

EARTH SYSTEM: STRUCTURE, DYNAMICS, AND MATERIALS

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Summary

Earth's systems are comprised of the solid Earth (or lithosphere), its watery and gaseous envelopes (the hydrosphere and atmosphere, respectively), and life (the biosphere), each of which has evolved and interacted continuously throughout geologic time. This interaction takes place at or near the Earth's surface, and the energy required is a combination of Earth's internal heat and radiant energy from the Sun.

Earth's lithosphere is divided into interlocking slabs, or plates, which float on a weak layer in the mantle. As these plates move relative to one another they cause earthquakes and volcanoes. Over time they can create and then destroy Earth's most visible features, including oceans and mountains. Although the exact mechanism of plate tectonics is unclear, it appears to be directly or indirectly related to the flow of heat in Earth's mantle, which results in mantle convection.

Our understanding of how the lithosphere has evolved through time has come from the ability to "date" or assign an age to Earth's materials, its minerals and rocks. Two complementary approaches are used: (a) relative age dating, which places geologic events in the order in which they occur, and (b) absolute age dating in which the age of a rock or mineral is determined by measuring the amount of radioactive decay.

Minerals are the basic building blocks of the lithosphere. They are naturally occurring, inorganic, crystalline solids with specific compositions and chemical formulas. Because the chemical composition of the crust is dominated by silicon and oxygen, most minerals are a combination of those elements and are called silicates. These minerals are dominated by silicon–oxygen bonds, which form a tetrahedral structure. Silicate minerals are divided into families depending on the linkages between adjacent tetrahedra, which may occur in isolation, linked in chains, double chains, or sheets, or in very complex three dimensional structures.

Most rocks are combinations of minerals and are divided into three fundamental categories. *Igneous* rocks are the products of cooling of hot, molten rock, or magma. *Sedimentary* rocks are the products of surface processes, involving water, ice or air, that disintegrate and decompose surface rocks. *Metamorphic* rocks are produced when rocks are subjected to geological conditions unlike those in which they formed. The relationship among these rocks is depicted by the "rock cycle." For example, volcanic igneous rocks may decompose or disintegrate at the surface to form unconsolidated sediments. Over time, these sediments consolidate to form sedimentary rock. Sedimentary rocks may be converted to metamorphic rocks if they are subjected to pressures and temperatures that cause the minerals to become unstable and react to form new minerals. This conversion typically occurs near plate margins. If tectonic activity and temperatures continue to increase, the metamorphic rocks may melt to form magma. At Earth's surface, weathering and erosion combine to decompose, disintegrate, and remove unconsolidated material. Streams carry both a solid and a dissolved load. The solid load is deposited wherever the stream's velocity is slowed, such as where the stream enters the sea. If weathering is not accompanied by significant erosion soils may form. Soil quality depends on parent rock type, rainfall, air temperature, organic activity, topography, and the length of time over which soil-forming processes operate.

The hydrosphere includes water in the oceans, surface waters such as lakes and streams, groundwater, and ice sheets. Ocean water circulation is driven by temperature contrasts between the poles and the equator. As warm water migrates towards the poles, it is influenced by Earth's spin, and the resulting Coriolis effect imparts a clockwise rotation on migrating waters in the northern hemisphere and a counter-clockwise rotation in the southern hemisphere.

Radiant energy from the Sun causes ocean waters to evaporate. Most of this evaporation

returns to the oceans directly by precipitation. The vast majority of the moisture that precipitates on land drains back to the oceans by way of streams. However, over tens of thousands of years, small amounts of water may contribute to the growth of glaciers or infiltrate the subsurface to form groundwater. Groundwater is our greatest source of accessible fresh water. An aquifer is a rock or sediment that can store and transmit groundwater. Like other resources, groundwater is extracted faster than nature can replenish it.

Surface waters transport 40 000 km³ of moisture to the ocean each year, mostly by stream flow. A stream's channel constantly changes position and, over time, a wide flood plain develops. Major streams are usually fed by a network of tributaries. Surface waters are frequently dammed for municipal water supply, irrigation, flood control, or hydroelectricity.

Earth's atmosphere is dominated by nitrogen and oxygen, which together compose 99% of its volume. Although volcanic eruptions are the primary source of Earth's atmospheric gases, the composition of the atmosphere is substantially modified by photosynthesis and by precipitation, which extract water and carbon dioxide.

The downward force of gravity on air exerts a pressure, which decreases with elevation. As warm air rises, it expands and so becomes cooler, up to an altitude of 8–18 km (depending on latitude). Colder air descends to take its place, setting up very efficient convection systems in which the air is turbulent and thoroughly mixed. Most of Earth's weather and climate are confined to this zone, known as the troposphere. Columns of unstable air either ascend to form low-pressure centers, called cyclones, or descend to form high-pressure centers, called anticyclones. Interaction between high- and low-pressure centers leads to colliding air masses and results in the generation of weather fronts. Intensification of low-pressure centers may result in hurricanes or typhoons.

Above the troposphere, the presence of ozone, which absorbs ultraviolet radiation, causes the air to become warmer. This air is stable and layered and is known as the stratosphere.

The geologic record suggests that interaction of Earth's systems today may not be typical of the past. For example, most researchers believe that some form of plate tectonics has operated over the past 2.0 billion years (Ga). Before that time the role of plate tectonics is controversial. There is strong evidence that the hydrosphere existed on the primitive Earth at least 4.0 Ga before present (BP). Most researchers believe that little new water has been added since that time and that most of the water has been recycled. The composition of Earth's atmosphere (especially its greenhouse gas content) initially changed dramatically from one dominated by hydrogen and helium, to one dominated by carbon dioxide. But over the past 4 Ga, precipitation and photosynthesis have reduced the atmosphere's carbon dioxide content substantially, and its present value is only 0.03%. During this time, nitrogen and oxygen have become the dominant gases.

The oldest life forms date from 3.5–4.0 Ga and were primitive single-celled organisms that lived in anaerobic environments. When the atmosphere became oxygenated, at ~2.0

Ga, habitats were reduced to local oxygen-starved environments until the organisms developed oxygen tolerance. Eukaryotes, which first appeared at 1.8 Ga, diversified the gene pool because they were capable of sexual reproduction. Diverse multicellular organisms evolved at ~600 million years (Ma), and, at ~545 Ma, the ability of these organisms to secrete shells resulted in a much better fossil record. By 400 Ma, vertebrates had evolved and plants had colonized the land, followed soon after by plant-eaters. A mass extinction at ~290 Ma resulted in the loss of 50% of animal life and 90 % of marine species. Its cause is unknown. A mass extinction at 66 Ma resulted in the loss of 75% of all known species, including all of the dinosaurs, and is widely believed to be the result of an extra-terrestrial impact. With the extinction of the dinosaurs, mammals became dominant, and, over the past 4 Ma, a family of primates, called hominids, slowly evolved to produce *Homo sapiens*, or modern humans, at ~200 000 years (a) BP.

For more detailed information see individual sections of this chapter dealing with rocks, minerals, soils, climate and geological time.

1. Introduction

Earth's evolution throughout geological time has been profoundly influenced by the interaction between its internal forces and external influences, such as solar radiation. This interaction has governed the composition of Earth's rocky outer layer, or lithosphere; the origin, composition, and circulation of Earth's watery and gaseous envelopes (the hydrosphere and atmosphere); and the origin and evolution of life itself (the biosphere) (see *Cosmic Influences on The Earth*).

The lithosphere, hydrosphere, atmosphere, and biosphere are known as Earth's systems. As these systems have evolved with time, so has the nature of their interactions. The study of these changing interactions is known as earth systems science.

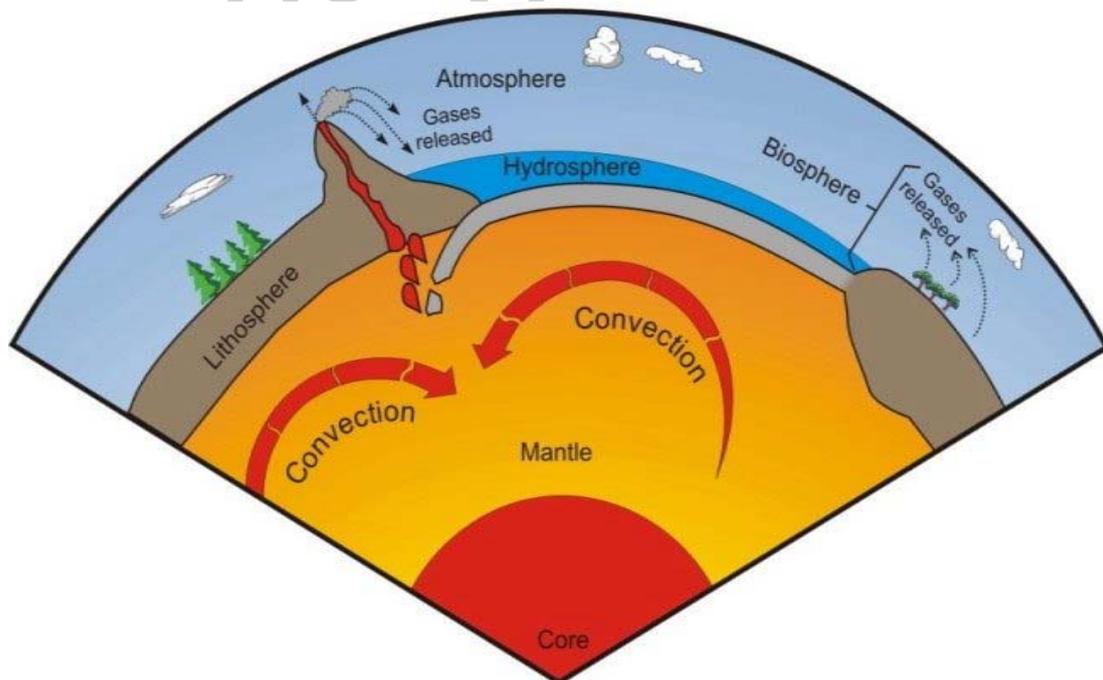


Figure 1. Earth systems science is the study of the interaction among Earth's surface reservoirs that include the atmosphere, biosphere, hydrosphere, and lithosphere.

Earth's systems are powered by a combination of solar energy and heat energy stored within Earth that flows towards its surface. Together, these energy sources have created mountains (a process known as orogenesis) and oceans, produced volcanoes and earthquakes, sculpted the landscape, controlled climate and climate change, driven the circulation of the atmosphere and oceans, and guided the evolution of life (see *The Geosphere and Plate Tectonics and Landform Evolution*).

This chapter introduces some of the basic concepts associated with Earth's systems. We start with an overview of Earth's interior, the internal forces within it, and the evidence used to deduce its character. We then focus on the uppermost layer of the solid Earth, the hard outer shell called the lithosphere, in which fundamental processes such as plate tectonics take place. We will see that plate tectonics is the near-surface expression of the flow of energy from the Earth's interior. We also describe the most important minerals and rocks, which are the end product of these processes, and the role of circulating fluids. We then turn our attention to Earth's surface processes and their role in weathering, erosion and soil development. We follow this by surveying Earth's watery and gaseous envelopes with an introduction to oceanography, weather, and climate. Finally, we examine Earth systems in the geologic past and their influence on the evolution of the biosphere.

2. Earth's Layers

2.1 Internal Layers

Earth is layered according to density from its core, which contains its densest elements, to its atmosphere, which contains the lightest. For example, the average density of Earth is 5.52 (i.e. ~ 5.52 times the density of water at sea level), whereas its surface rocks have densities between 2.5 and 3.0 times that of water, and the average density of the atmosphere is only 0.0129. This is because many of Earth's internal processes combine to transport light elements from the planet's interior towards its surface. Gases emanating from volcanoes are a dramatic example of this process, by which the lightest molecules escape from Earth's interior altogether and are vented into the atmosphere (see *Chapters Internal Forces and their Influence on the Earth's Surface and Volcanic and Magmatic Rocks*).

Although to a first approximation, the distribution and extent of Earth's surface rocks are adequately known from geological mapping, direct evidence of the planet's interior is limited to knowledge gained from drilling or subsurface mining—activities confined to the upper 10 km of Earth's crust. As a result, we must characterize the interior indirectly. Several clues tell us that Earth's interior must be quite unlike the rocks exposed at the surface. For example, if Earth were made entirely of rocks like those at the surface, its average density would be only 4.2. So the actual density of 5.52 requires Earth's interior to be made up of much heavier elements (and, hence, compositionally distinct materials) than those at the surface.

The most important clues regarding the composition of Earth's interior come from earthquakes. Although earthquakes are confined to the brittle rocky layers of Earth's lithosphere, each earthquake sends out waves of energy in all directions. We are most familiar with the devastating effects of this energy as it propagates along Earth's surface. However, this energy is also directed into the planet's interior, so that, following an earthquake, Earth "rings like a bell."

The velocity of an earthquake wave depends on the nature of the medium through which it travels. Just as the paths of X-rays provide an image of a patient's interior, so the paths of earthquake waves provide a picture of Earth's interior, revealing changes in its chemical and physical properties. Chemically, the planet can be divided into three layers: (a) the crust, which consists of strong rocks with an average thickness of 30–40 km beneath continents and 7–8 km beneath oceans; (b) the mantle, which is composed of relatively dense silicate and oxide minerals, and extends from the base of the crust to a depth of 2900 km; and (c) the core, which is made largely of metallic iron and extends from the base of the mantle to Earth's centre, 6370 km below the surface (Figure 2). The outer part of the core is an iron-rich liquid that is thought to be responsible for Earth's magnetic field. The inner core is an iron-rich solid.

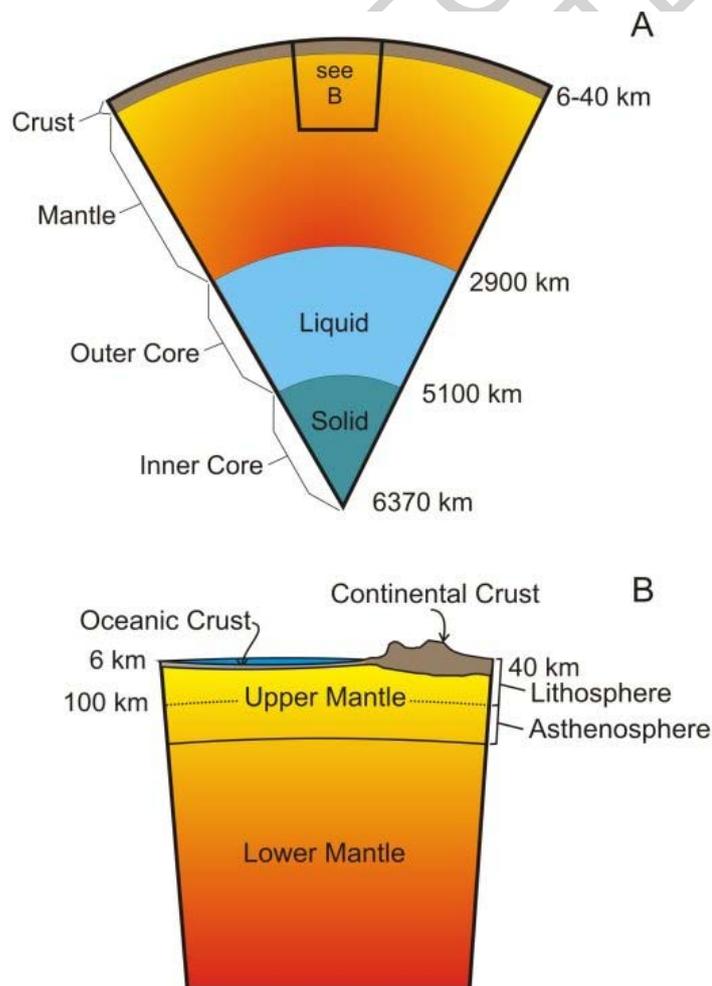


Figure 2. Earth's internal layers (inset shows Earth's outer part in more detail). The

asthenosphere is solid, but soft, behaves plastically, and flows. The lithosphere, which includes the crust and lithospheric (uppermost) mantle, is rigid. Note that the figures are not to scale.

Physically, Earth's crust and uppermost mantle are mechanically rigid, and together comprise the lithosphere (after the Greek *lithos*, meaning rock). The lithosphere varies in thickness from ~75 km beneath the oceans to ~125 km under the continents. The lithosphere rests on a mechanically weak layer within the mantle, known as the asthenosphere (after the Greek *asthenos*, meaning weak).

2.2 Internal Forces

Our knowledge of Earth's internal composition and layered structure allows us to characterize its internal forces and their surface expressions. One such force is Earth's magnetism, a property that has been used in navigation for centuries. Earth's magnetic field resembles that of a bar magnet, and is thought to be generated in the planet's outer core by the combined effects of convection and Earth's spin. This interaction results in spiraling columns of electrically conducting iron-rich liquid.

A form of convection also occurs in the mantle. Although temperatures in the mantle are below the melting points of the component substances, the material there is a soft solid and can convect by a process known as creep. Convection in the mantle is thought to be powered by the heat generated by the decay of its radioactive elements. As a result, lighter, hotter parts of the mantle are buoyant and rise towards the surface, whereas denser, cooler portions sink. This transfer of heat and energy towards the surface is a fundamental internal process that has affected the evolution of Earth's lithosphere throughout geologic time. The energy is transferred from the lower to the upper mantle, and ultimately powers plate tectonics, the most important process to affect the lithosphere.

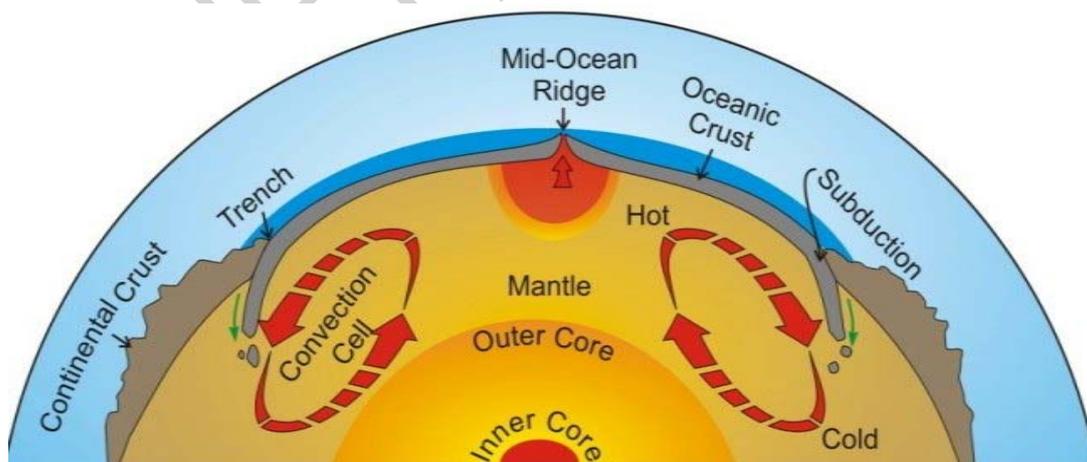


Figure 3. Convection in the mantle. Lithospheric plates form the uppermost part of large mantle convection cells. Plate motion is related to convection in the underlying mantle.

3. Plate Tectonics

Earth's rigid lithosphere is like a cracked eggshell. It is divided into an interlocking mosaic of slabs, or plates, of varying size (Figure 4A). These lithospheric plates, whether oceanic or continental, are less dense than the underlying mantle, and so are buoyant and "float" on the pliable asthenosphere, in the same manner that icebergs float on water. This state of floating balance is known as isostasy. The plates are mechanically decoupled from the planet's interior at the base of the lithosphere by the asthenosphere, which allows them to move relative to one another. It is generally believed that convection in the mantle provides the energy to drive plate motion, although the exact nature of the mechanism involved is unclear.

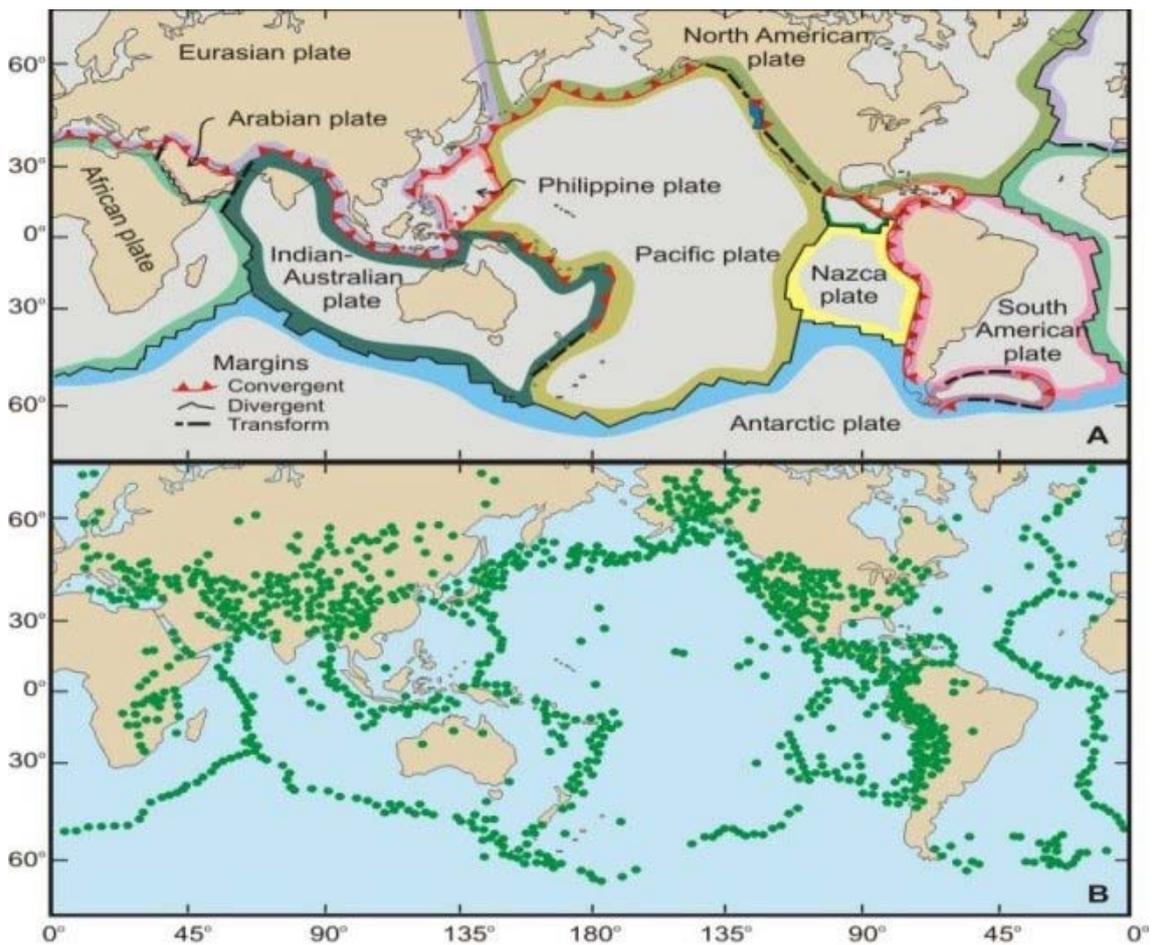


Figure 4. A. Earth's major plates B. Plate boundaries are seismically active and are outlined by the distribution of earthquakes (dots). Most volcanic eruptions also take place at or adjacent to the plate boundaries. Eruptions are explosive where plates collide and quiet where plates separate.

As plates move, they interact with one another along their margins. As a result, plate margins are characterized by earthquake activity, a correspondence that facilitates their identification (Figure 4B).

Plates interact with one another in one of three ways (Figure 5). They may move away from one another, or diverge; they can move towards one another, or converge; or they

may slip sideways past one another. Where oceanic plates diverge, hot molten material, or magma, rises from the asthenosphere below and cools and crystallizes to form new crust, a process known as seafloor spreading. Divergent plate boundaries are therefore known as constructive margins. Where continental plates diverge, the continental crust first thins and then separates such that new oceans form between the diverging crustal fragments. Where an ocean spreads, the region above the ascending magma is swollen with heat, and so forms a relatively elevated area, known as a mid-ocean ridge. Such a ridge extends the length of the Atlantic Ocean, and formed when North America separated from Europe, and South America separated from Africa. (See *Plate Tectonics and Landform Evolution, earthquakes*).

Where plates converge, the denser plate sinks beneath the lighter one, and begins an angled descent into the mantle, a process known as subduction. Since this process consumes ocean floor, convergent plate boundaries are also known as destructive margins. Although subduction partially recycles oceanic plates, subducting slabs have been traced to depths close to the core–mantle boundary at 2900 km. As a result, many scientists believe that subducting slabs pull the plate behind them (a force known as "slab-pull"), like a tablecloth sliding off a table.

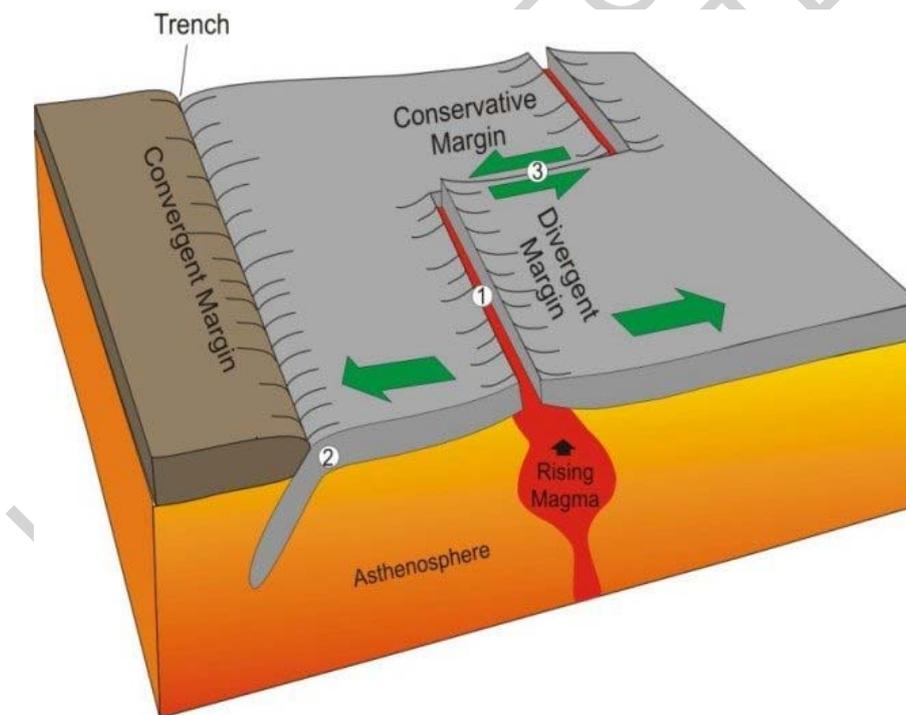


Figure 5. The three types of plate margins/boundaries: (1) a divergent/constructive margin, where plates separate; (2) a convergent/destructive margin, where plates collide; and (3) a transform/conservative margin, where plates slip past each other.

Where plates slide past one another, they neither create nor destroy crust. Such plate boundaries are therefore called conservative margins. However, friction between the plates may result in violent earthquakes, like those of the San Andreas Fault in California or the Anatolian Fault in Turkey.

4. Geologic Time

Modern Earth systems are the product of 4.6 billion years (Ga) of interaction and coevolution and provide us with a planet that is hospitable to life. However, the rock record, together with models of planetary evolution, tells us that today's lithosphere, hydrosphere, atmosphere, and biosphere are fundamentally different from those of primitive Earth. In order to understand how the earth systems have evolved, scientists need a way to "date" or assign an age to Earth's materials (i.e., its minerals and rocks). To accomplish this, two complementary approaches are used. The first makes use of relationships displayed by exposures, or outcrops, of rocks on Earth's surface from which a sequence of geologic events can be deduced. This approach places geologic events in the order in which they occurred and is known as relative age dating. The second involves determining the antiquity of a mineral or rock by measuring the amount of radioactive decay that has occurred since the mineral or rock first formed. This approach yields the actual age of the material (usually in millions of years) and is known as absolute age dating.

Relative age dating applies several simple principles to the geological relationships observed in the field. For example, the rock layers seen in many outcrops were originally deposited horizontally, so that any deviation from horizontality must be the result of subsequent tectonic forces. These layers were also deposited in laterally continuous sheets, so that any abrupt terminations must be due to subsequent events that severed the layers. Fractures along which the rock layering is broken and offset, for example, are known as faults and are often the preserved expression of ancient earthquake activity. Faults consequently show a crosscutting relationship with respect to the layering, which proves they are younger than the layers they sever.

Absolute age dating uses a sophisticated instrument, known as a mass spectrometer, to measure the amount of radioactive decay that has taken place within a mineral or rock. A mineral, by definition, has a chemical formula, which expresses its composition in terms of essential chemical elements. All minerals, however, contain impurities, some of which may be radioactive. Radioactive elements, known as parent elements, spontaneously decay to more stable products, known as daughter elements. The rate of decay of parent to daughter is constant, and is unaffected by any known natural process. The older the mineral, the greater the amount of decay from parent to daughter. A mass spectrometer can measure this decay, and, in so doing, can determine the age of geological materials (see Chapter *The Geosphere and Time in the Geological Past of the Earth* for a description of geologic time).

Many modern age-dating techniques utilize zircon, a mineral that is a minor constituent of many rocks. Because it is a highly resilient, the radioactive decay process is sealed within it under most geological conditions. As a result, analysis of zircons yields accurate information on the age of the mineral.

Absolute age dating is very expensive and not all rocks contain minerals that can be dated. Consequently, most geological studies use a combination of relative and absolute age dating to deduce the geological history of a region. By understanding and comparing the geology of individual regions, large-scale processes such as mountain

building, or orogenesis, can be interpreted.

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Biographical Sketches

Jaroslav Dostal: Jaroslav Dostal received his initial education in geology at Charles University in Prague, Czechoslovakia. He was a lecturer at that university before emigrating to Canada where he received his doctoral degree from McMaster University in Hamilton, Ontario, in 1974. After a year of postdoctoral studies at Dalhousie University, Halifax, Nova Scotia, he was hired by Saint Mary's University in Halifax where he is now a professor of geology. Dr. Dostal has also worked as a researcher at the Universite de Montpellier, and the Universite d'Aix-Marseille, France, and the Universita di Modena, Italy. He has authored or coauthored over 150 papers in academic journals as well as more than 200 conference abstracts and other publications.

J. Brendan Murphy: Brendan Murphy is an Irish citizen who completed high school and his bachelor's of science degree in Ireland, before emigrating to Canada in 1975. He acquired a master's of science from Acadia University in Wolfville, Nova Scotia, in 1977 and a doctorate degree from McGill University (Montreal, Quebec) in 1982. In 1982, he joined St. Francis Xavier University, where he is now a professor of geology. He has published over 100 scientific articles in academic journals, book chapters, monographs, or geological field guidebooks, and has authored or coauthored more than 120 conference abstracts.

R. Damian Nance: Damian Nance is from Cornwall, England, and is a citizen of both the United Kingdom and the United States. He received his education in geology in England with a B.Sc degree from the University of Leicester in 1972 and a doctoral degree from Cambridge University before emigrating to Canada in 1976 to teach at St. Francis Xavier University in Nova Scotia. In 1980, he joined Ohio University where he is now a professor of geology. The focus of much of his research has centred on the early evolution of the Appalachian Mountains and on the global-scale plate tectonic processes responsible for their development. He has published over 150 scientific articles in academic journals, books and government documents, and has authored or co-authored more than 180 conference abstracts.