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Deconstructing Tectonics: Ten Animated Explorations

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Key Points:

- Fundamentals of plate tectonics are explored with paleogeography
- Short animations and supporting write-ups illustrate key processes and properties of tectonics
- Presenting plate reconstructions from Cambrian to Today, and a permissible future Earth

Supporting Information:

- Movie S1
- Movie S2
- Movie S3
- Movie S4
- Movie S5
- Movie S6
- Movie S7
- Movie S8
- Movie S9
- Movie S10

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Abstract The configuration of continents and oceans of our tectonically active planet is ever changing. Using new, high-resolution paleogeographic base maps, we created a set of animations that examine key elements of plate tectonics. These time- and space-based paleoglobe reconstructions illustrate continental rifting, continental breakup, ocean ridges and fracture zones, hot spot tracks, arc-backarc systems, continental collision, terrane accretion, opening-closing of ocean basins, supercontinent formation, plate velocities, and future Earth. Each animation is supported by a narrative that offers a brief topical overview, some observations to guide a user's exploration, and key references that formulated the main ideas and concepts that became the foundations of modern plate tectonics.

1. Plate Tectonics

Earth is a dynamic planet, and the configuration of continents and oceans is ever changing through geologic time. The planet's outermost shell consists of discrete segments, called lithospheric plates, which continuously move relative to one another on the order of cm/yr. Lithospheric plates consist of the crust and the mechanically strong part of the upper mantle, ranging in thickness from kilometers in oceanic realms to 200+ km in continental regions of the plates. A plate can be viewed as a cap on the surface of a sphere, much like the cracked shell of a boiled egg (McKenzie & Parker, 1967; Morgan, 1968). The contact between two adjacent plates is called a plate boundary and is where tectonic deformation is concentrated. As plates move, the plate interior (the region away from the plate boundaries) stays relatively coherent, although regional structures can develop (such as rift zones, intracratonic basins, fault-and-fold zones, and plateaus).

Today's Earth has seven large plates (Pacific, North American, South American, Eurasian, African, Indo-Australian, and Antarctic plates), seven smaller plates (Juan de Fuca, Caribbean, Cocos, Nazca, Scotia, Arabian, and Philippine plates), and several microplates (Figure 1; Bird, 2003). A plate can consist entirely of oceanic lithosphere (such as the Pacific and Nazca plates), but most plates consist of both oceanic and continental lithosphere. For example, the North American Plate consists of the continent of North America and the western half of the Atlantic Ocean floor. This also means that continental margins, where continental lithosphere transforms into oceanic lithosphere, are not necessarily tectonic plate boundaries.

We identify three types of plate boundaries.

1. At divergent plate boundaries, typically ocean ridges, two plates move apart due to seafloor spreading. This process produces new oceanic lithosphere, for example, the boundary between the North American and Eurasian plates, between South American and African plates, and between Antarctic and Pacific, Nazca, South American, African, and Indo-Australian Pacific plates.
2. At convergent plate boundaries, the oceanic part of a plate sinks beneath an overriding plate into the deeper mantle. The overriding plate can be either a continental or oceanic plate. This sinking process, called subduction, gradually consumes the oceanic plate. Volatiles (such as water and carbon dioxide) released from the subducted plate often trigger melting in the overlying material. The resulting magma erupts in a chain of volcanoes, called a volcanic arc, that formed near the edge of the overriding plate. Arcs can be floored by continental or oceanic crust, with characteristic properties. Examples are the boundary between the Nazca and South American plates (with a continental arc), and the Pacific and Eurasian plates (with intraoceanic arcs).
3. The boundary where one plate moves past another is called a lateral-slip fault (or transform fault). No new plate is created nor consumed along a transform boundary fault. They can occur in continental or oceanic lithosphere and have comparatively little associated volcanism. For example, the boundary between the Pacific and North American plates in California, and the Indo-Australian and Pacific

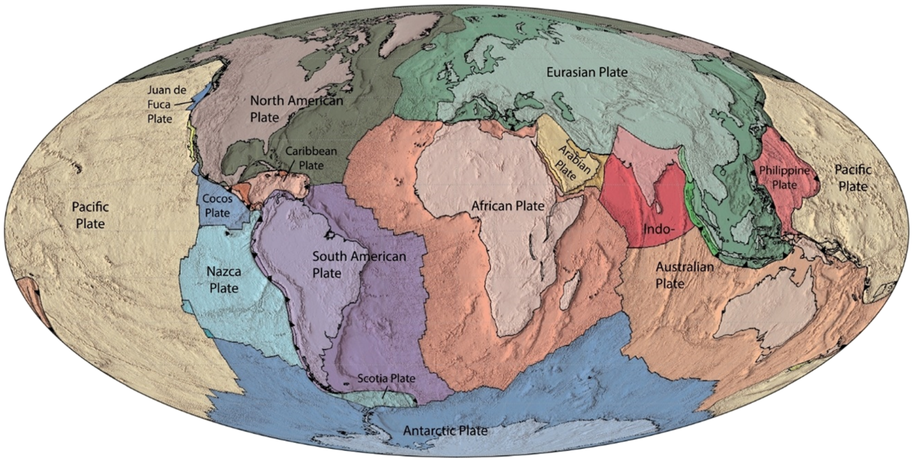


Figure 1. The seven major and several minor plates of Earth. Ocean ridges, transfers zones, and trenches (lines with teeth on the overriding plate) mark the surface expression of today's plate boundaries.

plates in New Zealand are large continental transforms, and many smaller transforms are found along ocean ridges.

The movement of plates generates major geologic structures. Plates that consist of continental lithosphere, volcanic arcs, or oceanic plateaus are too buoyant to be subducted. Instead, they create broad belts of deformation, igneous activity, and metamorphism, called collision zones. The buoyant blocks that collide form a larger contiguous continental block, with a zone, called a suture, that marks where they are joined. Larger continents occasionally form when smaller continents are sutured together creating a supercontinent. Rifting stretches a continent and splits it apart. As rifting proceeds, a new ocean ridge is formed that results in the production of oceanic lithosphere. At an unsuccessful (or failed) rift, rifting stops before the split is complete, and the rift remains as a permanent feature characterized by volcanic rock and partially filled with continental sediments.

We recognize two different reference frames for tectonic plate motion (Demets et al., 2010; Jurdy, 1990). The absolute reference frame describes plate motions with respect to a fixed point in Earth's interior. In contrast, the relative reference frame describes the motion of one plate with respect to another. To illustrate this distinction, consider the motion of two cars driving along a road. If we say that Car A travels at 60 km/hr and Car B travels at 40 km/hr, we are specifying the absolute velocity of the cars relative to a fixed point on the road. If we say that Car A drives 20 km/hr faster than Car B, we are specifying the relative velocity of Car A with respect to Car B.

In this contribution, we explore the fundamentals of plate tectonics in a series of 10 plate tectonic vignettes and paleogeographic animations. Each of these animations is accompanied by a brief description on tectonic principles, information about regional or local tectonic settings, and references pioneering research. The target audiences for this educational contribution are introductory Earth science courses, but it also offers foundational material for upper-level college courses in structure and tectonics. The literature of plate tectonics since its formulation in the early 1960s is vast, representing hundreds of thousands of studies. Here, we limit references to works that formulated the main ideas and concepts that became the foundations of modern plate tectonics and that continue to stand as seminal works. Tremendous progress has been made in the 50 years since these original contributions, which are summarized in thousands of review papers and books on plate tectonics theory.

One way to graphically illustrate the history of plate motions is a “tectonic tree” (Figure 2), which is a branching diagram that illustrates the continental elements and the timing of important plate tectonic events. It is analogous to the phylogenetic tree that paleontologists use to illustrate the timing of evolutionary events. A branching event on a phylogenetic tree represents the appearance of a new taxon. The termination of a branch on a phylogenetic tree represents an extinction event. Similarly, on a tectonic tree each

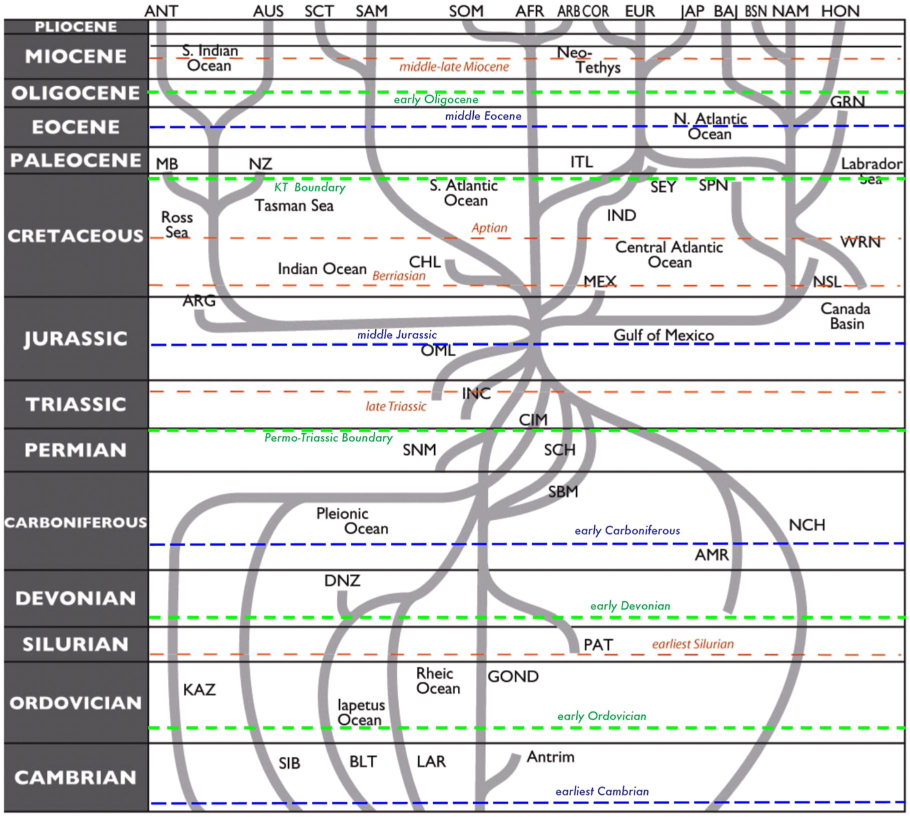


Figure 2. Global tectonic tree of the Phanerozoic (since ~450 Ma). Roots that join represent continental collisions. Upward branching events represent the breakup of continents and the formation of new ocean basins. A branch that terminates represents an ocean basin that stopped opening. AFR = Africa; AMR = Amuria; ANT = Antarctica; ARB = Arabia; ARG = Argoland; AUS = Australia; BAJA = Baja California; BLT = Baltica; BSN = Basin and Range; CHL = Chile; CIM = Cimmeria; COR = Corsica and Sardinia; DNZ = Donetz Basin; EUR = Europe; GOND = Gondwana; GRN = Greenland; HON = Honduras; INC = Indochina; IND = India; ITL = Italy; JAP = Japan; KAZ = Kazakhstan; LAR = Laurentia; MEX = Mexico; MB = Marie Byrdland; NAM = North America; NCH = North China; NSL = north slope of Alaska; NZ = New Zealand; OML = Omolon; PAT = Patagonia; SAM = South America; SBM = Sibumasu; SCH = South China; SCT = Scotia Arc; SEY = Seychelles; SIB = Siberia; SNM = Sonomia; SOM = Somalia; SPN = Spain; WRN = Wrangellia. (after Scotese, 2004).

branching event represents the splitting of a continent and the formation of a new ocean basin. The termination of each branch on a tectonic tree indicates that seafloor spreading has ceased in that ocean basin. Using a tectonic tree adds an important feature that is not present on a phylogenetic diagram. Branches can merge back together, which represents continent-continent or continent-terrane collisions. When multiple branches on a tectonic tree merge into a stem, a supercontinent is formed. Conversely, supercontinent breakup is indicated when a stem splits apart into multiple branches.

1.1. Making the Maps

Hundreds of new 0.25 to 1 Myr interval paleoelevation base maps were created to produce a set of animations that builds on several decades of plate tectonics and paleogeographic research (the PALEOMAP Project; Golonka et al., 1994; Scotese, 2001, 2004, 2009; Scotese et al., 1979; Scotese & Baker, 1975; Scotese & Elling, 2017; Scotese & McKerrow, 1990; Scotese & Sager, 1988; Scotese & Wright, 2018). These latest animations were created using the GPlates modeling software (Earthbyte; Scotese, 2016) and the resulting movies smoothed with Adobe® After Effects. The animations are presented without markup to allow a range of applications and use, except for the addition of geologic time in millions of years (Ma). The high resolution of the animations permits screengrabs for annotation.

Figure 3. Map of Africa, showing the East African Rift, the Red Sea, and the Gulf of Aden. The East African Rift consists of a belt of normal faults, bounding deep troughs, some filled with water (lakes). The Afar Triangle lies at the triple junction between the Red Sea, the Gulf of Aden, and the East African Rift. In the Red Sea and Gulf of Aden the rift has evolved to form a narrow ocean basin.

2. Continental Rifting (Movie S1)

Continental rifting is the process by which continental lithosphere undergoes horizontal extension, creating a rift zone (Burke & Dewey, 1973). During rifting, the lithosphere stretches roughly perpendicular to the trend of the rift. We distinguish between active and inactive rifts, based on the timing of extension. Active rifts are places where extension currently takes place. We find an array of active normal faults that cuts the plate, which is accompanied by earthquakes and volcanic eruptions. The faulting in active rifts yields a distinctive topography that is characterized by the occurrence of linear ridges that border depressions.

Inactive rifts are places where lithospheric extension ceased some time ago. Instead of earthquakes and eruptions, we find inactive normal faults and thick deposits of sandstones, conglomerates, and volcanics in depressions. The preservation of an inactive rift means that rifting stopped before it succeeded in splitting a continent. Such inactive rifts are also known as aulacogens (from the Greek for “furrow”).

Eastern Africa and the Arabian Peninsula preserve a recent record of continental rifting and incipient ocean basin formation (Figure 3). We see the evolution of a triple junction (today's Afar Triangle) since ~35 Ma, where one arm, the East African Rift, accommodates limited extension, possibly resulting in a failed continental rift in the future. Such failed rifts are found around the world, including the Paleozoic Donets Basin in Ukraine and the Proterozoic Midcontinent Rift of the United States.

The other two arms of the triple junction in Africa show the full rift-to-drift cycle, resulting in the formation of oceanic lithosphere in the Red Sea and Gulf of Aden. Opening of the northern arms of the triple junction continues today at a rate of 2–3 cm/yr. Further ocean spreading in the region may be limited, however, as the African and Arabian plates move northward and collide with the Eurasian continent.

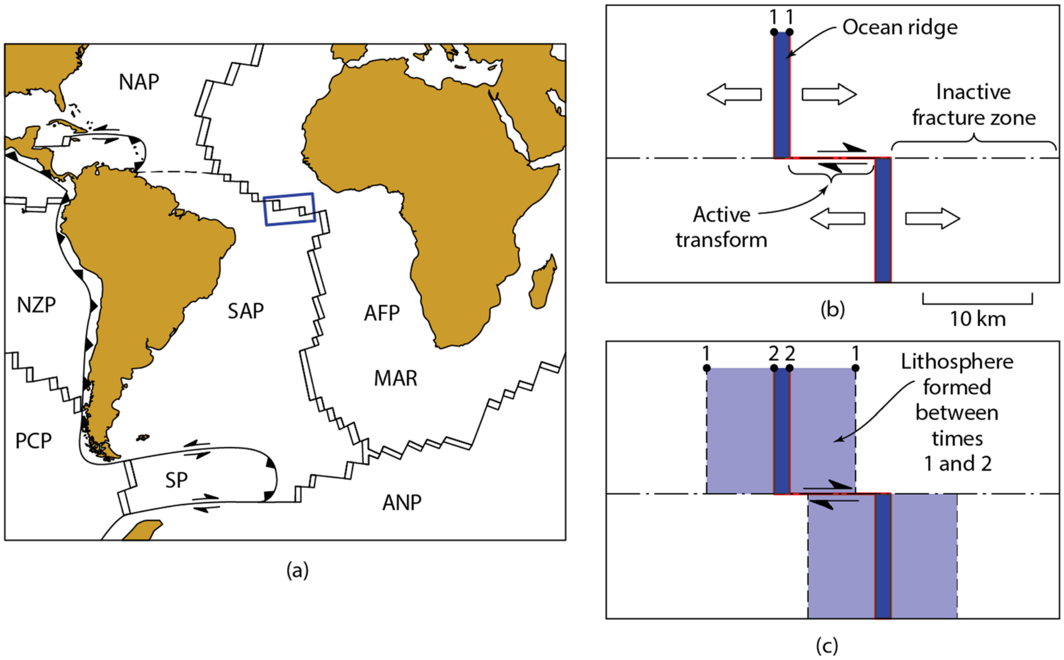
3. Continental Breakup, Ocean Ridges, and Fracture Zones (Movie S2)

Following initial rifting, the successful breakup of continents results in the formation of an oceanic ridge, which generates new oceanic lithosphere. (MacDonald, 1982; Vine, 1966). Ocean ridges are long, linear mountain ranges that divide the abyssal plain of the ocean floor. They occur in all modern oceans, though not necessarily in the middle, and can tower several kilometers above the ocean floor. In some places, the ridge even rises above sea level, such as Iceland. Stretched end-to-end, today's ocean ridges make a submarine mountain chain that encircles the planet (approximately 40,000 km long).

At slow-spreading ridges, such as the Mid-Atlantic Ridge, plates move apart at rates of <4 cm/yr, whereas at fast-spreading ridges, such as the East Pacific Rise, plates move apart at rates of >8 cm/yr. Slow-spreading ridges are steep, relatively narrow (100 s km) and have deep axial troughs bordered by step-like escarpments. Fast-spreading ridges have gentle slopes, are up to 1,500 km wide, and do not have axial troughs.

The separation of the North and South American plates from the Eurasian and African plates since the Triassic Period resulted in the formation of the Mid-Atlantic Ridge. The trajectory of an ocean ridge is accommodated by a special type of strike-slip faults, called ridge-to-ridge transform faults (Wilson, 1965). Unlike typical continental strike-slip faults (also called transcurrent faults), the sense of motion of a transform fault is opposite to the ridge offset (see Figure 4), as it reflects the relative plate motion on either side.

Once a plate grows beyond the location of the offset ridge segments, active faulting and earthquake activity stop. The traces of the once active transform faults form long, linear oceanic fracture zones, which, like railroad tracks, track the motions of the plates. Given a difference in age of the ocean floor on either side of fracture zone, these regions produce steep ocean floor scarps with the older, denser side sitting lower.



(a)

(b)

(c)

Figure 4. (a) Regional setting of the Mid-Atlantic Ridge in the South Atlantic Ocean. SAP = South American Plate, NAP = North American Plate, AFP = African Plate, ANP = Antarctic Plate, NZP = Nazca Plate, CS = Caribbean Sea, SS = Scotia Sea, MAR = Mid-Atlantic Ridge. (b) Evolution of an oceanic transform fault (red). At Time 1, the transform is 10 km long, which does not change over time as spreading at the ridges continues. (c) At Time 2, the amount of displacement on the fault exceeds the length of the fault. The inactive continuation of a transform fault is marked by a topographic lineament on the ocean floor, called a fracture zone.

The S-shaped margins of Africa and South America require major curvature of the Mid-Atlantic Ridge, which is accommodated by steps with transfer faults, some as long as hundreds of km. These strike-slip faults link straight ridge segments, with spreading of about 3 cm/yr. The animation also shows the evolution of the Caribbean plate that migrates eastward, closing of the Atlantic-Pacific seaway and connecting North and South America via Central America.

4. Hot Spots and Hot Spot Tracks (Movie S3)

Anomalously hot mantle can create continental and oceanic regions at the surface that are characterized by extensive volcanic activity. These volcanic regions are thought to be due to hot, buoyant, rising plumes of mantle, called mantle plumes, and the associated volcanic activity is called hot spot volcanism (Morgan, 1971). Hot spots are characterized by the deposition of a large volume of volcanic rocks with geochemical signatures that are distinct from subduction-related and ocean ridge or rift-related volcanism (Sleep, 1992). Especially voluminous hot spots produce oceanic island chains and plateaus (Figure 5).

One modern example of hot spot volcanism is the Hawaiian volcanic island chain in the Pacific Ocean. The mantle is more stationary than the overlying lithospheric plate (moving faster by at least 1 order of magnitude), so the location of active volcanism changes as the plate moves over the mantle plume with time. This creates a trail of volcanic islands that become older as they move away from the active hot spot (Wilson, 1963). Today, Hawaii's Big Island is the active part of one such hot spot track, while a series of extinct volcanic islands and submarine volcanoes extend off to the northwest and north, forming the Hawaiian-Emperor island chain.

Some mantle plumes are long lived, lasting 100 Myr or more, while others are short lived, lasting less than 10 Myr. The orientation of a hot spot track provides the direction of plate motion relative to a mantle reference frame, so absolute motion, and the age of volcanic rocks along the track records the velocity of overlying plates.

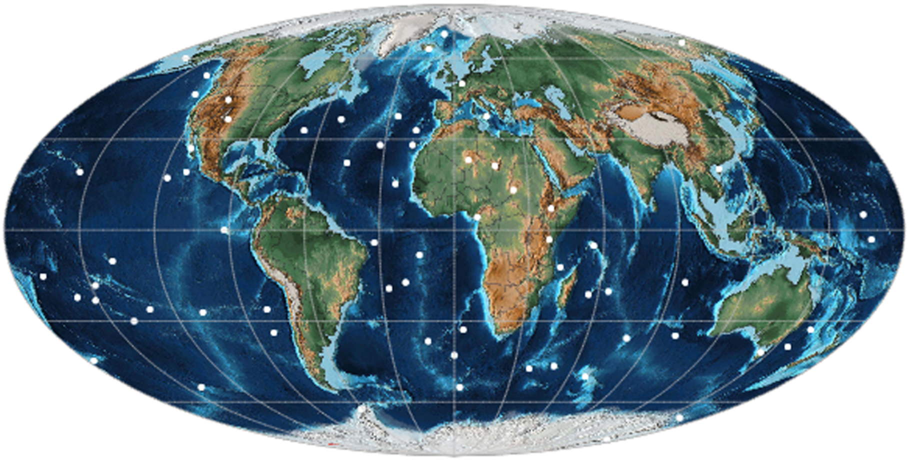


Figure 5. Hot spots of the modern world (data from Whittaker et al., 2015).

The opening of the Atlantic Ocean along the Mid-Atlantic Ridge was accompanied by several mantle plumes under the late Paleozoic supercontinent Pangea, including Iceland in the North Atlantic and Tristan da Cunha in the South Atlantic. The South Atlantic preserves a trail of progressively older hot spot volcanism from the southern Mid-Atlantic Ridge, marked today by Tristan da Cunha, to northern Namibia in Africa and southern Brazil in South America.

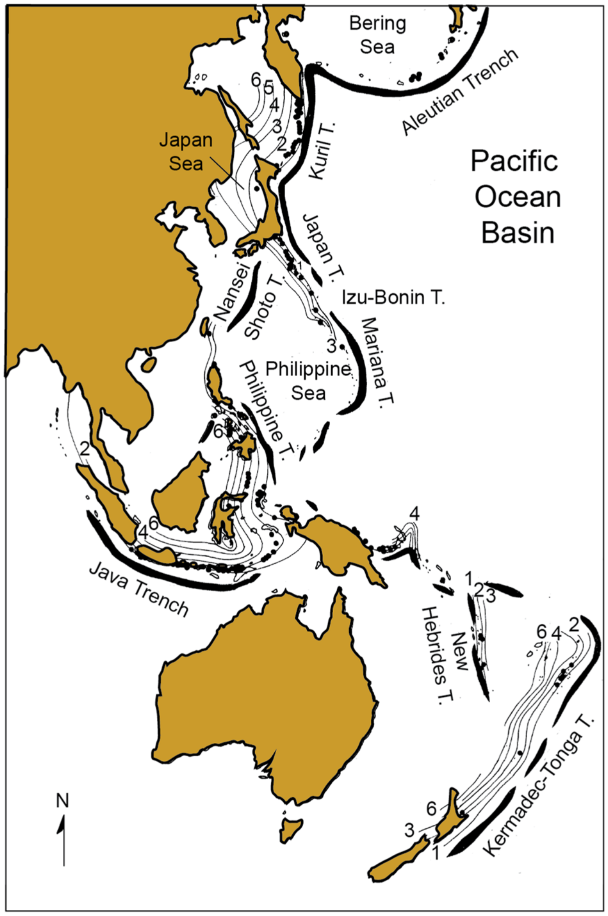


Figure 6. Trenches (heavy lines), arc volcanoes (black dots) and back-arc basins related to subduction in the western Pacific Ocean Basin. The depth to the subducted plate interface is shown by contour lines, given in multiples of 50 km (e.g., 2 means 100 km).

Closing the Atlantic Ocean shows these two continental areas coming together at ~140 Ma and marks the location of a mantle plume under Pangea at the start of ocean spreading. The Tristan da Cunha hot spot track is especially pronounced in the eastern South Atlantic and is mirrored by a track to the west of the mid-Atlantic Ridge. Notice also that the mirror-image tracks are not parallel to the ridge's spreading direction, showing that the ridge and plates were together moving in a northerly direction relative to the hot spot (absolute) framework.

5. Volcanic Arcs and Back-Arc Basins (Movie S4)

Trenches are linear or curvilinear troughs that mark the boundary, at Earth's surface, between the downgoing (or subducting) plate and the overriding plate (Mitchell and Mitchell & Reading, 1971). The floor of the Mariana Trench in the western Pacific reaches a depth of over 11 km (Figure 6), which is deeper than the highest mountains (Mt. Everest is ~9 km high). Trenches form as the downgoing oceanic lithosphere pulls the ocean floor into the mantle.

A volcanic arc is a chain of volcanoes that forms along the edge of the overriding plate about 200–300 km from the trench and about 100–150 km above the surface of the subducted oceanic lithosphere. Most of the magma that rises to feed the volcanic arc forms by partial melting of mantle above the downgoing oceanic slab. Partial melting takes place primarily because volatiles (H_2O) released from the downgoing plate reduce the melting point of the overlying mantle rock.

The region on the other side of the volcanic arc, away from the subducting oceanic lithosphere, is the back-arc region (Karig, 1970; Uyeda & Kanamori, 1979). Its character varies with tectonic setting and can be contractional, extensional, or tectonically stable. Extensional back-arc

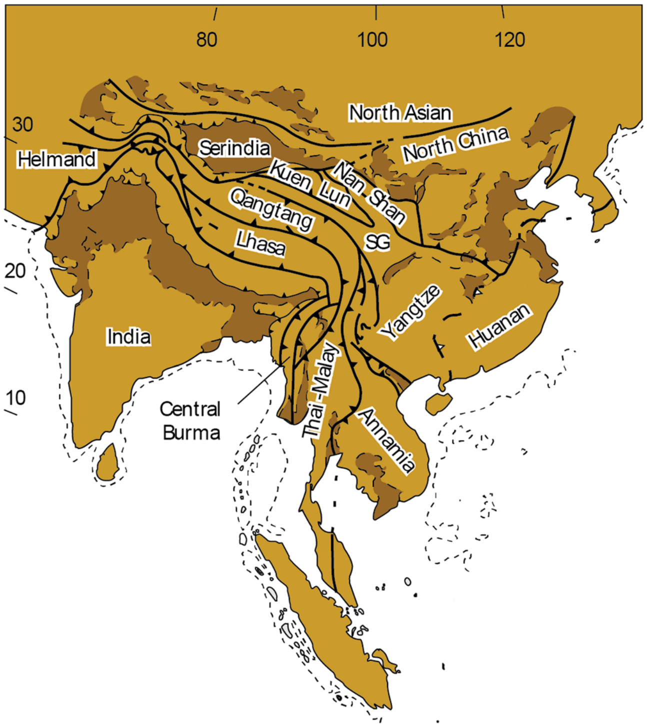


Figure 7. Tectonic elements that accreted in south central Asia during the Late Paleozoic and Mesozoic, culminating with India's collision in Early Cenozoic time. The sutures between fragments are shown by barbed lines with the barbs indicating the upper plate of the former subduction zone. The suture between the Qangtang and Songpan Ganze (SG) fragments is of early Mesozoic age representing the closure of the Paleotethys Ocean. All sutures to the north are Paleozoic. The southern boundary of the Lhasa block is the Indus-Tsangpo suture and represents the closure of Neotethys. Dark regions are variably deformed, Cenozoic sedimentary rocks.

settings contain rift zones that may evolve into basins floored by oceanic lithosphere. One example of a large back-arc basin with active seafloor spreading occurs behind the Mariana Volcanic Arc in the western Pacific Ocean. Another example of a back-arc basin in the northwestern Pacific is the Japan Sea, which formed about 30 Myr ago by rifting of the Japan Volcanic Arc from eastern Asia, due to subduction along the Japan Trench.

Back-arc regions may also be contractional, producing fold-thrust belts and basement uplifts, such as those found along the Andean margin of South America. Lastly, back-arc region where no deformation occurs are called stable backarcs, such as the Bering Sea that is located north of the Aleutian Islands, which connects Alaska and Kamchatka.

6. Continental Collision (Movie S5)

As subduction progressively consumes an oceanic plate, a piece of buoyant crust on the downgoing plate eventually reaches the trench. Examples of buoyant crust include large continents but also smaller continental fragments, island arcs, oceanic plateaus (regions of anomalously thick oceanic crust formed by hot spot volcanism), and spreading ridges. Buoyant lithosphere cannot be subducted, so when it impinges on the overriding plate, the area becomes a tectonic collision zone. The boundary between the once separate plates, called a suture zone, often preserves slivers of oceanic crust and mantle (a rock suite called ophiolites) that have become trapped and exposed in the collision zone (Coleman, 1971; Dewey & Bird, 1970).

The collision of India with Southern Asia is the modern culmination of a long history of convergence and successive collisions in the region since the Paleozoic (Figure 7; Molnar & Tapponnier, 1975). Northward motion of India continues today, resulting in the tectonically active Himalayan Mountain range and Tibetan Plateau (which includes the Qangtang and Lhasa blocks). The region's latest collision started around 50 Ma and formed the Indus-Tsangpo suture zone. The closure of smaller ocean basins preceded the terminal India-Asia collision, recorded by accretion of volcanic arcs (Şengör, 1979).

7. Terrane Accretion (Movie S6)

The parts of plates that are relatively buoyant (meaning less dense than surrounding material) cannot be subducted. Therefore, such pieces eventually collide with, detach, and suture to other buoyant plate segments (see section 7). After each collision, a new convergent margin forms on the oceanic side of the collision zone, and the continent grows. This process is called accretion, and the pieces that are added to larger continental blocks by this process are called accreted (or exotic) terranes (Coney et al., 1980).

The recognition that part of a continent is an accreted terrane comes from analysis of the geologic histories of terranes and adjacent regions. If the rocks and structures of these fault-bounded blocks do not readily correlate with adjacent regions, then that block was likely accreted. In addition, paleomagnetism is used to test whether an accreted block and the continent to which it is now attached occupied different paleogeographic locations. Fossils are also used to determine if a terrane originated at a different location than its neighboring continent.

Based on geologic mapping, geochronology, paleomagnetism, and paleontology, we learn that, during the Mesozoic and Cenozoic, the North American Cordillera grew westward by as much as 1,500 km due to accretion of exotic terranes. Much of the land that now comprises California, Oregon, Washington, and Alaska in the United States and British Columbia and the Northwest Territories in Canada originated as accreted terranes (Figure 8).

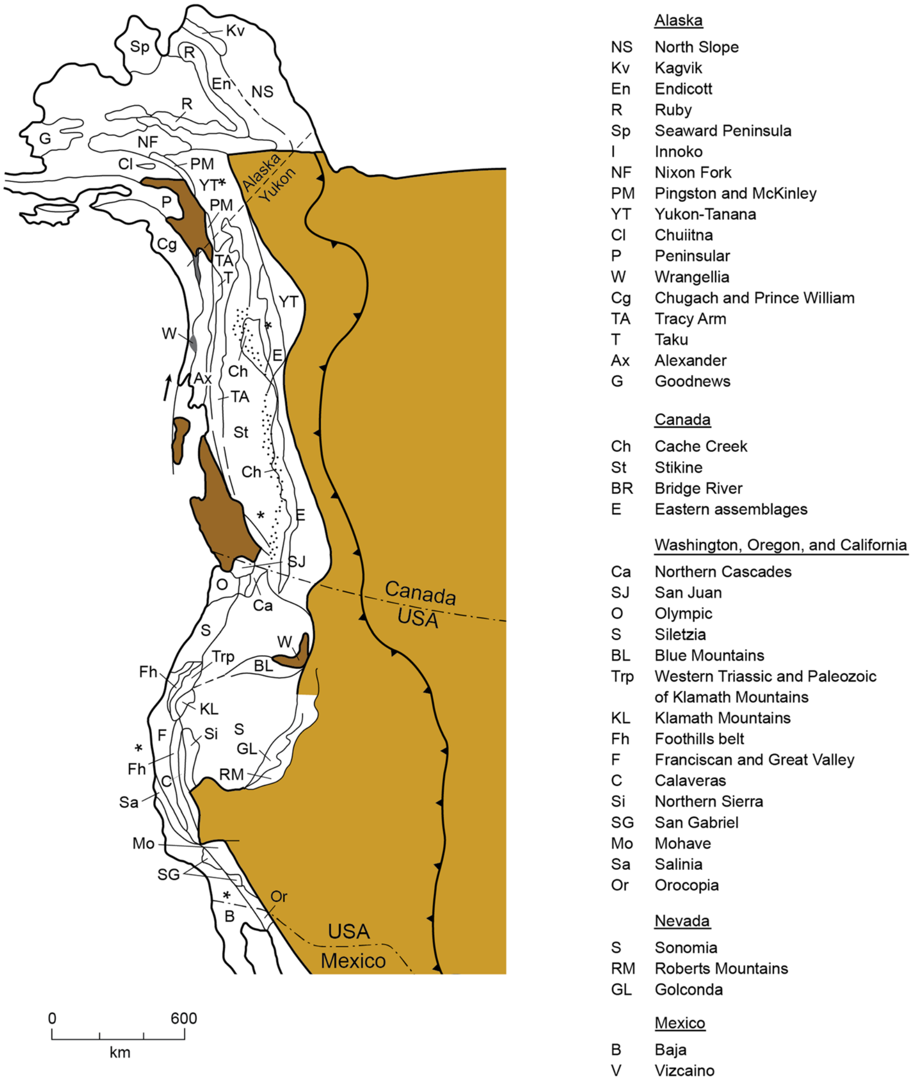


Figure 8. Map of western North America that shows the regions consisting of accreted terranes. The oblique convergence of terranes resulted in strike-slip faulting along the western North American continental margin that sliced the original tectonic terranes into separate blocks. For example, the accreted Wrangellia terrane (dark brown) is found today as dismembered blocks along the North American margin, from Idaho to Alaska.

During the Jurassic and Cretaceous (150–100 Ma) two major terranes, Stikine and Wrangellia, collided with the western margin of North America (Monger et al., 1982). These terranes originated at a more southerly latitude than their current location. Convergence and collision were oblique, so right-lateral strike-slip faults cut and moved slivers of these accreting terranes northward along the North American plate margin.

8. Closing and Opening of Ocean Basins (Movie S7)

The formation of the Appalachians and Caledonides mountains in eastern North America and western Europe, respectively, resulted from closure of a vanished ocean basin, called the Iapetus Ocean. Today, a modern ocean separates these continental blocks, the Atlantic Ocean. In late Proterozoic to early Paleozoic times, the ancient Iapetus Ocean opened and grew by rifting and seafloor spreading and closed in the late Paleozoic when the bordering continents collided, forming the Appalachians-Caledonides collisional mountain belt. In Mesozoic times, the Atlantic Ocean opened in about the same relative position between the continental blocks of North and South America on one side, and Europe and Africa on the other

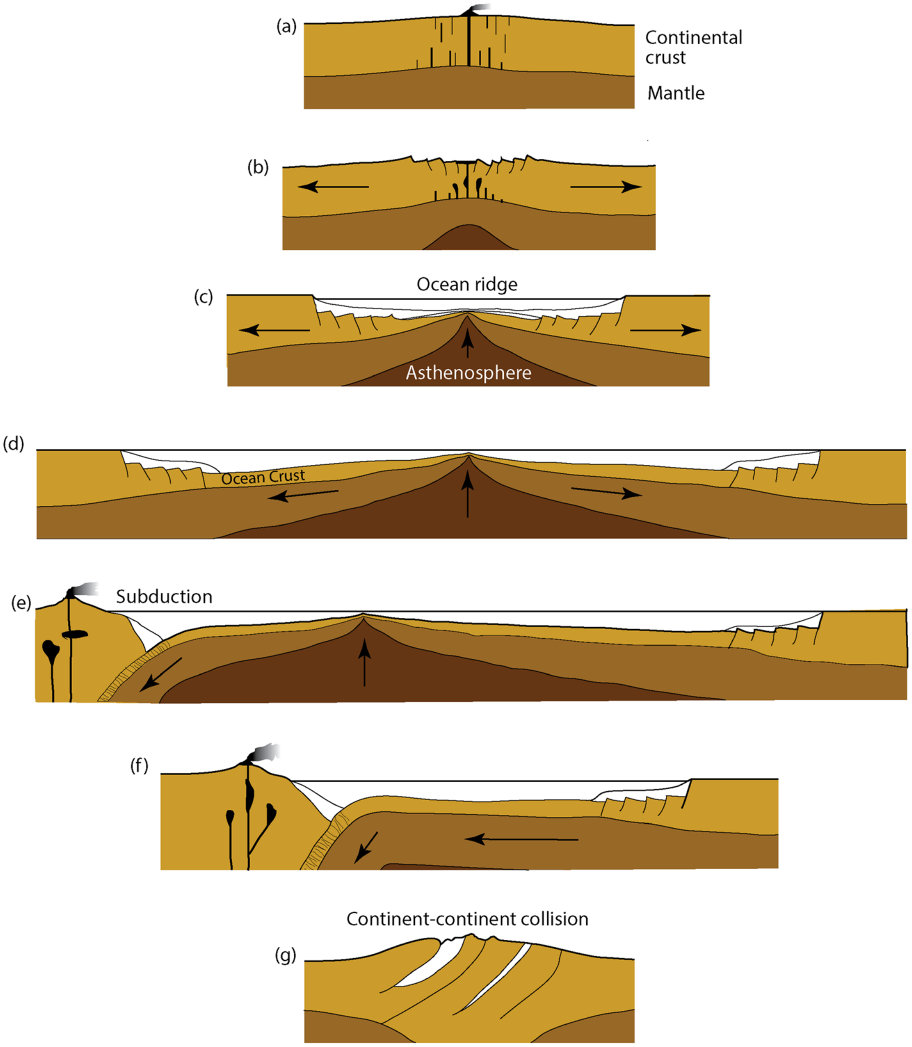


Figure 9. (a, b) A continent rifts, such that the crust stretches, faults, and subsides. (c) Seafloor spreading begins, forming a new ocean basin. (d) The ocean widens and is flanked by passive margins. (e) Subduction of oceanic lithosphere begins on one of the passive margins, closing the ocean basin by subduction of the oceanic part of plate and the ridge. (f, g) The closure of the ocean basin culminates with continental collision. At a later time, continental rifting begins 3again and the process repeats, in what is called the Wilson Cycle (modified from S. Stein, used with permission).

side. Today, small subduction zones exist in the Caribbean region and the South Georgia-South Sandwich Islands of the Atlantic Ocean, which may lead to the future demise of the Atlantic Ocean and new America-Europe/Africa collision (see “Future Earth” section 11).

The repetition of successive stages of rifting, seafloor spreading, convergence, and collision is called the “Wilson Cycle,” in recognition of the person who first highlighted this pattern (Figure 9; Wilson, 1966). As a result of this process, we do not find oceanic lithosphere in today's ocean basins that is older than about 200 Ma. All older oceanic lithosphere has been subducted, except for a few slivers preserved as ophiolites in ancient mountain ranges, which mark the tectonic sutures between colliding continents (Dewey & Bird, 1970). In contrast, older continental lithosphere is widely preserved on today's surface, because it was too buoyant to be subducted. This explains why Proterozoic and Archean rocks, some as old as 4 Gyr, are found on most of today's continents.

The Paleozoic evolution of the Appalachians of North America and the Caledonides of Western Europe records the progressive closure of the Iapetus Ocean (Dewey, 1969). This past ocean basin contained several terranes that were accreted during convergence, including volcanic arcs and ocean islands (Mac Niocaill

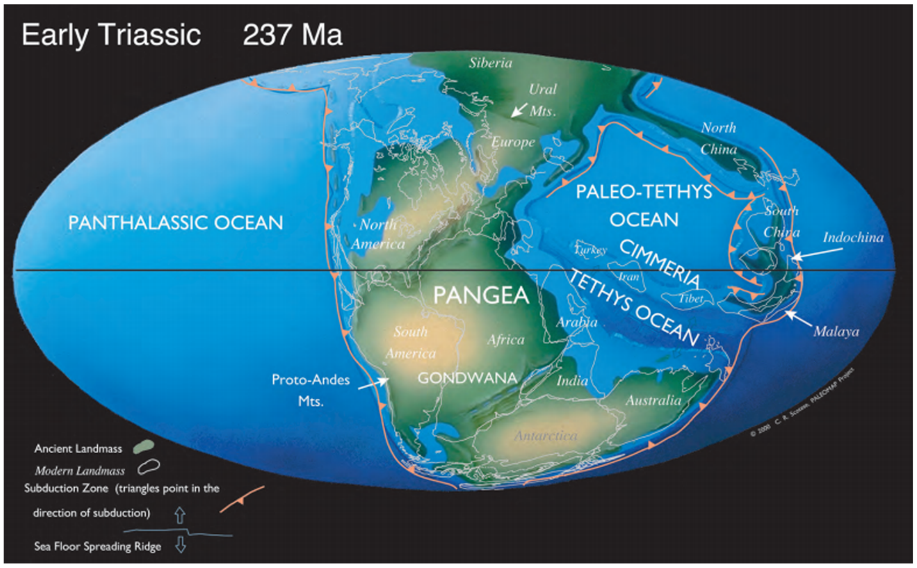


Figure 10. The Pangea supercontinent formed after the closure of ancient ocean basins in approximately the same relative location as today's Atlantic Ocean. The subducted ocean basins included the ancient Rheic, Theic, and Iapetus Oceans. Final closure of these ocean basins resulted in the Appalachian-Caledonian mountain chain of North America and western Europe. Pangea contained all major Paleozoic landmasses. The large internal ocean, Tethys, is later subducted as the Indian plate moved northward and collided with the China block of Asia.

et al., 1997). The Iapetus Ocean formed in the same relative position as today's Atlantic Ocean but was rimmed by the E-W oriented continental margins of North America (Laurentia) and Europe-Africa (Gondwana). The Iapetus Ocean first opened around the late Precambrian and fully closed by the Late Carboniferous, forming the Appalachian-Caledonide collisional mountain belt of the supercontinent Pangea. The area's later history is marked by counterclockwise rotation into today's N-S configuration of the successor ocean basin, the Atlantic Ocean. The opening of the Atlantic Ocean started in the north and continued to the south, as part of the Tethys Ocean to the east closed.

9. Formation of Supercontinents (Movie S8)

The closure of the Iapetus Ocean led to the formation of a large continental landmass, or supercontinent, called Pangea (meaning “all-land”; Wegener, 1929; Wegener, 1966). At various times in the geologic past, plate movements and continental collisions produced similar supercontinents that lasted for several tens of millions of years before they broke apart.

The supercontinent Pangaea was formed in the late Paleozoic (260 Ma) and rifted apart during the early Mesozoic (Figure 10). An older supercontinent Rodinia was formed at the end of the Mesoproterozoic (~1.1 Ga) and dispersed by ~750 Ma (Hoffman, 1991). There is also evidence that supercontinents formed even earlier in Earth history, such as the supercontinent Nuna that formed at the end of the Paleoproterozoic (~1.8Ga), indicating that supercontinents repeatedly formed and subsequently broke up. This megatectonic process is called the Supercontinent Cycle or the “Wegener Cycle” after the German scientist who championed the idea that the landmasses were once joined together in a large continent that he called “Pangea.”

The supercontinent cycle may be related to long-term (>100 Myr) convection patterns in the deeper mantle. The relative motion of a continent is controlled by plate forces, particularly the downward pull from negative buoyancy of cold and dense plate material (Forsyth & Uyeda, 1975), but over longer periods of time the continental components accumulate over a mantle downwelling to form a supercontinent. Once formed, the thermal structure of the mantle beneath it changes, because the supercontinent acts as a giant insulator that blocks escaping heat from the mantle. In response, the mantle below the supercontinent heats up and is no

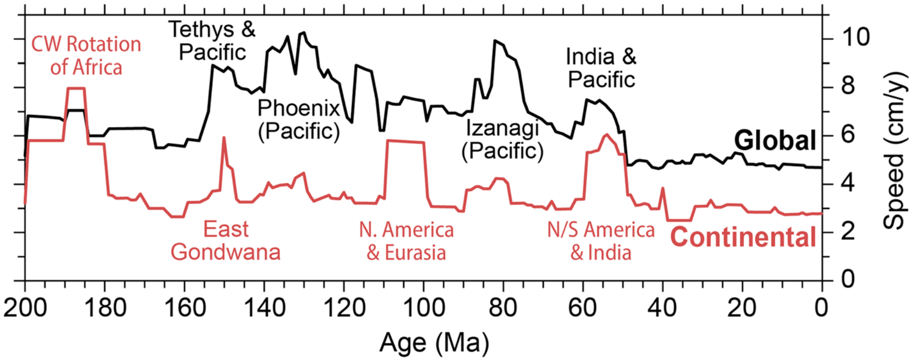


Figure 11. Global (black) and continent-only (brown) plate velocities. The continental curve represents the motion of continents alone, without the oceanic portion of a plate. Plates and continents with large areas and/or high velocities dominate fast velocity intervals. Horizontal scale is age in million years; vertical scale is speed in cm/yr. From Zahirovic et al. (2015).

longer a region of downwelling. Instead, hot mantle begins to upwell beneath the supercontinent, causing it to heat up and weaken the overlying plate (Anderson, 1982). Eventually, a rift system forms that evolves into a new ocean basin, dispersing the supercontinent.

With the last supercontinent ~250 Myr old, we are still in the dispersal stage of the supercontinent cycle, but in the next 200 Myr or so, the continents may once again coalesce to form a new supercontinent that we call "Pangea Proxima" (see section 12).

10. Plate Velocities (Movie S9)

Linear magnetic anomalies on the ocean floor, which preserve the reversing polarity of the Earth's magnetic field over time, and geochronologic data offer a robust geologic estimate of plate velocities during the last 200 Myr. Latitudinal velocities measured by paleomagnetic measurements offer estimates of plate velocities for times before that, but with greater uncertainty. For these reasons, we use the history of plate motions from 200 Ma to today to explore tectonic plate velocities. Plate velocities are given in cm/yr, which is equivalent to tens of km per million years (Figure 11).

The paleogeographic evolution of the oceans and continents since 200 Ma shows that some plates move fast and others slower, in the range of 1–20 cm/yr, and that accelerations and decelerations are common. Opening of the Atlantic was relatively slow, whereas opening of the Pacific was fast. The subduction of the Tethys Ocean was very fast at times, until collision between India and Asia which greatly slowed India's northward movement.

Using the PALEOMAP model of plate motions, Zahirovic et al. (2015) tracked the velocities of about a dozen plates, which traveled at an average global plate velocity of ~4 cm/yr. Notably, plates with continental components tend to be relatively slow. Given that continental lithosphere is thicker and more buoyant than oceanic lithosphere, the continental component of a plate introduces drag on plate motion. Plates do not move at constant velocity over time and may move as fast as 18 cm/yr, as exemplified by the Cenozoic northward motion of India. The plate velocities estimated from the global plate model match modern plate velocities that are based on geodetic measurements.

11. Future Earth (Movie S10)

There is no certainty about the future plate geometry of the Earth, but using current plate motions and tectonic principles, we can make educated guesses about future plate configurations. We surmise that the Atlantic and Indian Oceans will continue to widen until a new subduction zone brings these continents back together, eventually forming a new supercontinent, "Pangea Proxima." The northward trajectory of Africa suggests that the Red Sea and Gulf of Aden will close and that the East African Rift will not grow into an ocean basin. Africa will collide with Europe and Arabia closing the Mediterranean Sea and the Red Sea. A

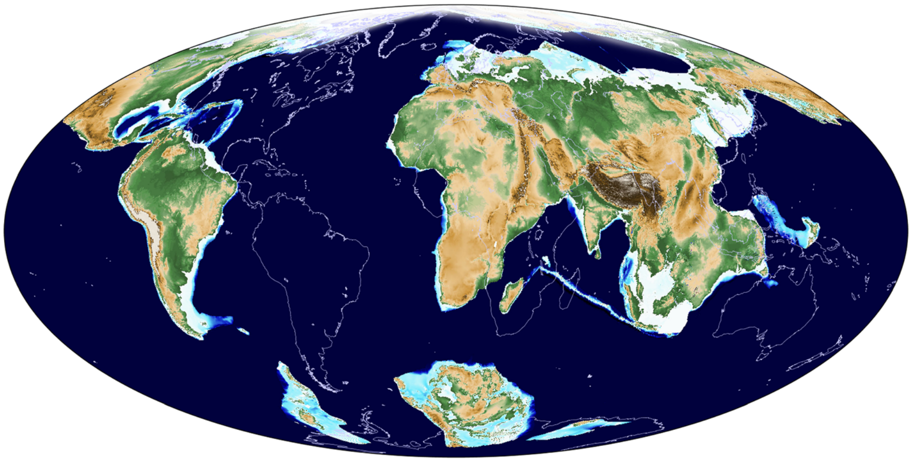


Figure 12. The tectonic setting of a future supercontinent, Pangea Proxima. After 100 my into the future, the Atlantic Ocean becomes subducted, while the Pacific Ocean continues to grow and a small remnant of the Indian Ocean eventually becomes land locked after the northward convergence and accretion of Antarctica.

Himalayan-scale mountain range will extend from Spain, across Southern Europe, through the Middle East, and into Asia. Similarly, Australia will collide with Southeast Asia, and a new subduction zone will encircle Australia, extending westward across the Central Indian Ocean.

One of the key events in this geography of the future is the beginning of subduction along the eastern coasts of North America and South America (Figure 12). As the Atlantic Ocean widens, the Puerto Rican Trough and Scotia Arc propagate northward and southward along the east coast of North and South America. In time, this new westward dipping subduction zone will consume the Atlantic Ocean.

The Atlantic Ocean, 100 Myr in the future, will begin to narrow by subduction beneath the Americas. The Indian Ocean will also contract due to northward subduction into the Central Indian trench. Antarctica will collide along the southern margin of Australia, and the Mid-Atlantic Ridge, the last vestige of seafloor spreading in the Atlantic Ocean basin, will be subducted beneath eastern North America. Once the last bit of the Atlantic Ocean's spreading ridge is subducted beneath the Americas, the Atlantic Ocean will rapidly close, and a new supercontinent will begin to form. The rocks that contain the remains of ancient New York City, Boston, and Washington DC will be sitting atop high mountain ranges.

About 250 Myr in the future, the Atlantic and Indian oceans will have closed. North America will have collided with Africa but in a more southerly position than from where it rifted. In this new supercontinent, South America is wrapped around the southern tip of Africa, with Patagonia in contact with Antarctica and Indonesia, enclosing a remnant of the Indian Ocean. The Pacific has grown much wider, encircling more than half the Earth. We call this future supercontinent “Pangea Proxima,” because it would be the next Pangea, but not necessarily the last!

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Data Availability Statement

The PALEOMAP data set is found online (https://www.earthbyte.org/paleomap-paleoatlas-for-gplates/); the open-source GPlates software is found online (https://www.gplates.org/).

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