

The Story of Earth



David Parker, Science Photo Library/Photo Researchers

by Eldridge Moores
 President, Geological Society of America

Of all the things we've learned about Earth's crust in the past 200 years, none has been as revolutionary as plate tectonics. Motions of the rigid plates that make up Earth's outer shell have profoundly shaped our world and continue to do so.

Although many of us are not aware of it, every day we walk on a history book. Earth's surface and the crust below archive a historical record of Earth's past. Just as a historian can decipher the story of Pharaonic Egypt by reading the hieroglyphics on the walls of ancient temples, so can scientists read this story of planet Earth by knowing its language — the language of geology.

Earth scientists have been reading that story for more than 200 years, and we've made many breakthroughs. Today we understand the fundamental nature of geological processes and we know when Earth formed. Most important, we now understand that the face of our world is constantly being rearranged by the process known as plate tectonics. But we haven't learned everything yet. Much more of the story will have to be translated if we are going to understand fully how Earth works.

Geology is in action all around us. Molten material rises from Earth's interior and forms igneous rocks in the crust or volcanoes atop it. Rocks are uplifted to form mountains. They are worn down by wind and weather to form sediments that in turn become sedimentary rocks. And both igneous and sedimentary rocks are later transformed by heat and pressure to form metamorphic rocks. These basic geologic processes have acted in Earth's distant past and are still acting today. They create the landscapes we see, the rocks and soil we walk on.

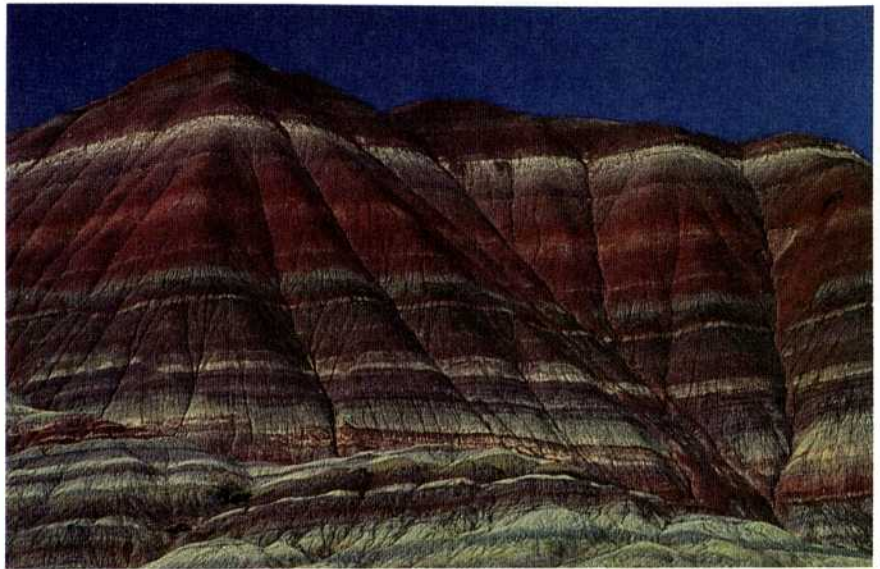
Earth scientists once believed that these processes accounted for

The discovery that revolutionized earth science — that of plate tectonics — is evident in only a few locations on the planet, such as the San Andreas Fault. It runs almost the length of California and marks the zone along which the North American and Pacific Plates grind past each other and produce earthquakes.

many of the changes that occur to the crust over time. But in the 1960s, they discovered something quite remarkable: The outer skin, or lithosphere, of Earth, consisting of the crust and dense uppermost mantle, is in constant motion. A new paradigm was born: plate tectonics. Of all the discoveries about our planet that have been made in the last two centuries, none have been more important than this one. It transformed the way we view our planet.

According to this new paradigm, the lithosphere is segmented into individual tectonic plates that are in motion with respect to each other, riding on an underlying weak, less dense, mantle layer called the asthenosphere. (On average, plates move at about the rate that fingernails grow.) Most earthquakes and volcanoes occur along the boundaries between the plates. One such boundary is a mid-ocean ridge. Here, plates move apart. As they do so, material from inside the Earth wells up and partly melts. The melt rises to the seafloor and solidifies, forming new oceanic crust, which is uniformly about 3 to 5 miles thick. The mantle part of the plate is almost non-existent at the ridge. As the newly formed plate moves away from the ridge and cools, the mantle lithosphere thickens as the plate gets older, reaching a thickness of about 60 miles after about 60 million years. At another kind of boundary, neighboring plates slide past each other, as is the case along the San Andreas Fault in California. And at a third kind of boundary, plates converge, and one founders, or subducts, into the mantle beneath the other plate.

Continents are passive riders on the plates. Today's six continents are formed of the fragments of two supercontinents, Laurasia and Gondwana, which broke apart about 150 million years ago. These two supercontinents in turn were formed out of a single supercontinent, called Pangea, which existed from about 250 million to 150 million years ago. Prior to that, the future supercontinent was in pieces. And about 700 million to 600 million years ago, the continents were united in still another supercontinent named Rodinia.



M. Lustbader/Photo Researchers

The walls of this rock formation in the Kodachrome Basin of southern Utah betray its past. Layer upon layer of sediment settled on what was once ocean bottom. Over millions of years, pressure turned the sediments to rock. Geologists examine the layers for such clues as fossils and chemical traces in order to reconstruct the history of the planet.

Lithospheric plates are denser than the asthenospheric mantle beneath them and, given a chance, will "fall" back into the interior. In fact, one theory states that plates move because they are being pulled along as one of their edges falls into the mantle. Another theory holds that plates are pushed forward by processes acting at mid-ocean ridges. Although each idea may be correct in some places, it is only part of the explanation.

We know that slow convective movements in Earth's interior accompany plate tectonics. We believe these movements are linked to the movement of plates above, but we're not sure how. The movements are caused by differences in density of the material in the mantle. Dense material tends to sink. Hot and less dense material tends to rise, often in giant plumes that burn holes in the lithosphere, creating hot spot volcanoes like those that created the Hawaiian Islands.

Lava from a volcanic eruption in Hawaii meets the ocean. The Hawaiian Islands are an example of hot-spot volcanism. As the Pacific Plate moves, molten rock from the mantle burns a series of holes through the crust. Eruptions then pile up enough debris on the ocean floor to break the surface, creating new islands.

The density differences may occur because different portions of the mantle are at different temperatures. But it's also possible that carbon-bearing minerals, specifically iron-carbonate (siderite) and magnesium carbonate (magnesite), are present in the mantle, thereby accounting for at least some of the density differences. No one knows for sure. And no one knows exactly how these density differences are linked to the movement of tectonic plates. In other words, we don't yet know why plates move.

We are, however, beginning to



Bob Cranston

have a fairly good idea of when plate tectonics first began. We can identify regions where plate movements once brought continents into collision by looking for the roots of old mountains. We call these ancient mountainous regions orogenic belts. By studying rocks from orogenic belts, geologists are fairly certain that plate tectonics as we know it today has existed since about 1 billion years ago.

Between that time and 3 billion to 2.5 billion years ago, the geologic record shows that continents existed, but the oceanic lithosphere formed at spreading centers may have been younger and thinner, on average. Paradoxically, the oceanic crust may have been thicker and thus, the mantle part would have been considerably thinner. As a result, plates may have been, on average, less capable of being subducted than today. Prior to

Plate tectonics has done much more than form and rearrange the surface of the Earth. It has also profoundly affected life.

about 3 billion to 2.5 billion years ago, there may have been no large continents and no plate tectonics as we know these things today.

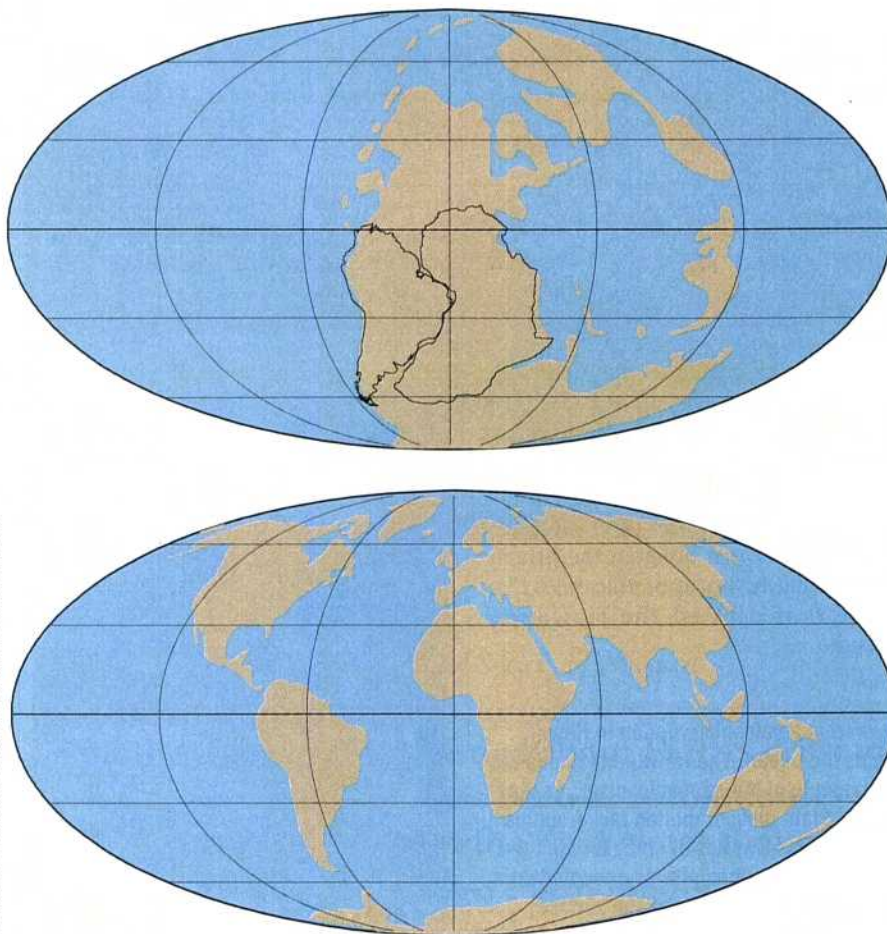
The very oldest rocks we have found in the continents formed 4 billion years ago. Any land that existed may have been small islands. The cores of the continental masses that exist today formed during the next 1.5 billion years. Volcanism on the surface and intrusion of molten material from below has added material to those original continental cores. And plate movements have caused

all manner of crustal flotsam and jetsam — seafloor volcanoes and chains of volcanic islands, for example — to “wash ashore” on the edges of continents, expanding them even further. Today, these processes may still be making additions to the continents.

Plate tectonics has done much more than form and rearrange the surface of the Earth. It has also profoundly affected life. As ocean basins expanded, contracted and re-expanded, ocean chemistry and circulation changed. And as supercontinents split up, re-formed and split up again, habitats and continental climates changed. Sea level rose and fell as the rapidity of plate motions and the total length of mid-ocean ridges fluctuated, or as large continental ice sheets formed. Paleontologists studying the fossil record have learned that these changes are linked to mass extinctions of species and subsequent explosions in biodiversity as new species evolve to take advantage of new situations.

One mystery in the history of life is what happened some 600 million to 550 million years ago to give rise to the development of animals. This major event is seen in the geologic record as the first appearance of shelly fossils. The sedimentary record suggests that some time between about 1 billion years and 550 million years ago, the oxygen content of the atmosphere increased from less than 2 percent to 20 percent. This, scientists believe, made possible the development of organisms that consume oxygen: animals.

What caused that increase in oxygen? Flourishing marine organisms called phytoplankton would have extracted carbon dioxide from and



A single supercontinent called Pangea (top) made up Earth's surface 255 million years ago. Since then, the continuous motions of the rigid tectonic plates have ripped it apart, transporting the land masses to the arrangement we know today (bottom).

added oxygen to the atmosphere. The question is, why did the phytoplankton flourish? These events occurred during or even before the breakup of Rodinia and the early stages of the assembly of Gondwana, so it is not unreasonable to ask whether there might be a tectonic reason for such a change in atmospheric composition.

I have speculated that although the continents were more or less completely formed by 2 billion years ago, they may have been nearly covered by shallow seas until about 1 billion to 800 million years ago. As oceanic lithosphere plates became older and thicker, on average, and the oceanic crust became relatively thinner, the ocean basins became deeper. (Older thicker oceanic plates would be less buoyant and lie lower compared to continental plates.) The ocean basins could hold more water, and water in the extensive shallow seas drained off the continents. The emergence of continents would have made Earth's climate more seasonal, which would have invigorated oceanic circulation and led to the flourishing of phytoplankton. This simple, seemingly attractive idea is by no means convincing to many scientists, however.

Plate tectonics has affected life in other ways. In the 1980s, scientists came to realize that water and plate motion together act as a kind of climate thermostat that turns down the heat when it gets too hot and turns it up when it gets too cold. This thermostat has helped maintain the stable conditions that fostered the evolution of life.

According to this theory, when the planet warms, rainfall increases, especially in mountainous regions like the Himalaya, which resulted from the collision of continents. This causes more chemical weathering of silica-rich rocks, a process that removes carbon dioxide, a "greenhouse gas" that keeps Earth warm, from the atmosphere and binds it to tiny particles of mineral debris. This debris with its load of carbon dioxide washes into the oceans, where some of it dissolves in the seawater, and microscopic marine creatures use it as raw material to create their cal-



Gregory G. Dimijian/Photo Researchers

One theory holds that until about 1 billion years ago, shallow seas covered the continents. Then thinning of the oceanic crust and thickening of oceanic plates resulted in deep basins. Water drained off the continents into these basins, creating conditions that ultimately resulted in animal life.

cium carbonate shells. As they die, the organisms settle to the seafloor, and their remains slowly are transformed into limestone rock.

In this way, the thermostat locks away vast amounts of carbon dioxide on the ocean floor, cooling the atmosphere. In fact, weathering of rocks exposed during the uplift and erosion of the Himalaya might have produced the last ice age. If this is true, do major continental collisions cause ice ages? An unanswered question.

One thing is clear, however. If the reverse greenhouse, or "icehouse" effect continued unabated, chemical weathering would strip all the carbon dioxide from the atmosphere. Plate tectonics prevents this by slowly returning some carbon dioxide to the atmosphere. As carbonate rock slides into subduction zones, it's heated and metamorphosed, releasing carbon dioxide. The gas then seeps back into the atmosphere through volcanic eruptions. The thermostat also prevents the planet from becoming too cool. When Earth cools, there is less rainfall. This in turn leads to a drop in chemical weathering. Less carbon dioxide is removed from the atmosphere. Slowly but surely, the concentration of the gas rises, eventually causing temperatures to increase again.

Just because we don't have company in our own neighborhood of the universe doesn't mean that life isn't flourishing somewhere else. Do we,

in fact, have company? This is perhaps the most fascinating question of all. One of NASA's goals for the next 25 years is to develop a means to detect Earth-like planets out to 40 light years (240 quadrillion miles) — ones with continents, oceans and mountains. If any are found, they might very well harbor life.

While Earth has yielded many stories to geologists, challenging and important questions continue to arise. The more we learn, the more we realize how much we do not yet know. Our understanding of the Earth is still insufficient; our knowledge of the geology of other planets in our solar system is still very fragmentary. And if we find new Earth-like planets in other solar systems, what new challenges will lie ahead for geologists who want to decipher the rocks of these new worlds? ⊕

Eldridge Moores is a professor of geology at the University of California, Davis, and President of the Geological Society of America. A field geologist specializing in tectonics and structural geology, he has participated in geologic excursions to all continents and has worked extensively with students in the Western United States (particularly California and Nevada), Greece, Cyprus and the Andes of Argentina. He was the first recipient of the Geological Association of Canada Medal in 1994.