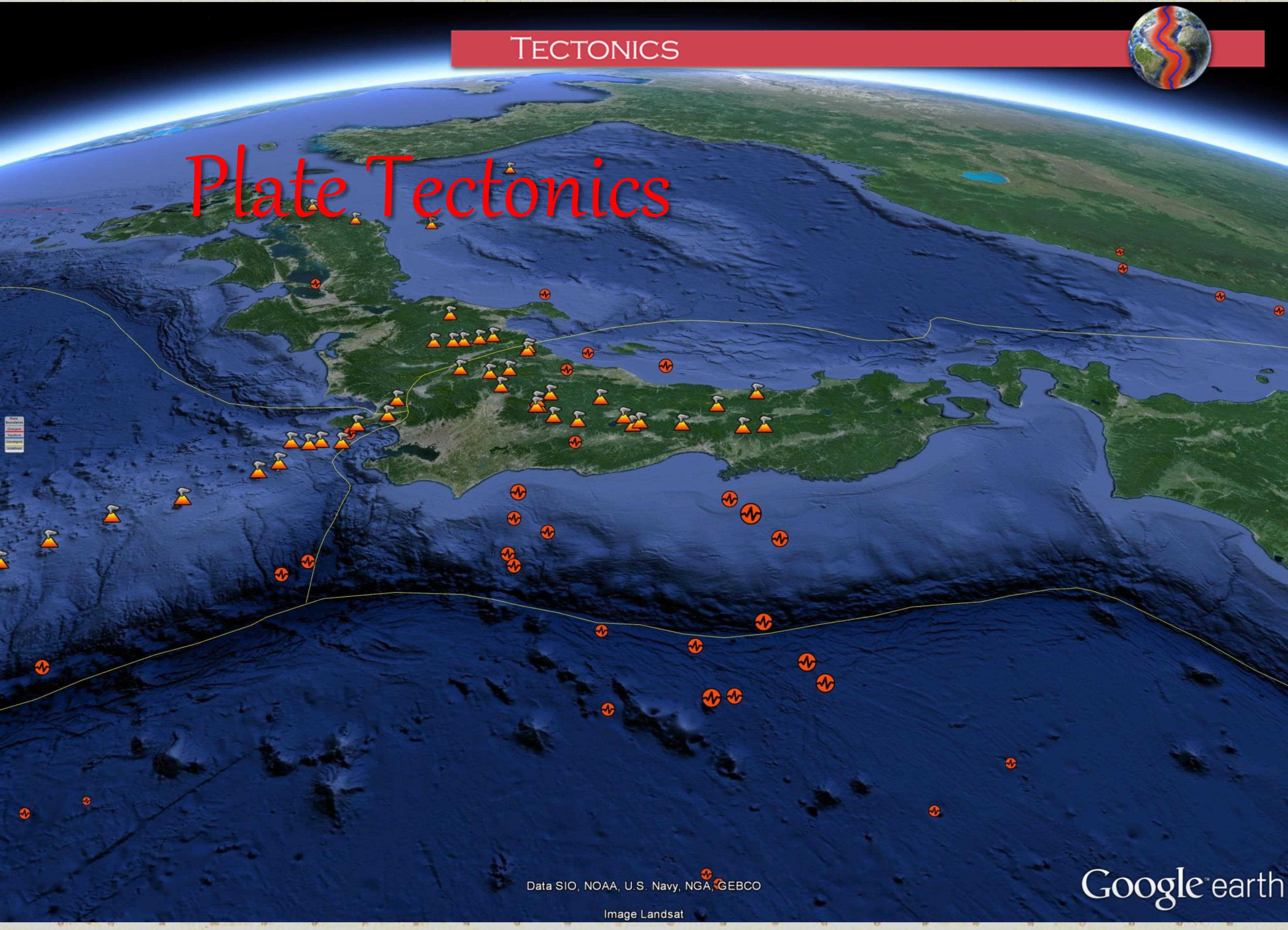
TECTONICS

Plate Tectonics



Learning Objectives

To understand the earthquakes, volcanic eruptions, and hazardous landscapes will will study the rest of the semester, we must first understand the background cause for them – plate tectonics.

Your goals in studying this chapter are to:

- Understand how Plate Tectonics theory was developed.
- Understand what features on Earth were created by plate tectonics.
- Understand the structure of Earth's interior and tectonic driving forces
- Understand how plates move and interact with one another.
- Understand the geologic features at each type of plate boundary, and how these relate to hazards.
- Understand what hot spots are and what features they form.

USGS

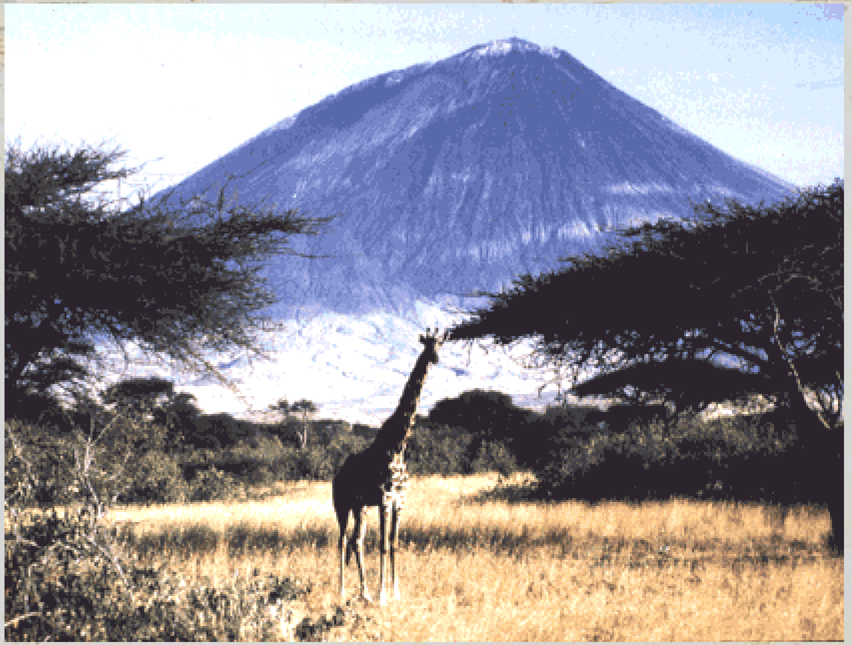
This document was supplemented and modified by faculty of Brigham Young University – Idaho.

Preface

In the early 1960s, the emergence of the *theory of plate tectonics* started a revolution in the earth sciences. Since then, scientists have verified and refined this theory, and now have a much better understanding of how our planet has been shaped by plate-tectonic processes. We now know that, directly or indirectly, plate tectonics influences nearly all geologic processes, past and present. Indeed, the notion that the entire Earth's surface is continually shifting has profoundly changed the way we view our world.

People benefit from, and are at the mercy of, the forces and consequences of plate tectonics. With little or no warning, an earthquake or volcanic eruption can unleash bursts of energy far more powerful than anything we can generate. While we have no control over plate-tectonic processes, we now have the knowledge to learn from them. The more we know about plate tectonics, the better we can appreciate the grandeur and beauty of the land upon which we live, as well as the occasional violent displays of the Earth's awesome power.

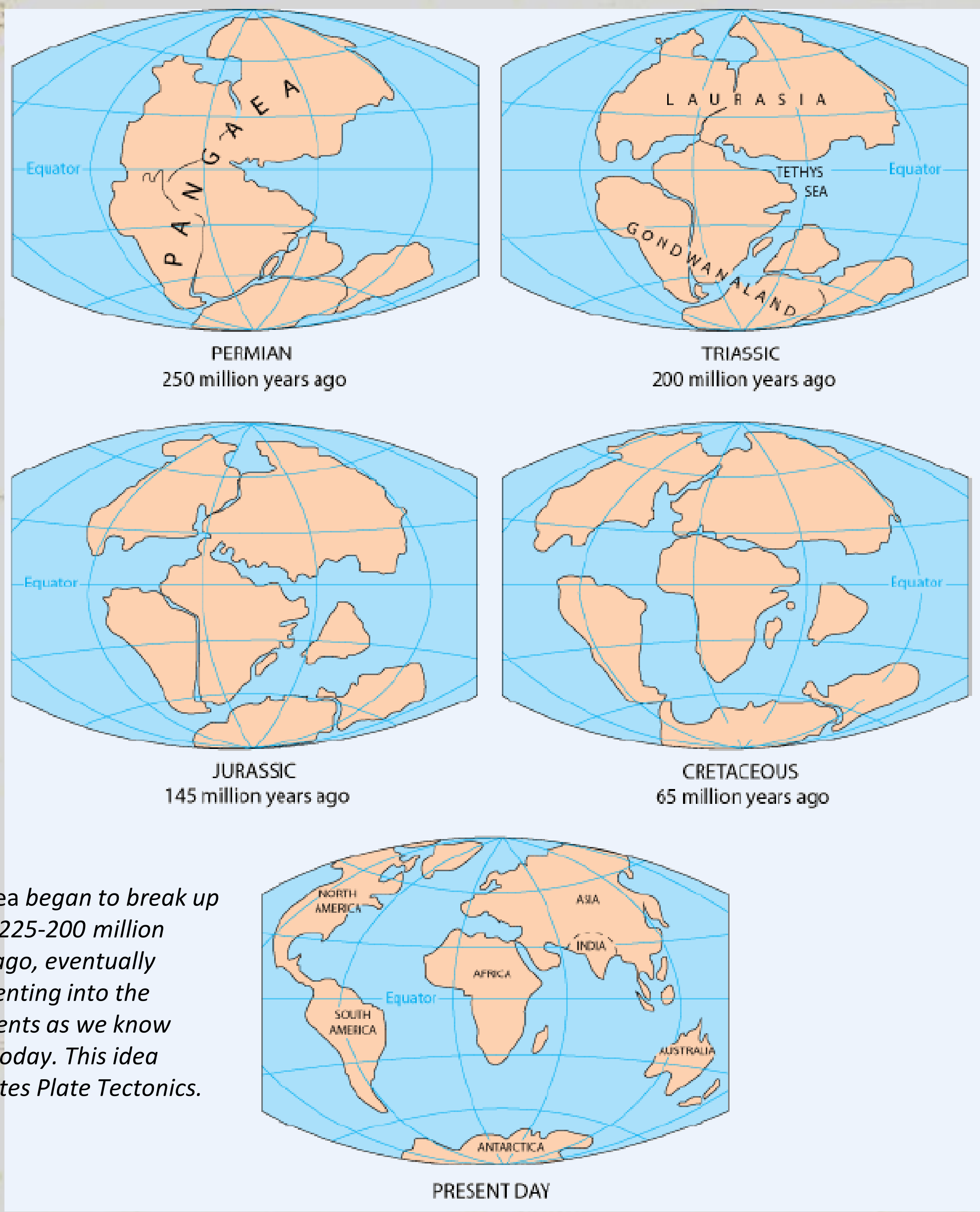
This booklet gives a brief introduction to the concept of plate tectonics and complements the visual and written information in *This Dynamic Planet* (see Further reading), a map published in 1994 by the U.S. Geological Survey (USGS) and the Smithsonian Institution. The booklet highlights some of the people and discoveries that advanced the development of the theory and traces its progress since its proposal. Although the general idea of plate tectonics is now widely accepted, many aspects still continue to confound and challenge scientists. The earth-science revolution launched by the theory of plate tectonics is not finished.



Oldoinyo Lengai, an active volcano in the East African Rift Zone, where Africa is being pulled apart by plate-tectonic processes. (Photograph by Jorg Keller, Albert-Ludwigs-Universität Freiburg, Germany.)

Historical Perspective

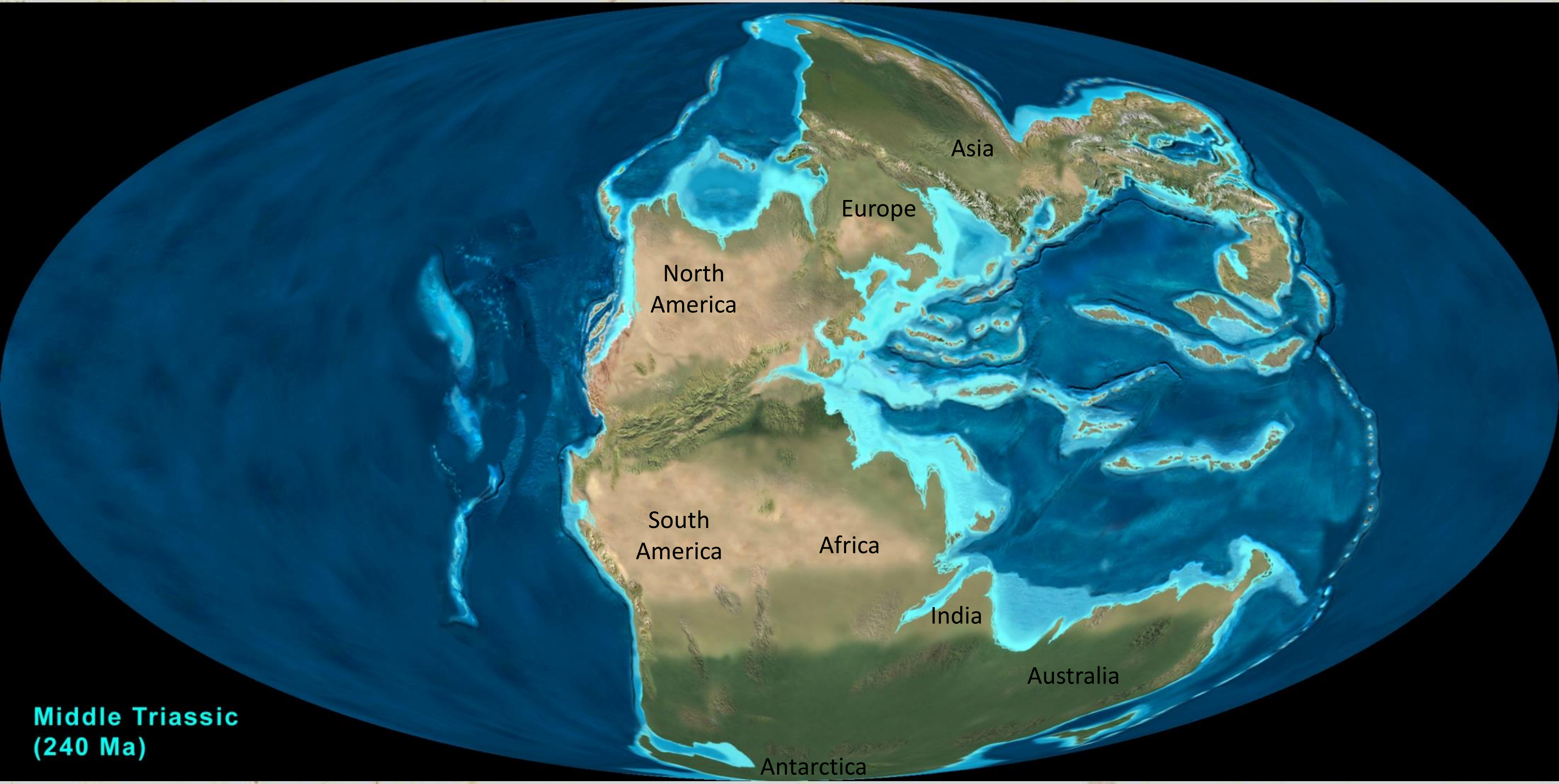
In geologic terms, a ***plate*** is a large, rigid slab of solid rock. The word ***tectonics*** comes from the Greek root "to build." Putting these two words together, we get the term *plate tectonics*, which refers to how the Earth's surface is built of plates. The *theory of plate tectonics* states that the Earth's outermost layer is fragmented into a dozen or more large and small plates that are moving relative to one another as they ride atop hotter, more mobile material. Before the advent of plate tectonics, however, some people already believed that the present-day continents were the fragmented pieces of preexisting larger landmasses ("supercontinents"). The diagrams below show the break-up of the supercontinent *Pangaea* (meaning "all lands" in Greek), which figured prominently in the hypothesis of ***continental drift*** -- the forerunner to the theory of plate tectonics.



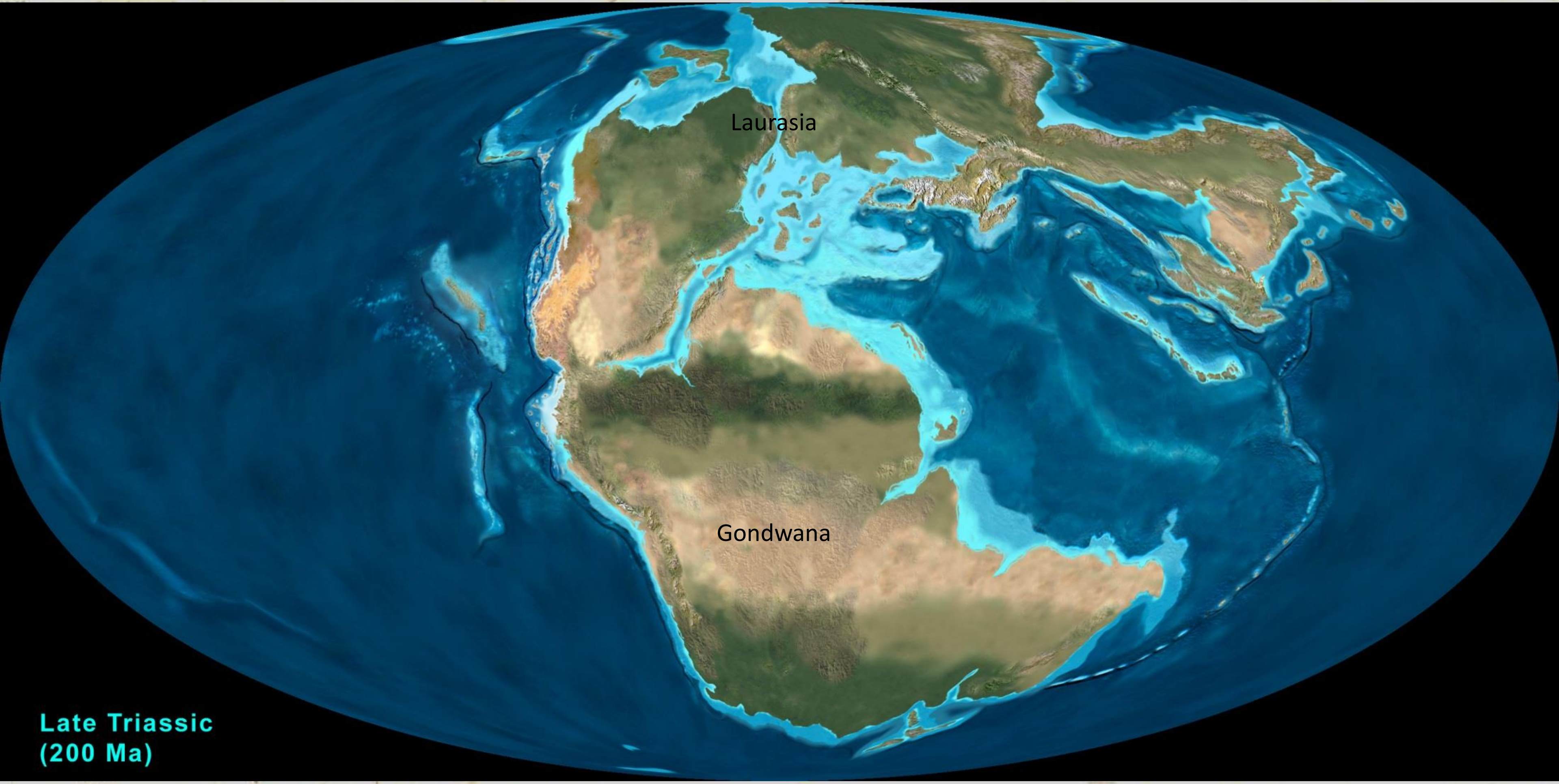
Pangaea *began to break up about 225-200 million years ago, eventually fragmenting into the continents as we know them today. This idea pre-dates Plate Tectonics.*

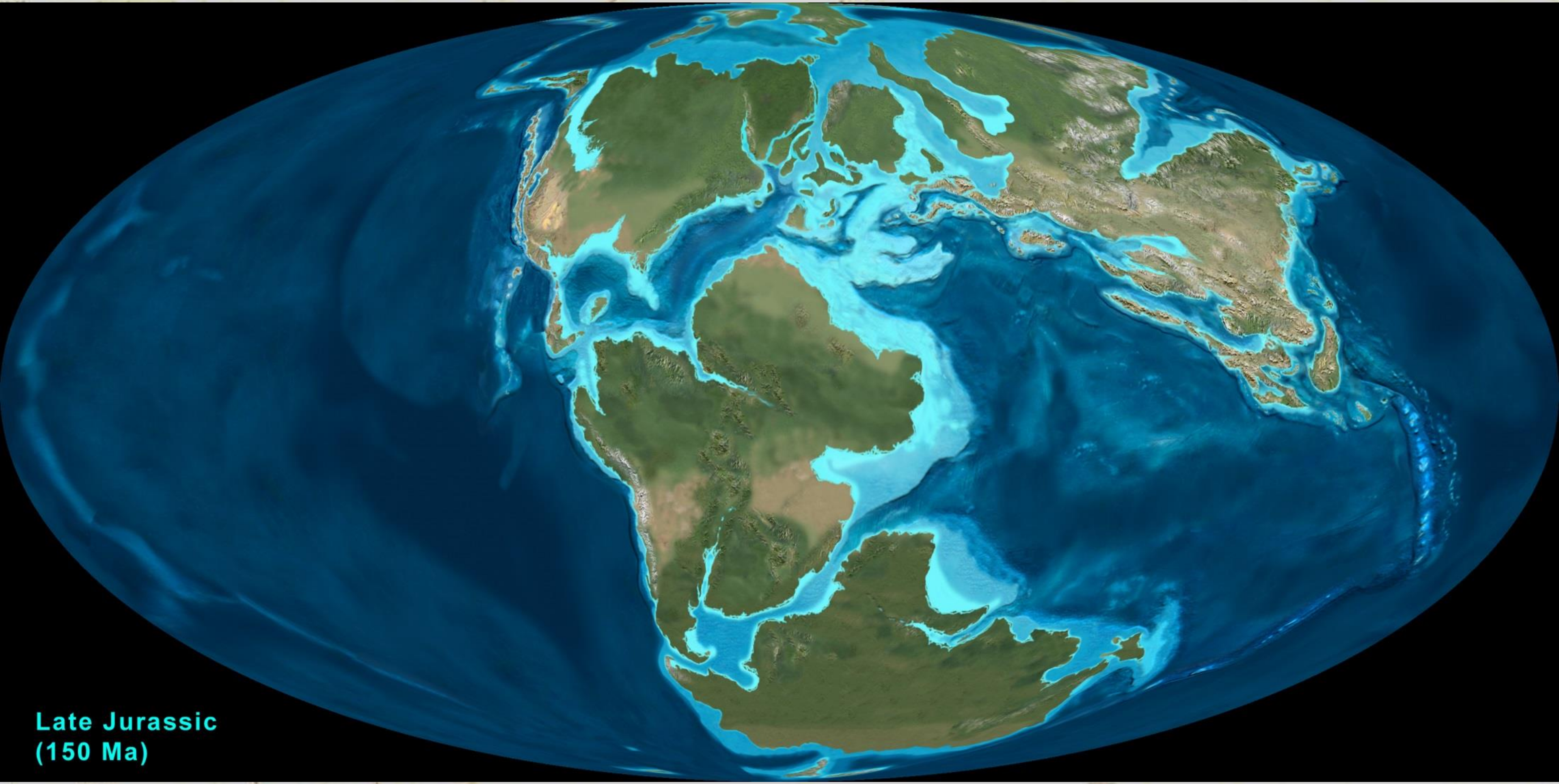
A more detailed reconstruction

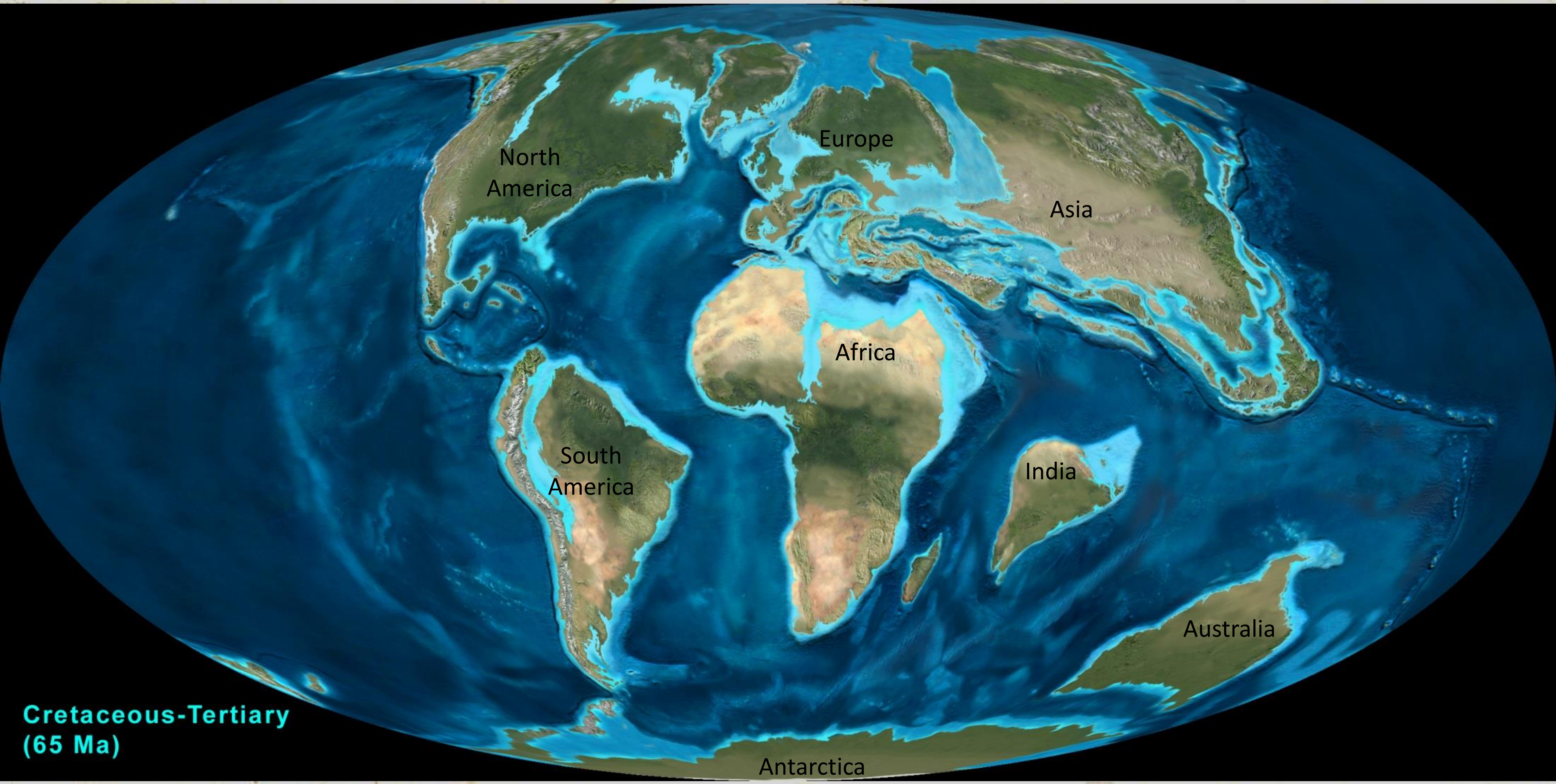
These reconstructions are based on thousands of geologic and geophysical investigations around the world.



Ma = “mega-annum,” or “million years”
240 Ma = 240 million years, or 240,000,000 years


Laurasia
Gondwana
Late Triassic
(200 Ma)

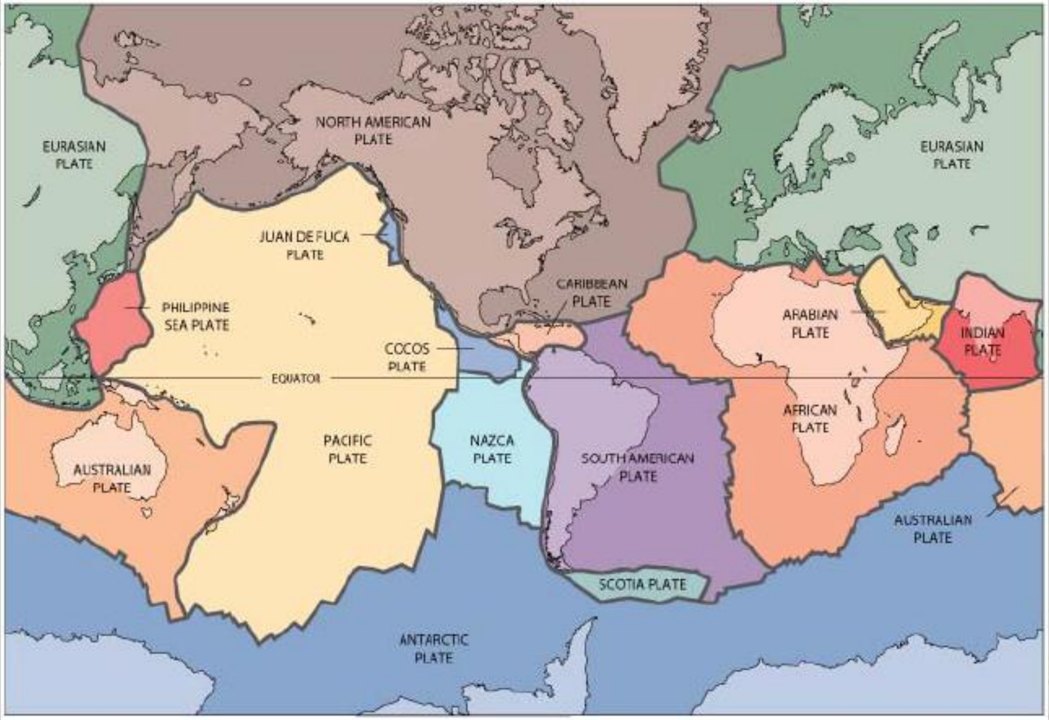

Late Jurassic
(150 Ma)



Europe
North
America
Asia
Africa
South
America
India
Australia
Cretaceous-Tertiary
(65 Ma)
Antarctica

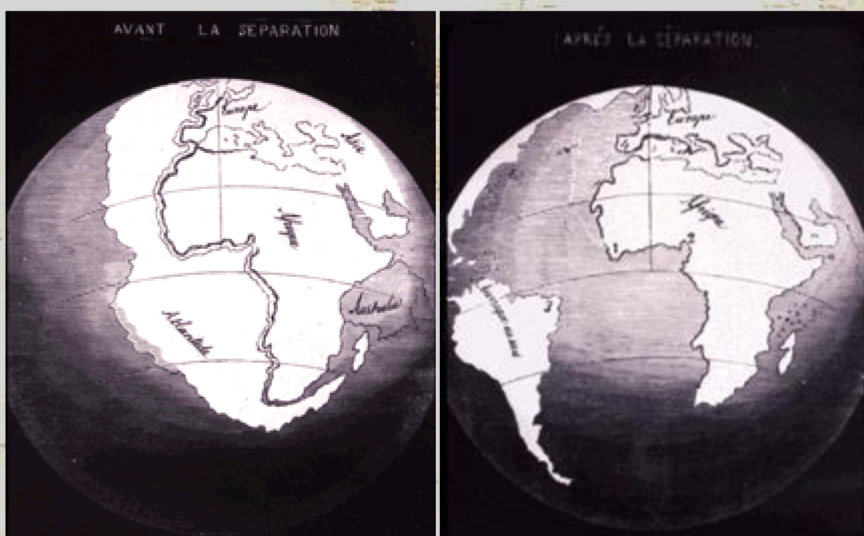
Plate tectonics is a relatively new scientific concept, introduced in the early 1960's, but it has revolutionized our understanding of the dynamic planet upon which we live. The theory has unified the study of the Earth by drawing together many branches of the earth sciences, from *paleontology* (the study of fossils) to *seismology* (the study of earthquakes). It has provided explanations to questions that scientists had speculated upon for centuries -- such as why earthquakes and volcanic eruptions occur in very specific areas around the world, and how and why great mountain ranges like the Alps and Himalayas formed.

Why is the Earth so restless? What causes the ground to shake violently, volcanoes to erupt with explosive force, and great mountain ranges to rise to incredible heights? Scientists, philosophers, and theologians have wrestled with questions such as these for centuries. Until the 1700s, most Europeans thought that a Biblical Flood played a major role in shaping the Earth's surface. This way of thinking was known as "**catastrophism**," and ***geology*** (the study of the Earth) was based on the belief that all earthly changes were sudden and caused by a series of catastrophes. However, by the mid-19th century, catastrophism gave way to "**uniformitarianism**," a new way of thinking centered around the "Uniformitarian Principle" proposed in 1785 by James Hutton, a Scottish geologist. This principle is commonly stated as follows: ***The present is the key to the past.*** Those holding this viewpoint assume that the geologic Forces and processes -- gradual as well as catastrophic – acting on The Earth today are the same as those that have acted in the geologic past.



The layer of the Earth we live on is broken into a dozen or so rigid slabs that are moving relative to one another. This is the central idea of the theory of plate tectonics.

The belief that continents have not always been fixed in their present positions was suspected long before the 20th century; this notion was first suggested as early as 1596 by the Dutch map maker Abraham Ortelius in his work *Thesaurus Geographicus*. Ortelius suggested that the Americas were "torn away from Europe and Africa . . . by earthquakes and floods" and went on to say: "The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three [continents]." Ortelius' idea surfaced again in the 19th century. However, it was not until 1912 that the idea of moving continents was seriously considered as a full-blown scientific hypothesis -- called *Continental Drift* -- introduced in two articles published by a 32-year-old German meteorologist named **Alfred Lothar Wegener**. He contended that, around 200 million years ago, the supercontinent **Pangaea** began to split apart. Alexander Du Toit, Professor of Geology at Witwatersrand University and one of Wegener's staunchest supporters, proposed that Pangaea first broke into two large continental landmasses, *Laurasia* in the northern hemisphere and *Gondwanaland* in the southern hemisphere. Laurasia and Gondwanaland then continued to break apart into the various smaller continents that exist today (see the previous figures).

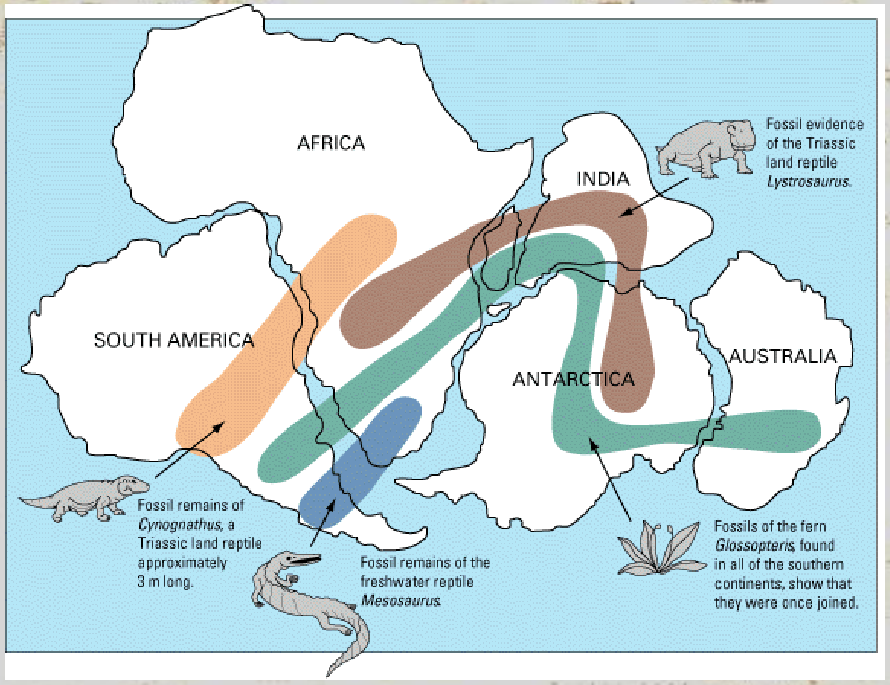


In 1858, geographer Antonio Snider-Pellegrini made these two maps showing his version of how the American and African continents may once have fit together, then later separated. Left: The formerly joined continents before (avant) their separation. Right: The continents after (aprés) the separation. (Reproductions of the original maps courtesy of University of California, Berkeley.)

Wegener's hypothesis was based in part on what appeared to him to be the remarkable fit of the South American and African continents, first noted by Abraham Ortelius three centuries earlier. Wegener was also intrigued by the occurrences of unusual geologic structures and of plant and animal fossils found on the matching coastlines of South America and Africa, which are now widely separated by the Atlantic Ocean. He reasoned that it was physically impossible for most of these organisms to have swum or have been transported across the vast oceans. To him, the presence of identical fossil species along the coastal parts of Africa and South America was the most compelling evidence that the two continents were once joined.

In Wegener's mind, the drifting of continents after the break-up of Pangaea explained not only the matching fossil occurrences but also the evidence of **paleoclimates** on some continents. For example, the discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica led to the conclusion that this frozen land previously must have been situated closer to the equator, in a more temperate climate where lush, swampy vegetation could grow. Other mismatches of geology and climate included distinctive fossil ferns *(Glossopteris)* discovered in now-polar regions, and the occurrence of glacial deposits in present-day arid Africa, such as the Vaal River valley of South Africa.

As noted by Snider-Pellegrini and Wegener, the ***locations of certain fossil plants and animals*** *on present-day, widely separated continents would form definite patterns (shown by the bands of colors), if the continents are rejoined*



Alfred Wegener

Educated as an astronomer and working as a meteorologist, Wegener's interest in continental movement began as an investigation into paleoclimates. He noted that climate-dependent rocks, including coal, reefs, and evaporites, are distributed across the globe without relation to today's geography.
His lack of geological knowledge handicapped him in formulating his hypothesis of continental drift.

The hypothesis of *continental drift* would become the spark that ignited a new way of viewing the Earth. But at the time Wegener introduced his ideas and evidence, the scientific community firmly believed the continents and oceans to be permanent features on the Earth's surface. Not surprisingly, his proposal was not well received, even though it seemed to agree with the scientific information available at the time. A **fatal weakness** in Wegener's theory was that it could not satisfactorily answer the most fundamental question raised by his critics: What kind of forces could be strong enough to move such large masses of solid rock over such great distances? Wegener suggested that the continents simply plowed through the ocean floor, but Harold Jeffreys, a noted English geophysicist, argued correctly that it was physically impossible for a large mass of solid rock to plow through the ocean floor without breaking up. From studies of coastlines and shallow continental shelves in the northern Atlantic, most geologists realized the continents and ocean floors were solidly connected, and Wegener's explanation was implausible.

Undaunted by rejection, Wegener devoted the rest of his life to doggedly pursuing additional evidence to defend his ideas. He froze to death in 1930 during an expedition crossing the Greenland ice cap, but the controversy he spawned raged on. However, after his death, new evidence from ocean floor exploration and other studies rekindled interest in Wegener's theory, ultimately leading to the development of the *theory of plate tectonics*.

The **fundamental difference** between continental drift and plate tectonics is their explanations of the role of the seafloor crust. Continental drift said the oceanic crust was fixed and does not move. Plate tectonics says that the oceanic crust is part of the mobile plates, and moves along with the continents. And so it is no surprise that study of the seafloor was key in development of the theory of plate tectonics.

Plate tectonics has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physics and chemistry and the theory of evolution was to the life sciences. Even though the theory of plate tectonics is now widely accepted by the scientific community, aspects of the theory are still being investigated today. Ironically, one of the chief outstanding questions is the one Wegener failed to resolve: What is the nature of the forces propelling the plates? Scientists also debate how plate tectonics may have operated (if at all) earlier in the Earth's history and whether similar processes operate, or have ever operated, on other planets in our solar system.

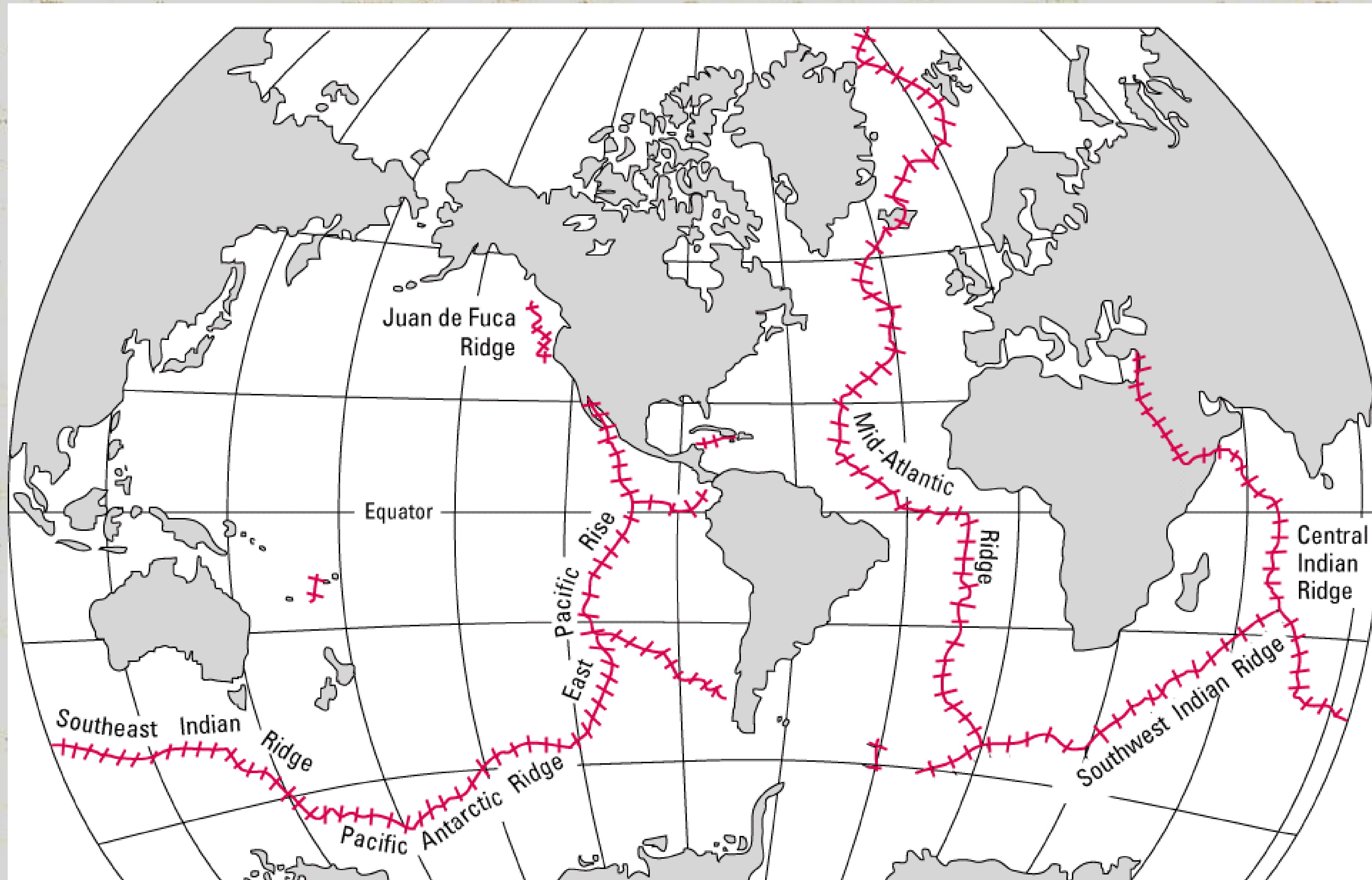
See tectonics pioneer J. Tuzo Wilson discuss Wegener (YouTube) 46 sec.

Developing the theory

Continental drift was hotly debated off and on for decades following Wegener's death before it was largely dismissed as being eccentric, preposterous, and improbable. However, beginning in the 1950s, a wealth of new evidence emerged to revive the debate about Wegener's provocative ideas and their implications. In particular, **four major scientific developments** spurred the formulation of the plate-tectonics theory: **(1)** demonstration of the ruggedness and youth of the ocean floor; **(2)** confirmation of repeated reversals of the Earth magnetic field in the geologic past; **(3)** emergence of the seafloor-spreading hypothesis and associated recycling of oceanic crust; and **(4)** precise documentation that the world's earthquake and volcanic activity is concentrated along oceanic trenches and submarine mountain ranges.

Ocean floor mapping

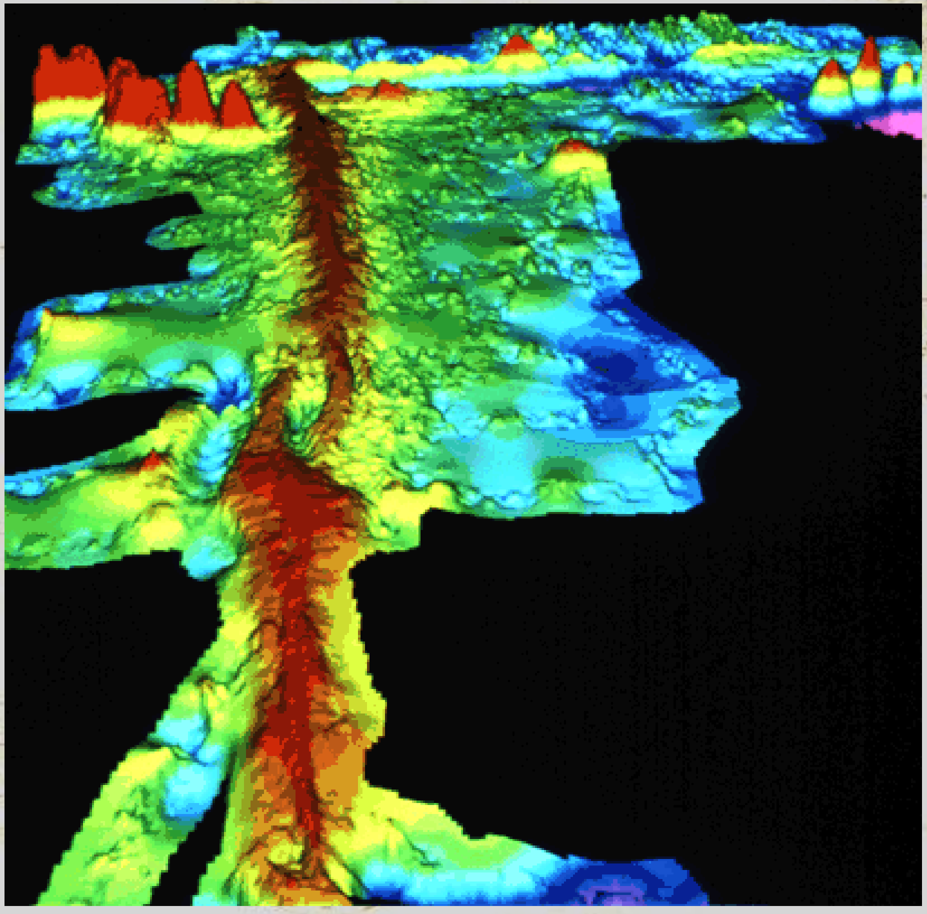
About two thirds of the Earth's surface lies beneath the oceans. Before the 19th century, the depths of the open ocean were largely a matter of speculation, and most people thought that the ocean floor was relatively flat and featureless. Our picture of the ocean floor greatly sharpened after World War I (1914-18), when echo-sounding devices -- primitive **sonar** systems -- began to measure ocean depth by recording the time it took for a sound signal (commonly an electrically generated "ping") from the ship to bounce off the ocean floor and return. Time graphs of the returned signals revealed that the ocean floor was much more rugged than previously thought. Such echo-sounding measurements clearly demonstrated the continuity and roughness of the submarine mountain chain in the central Atlantic (later called the ***Mid-Atlantic Ridge***) suggested by the earlier bathymetric measurements. Mapping of the ocean floor accelerated during World War II, when submarine warfare became important.



The mid-ocean ridge (shown in red) winds its way between the continents much like the seam on a baseball.


Mid-Atlantic Ridge
Tour in Google Earth
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image IBCAO
Image Landsat
Image U.S. Geological Survey
Google earth

In 1947, seismologists on the U.S. research ship *Atlantis* found that the sediment layer on the floor of the Atlantic was much thinner than originally thought. Scientists had previously believed that the oceans have existed for at least 4 billion years, so therefore the sediment layer should have been very thick. Why then was there so little accumulation of sedimentary rock and debris on the ocean floor? The answer to this question, which came after further exploration, would prove to be vital to advancing the concept of plate tectonics.



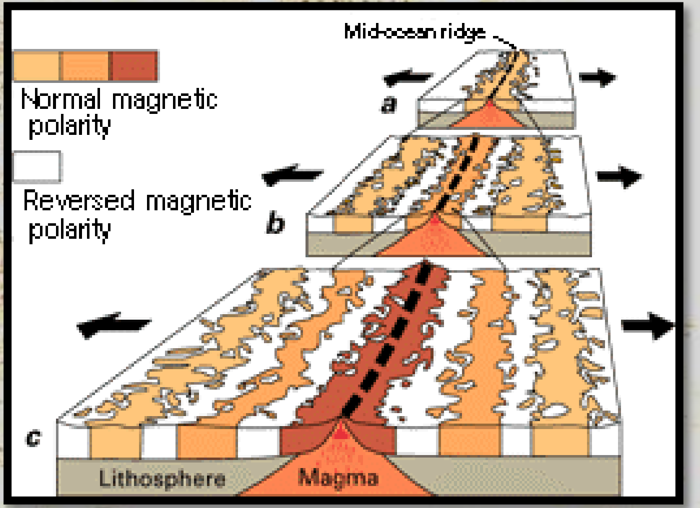
Computer-generated detailed topographic map of a segment of the Mid-Oceanic Ridge. "Warm" colors (yellow to red) indicate the ridge rising above the seafloor, and the "cool" colors (green to blue) represent lower elevations. This image (at latitude 9° north) is of a small part of the East Pacific Rise. (Imagery courtesy of Stacey Tighe, University of Rhode Island.)

In the 1950s, oceanic exploration greatly expanded. Data gathered by oceanographic surveys conducted by many nations led to the discovery that a great mountain range on the ocean floor virtually encircled the Earth. Called the ***global mid-ocean ridge***, this immense submarine mountain chain -- more than 50,000 kilometers (km) long and, in places, more than 800 km across -- zig-zags between the continents, winding its way around the globe like the seam on a baseball. Rising an average of about 4,500 meters(m) above the sea floor, the mid-ocean ridge overshadows all the mountains in the United States except for Mount McKinley (Denali) in Alaska (6,194 m). Though hidden beneath the ocean surface, the global mid-ocean ridge system is the most prominent topographic feature on the surface of our planet.

Magnetic striping and polar reversals

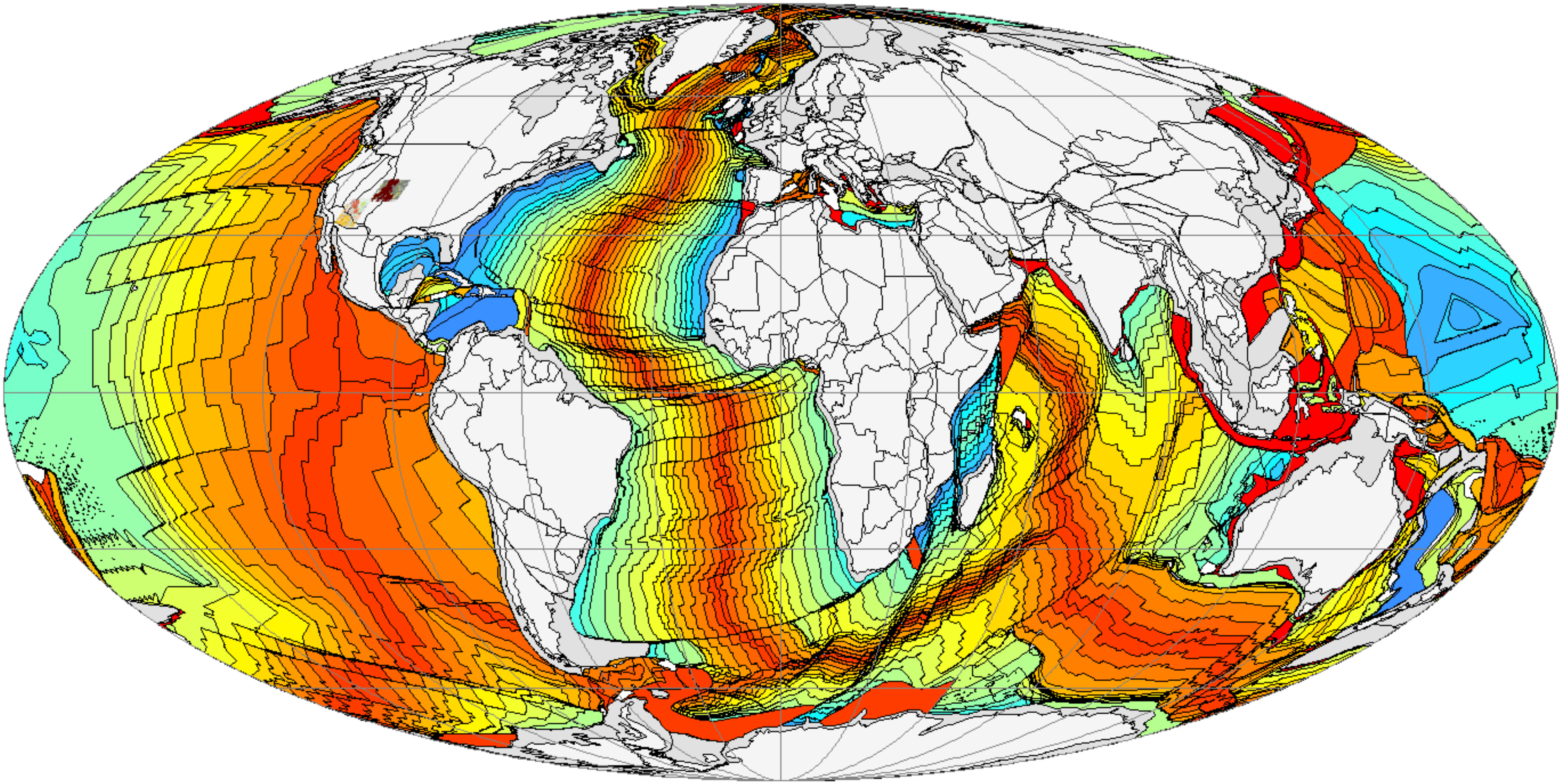
Beginning in the 1950s, scientists, using magnetic instruments *(magnetometers)* adapted from airborne devices developed during World War II to detect **submarines**, began recognizing odd magnetic variations across the ocean floor. This finding, though unexpected, was not entirely surprising because it was known that ***basalt*** -- the iron-rich, volcanic rock making up the ocean floor-- contains a strongly magnetic mineral *(magnetite)* and can locally distort compass readings. This distortion was recognized by Icelandic mariners as early as the late 18th century. More important, because the presence of magnetite gives the basalt measurable magnetic properties, these newly discovered magnetic variations provided another means to study the deep ocean floor.

P*aleomagnetists* (those who study the Earth's ancient magnetic field) began to recognize that rocks generally belong to two groups according to their magnetic properties. One group has so-called ***normal polarity***, characterized by the magnetic minerals in the rock having the same polarity as that of the Earth's present magnetic field. This would result in the north end of the rock's "compass needle" pointing toward magnetic north. The other group, however, has ***reversed polarity***, indicated by a polarity alignment opposite to that of the Earth's present magnetic field. In this case, the north end of the rock's compass needle would point south. How could this be? This answer lies in the magnetite in volcanic rock. Grains of magnetite -- behaving like little magnets -- can align themselves with the orientation of the Earth's magnetic field. When *magma* (molten rock containing minerals and gases) cools to form solid volcanic rock, the alignment of the magnetite grains is "locked in," recording the Earth's magnetic orientation or polarity (normal or reversed) at the time of cooling.



A theoretical model of the formation of magnetic striping. New oceanic crust forming continuously at the crest of the mid-ocean ridge cools and becomes increasingly older as it moves away from the ridge crest with seafloor spreading (see text): ***a.*** *the spreading ridge about 5 million years ago;* ***b.*** *about 2 to 3 million years ago; and* ***c.*** *present-day.*

As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern. Alternating stripes of magnetically different rock were laid out in rows on either side of the mid-ocean ridge: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as **magnetic striping**.



The magnetic stripes on the seafloor correspond to ages of the oceanic crust. The newest crust is at the mid-oceanic ridges, shown here as dark red. The oldest seafloor is Jurassic, shown as dark blue. The observation that oceanic crust is much younger than continental crust was important in developing the theory of plate tectonics – it meant that oceanic crust forms at the mid-oceanic ridges and is consumed, or subducted into the mantle, at the trenches. The mid-oceanic ridges are divergent plate boundaries. The trenches are convergent plate boundaries.   (USGS)

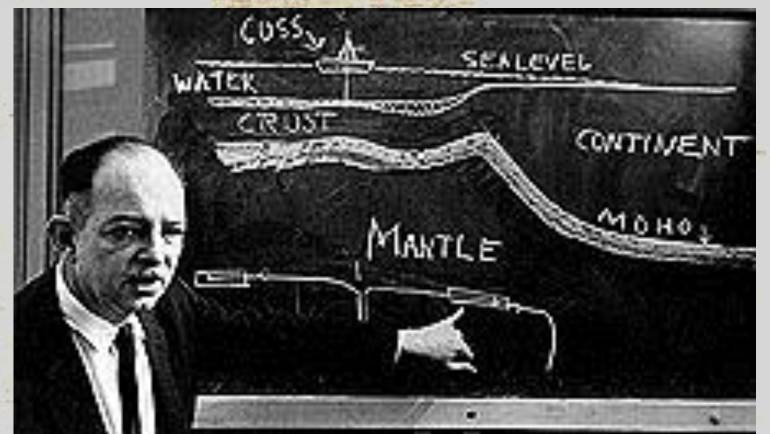
Seafloor spreading and recycling of oceanic crust

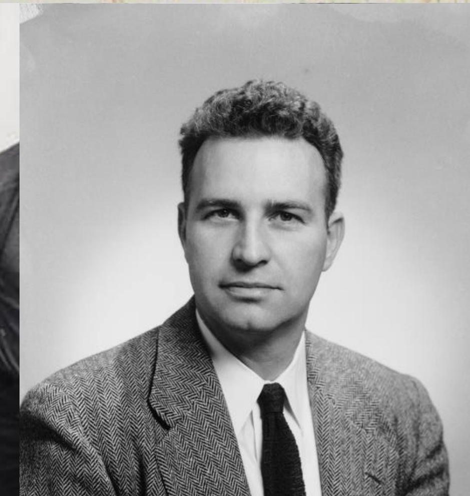
The discovery of magnetic striping naturally prompted more questions: How does the magnetic striping pattern form? And why are the stripes symmetrical around the crests of the mid-ocean ridges? These questions could not be answered without also knowing the significance of these ridges. In 1961, scientists began to theorize that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest. New magma from deep within the Earth rises easily through these weak zones and eventually erupts along the crest of the ridges to create new oceanic crust. This process, later called ***seafloor spreading***, operating over many millions of years has built the 50,000 km-long system of mid-ocean ridges. This hypothesis was supported by several lines of evidence: **(1)** at or near the crest of the ridge, the rocks are very young, and they become progressively older away from the ridge crest; **(2)** the youngest rocks at the ridge crest always have present-day (normal) polarity; and **(3)** stripes of rock parallel to the ridge crest alternated in magnetic polarity (normal-reversed-normal, etc.), suggesting that the Earth's magnetic field has flipped many times. By explaining both the magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural recording of the history of the reversals in the Earth's magnetic field.

Additional evidence of seafloor spreading came from an unexpected source: petroleum exploration. In the years following World War II, continental oil reserves were being depleted rapidly and the search for offshore oil was on. To conduct offshore exploration, oil companies built ships equipped with a special drilling rig and the capacity to carry many kilometers of drill pipe. This basic idea later was adapted in constructing a research vessel, named the *Glomar Challenger*, designed specifically for marine geology studies, including the collection of drill-core samples from the deep ocean floor. In 1968, the vessel embarked on a year-long scientific expedition, criss-crossing the Mid-Atlantic Ridge between South America and Africa and drilling core samples at specific locations. When the **ages** of the samples were determined by paleontologic and isotopic dating studies, they provided **the clinching evidence** that established the seafloor spreading hypothesis as an integral part of the theory of plate tectonics.

Above: *The* Glomar Challenger *was the first research vessel specifically designed in the late 1960s for the purpose of drilling into and taking core samples from the deep ocean floor.* Right: *The* JOIDES Resolution *is the deep-sea drilling ship of the 1990s* (JOIDES= ***J**oint **O**ceanographic **I**nstitutions for **D**eep **E**arth **S**ampling). This ship, which carries more than 9,000 m of drill pipe, is capable of more precise positioning and deeper drilling than the* Glomar Challenger. *(Photographs courtesy of Ocean Drilling Program, Texas A & M University.)*

But how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? This question particularly intrigued **Harry H. Hess**, a Princeton University geologist and a Naval Reserve Rear Admiral, and **Robert S. Dietz**, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading*. Dietz and Hess were among the small handful who really understood the broad implications of sea floor spreading, and were the first to publish papers proposing Plate Tectonics. If the Earth's crust was expanding along the oceanic ridges, Hess reasoned, it must be consumed elsewhere. He suggested that new oceanic crust continuously spread away from the ridges in a conveyor belt-like motion. Many millions of years later, the oceanic crust eventually descends into the oceanic ***trenches*** -- very deep, narrow depressions along the rim of the Pacific Ocean basin. According to Hess, the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust was consumed in the trenches, new magma rose and erupted along the spreading ridges to form new crust. In effect, the ocean basins were perpetually being "recycled," with the creation of new crust and the destruction of old oceanic lithosphere occurring simultaneously. Thus, Hess' ideas neatly explained why the Earth does not get bigger with sea floor spreading, why there is so little sediment accumulation on the ocean floor, and why oceanic rocks are much younger than continental rocks.





Robert Dietz

Dietz served as an adjunct professor at the Scripps Institution of Oceanography from 1950-1963, coincident with his service at the Naval Electronics Laboratory, 1946-1963. At his home at La Jolla Shores he hosted discussions among marine geologists and graduate students. On January 23, 1960, Dietz supervised the deepest dive, 35,800 feet, almost seven miles to the seafloor in the Challenger Deep, a location southwest of Guam. Dietz coauthored a book describing this feat entitled, *Seven Miles Down:The Story of the Bathyscaph TRIESTE*.
(New York: Putnam, 1961). He later worked at the U.S. Coast and Geodetic Survey in Washington, DC., and retired from Arizona State University in 1985. He passed away in 1995. He is remembered for his rigorous science in diverse fields.

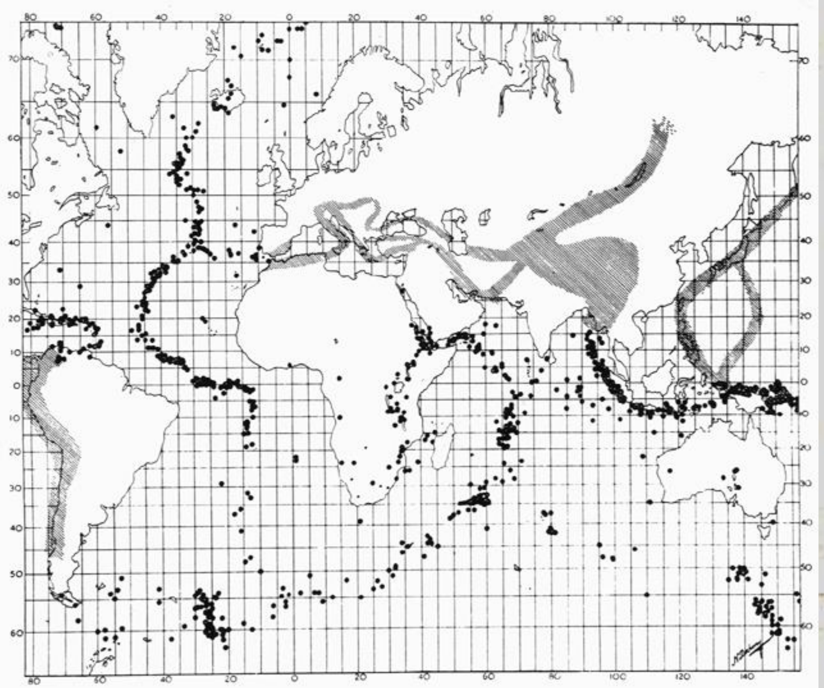
Harry Hess

(1906-1969) In World War II, he took part in four major landings in the Pacific as commander of the attack transport *U.S.S. Cape Johnson.* Utilizing the transport's sounding gear, he was able to take thousands of miles of depth soundings as part of his life-long study of the ocean floor that eventually led him to propose "Plate Tectonics" in 1962. In a faculty memorial minute after he passed away, his Princeton colleagues observed: ``Harry Hess had a deep, almost a religious, reverence for the awesome order of the universe. He possessed that combination of a driving urge to discover truth and a profound humility before the vast truths yet unknown which is the mark of the truly creative scholar." (Princeton University)

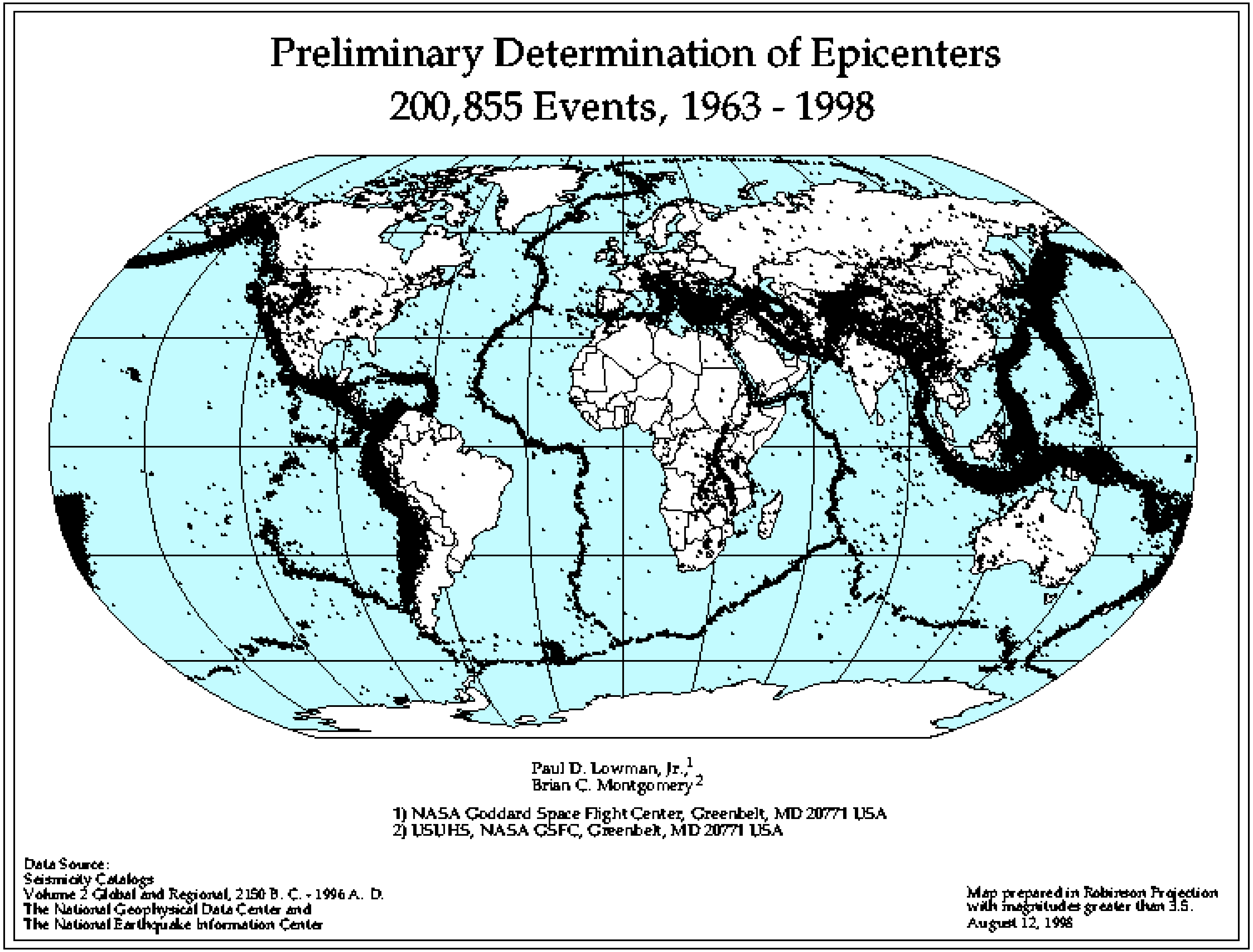
Concentration of earthquakes

During the 20th century, improvements in seismic instrumentation and greater use of earthquake-recording instruments *(seismographs)* worldwide enabled scientists to learn that earthquakes tend to be concentrated in certain areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40-60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as *Wadati-Benioff zones*, or simply ***Benioff zones***, in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of Cal Tech in the United States. Today, we also know them as *subduction zones*. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN) to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much-improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration worldwide.

But what was the significance of the connection between earthquakes and oceanic trenches and ridges? The recognition of such a connection helped confirm the seafloor-spreading hypothesis by pin-pointing the zones where Hess had predicted oceanic crust is being generated (along the ridges) and the zones where oceanic lithosphere sinks back into the mantle (beneath the trenches).



As early as the 1920s, scientists noted that earthquakes are concentrated in very specific narrow zones (see text). In 1954, French seismologist J.P. Rothé published this map showing the concentration of earthquakes along the zones indicated by dots and cross-hatched areas. (Original illustration reproduced with permission of the Royal Society of London.)



The locations of earthquakes closely matches the locations of tectonic plate boundaries.

Current Quakes in Google Earth

continue to part 2