Article

Basic Principles of Geology
Plate Tectonics

This series began with a discussion of the component of geophysics that describes Earth's structural layers, continued with the processes that drive our ever-changing planet (Earth's dynamo), and now concludes with the Theory of Plate Tectonics that describes the drift of the continents through time across the surface of the planet, and the resulting consequences.

Since the days of the great sailing ships, when sailors first started exploring distant shores and sketching their contours, even the early cartographers noticed a compelling feature that began to evolve on their primitive maps…the shapes of the continents seemed to fit one to another like pieces of a giant jigsaw puzzle! Defying coincidence, the symmetry demanded explanation. However, that elusive answer would not present itself for generations to come.

During that interval, researchers across the globe discovered persuasive clues that the crust of the Earth was not stationary. Paleontologists could not explain how fossils of equivalent species were ensconced in rock formations separated by vast geological distance; climatologists noted evidence on a global scale of analogous indications of glaciation on widely separated lands; geologists pondered how mountain ranges with identical lithology could exist on continental margins thousands of miles apart.

History

Rival hypotheses were proposed and competed for widespread acceptance to explain those clues. Among them was *Continental Drift*, coined by German scientist Alfred Wegener, circa 1912, that sought to address and resolve the shape, location, and apparent dislocation of the continents. But science is a skeptical audience.

The first line of thought suggested that the continents *floated* on—and through—the crust like icebergs in the ocean; but how can granitic rocks plow through denser basalt? Later, the thought process changed to envision the continents embedded *in* the crust, thus moving *with* it as it expanded; but that still begged the question as to how the crust could expand without the Earth getting larger as a result? The problem was that such hypotheses emanated hypothetically sans empirical evidence. Fast forward to the 1960s.

Following World War 2, seismometers installed world wide to monitor nuclear testing revealed much more than intended. Earthquakes, volcanoes, oceanic trenches, and many other manifestations of enigmatic geologic processes aligned along distinct regions around the globe, defining the boundaries of what we now call tectonic plates. One such belt recognized since the early 1800s contains about 75% of the planet's active and dormant volcanoes (and 90% of all earthquakes); it is called the "Ring of Fire," which encircles almost the entirety of the Pacific Plate.

What follows, then, is a systematic evaluation of all the clues and observations collected by multitudes of researchers that over time has been molded and formulated into a general understanding of the innate workings of our amazing planet…knowledge that has evolved into the concept we now call the *Theory of Plate Tectonics*.

Mantle Convection Cells

As discussed in the previous issue of Discover Minerals (Volume 2 Issue 2), tectonic plates are created by the immense internal geologic forces exerted on the solid exterior crust. Movements of these plates are initiated and perpetuated by the tremendous heat produced in the Earth's interior that give rise to the planet's "dynamic engine." Thus, such movements are the direct and inexorable consequences of a geologically active planet, and are directly responsible for all the features we observe on the planet's surface, such as continents, folded mountains and valleys, volcanoes, and so forth. Essentially, the theory of plate tectonics can be thought of as an updated version of our comprehension of crustal movement, introduced and envisaged by the concepts of continental drift.

High temperatures generated by pressure, friction, and radioactive decay of unstable elements, heat mantle rocks, causing them to rise from below and replace cooler material, which in turn sinks to the depths of the mantle. This sets up a process called *convection*, (which we all recognize in commonplace occurrences, such as warming water in a teapot).

As the hot mantle flow reaches the lower layers of the crust—if it fails to exploit a weakness and break through to the surface—it is forced to spread out away from the center of upwelling, whereby it cools (becoming denser) and sinks back into the depths, completing the convection cycle. However, this viscous undercurrent of elasticized rock imposes relentless strain on the relatively thin and fragile crust. Inevitably, weaknesses in the rocks of the crust lead to ruptures that allow the mantle material to liquefy (due to reduced pressure) and exude onto the surface to form new basaltic crust. These eruptions build huge volcanic mountain ranges, and the process itself pushes apart the crust on both sides of the fractures, thus creating diverging crustal plates, and initiating the process of plate tectonics. The consequences of relentlessly moving plates are manifold, including generation of earthquakes, development of volcanic activity, episodes of mountain building and destruction, and recycling of crustal material.

Patchwork of Plates

For the sake of visualization, if we were able to remove the oceans to obtain an unobstructed view of the hidden portions of the crust, we would observe that the surface of the planet is divided into a patchwork of tectonic plates, each moving in various directions relative to each other. However, if new crust is created at spreading centers, one would conclude that Earth has to expand to accommodate the accumulation of new material. Of course, this is not the case, as Earth's diameter remains essentially constant! Therefore, a mechanism must be in place to account for the apparent discrepancy. *Nature always balances the books!*

A significant concept that differentiates continental drift from plate tectonics is that the planet's surface is constantly being recycled by various processes. But how is this material reprocessed to maintain an equilibrium? The answer resides with the moving crustal sections. With the various plates spreading across the planet's surface in conflicting directions, inevitably—and obviously—something's got to give! And indeed, it does! The consequences are hardly subtle.

Plate Boundaries

Plate boundaries manifest themselves primarily in three distinct forms. The first type has already been introduced. Emanating at spreading centers where liquid mantle material constantly oozes out of the fissures and solidifies, a **Divergent Boundary** is a *constructive* contact where new crust is formed, and the plates on either side of the fracture "drift" away from each other. ***Oceanic rifting*** is characterized by tall and extensive volcanic ranges, such as the Mid-Atlantic Ridge, the longest mountain range on the planet! ***Continental rifting*** emerges at so-called "triple junctions" that ultimately split a continent and create a new ocean basin. A classic example is the Great Rift Valley in northeast Africa.

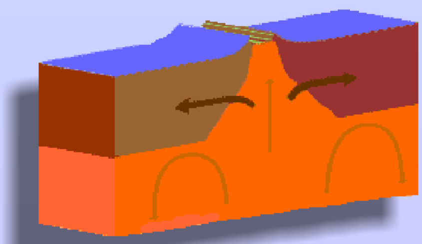
Contrarily, if new crust is deposited and expanded at one location, by necessity compensation must be attributed elsewhere to maintain the equilibrium of the planet's circumference. This remuneration is the site of a **Convergent Boundary**, a *destructive* contact where plates collide. One of three scenarios are presented, depending on the composition of the colliding plates. Oceanic plates are composed of *basalt*, a very dense, iron-rich rock. By contrast, continental plates are comprised mainly of *granite*, which is less dense and iron poor. Thus, at the contact of these two opposing plates, the denser ocean plate will subduct below the continent. At depth, the subducting plate will eventually begin to liquefy, and the melt—which is less dense than the surrounding mantle rocks—will rise up into the overlying crust. Thus, volcanoes, earthquakes, and trenches are characteristic of this type of contact. A classic example formed the Andes Mountains in South America.

This explains why oceanic crust is no older than about 200 million years—at a spreading rate of just a few inches a year, it would take this long for crust created at a spreading center to travel to a subduction zone and descend back into the mantel. By contrast, continental crust can reach ages of up to about 2 *billion* years!

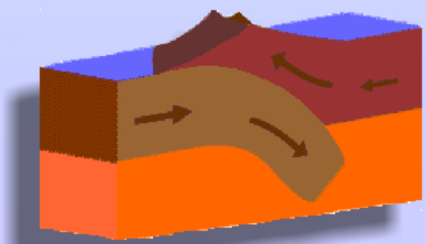
When two continental plates converge, neither plate is inclined to subduct below the other. In this case, the margins of the plates along the contact zone are pushed up, creating huge mountain ranges, the best known of which is the Himalayas that formed when the Indian Plate met the uncompromising Eurasian Plate.

There are locations where two oceanic plates collide. Here, the older plate (denser due to being relatively cooler) slides below the younger crust. Such a contact is manifested by earthquakes and the formation of deep trenches. The Marianas Trench, the deepest location on the planet, is a famous example.

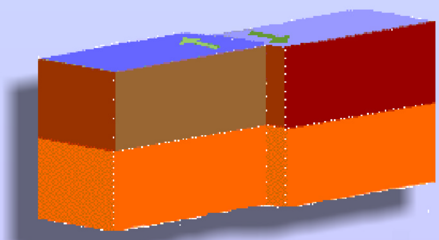
Finally, sites exist where plates are neither separating nor colliding, but rather sliding past one another along pre-existing *transverse faults* that originally formed as perpendicular cracks cutting across and offsetting the central ridges of spreading centers in response to mantel currents tugging on the overlying crust at varying speeds. Such a **Transform Boundary,** which is *neither constructive nor destructive,* occurs when a continental mass intersects one of these faults. The most profound example is the San Andreas Fault System in the western US where the leading edge of the North American Plate moving to the southwest is sliding past the Pacific Plate moving to the northwest.



Divergent Boundary



Convergent Boundary



Transform Boundary

Tectonic Evidence

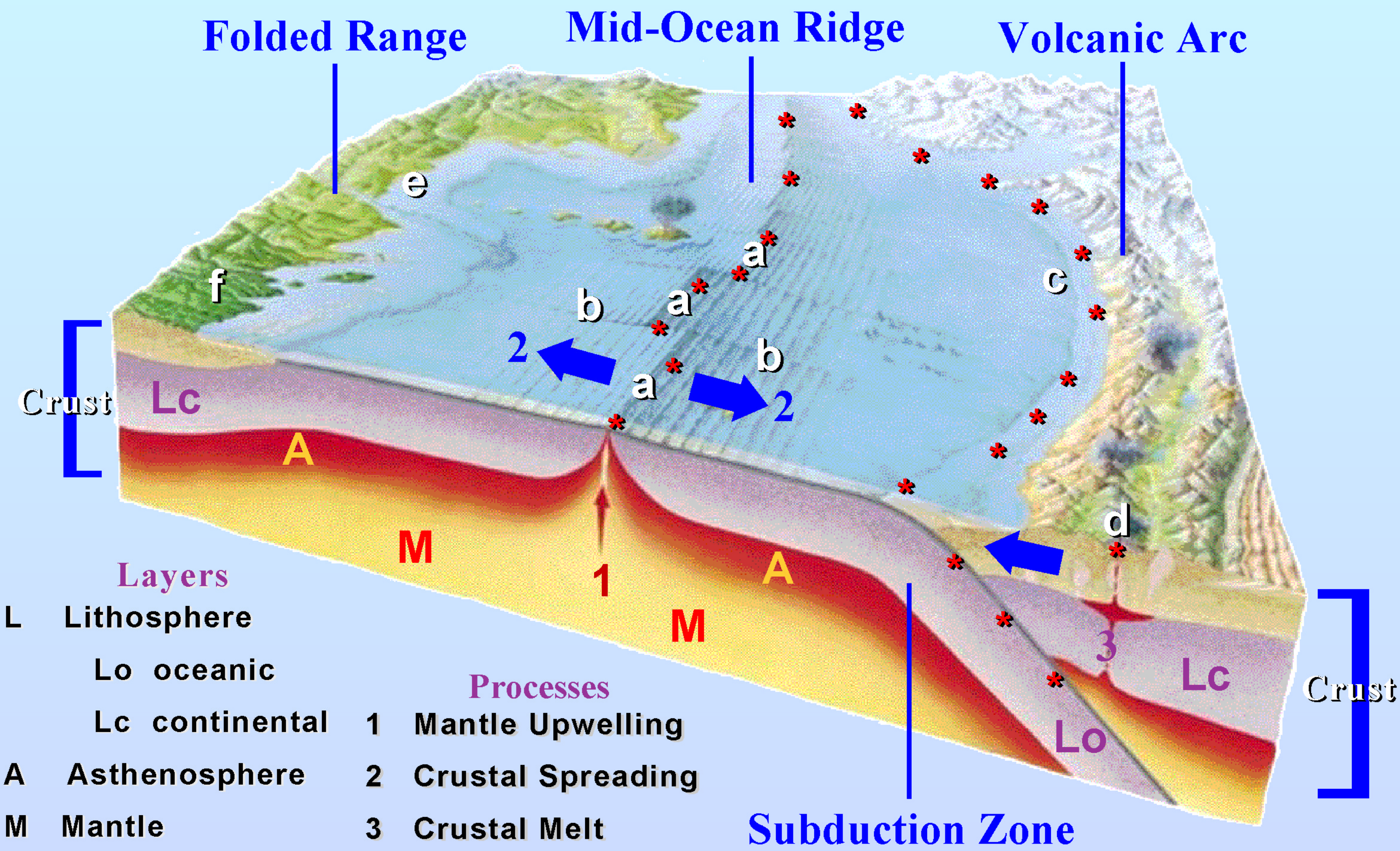
Once the mechanism of plate movements revealed itself, Earth's surface features made rational sense:

the rise of towering mountains?…converging continental plates;

arcs of stratovolcanoes?…subducting oceanic plates;

continuous shallow-depth earthquakes?...transverse strike-slip faults along transform boundaries.

Idealized Tectonic Process



Landforms

a Spreading Center b Transform Fault c Trench d Volcano

e Continental Margin f Fossil-Bearing Rock Layers

* Earthquakes

The plethora of ancillary evidence—the shapes of continental margins, lithology of widely separated mountain ranges, dispersed rock formations bearing equivalent fossils, magnetic striping, seismographic readings, and on and on—supports the authenticity of our basic understanding of how geological processes continually shape our planet's crust. And while there is still much debate concerning specific details, the overall consensus is that these processes are best explained by the **Theory of Plate Tectonics.**