Chapter 11

# Plates, Plate Motions, and Plate-Boundary Processes

Continental drift and sea-floor spreading became widely accepted around 1965 as more and more geologists started thinking in these terms. By the end of 1967, Earth’s surface had been mapped into a series of plates (Figure 11.1). The major plates are Eurasia, Pacific, India, Australia, North America, South America, Africa, and Antarctic. There are also numerous small plates (e.g., Juan de Fuca, Nazca, Scotia, Philippine, Caribbean), and many very small plates or sub-plates. For example the Juan de Fuca Plate is actually three separate plates (Gorda, Juan de Fuca, and Explorer) that all move in the same general direction but at slightly different rates.

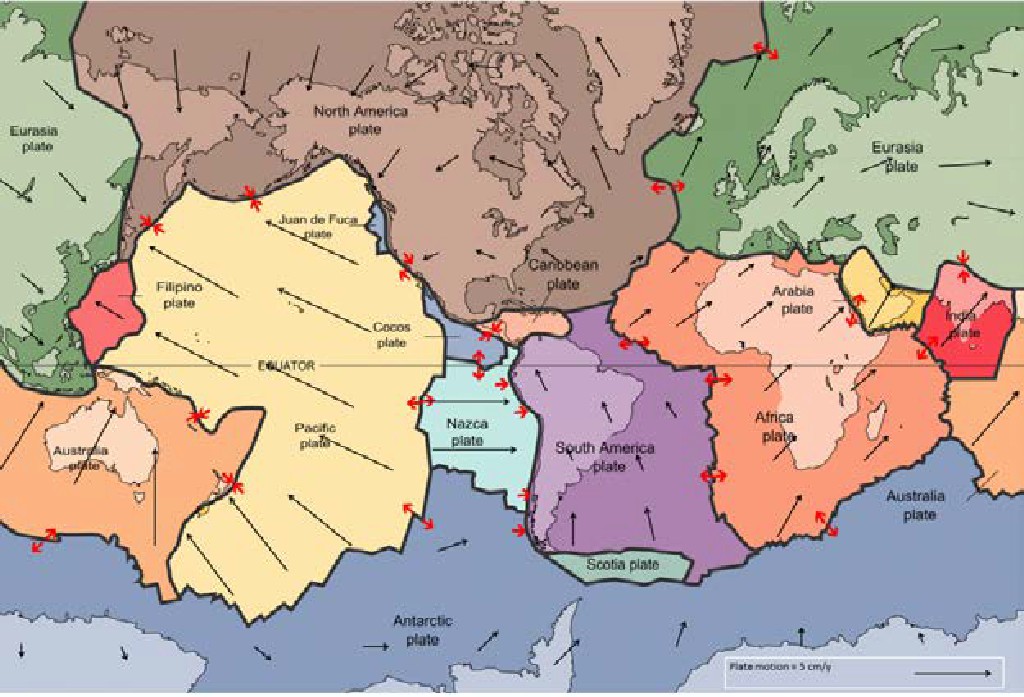
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Figure 11.1 A map showing 15 of the Earth’s tectonic plates and the approximate rates and directions of plate motions. [SE after USGS, [http://en.wikipedia.org/wiki/Plate\_tectonics#/media/](http://en.wikipedia.org/wiki/Plate_tectonics%23/media/) File:Plates\_tect2\_en.svg]

Rates of motions of the major plates range from less than 1 cm/y to over 10 cm/y. The Pacific Plate is the fastest at over 10 cm/y in some areas, followed by the Australian and Nazca Plates. The North American Plate is one of the slowest, averaging around 1 cm/y in the south up to almost 4 cm/y in the north.

Plates move as rigid bodies, so it may seem surprising that the North American Plate can be moving at different rates in different places. The explanation is that plates move in a rotational manner. The North American Plate, for example, rotates counter-clockwise; the Eurasian Plate rotates clockwise.

Boundaries between the plates are of three types: **divergent** (i.e., moving apart)*,* **convergent** (i.e., moving together), and **transform** (moving side by side). Before we talk about processes at plate boundaries, it’s important to point out that there are never gaps between plates. The plates are made up of crust and the lithospheric part of the mantle (Figure 11.2), and even though they are moving all the time, and in different directions, there is never a significant amount of space between them. Plates are thought to move along the lithosphere-asthenosphere boundary, as the asthenosphere is the zone of partial melting. It is assumed that the relative lack of strength of the partial melting zone facilitates the sliding of the lithospheric plates.

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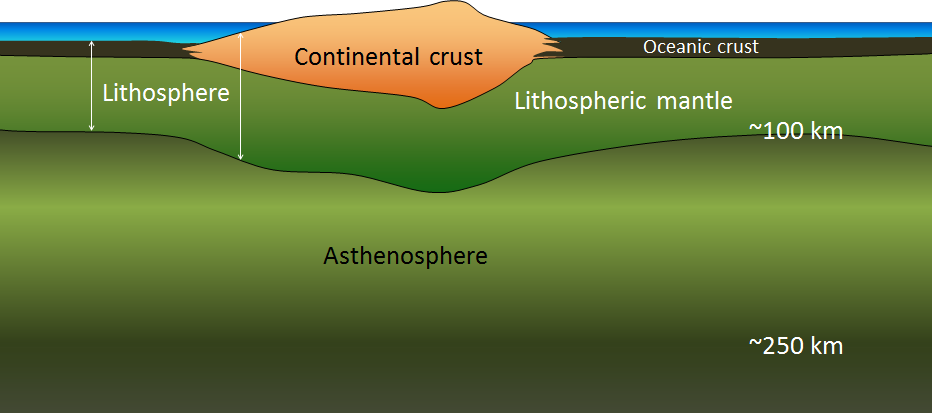
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Figure 11.2 The crust and upper mantle. Tectonic plates consist of lithosphere, which includes the crust and the lithospheric (rigid) part of the mantle. [SE]

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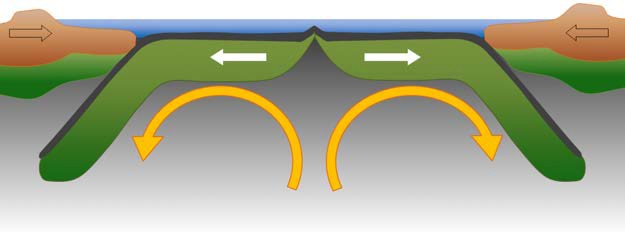
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Figure 11.3 A representation of Harold Hess’s model for sea-floor spreading and subduction [SE]

Phenomenon of reversals in Earth’s magnetic field.

At spreading centers, the lithospheric mantle may be very thin because the upward convective motion of hot mantle material generates temperatures that are too high for the existence of a significant thickness of rigid lithosphere (Figure 11.2). The fact that the plates include both crustal material and lithospheric mantle material makes it possible for a single plate to be made up of both oceanic and continental crust. For example, the North American Plate includes most of North America, plus half of the northern Atlantic Ocean. Similarly the South American Plate extends across the western part of the southern Atlantic Ocean, while the European and African plates each include part of the eastern Atlantic Ocean. The Pacific Plate is almost entirely oceanic, but it does include the part of California west of the San Andreas Fault.

##### Divergent Boundaries

Divergent boundaries are spreading boundaries, where new oceanic crust is created from magma derived from partial melting of the mantle caused by decompression as hot mantle rock from depth is moved toward the surface (Figure 11.4). The triangular zone of partial melting near the ridge crest is approximately 60 km thick and the proportion of magma is about 10% of the rock volume, thus producing crust that is about 6 km thick. Most divergent boundaries are located at the oceanic ridges (although some are on land), and the crustal material created at a spreading boundary is always oceanic in character; in other words, it is mafic igneous rock (e.g., basalt or gabbro, rich in ferromagnesian minerals). Spreading rates vary considerably, from 1 cm/y to 3 cm/y in the Atlantic, to between 6 cm/y and 10 cm/y in the Pacific. Some of the processes taking place in this setting include:

* Magma from the mantle pushing up to fill the voids left by divergence of the two plates
* **Pillow lavas** forming where magma is pushed out into seawater (Figure 11.5)
* **Vertical** sheeted dykes intruding into cracks resulting from the spreading
* Magma cooling more slowly in the lower part of the new crust and forming gabbro bodies

Spreading is hypothesized to start within a continental area with up-warping or doming related to an underlying mantle plume or series of mantle plumes. The buoyancy of the mantle plume material creates a dome within the crust, causing it to fracture in a radial pattern, with three arms spaced at approximately 120° (Figure 11.6). When a series of mantle plumes exists beneath a large continent, the resulting rifts may align and lead to the formation of a rift valley (such as the present-day Great Rift Valley in eastern Africa). It is suggested that this type of valley eventually develops into a linear sea (such as the present-day Red Sea), and finally into an ocean (such as the Atlantic). It is likely that as many as 20 mantle plumes, many of which still exist, were responsible for the initiation of the rifting of Pangea along what is now the mid-Atlantic ridge (see Figure 11.6).

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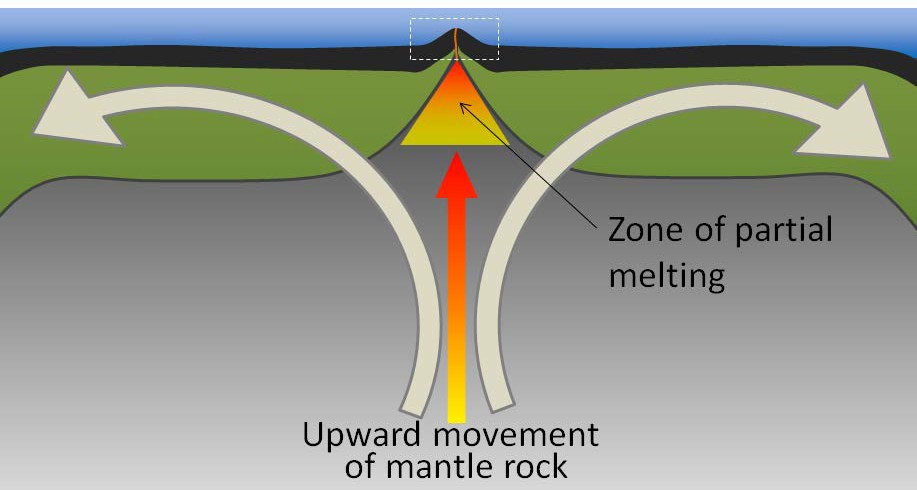
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Figure 11.4 The general processes that take place at a divergent boundary. The area within the dashed white rectangle is shown in Figure 10.19. [SE]

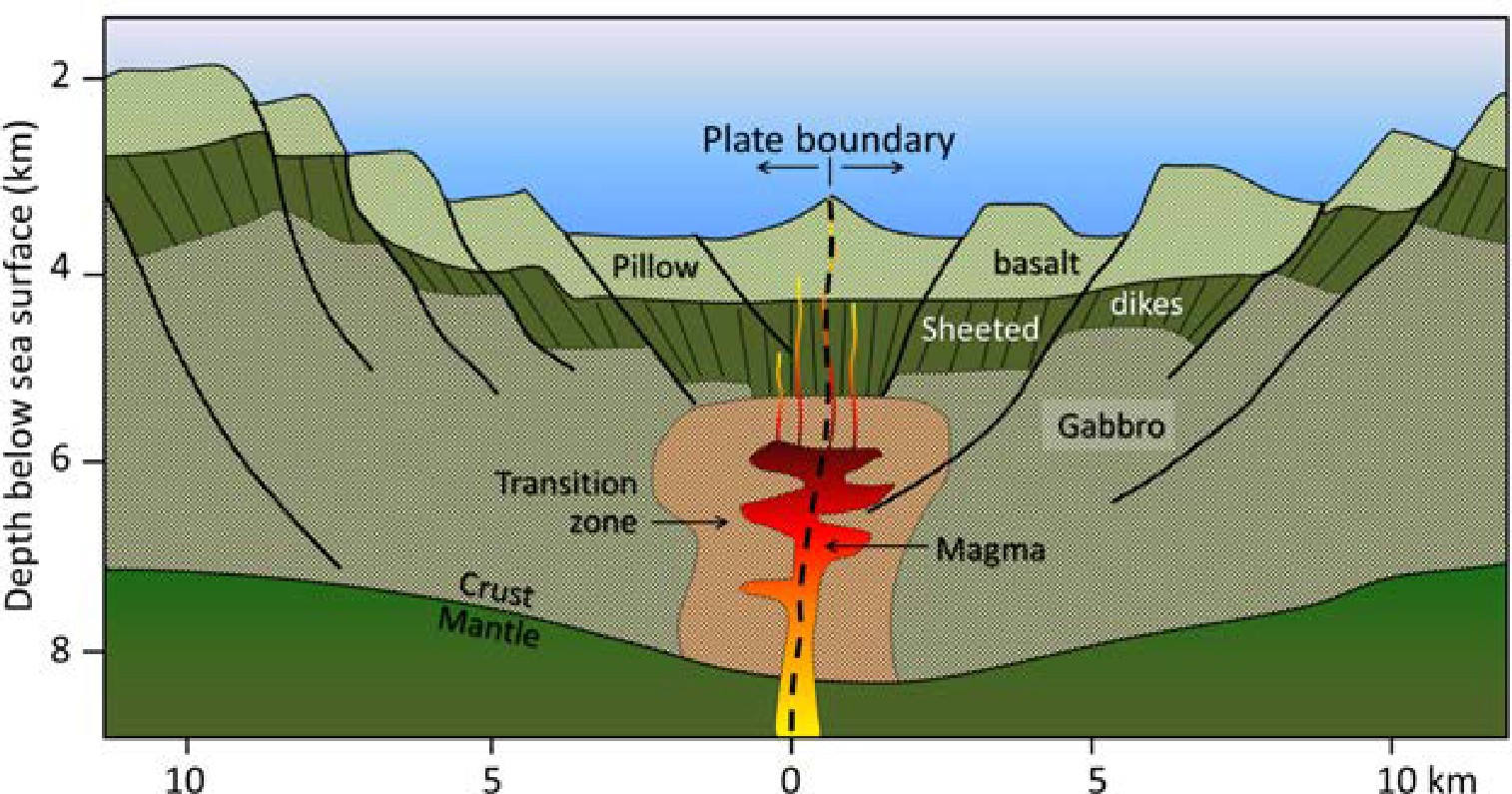
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Figure 11.5 Depiction of the processes and materials formed at a divergent boundary [SE after Keary and Vine, 1996, Global Tectonics (2ed), Blackwell Science Ltd., Oxford]

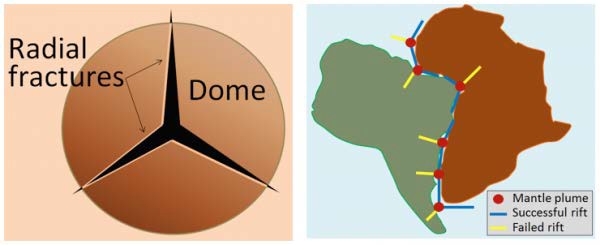
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Figure 11.6 Depiction of the process of dome and three-part rift formation (left) and of continental rifting between the African and South American parts of Pangea at around 200 Ma (right) [SE]

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##### Convergent Boundaries

Convergent boundaries, where two plates are moving toward each other, are of three types, depending on the type of crust present on either side of the boundary — oceanic or continental. The types are ocean-ocean, ocean- continent, and continent-continent.

At an ocean-ocean convergent boundary, one of the plates (oceanic crust and lithospheric mantle) is pushed, or subducted**,** under the other. Often it is the older and colder plate that is denser and subducts beneath the younger and hotter plate. There is commonly an ocean trench along the boundary. The subducted lithosphere descends into the hot mantle at a relatively shallow angle close to the subduction zone, but at steeper angles farther down (up to about 45°). Significant volume of water within the subducting material is released as the subducting crust is heated. This water is mostly derived from alteration of pyroxene and olivine to serpentine near the spreading ridge shortly after the rock’s formation. It mixes with the overlying mantle, and the addition of water to the hot mantle lowers the crust’s melting point and leads to the formation of magma (flux melting). The magma, which is lighter than the surrounding mantle material, rises through the mantle and the overlying oceanic crust to the ocean floor where it creates a chain of volcanic islands known as an island arc. A mature island arc develops into a chain of relatively large islands (such as Japan or Indonesia) as more and more volcanic material is extruded and sedimentary rocks accumulate around the islands.

Earthquakes take place close to the boundary between the subducting crust and the overriding crust. The largest earthquakes occur near the surface where the subducting plate is still cold and strong.

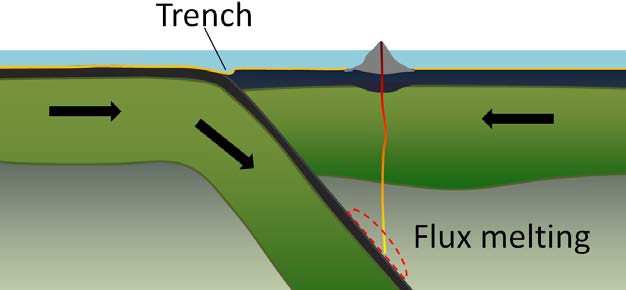
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Figure 11.7 Configuration and processes of an ocean-ocean convergent boundary [SE]

Examples of ocean-ocean convergent zones are subduction of the Pacific Plate south of Alaska (Aleutian Islands) and west of the Philippines, subduction of the India Plate south of Indonesia, and subduction of the Atlantic Plate beneath the Caribbean Plate (Figure 11.7).

At an ocean-continent convergent boundary, the oceanic plate is pushed under the continental plate in the same manner as at an ocean-ocean boundary. Sediment that has accumulated on the **continental slope** is thrust up into an accretionary wedge, and compression leads to thrusting within the continental plate (Figure 11.8). The mafic magma produced adjacent to the subduction zone rises to the base of the continental crust and leads to partial melting of the crustal rock. The resulting magma ascends through the crust, producing a mountain chain with many volcanoes.

Examples of ocean-continent convergent boundaries are subduction of the Nazca Plate under South America (which has created the Andes Range) and subduction of the Juan de Fuca Plate under North America (creating the mountains Garibaldi, Baker, St. Helens, Rainier, Hood, and Shasta, collectively known as the Cascade Range).

A continent-continent collision occurs when a continent or large island that has been moved along with

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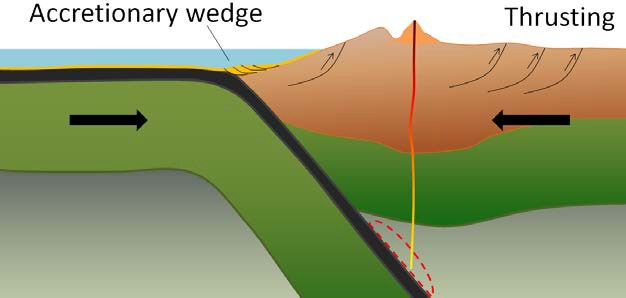
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Figure 11.8 Configuration and processes of an ocean-continent convergent boundary [SE]

subducting oceanic crust collides with another continent (Figure 11.9). The colliding continental material will not be subducted because it is too light (i.e., because it is composed largely of light continental rocks [SIAL]), but the root of the oceanic plate will eventually break off and sink into the mantle. There is tremendous deformation of the pre-existing continental rocks, and creation of mountains from that rock, from any sediments that had accumulated along the shores (i.e., within geosynclines) of both continental masses, and commonly also from some ocean crust and upper mantle material.

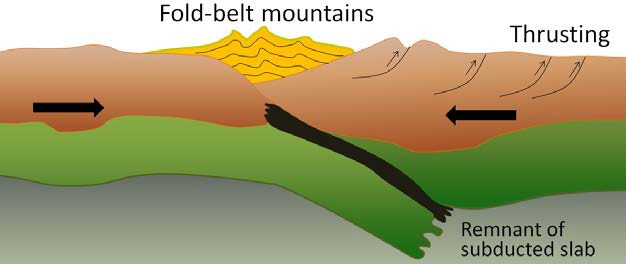
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Figure 11.9 Configuration and processes of a continent-continent convergent boundary [SE]

Examples of continent-continent convergent boundaries are the collision of the India Plate with the Eurasian Plate, creating the **Himalaya Mountains**, and the collision of the African Plate with the Eurasian Plate, creating the series of ranges extending from the **Alps** in Europe to the **Zagros Mountains** in Iran. The **Rocky Mountains** in B.C. and Alberta are also a result of continent-continent collisions.

**Transform Boundaries**

Transform boundaries exist where one plate slides past another without production or destruction of crustal material. As explained above, most transform faults connect segments of mid-ocean ridges and are thus ocean-ocean plate boundaries (Figure 11.10). Some transform faults connect continental parts of plates. An example is the San Andreas Fault, which connects the southern end of the Juan de Fuca Ridge with the northern end of the East Pacific Rise (ridge) in the Gulf of California (Figures 11.10 and 11.11). The part of California west of the San Andreas Fault and all of Baja California are on the Pacific Plate. Transform faults do not just connect divergent boundaries. For example, the Queen Charlotte Fault connects the north end of the Juan de Fuca Ridge, starting at the north end of Vancouver Island, to the Aleutian subduction zone.

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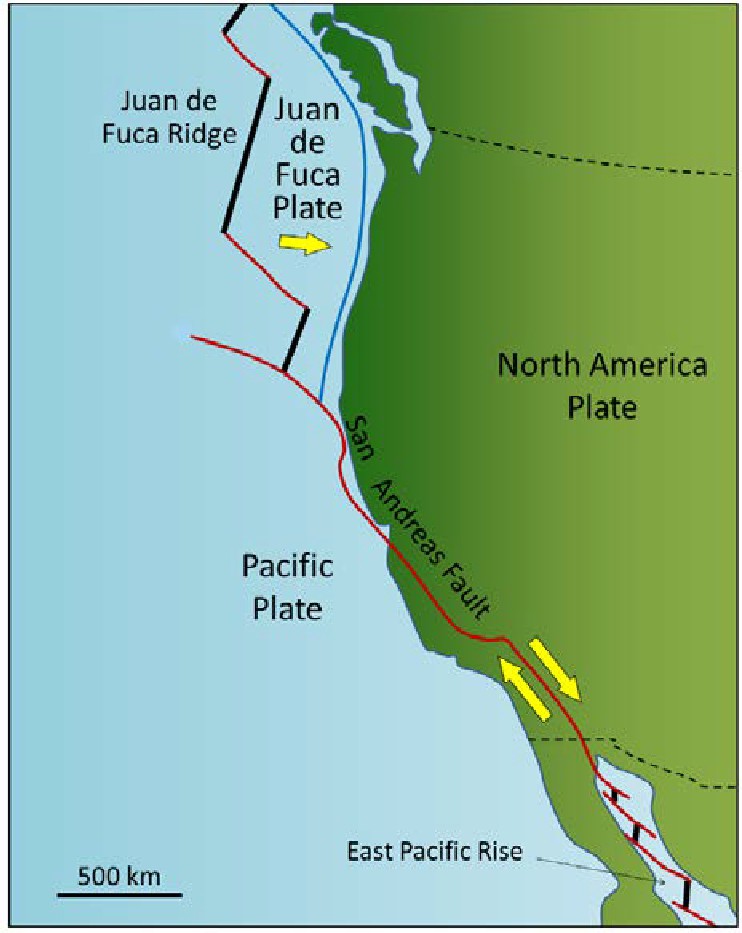
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Figure 11.10 The San Andreas Fault extends from the north end of the East Pacific Rise in the Gulf of California to the southern end of the Juan de Fuca Ridge. All of the red lines on this map are transform faults. [SE][](http://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/image063.jpg)

Figure 11.11 The San Andreas Fault at Parkfield in central California. The person with the orange shirt is standing on the Pacific Plate and the person at the far side of the bridge is on the North American Plate. The bridge is designed to slide on its foundation. [SE]

As originally described by Wegener in 1915, the present continents were once all part of a supercontinent, which he termed **Pangea** (*all land*). More recent studies of continental matchups and the magnetic ages of ocean-floor rocks have enabled us to reconstruct the history of the break-up of Pangea.

Pangea began to rift apart along a line between Africa and Asia and between North America and South America at around 200 Ma. During the same period, the Atlantic Ocean began to open up between northern Africa and North America, and India broke away from Antarctica. Between 200 and 150 Ma, rifting started between South America and Africa and between North America and Europe, and India moved north toward Asia. By 80 Ma, Africa had

separated from South America, most of Europe had separated from North America, and India had separated from Antarctica. By 50 Ma, Australia had separated from Antarctic, and shortly after that, India collided with Asia. To see the timing of these processes for yourself go to: <http://barabus.tru.ca/geol1031/plates.html>.

Within the past few million years, rifting has taken place in the Gulf of Aden and the Red Sea, and also within the Gulf of California. Incipient rifting has begun along the Great Rift Valley of eastern Africa, extending from Ethiopia and Djibouti on the Gulf of Aden (Red Sea) all the way south to Malawi.

Over the next 50 million years, it is likely that there will be full development of the east African rift and creation of new ocean floor. Eventually Africa will split apart. There will also be continued northerly movement of Australia and Indonesia. The western part of California (including Los Angeles and part of San Francisco) will split away from the rest of North America, and eventually sail right by the west coast of Vancouver Island, en route to Alaska. Because the oceanic crust formed by spreading on the mid-Atlantic ridge is not currently being subduct

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(except in the Caribbean), the Atlantic Ocean is slowly getting bigger, and the Pacific Ocean is getting smaller. If this continues without changing for another couple hundred million years, we will be back to where we started, with one supercontinent.

Pangea, which existed from about 350 to 200 Ma, was not the first supercontinent. It was preceded by Pannotia (600 to 540 Ma), by Rodinia (1,100 to 750 Ma), and by others before that.

In 1966, Tuzo Wilson proposed that there has been a continuous series of cycles of continental rifting and collision; that is, break-up of supercontinents, drifting, collision, and formation of other supercontinents. At present, North and South America, Europe, and Africa are moving with their respective portions of the Atlantic Ocean. The eastern margins of North and South America and the western margins of Europe and Africa are called **passive margins** because there is no subduction taking place along them.

This situation may not continue for too much longer, however. As the Atlantic Ocean floor gets weighed down around its margins by great thickness of continental sediments (i.e., geosynclines), it will be pushed farther and farther into the mantle, and eventually the oceanic lithosphere may break away from the continental lithosphere (Figure 11.12). A subduction zone will develop, and the oceanic plate will begin to descend under the continent. Once this happens, the continents will no longer continue to move apart because the spreading at the mid-Atlantic ridge will be taken up by subduction. If spreading along the mid-Atlantic ridge continues to be slower than spreading within the Pacific Ocean, the Atlantic Ocean will start to close up, and eventually (in a 100 million years or more) North and South America will collide with Europe and Africa.

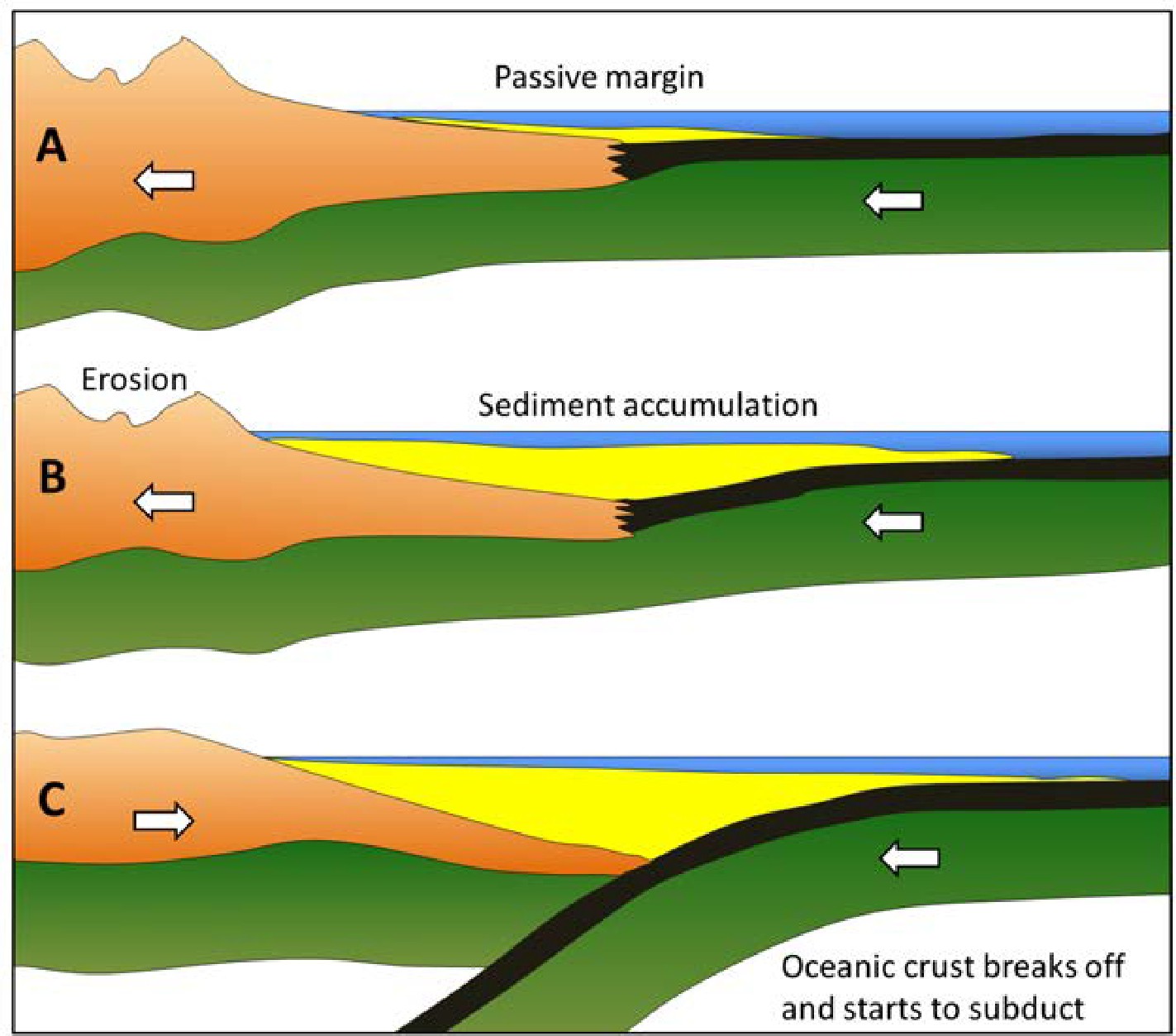
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Figure 11.12 Development of a subduction zone at a passive margin. Times A, B, and C are separated by tens of millions of years. Once the oceanic crust breaks off and starts to subduct the continental crust (North America in this case) will no longer be pushed to the west and will likely start to move east because the rate of spreading in the Pacific basin is faster than that in the Atlantic basin. [SE]

There is strong evidence around the margins of the Atlantic Ocean that this process has taken place before. The roots of ancient mountain belts, which are present along the eastern margin of North America, the western margin of Europe, and the northwestern margin of Africa, show that these land masses once collided with each other to form a mountain chain, possibly as big as the Himalayas. The apparent line of collision runs between Norway

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and Sweden, between Scotland and England, through Ireland, through Newfoundland, and the Maritimes, through the northeastern and eastern states, and across the northern end of Florida. When rifting of Pangea started at approximately 200 Ma, the fissuring was along a different line from the line of the earlier collision. This is why some of the mountain chains formed during the earlier collision can be traced from Europe to North America and from Europe to Africa.

That the Atlantic Ocean rift may have occurred in approximately the same place during two separate events several hundred million years apart is probably no coincidence. The series of hot spots that has been identified in the Atlantic Ocean may also have existed for several hundred million years, and thus may have contributed to rifting in roughly the same place on at least two separate occasions (Figure 11.13).

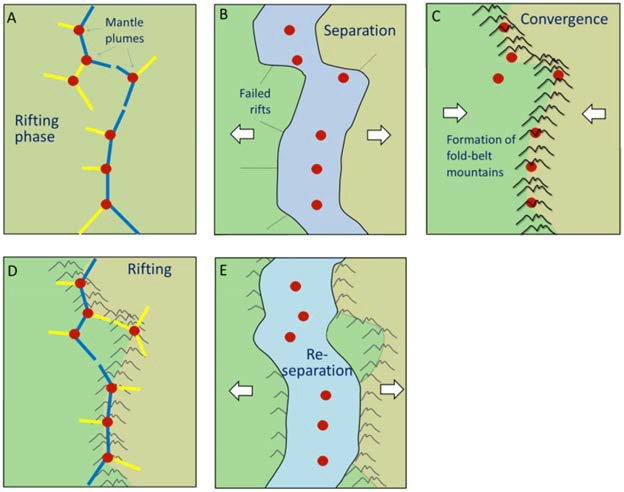
[](http://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/Wilson-cycle.png)

Figure 11.13 A scenario for the Wilson cycle. The cycle starts with continental rifting above a series of mantle plumes (A). The continents separate (B), and then re-converge some time later, forming a fold-belt mountain chain. Eventually rifting is repeated, possibly because of the same set of mantle plumes (D), but this time the rift is in a different place. [SE]

# Isostasy

Theory holds that the mantle is able to convect because of its plasticity, and this property also allows for another very important Earth process known as **isostasy**. The literal meaning of the word isostasy is “equal standstill,” but the importance behind it is the principle that Earth’s crust is *floating* on the mantle, like a raft floating in the water, rather than *resting* on the mantle like a raft sitting on the ground.

The relationship between the crust and the mantle is illustrated in Figure 11.14. On the right is an example of a non-isostatic relationship between a raft and solid concrete. It’s possible to load the raft up with lots of people, and it still won’t sink into the concrete. On the left, the relationship is an isostatic one between two different rafts and a swimming pool full of peanut butter. With only one person on board, the raft floats high in the peanut butter, but with three people, it sinks dangerously low. We’re using peanut butter here, rather than water, because its viscosity more closely represents the relationship between the crust and the mantle. Although it has about the same density as water, peanut butter is much more viscous (stiff), and so although the three-person raft will sink into the peanut butter, it will do so quite slowly.

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[](http://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/image041.png)

Figure 11.14 Illustration of a non-isostatic relationship between a raft and solid ground (right) and of isostatic relationships between rafts and peanut butter (left). [SE]

The relationship of Earth’s crust to the mantle is similar to the relationship of the rafts to the peanut butter. The raft with one person on it floats comfortably high. Even with three people on it the raft is less dense than the peanut butter, so it floats, but it floats uncomfortably low for those three people. The crust, with an average density of around 2.6 grams per cubic centimetre (g/cm3), is less dense than the mantle (average density of approximately 3.4 g/cm3 near the surface, but more than that at depth), and so it is floating on the “plastic” mantle. When more weight is added to the crust, through the process of mountain building, it slowly sinks deeper into the mantle and the mantle material that was there is pushed aside (Figure 11.15, left). When that weight is removed by erosion over tens of millions of years, the crust rebounds and the mantle rock flows back (Figure 11.15, right).

[](https://opentextbc.ca/physicalgeologyearle/wp-content/uploads/sites/145/2016/06/rebound-2.png)

Figure 11.15 Illustration of the isostatic relationship between the crust and the mantle. Following a period of mountain building, mass has been added to a part of the crust, and the thickened crust has pushed down into the mantle (left). Over the following tens of millions of years, the mountain chain is eroded and the crust rebounds (right). The green arrows represent slow mantle flow. [SE]

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The crust and mantle respond in a similar way to glaciation. Thick accumulations of glacial ice add weight to the crust, and as the mantle beneath is squeezed to the sides, the crust subsides. This process is illustrated for the current ice sheet on Greenland in Figure 11.16. The Greenland Ice Sheet at this location is over 2,500 m thick, and the crust beneath the thickest part has been depressed to the point where it is below sea level over a wide area. When the ice eventually melts, the crust and mantle will slowly rebound, but full rebound will likely take more than 10,000 years.

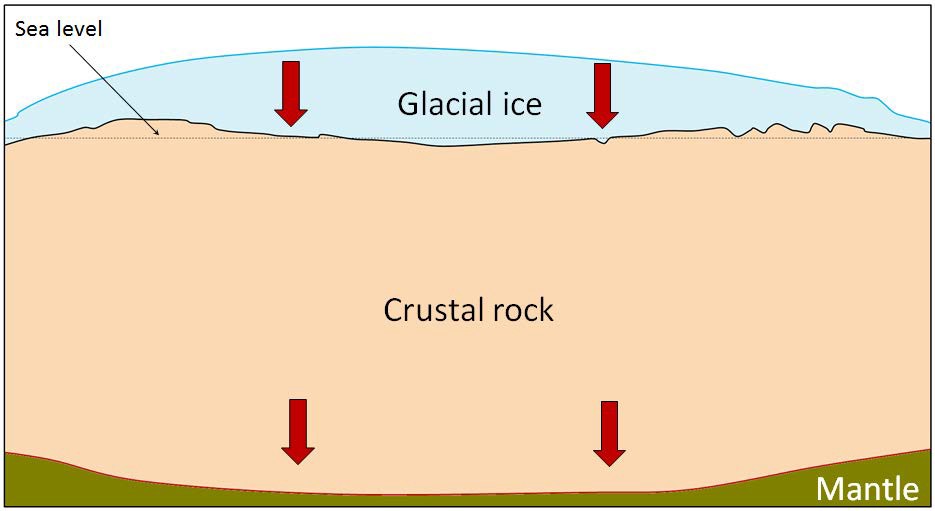
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Figure 11.16a A cross-section through the crust in the northern part of Greenland (The ice thickness is based on data from NASA and the Center for Remote Sensing of Ice Sheets, but the crust thickness is less than it should be for the sake of illustration.) The maximum ice thickness is over 2,500 m. The red arrows represent downward pressure on the mantle because of the mass of the ice.

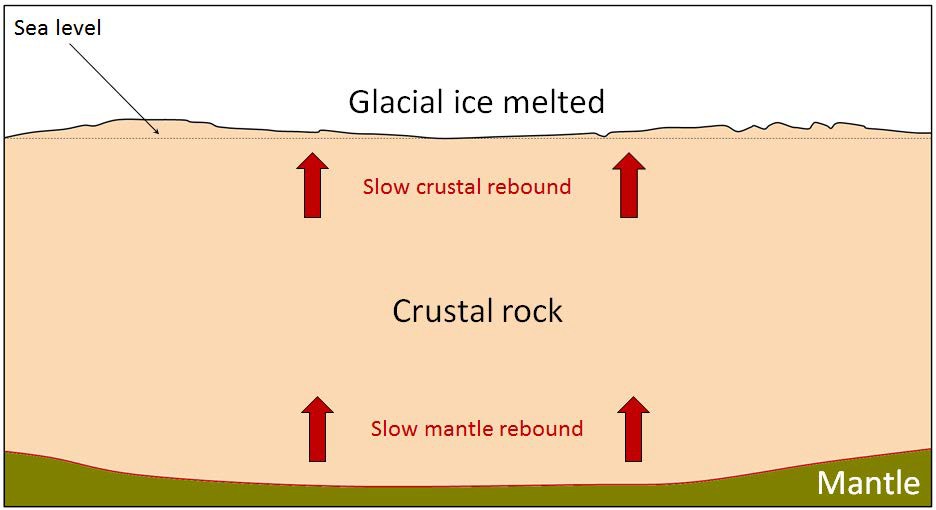
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Figure 11.16b Depiction of the situation after complete melting of the ice sheet, a process that could happen within 2,000 years if people and their governments continue to ignore climate change. The isostatic rebound of the mantle would not be able to keep up with this rate of melting, so for several thousand years the central part of Greenland would remain close to sea level, in some areas even below sea level.

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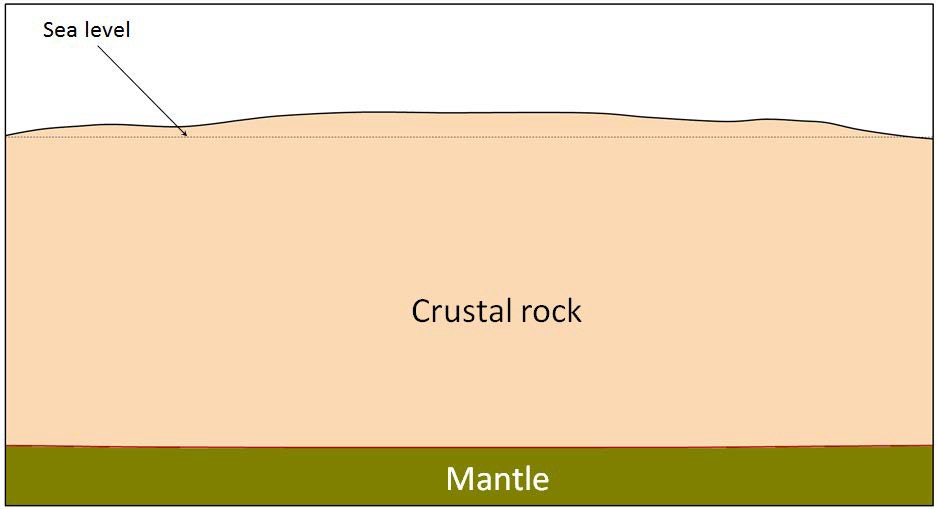
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Figure 11.16c It is likely that complete rebound of the mantle beneath Greenland would take more than 10,000 years.

#### How can the mantle be both solid and plastic?

[](http://opentextbc.ca/geology/wp-content/uploads/sites/110/2015/07/image0531.jpg)

Figure 11.17. Picture of silly putty’s non-Newtonian flow

[https://upload.wikimedia.org/wikipedia/commons/f/f3/Silly\_putty\_dripping.jpg]

You might be wondering how it is possible that Earth’s mantle is rigid enough to break during an earthquake, and yet it convects and flows like a very viscous liquid. The explanation is that the mantle behaves as a non- Newtonian fluid, meaning that it responds differently to stresses depending on how quickly the stress is applied. A good example of this is the behavior of the material known as Silly Putty (Figure 11.17), which can bounce and will break if you pull on it sharply, but will deform in a liquid manner if stress is applied slowly. In this photo, Silly Putty was placed over a hole in a glass tabletop, and in response to gravity, it slowly flowed into the hole. The mantle will flow when placed under the slow but steady stress of a growing (or melting) ice sheet.

Large parts of Canada are still rebounding as a result of the loss of glacial ice over the past 12 ka, and as shown in Figure 11.18, other parts of the world are also experiencing isostatic rebound. The highest rate of uplift is in within a large area to the west of Hudson Bay, which is where the Laurentide Ice Sheet was the thickest (over 3,000 m). Ice finally left this region around 8,000 years ago, and the crust is currently rebounding at a rate of nearly 2 cm/year. Strong isostatic rebound is also occurring in northern Europe where the Fenno-Scandian Ice Sheet was thickest, and in the eastern part of Antarctica, which also experienced significant ice loss during the Holocene.

There are also extensive areas of subsidence surrounding the former Laurentide and Fenno-Scandian Ice

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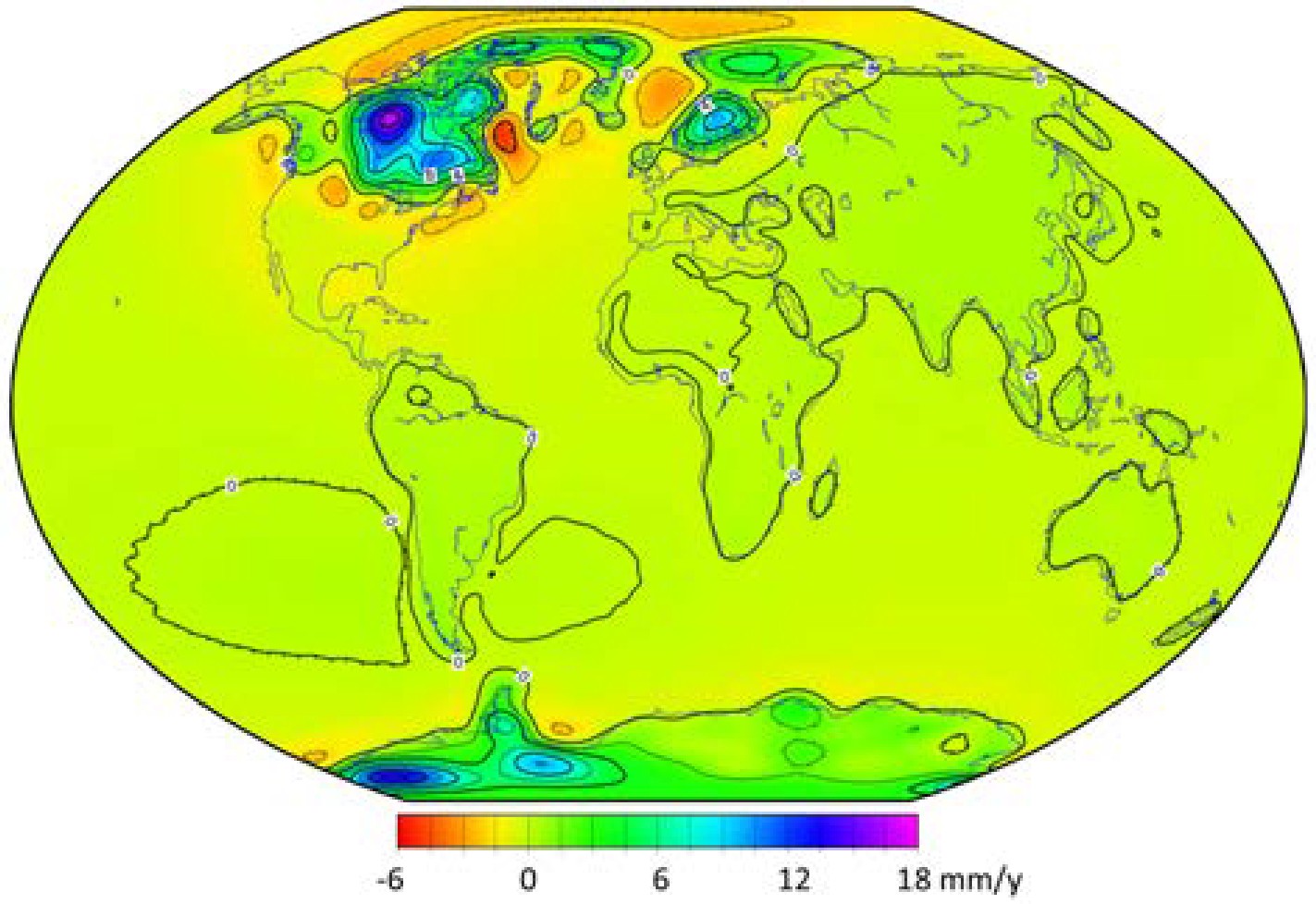
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Figure 11.18 The current rates of post-glacial isostatic uplift (green, blue, and purple shades) and subsidence (yellow and orange). Subsidence is taking place where the mantle is slowly flowing back toward areas that are experiencing post-glacial uplift. [From: Paulson, A., S. Zhong, and

J. Wahr. Inference of mantle viscosity from GRACE and relative sea level data, Geophys. J. Int. (2007) 171, 497–508. Accessed at: [http://en.wikipedia.org/wiki/Hudson\_Bay#/media/](http://en.wikipedia.org/wiki/Hudson_Bay%23/media/) File:PGR\_Paulson2007\_Rate\_of\_Lithospheric\_Uplift\_due\_to\_PGR.png]

Sheets. During glaciation, mantle rock flowed away from the areas beneath the main ice sheets, and this material is now slowly flowing back, as illustrated in Figure 9.18b.

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