Evolution of the earth 8: Plate tectonics

Scientific Revolutions

In his legendary 1962 book, The Structure of Scientific Revolutions, philosopher of science Thomas Kuhn pointed out that science works quite differently than most people think. It is not a slow, steady, uninterrupted march toward ultimate truth. Instead, it goes through periods when everyone does "normal science" and accepts certain basic premises and assumptions (a paradigm in Kuhn's sense).

Over time, however, anomalies, problems, and disagreements with the prevailing paradigm accumulate. Then someone thinks "outside the box" and develops an entirely new paradigm for their science that discards the assumptions of the old paradigm. This paradigm shift leads to a scientific revolution.

Kuhn's most important example was the Copernican revolution in astronomy, in which just a simple change in the basic model (placing the Sun, not the Earth, at the center of the solar system) solved many problems with the old Ptolemaic geocentric system and led to a completely new worldview. Newtonian physics changed the areas of mechanics that were still entrenched in the misconceptions of Aristotle. Einstein's theory of relativity revolutionized physics yet again, as Newtonian mechanics is inapplicable in the realm of things moving near the speed of light.

Likewise, Darwinian evolution overturned the old creationist ideas about life, and biology has never been the same since. It is not clear whether there has been a real scientific revolution in chemistry, although some key ideas have been proposed, such as Mendeleev's development of the periodic table.

Unlike other sciences, geology experienced its scientific revolution only recently, during the lifetime of many geologists still alive today. The old paradigm had long assumed that the continents were solid and stable, and the first real challenge to this idea came in 1915, when the German meteorologist Alfred Wegener (Fig. 1) published The Origin of the Continents and Oceans. However, the idea was dismissed for decades until the 1950s, when new data accumulated from marine geology and from the study of ancient magnetic fields of rocks on land showed that the continents had indeed moved. In 1962 and 1963, a series of key discoveries established the new paradigm of geology, plate tectonics.

Fig. 1: Alfred Wegener

Wegener‘s Hypothesis

Let's take a look at the African and South American continents (Fig. 2). As early as 1500, when the first good maps of the South Atlantic were published, some speculated that South America and Africa might once be a common continent, because the coastline of West Africa matches the east coast of South America. But it was Alfred Wegener who tried to scientifically substantiate this theory.

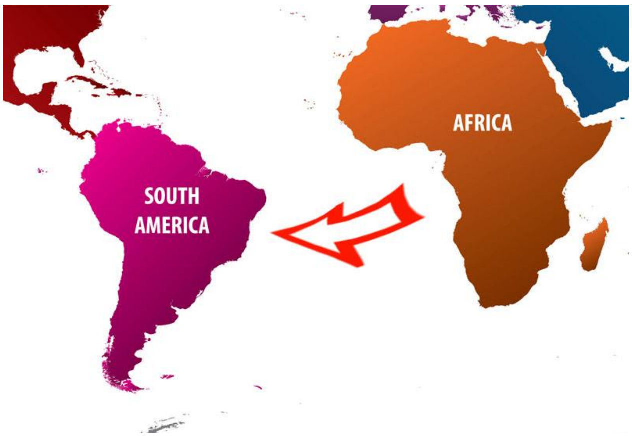

Fig. 2: Africa, South America

During the Christmas vacations of 1910, Wegener happened to glance at a world atlas he had given to one of his friends. As he later recalled, he was amazed at how well the Atlantic coasts of South America and Africa seemed to fit together. But he soon began collecting evidence of the distribution of fossils and rocks that indicated ancient climates and ancient latitudes of the continents, as well as other data that suggested that all the continents had once been united into one supercontinent, which he called Pangaea (meaning "all lands" in Greek). By 1912, he had given a few lectures on his ideas and published three short articles in a German geographic journal.

During World War I, with Wegener drafted into the army and working for the weather service, he finished writing his book on the formation of the continents, which was published in late 1915. His ideas, however, remained little known and little accepted. Finally, in 1926, he presented his ideas at the American Association of Petroleum Geologists meeting in New York City, where everyone rejected his ideas except the chairman of the meeting, who had invited him. Although his theories continued to be scorned by geologists, Wegener continued to work hard and collected data in Greenland in 1929. In 1930 he made his fourth and final expedition to Greenland, the largest he had ever undertaken. In November 1930, he and a partner were returning from a supply run to their remote camp in the center of the Greenland Ice Sheet when they ran out of food and ran into bad weather.

There, Wegener froze to death at the relatively young age of 50. His partner buried his body on the Greenland ice sheet, where he still rests under several feet of ice. Wegener did not live to see his revolutionary ideas gain support, which would not come for another 30-35 years.

Wegner's book, The Origin of Continents and Oceans, collected all the circumstantial evidence available to him to support his hypothesis.

As a climatologist, Wegener was particularly impressed by the way certain geological deposits are strongly controlled by climate and latitude: Ice caps at the poles, rainforests in the tropics, and desert deposits in the mid-latitude high pressure belt between 10° and 40° north and south of the equator. However, if we go back to the Permian period (250-300 million years ago), the location of these ancient deposits on a modern globe no longer makes sense (Fig. 3).

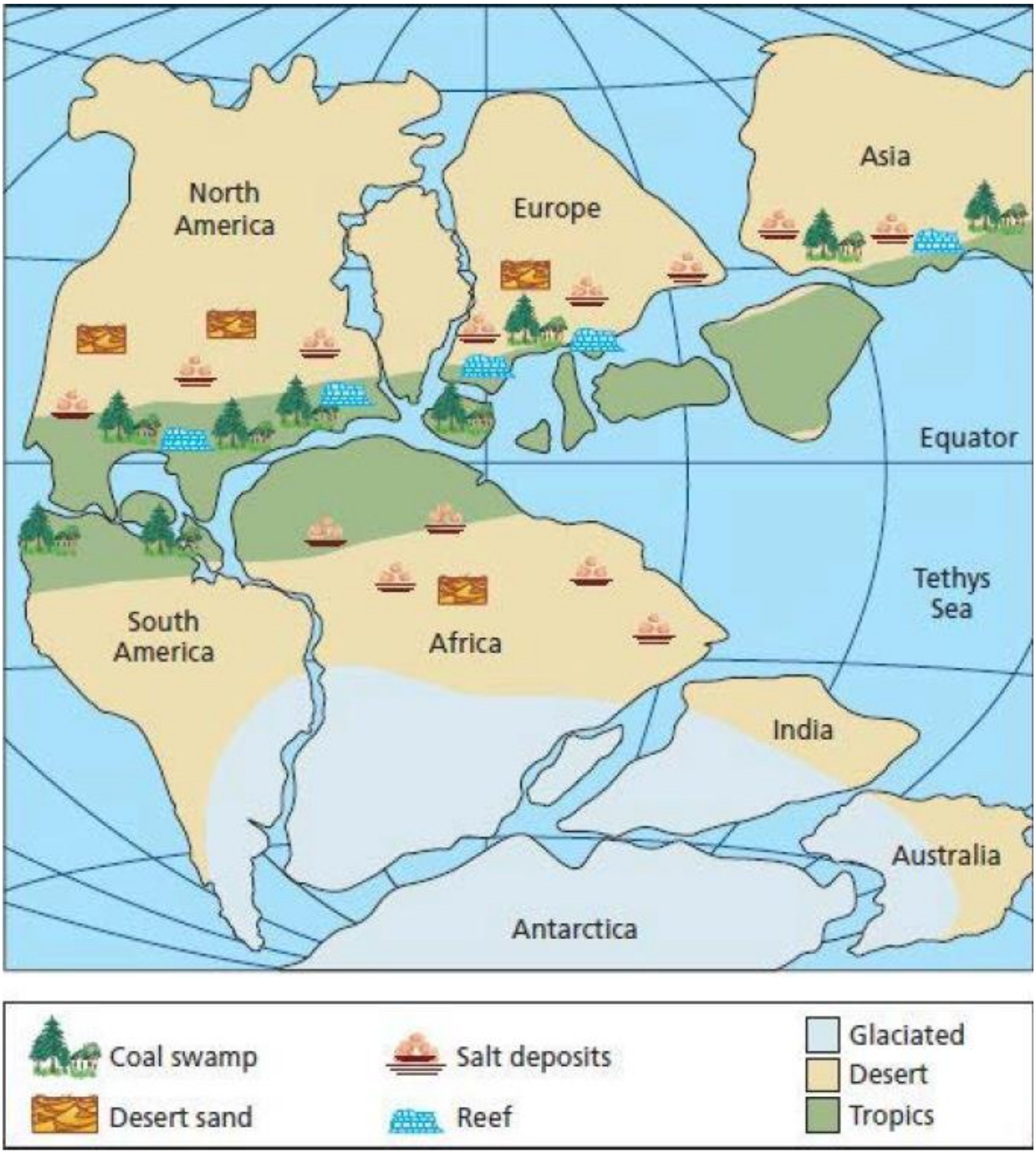

Fig. 3: The rock types representing the major Permian climate belts (polar ice cap, subtropical deserts, and tropical swampy rainforests forming coal) only make sense in a Pangea configuration. If these continents were moved to their present positions, these deposits would be at the wrong latitudes to form as they do today.

The south polar ice sheets extended from South America and Africa across the equator to India, which is a climatological absurdity (Fig. 4). Only when the continents are restored to their Permian configuration as part of a single supercontinent, Pangea, do they make sense.

If the continents had not moved, why did the scratches in the bedrock, created by rocks carried by Permian glaciers, run from Africa to South America (Fig. 4)? This would require the glacier to jump into the Atlantic, flow in a straight line across the Atlantic from Africa to Brazil, and then jump out of the ocean again! Likewise, all the ancient

Permian desert deposits and charcoal swamps of the tropical Permian rainforests only make sense if you put them back in their Pangea position, not in their present latitudes. Even the ancient Precambrian rocks in South America and Africa under the Permian deposits fit together exactly, like pieces of a puzzle.

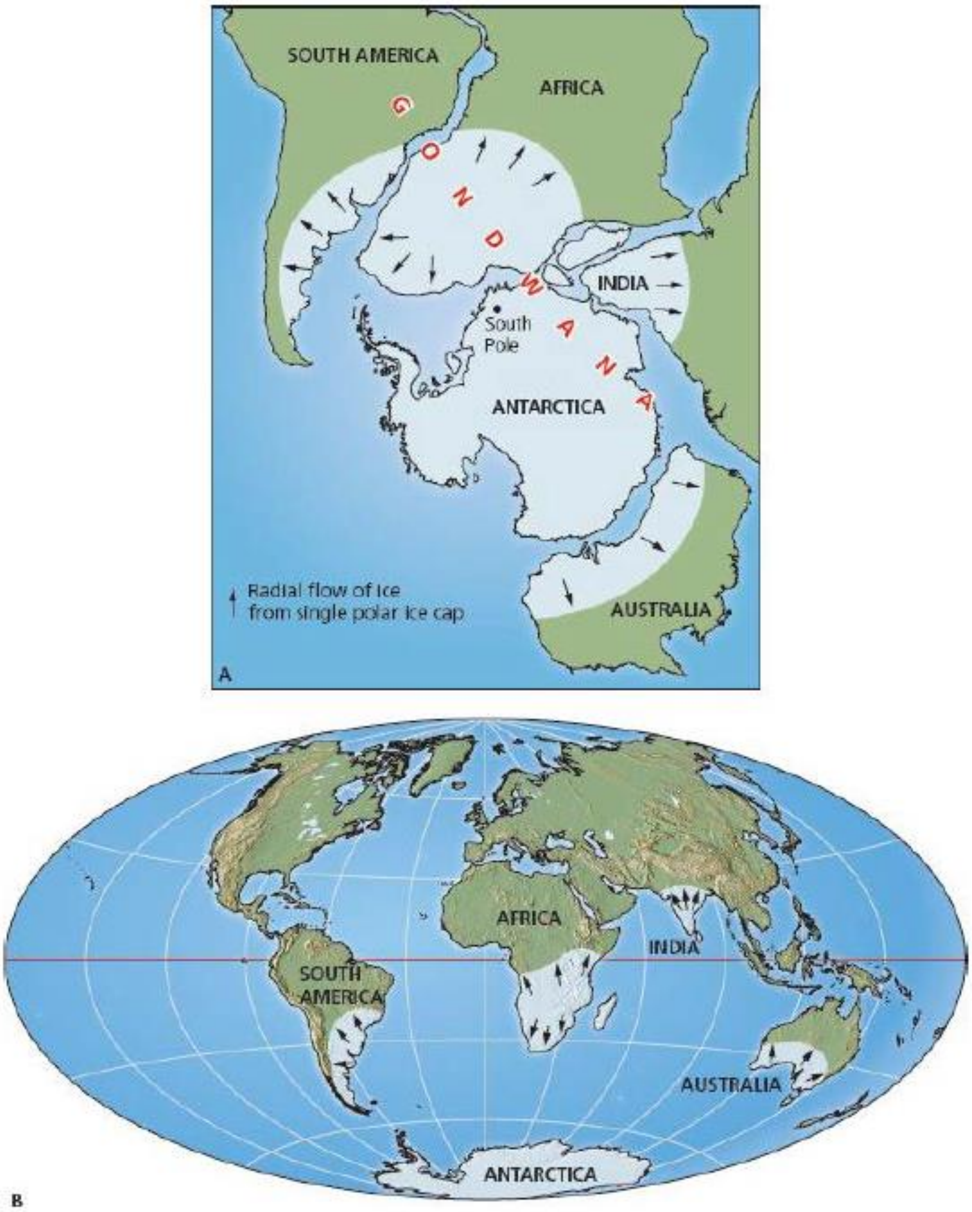

Fig. 4: A. The occurrence of the Permian glacial deposits only makes sense if the ice sheet once covered Gondwana and the South Pole. B. Given the present location of the continents, the Permian ice cap would have to do absurd things, such as cross the equator to reach India, and cover large areas of the Indian and South Atlantic Oceans. Moreover, glacial scrapes and grooves (e.g., in southwestern Africa) coincide with those in Brazil and Argentina, implying that glaciers would have had to dip into the Atlantic, cross it by a strangely curved path, and then climb ashore in South America if the modern Atlantic had existed in the Permian.

The circumstantial evidence from the Permian fossils (Fig. 5) has confirmed this. South America was full of distinctive fossils that it shared with other continents, especially southern Africa. There were characteristic extinct seed ferns known as *Glossopteris* found on all continents of the southern landmass known as Gondwana. There were small aquatic reptiles like *Mesosaurus*, found in lakes in Brazil and South Africa, and synapsids like the bulldog-sized, beaked herbivore *Lystrosaurus* and the bear-like predator *Cynognathus*, which could never have swum across what is now the Atlantic Ocean. To Wegener (and to any modern geologist), this evidence should have been clear and unambiguous: The continents were drifting apart.

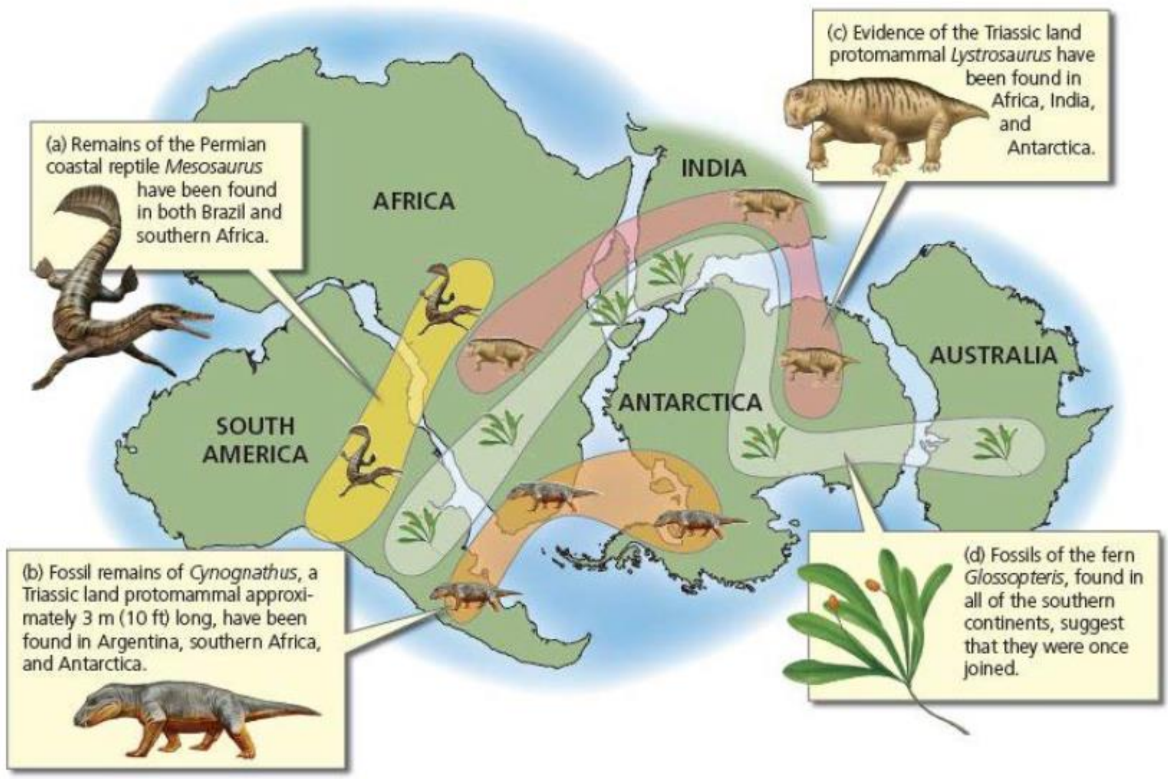

Fig. 5: The characteristic plants and animals of the Permian connect the different continents of Gondwana. The small aquatic reptile *Mesosaurus* and the bear-sized primitive mammal *Cynognathus* are both found in Brazil and South Africa. The pig-like, beaked protomammal *Lystrosaurus* is found in Africa, Madagascar, India, and Antarctica. The seed fern *Glossopteris* is found on all continents of Gondwana.

But then why didn't Wegener's hypothesis find any supporters?

For one thing, there were sociological implications. First, Wegener was not a formally trained geologist, and there is a natural reluctance to accept ideas from outside one's own field that seem to go against one's basic assumptions.

Another problem was that Wegener's evidence came mainly from the Southern Hemisphere (mainly South America and Africa), but almost all the world's geologists at the time lived in Europe or North America. Very few had ever traveled to South Africa or Brazil, which at the time meant long and expensive trips by ocean liner. Of course, the evidence is much more compelling when you can see it in person, rather than reading it in writing and tiny black-and-white photos that were common in magazines at the time. In fact, Wegener's biggest proponents, like the South African geologist Alexander du Toit, were mostly in the southern hemisphere and saw the evidence firsthand. They pointed out that the Permian rocks of South Africa and Brazil were virtually identical; the only difference was that the former had names in Afrikaans and the latter in Portuguese. Another proponent was the British geologist Arthur Holmes, known as the "father of the geologic time scale" because of his pioneering work in radiometric dating in 1913-1915. He adopted Wegener's ideas - though he had worked as a geologist in Africa before returning to England. Holmes first boldly published diagrams showing the drift of continents and mantle currents that moved those continents around in his widely used geology textbooks in the 1920s - 40 years before the geological community accepted the idea.

But Wegener's rejection was not just due to sociological biases. Wegener had no mechanism to explain how the continents drifted, and the ideas he proposed (such as centrifugal force) were not very plausible. Wegener postulated that the continents were driven away from the poles by the gravitational pull of the Earth's equatorial bulge or by tidal forces, but geophysicists showed that this was impossible. Wegener's critics argued that if the continents had plowed through the ocean basins, there must be vast areas of oceanic crust at their leading edges, compressed like the snow on a snowplow blade-and such deposits had never been found. Meanwhile, they dismissed the matches in the rocks of the continents as inconclusive and thought up fanciful land bridges to explain how animals could have crossed the Atlantic Ocean. They continued to denigrate Wegener and expose his ideas to ridicule for decades. In the 1940s, leading American paleontologist George Gaylord Simpson published numerous papers arguing that the fossil record did not require continental drift. His institution, the American Museum of Natural History, held a major symposium in 1949 that rejected all evidence for continental drift.

The birth of plate tectonics

Ironically, just as Wegener's scorn was reaching its peak, new evidence was coming from an unexpected direction: the bottom of the ocean. Both Wegener and his critics did not know at all what the oceanic crust was really like. No one really knew anything about the Earth's crust beneath the oceans. In fact, the answers didn't come until after World War II, when modern marine geology was born. After the war ended, the U.S. Navy gladly sold or gave away surplus ships and equipment (rather than scrapping them) to newly formed oceanographic institutes. In addition, submarine tactics during the war taught the military and the U.S. government that they knew too little about the world's oceans. Federal funds for ocean exploration during the Cold War, when U.S. and Soviet submarines stalked each other, would have been a good investment. In the late 1940s and 1950s, several oceanographic institutes funded ships that routinely traversed the world's oceans, closely examining the depth of the seafloor and the structure of the rocks beneath it, collecting seismic, gravimetric, and magnetic data and sediment cores everywhere. In the late 1950s, thanks to the first detailed maps of the seafloor by Marie Tharp and her partner Bruce Heezen (Fig. 6), scientists for the first time had a true picture of what 70% of the Earth's surface actually looked like. In the mid-1950s, Tharp realized that there was a giant mountain range under the sea known as the Mid-Atlantic Ridge. Not only was it the longest mountain range on Earth, but at over 5000 meters it was also higher than most mountain ranges on Earth.

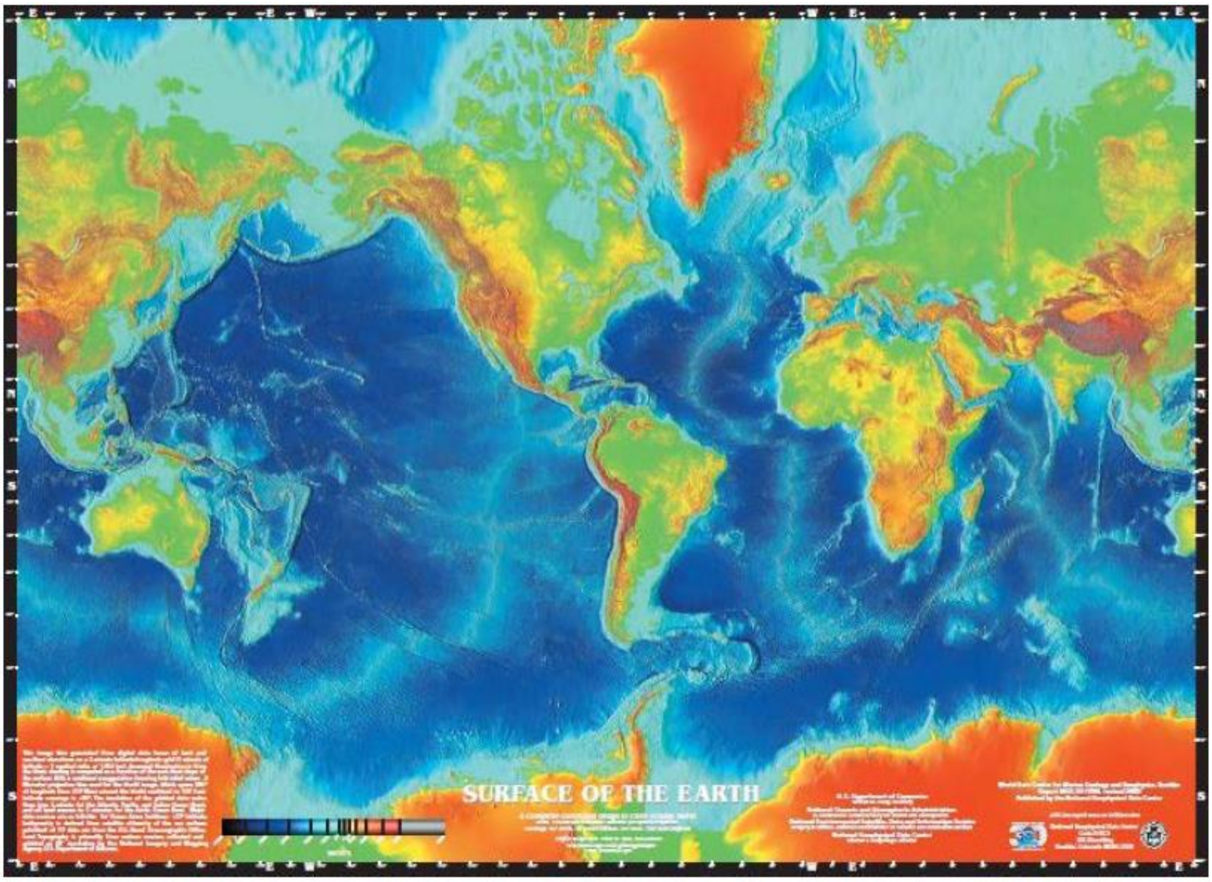

Fig. 6: A modern version of Heezen and Tharp's map of the world ocean floor, showing the Mid-Atlantic Ridge, the East Pacific Ridge, the trenches in the western Pacific, and other features of the ocean floor.

In addition, the entire length of the Mid-Atlantic Ridge had a huge trench deeper than the Grand Canyon, where it had pulled apart and crustal blocks had fallen down along faults. Tharp was a good geologist and immediately recognized that a trench rupture indicated that the ocean floor was pulling apart and spreading out. However, her co-authors Heezen and Lamont director Maurice Ewing were too cautious to publish and spread such a heretical idea, so credit for her discovery fell to others.

Confirmation of the seafloor spreading idea in 1963 was the crucial evidence that launched the plate tectonics revolution.

Ancient magnetic data were collected in the 1950s from rocks on land on many different continents. Many rock types record the Earth's magnetic field as they form, indicating not only its direction but also its strength. As paleomagnetists studied and measured older and older rocks, their results seemed to show that the magnetic north pole was far from the present pole and appeared to migrate through time. This was first called the "pole migration hypothesis." But then they ran into a problem. Each continent had a completely different polar migration curve that only converges on a common magnetic pole today (Fig. 7).

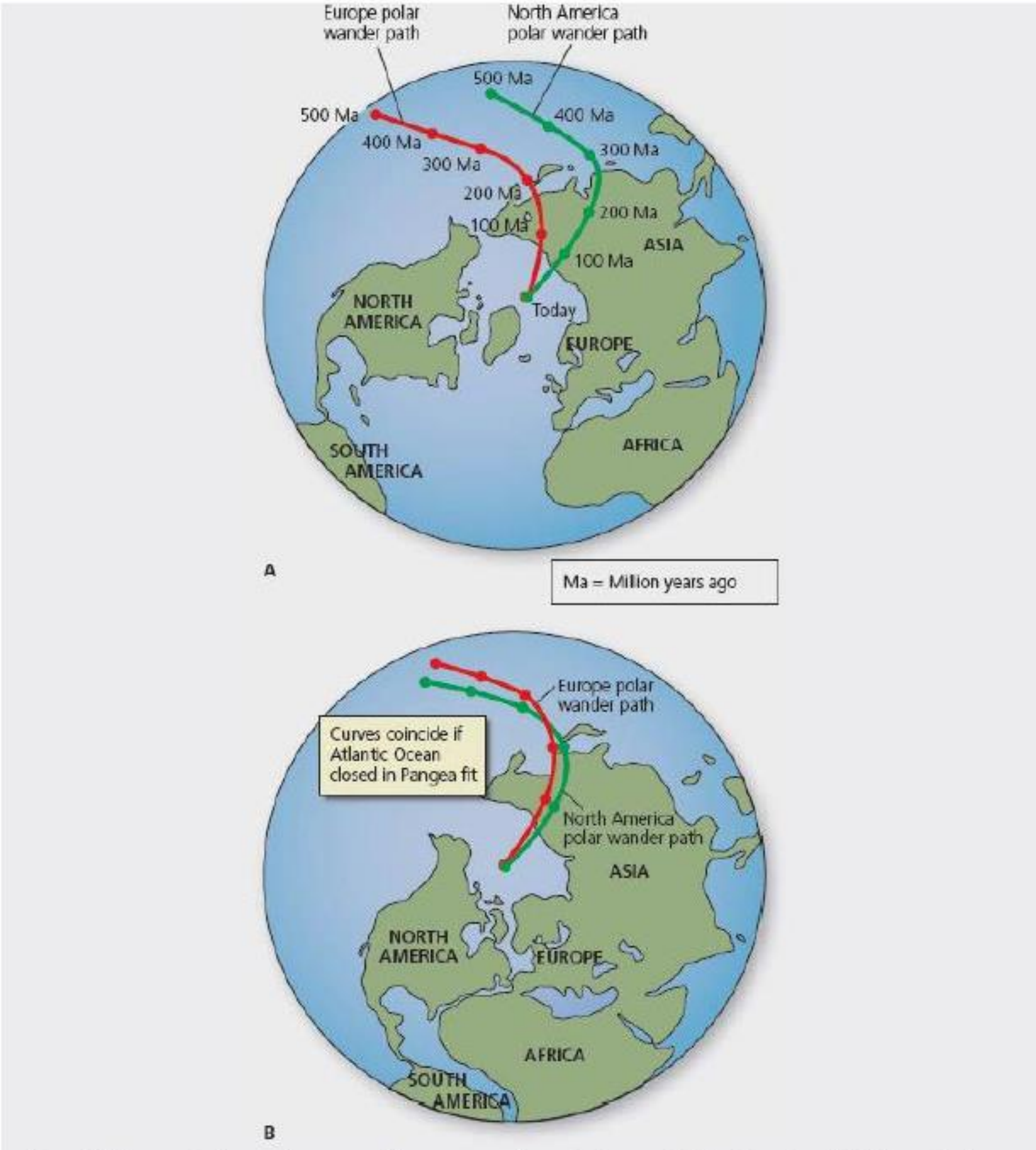

Fig. 7: Apparent polar migration curves. If one measures the ancient magnetic directions from North America (green curve), the magnetic north pole seems to be far away from its present position and reaches its present position only in the magnetic direction of the youngest rocks. Doing the same for the European rocks, we get a completely different position of the magnetic north pole in the geologic past (red curve), which happens to coincide with the modern magnetic north pole in the youngest rocks. So either there were many different magnetic poles that were far apart in the past and only converged in recent times, or if you shift the continents to their ancient positions, the pole migration curves agree.

These data seemed to suggest that the magnetic field had behaved very strangely in the past, with multiple directions of magnetic north that no longer exist today. As outrageous as this idea seemed, the only alternative was equally radical: the continents had moved over time, so it was not the magnetic pole that changed, but the continents that recorded their directions. But when the polar migration curves for two different continents (Fig. 7), such as Europe and North America, were lined up, they were found to match once the continents were brought back together, as Wegener had suggested. In other words, the "polar migration curves" were only apparent polar migration curves because the continents were moving, not the magnetic poles.

Other paleomagnetists discovered a curious phenomenon in the 1950s and 1960s: some rocks had magnetic directions that pointed in the opposite direction of today's (Fig. 8).

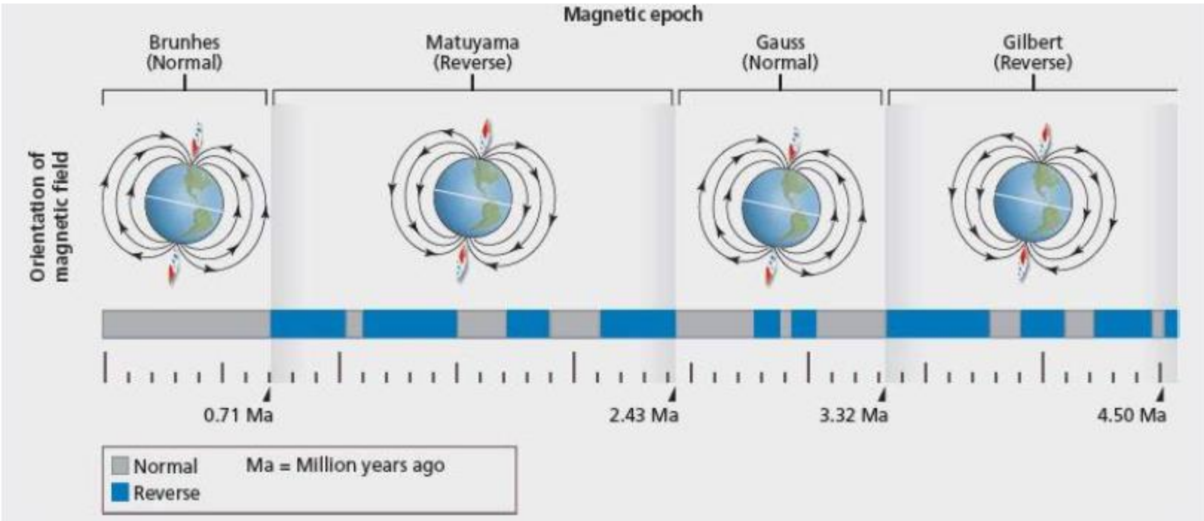

Fig. 8: The magnetic polarity of the Earth has changed hundreds of times in the last 50 million years from normal (as today) to 180° opposite to the present pole. In the last 5 million years alone, there have been over a dozen polarity reversals, or "magnetic reversals."

For example, 800,000 years ago, if you picked up a compass in the northern hemisphere, the needle pointed south and not north. At first, this was attributed to a special property of the rock samples. But as more examples were found, the idea that the Earth's field had changed direction in the geological past seemed less and less far-fetched. To test this idea, Allan Cox of Stanford University and Bob Doell of the U.S. Geological Survey and G. Brent Dalrymple of the U.S. Geological Survey conducted a crucial analysis. They took samples of lava flows from around the world, measured their magnetic directions, and determined their ages. If rocks of the same age had the same magnetic direction all over the world, then direction reversal was no longer a peculiarity of individual, self-reversing rocks, but had to be a global phenomenon, like the Earth's magnetic field.

By the early 1960s, Cox, Doell, and Dalrymple (in friendly competition with Ian McDougall, François Chamalaun, and Don Tarling of the Australian National University) had established that the Earth's magnetic field reverses from its present direction to one 180° opposite to the direction we measure today.

Since then, the pattern of magnetic flip-flops has been documented in detail. It has flipped hundreds of times over the last 100 million years, resulting in a random pattern of normal and reversed polarity that looks like the black and white stripes of a bar code.

Like a barcode, this pattern contains a signal and is often used to assign flip-flops in thick rock layers and to date them accurately (Fig. 9). This record of changes in the Earth's magnetic field over time is called the time scale of magnetic polarity. This history of magnetic field reversals was the key, the "Rosetta Stone" that solved the final problem of continental motion. It provided the last crucial data that helped to take the idea of plate tectonics seriously. Since the 1940s, oceanographic ships have towed proton magnetometers that recorded the magnetic signal over the ocean floor. These devices look like a long torpedo on a cable and were originally developed during World War II to detect submarines. Over the years, they collected magnetic data over the seafloor, but at first marine geophysicists couldn't make sense of what they were seeing. For example, when they towed the magnetometer over a mid-ocean ridge, the magnetic field recorded was stronger than the normal Earth magnetic field we are always exposed to (Fig. 9). This stronger than average field direction was called a positive magnetic anomaly. However, when they dragged the magnetometer a few dozen kilometers to either side of the ridge, they obtained a weaker than average magnetic field strength, or a negative magnetic anomaly. What did these strange results mean? For over a decade this was a great mystery, mainly because the first magnetic surveys, like those of the eastern Pacific, were very complicated and difficult to decipher. The key came in 1963, when Fred Vine and Drummond Matthews of Cambridge University analyzed a much simpler profile over the Mid-Atlantic Ridge. They found that the pattern of magnetic anomalies was symmetrical, with positive magnetic anomalies in the center of the ridge, but negative anomalies on either side, and then a series of symmetrical magnetic "stripes" moving outward away from the ridge (Fig. 9).

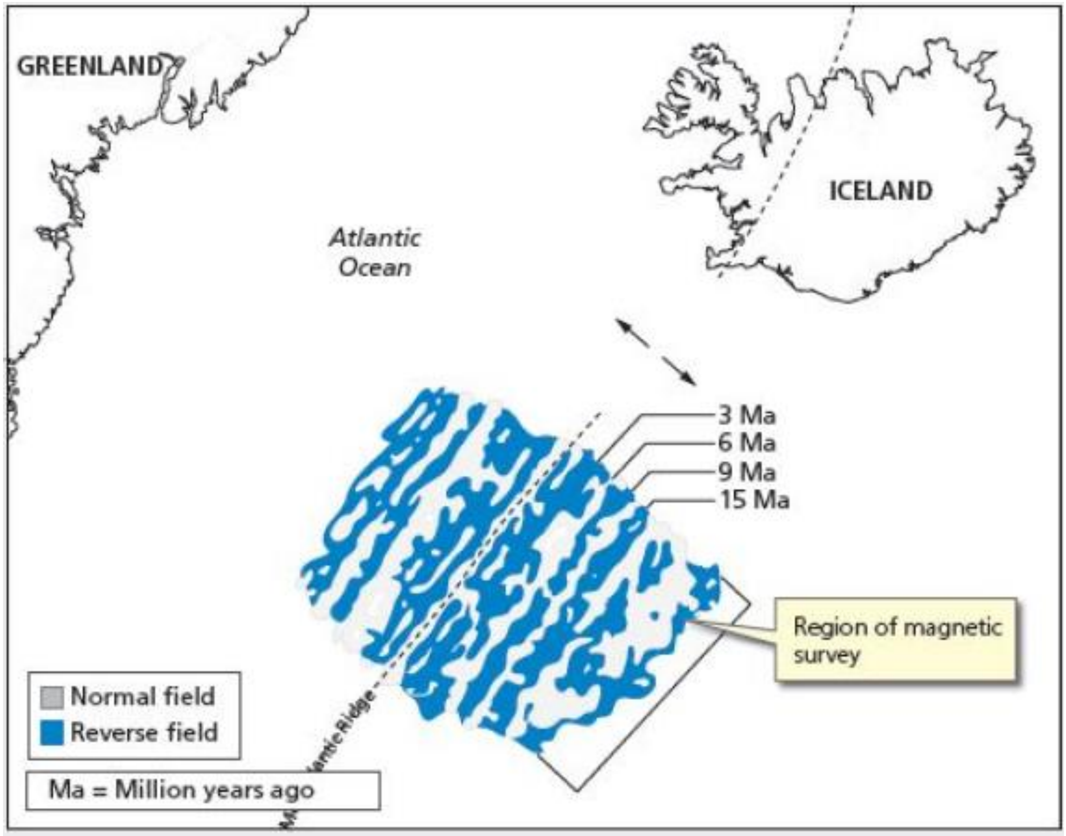

Fig. 9: The magnetic anomalies were symmetrical over the mid-ocean ridge (here the data from the Reykjanes Ridge segment of the mid-Atlantic ridge south of Iceland), which only makes sense if it is the record of the ancient magnetic field with normal and reversed polarity frozen in the rocks of the spreading seafloor, gradually moving away from the crest of the mid-Atlantic ridge like two conveyor belts.

Vine and Matthews realized that the rocks on the seafloor must be magnetized in different directions. The rocks in the center of the mid-ocean ridge had erupted in the last 800,000 years, so their normal magnetic polarity would reinforce the direction of the modern background field, resulting in a stronger than average field reading on the magnetometer. However, the rocks farther from the center of the ridge were erupted and magnetized more than 800,000 years ago, giving them a reversed magnetic polarity. When the reversed directions interact with the modern Earth's field, they are partially subtracted from the background field because they are polarized in the opposite direction. For this reason, the magnetometer records a weaker than average reading or a negative magnetic anomaly. Thus, the seafloor is like a magnetic tape recorder that picks up a signal from the Earth's field when it breaks out in the middle of the ridge, and then passively moves away from the "recording head" carrying its magnetic signal with it (Fig. 10). The fact that the magnetic signal was symmetrical on both sides of the ridge implies that the oceanic crust is propagating away from the ridge like two conveyor belts moving away from a common center.

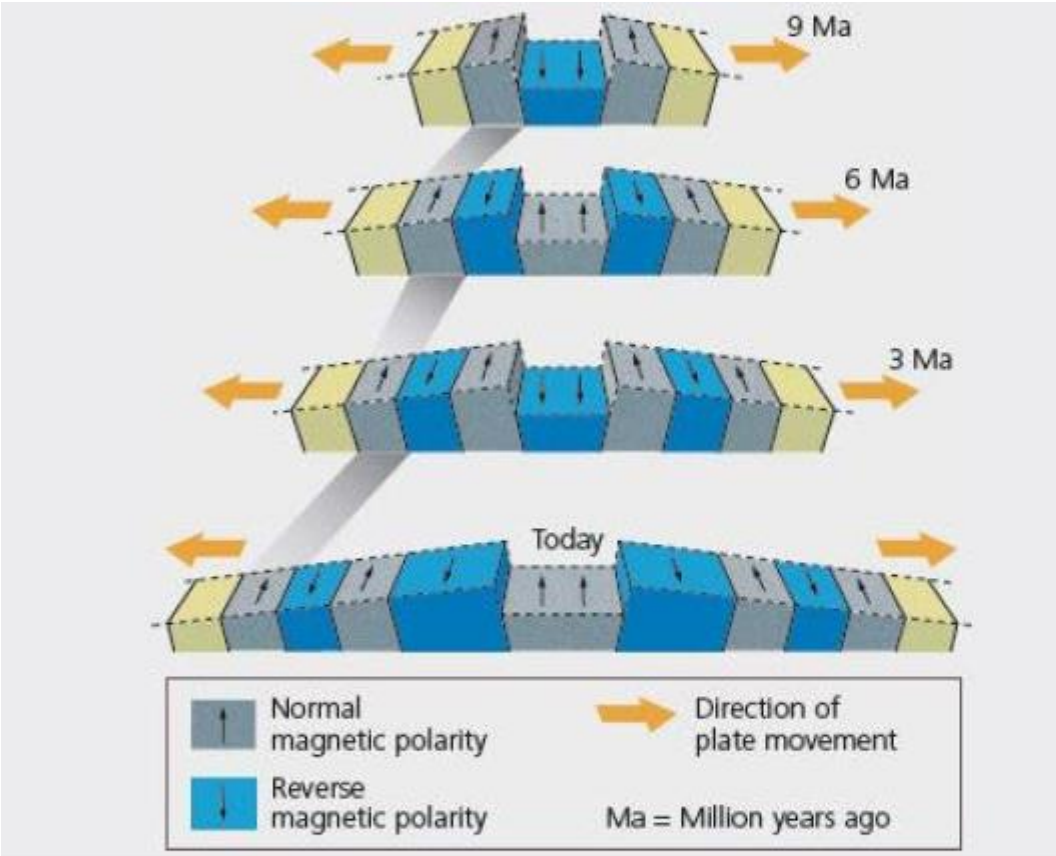

Figure 10: Reversal patterns of mid-ocean ridges that erupted along the mid-ocean ridge, then broke apart and moved away from the ridge as new seafloor formed. The magnetic reversal patterns were symmetrical, indicating seafloor spreading.

Plate tectonics

According to the theory accepted today, the lithosphere is divided into tectonic plates and moves on the underlying viscous asthenosphere. Here, a distinction is made between numerous small plates and the seven major continental plates (Fig. 11):

Eurasian Plate, North American Plate, South American Plate, African Plate, Australian Plate, Antarctic Plate, Pacific Plate.

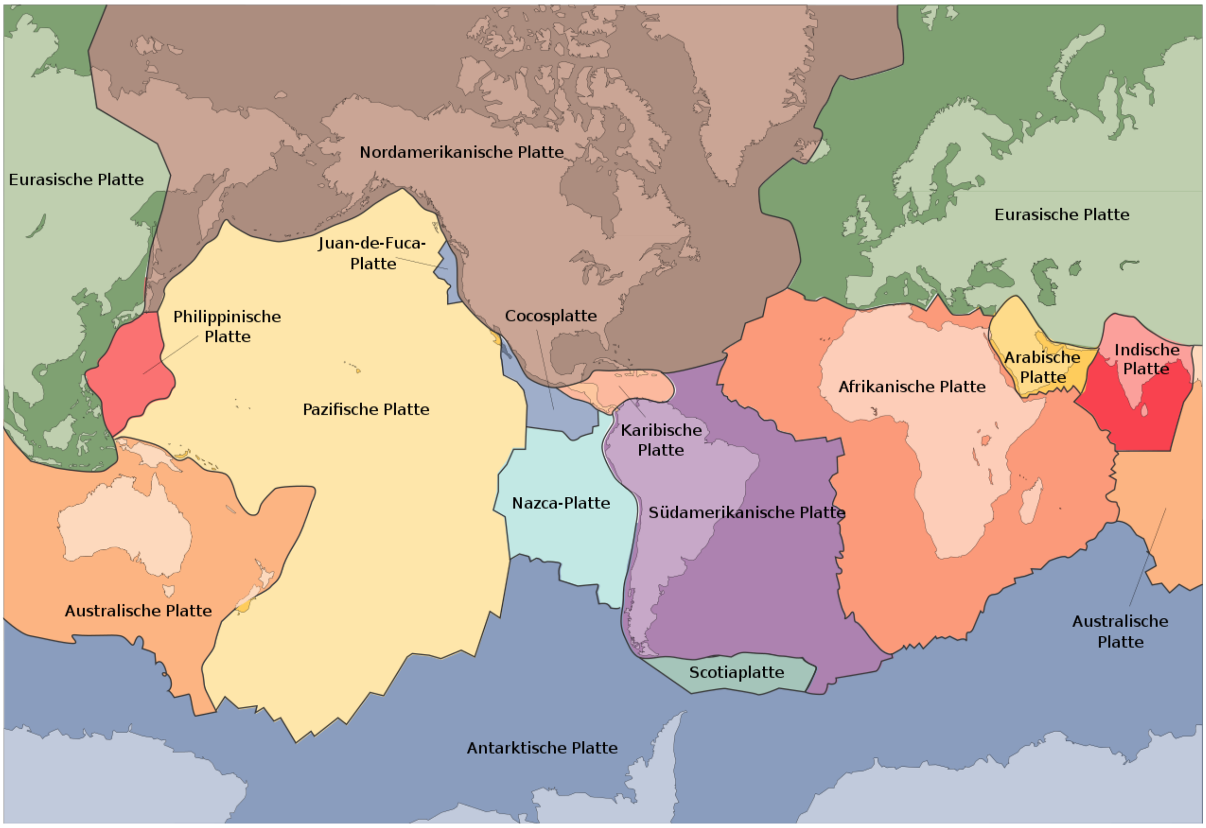

Abb. 11: tectonic plates

They are named after the continents, countries, or seas they support. For example, the Eurasian Plate carries large parts of Asia and the entire continent of Europe, including Germany. In addition to the seven continental plates, there are a number of other smaller plates, such as the Arabian, Indian, Carribean, and Nazca plates. The tectonic plates move on the underlying layer, but how does this work? Convection currents are primarily responsible. In the process, liquid rock, also called magma, rises from deeper layers. There, the hot material cools down and sinks back into deeper layers. This creates a current that slowly but surely causes the plates to move in a certain direction.

However, since our Earth is covered by plates, plate displacement causes various processes to occur at the plate boundaries:

Divergence:

Diverging plates (Fig. 12) drift away from each other. Wherever plates move away from each other, they rupture the ground - whether on the ocean floor or on land. In the process, hot rock reaches the earth's surface - more precisely, magma from the deeper layers of the earth penetrates upward and cools there. The rock additionally pushes the earth's plates apart. Examples of this are the mid-Atlantic ridge or rift valley fractures such as the African rift valley.

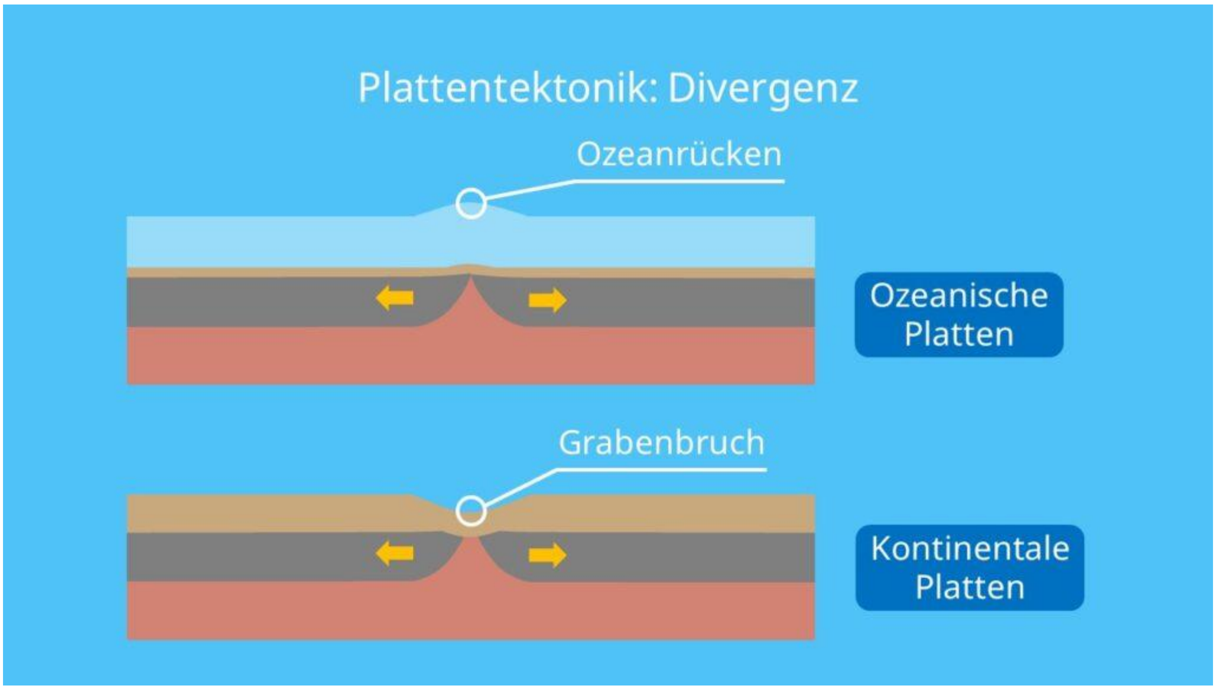

Abb. 12: Divergence

Konvergence:

In convergence, the Earth's plates move toward each other. However, since there is no free area between them to occupy, the converging plates collide. The consequences of the collision depend on what type of Earth plates are colliding.

If a continental and an oceanic plate meet (Fig. 13), a so-called subduction zone is formed. This means that the oceanic plate dips below the continental one. In the process, the subsided (subducted) plate heats up and partially melts.

At this point hot magma rises, which can then be observed in the form of volcanoes. This is how, for example, the volcanoes in New Zealand and in the South American Andes were formed.

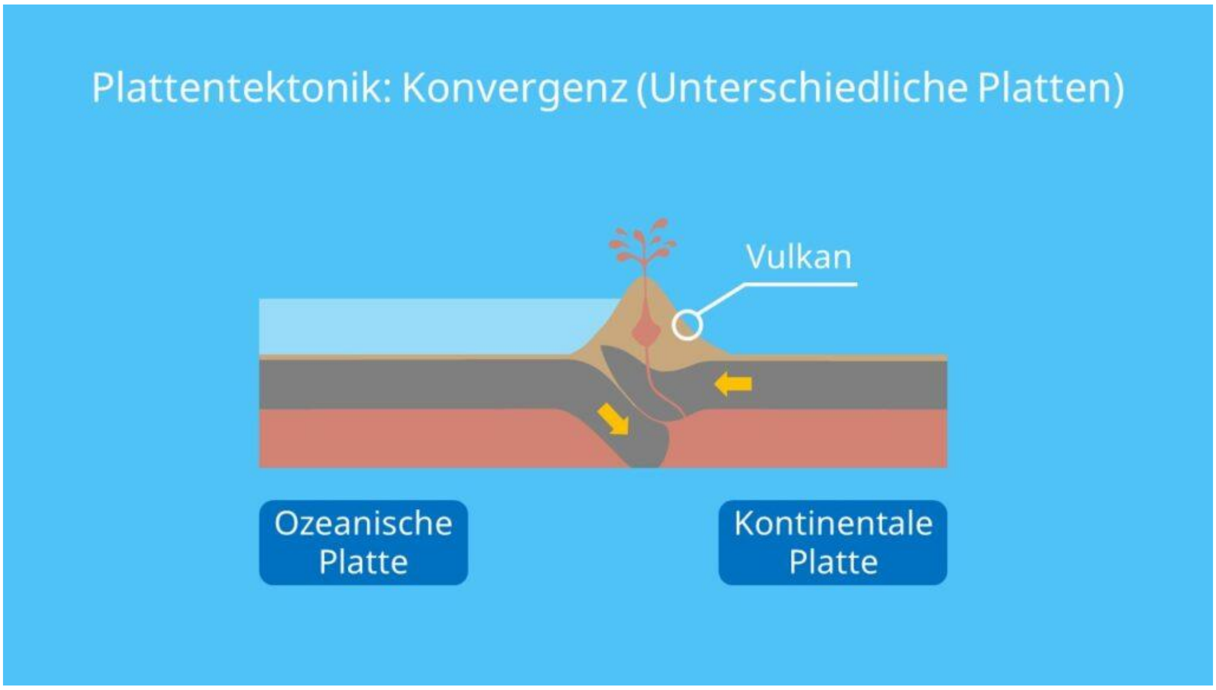

Abb. 13: Konvergence, different plates

If two continental plates meet (Fig. 14), neither of them sinks deep into the interior. This is because the continental plates are too light to sink. So rather, the plates bump against each other, forcing one of them to move upward. This process of plate tectonics results in the formation of mountains from the earth's crust, such as the Alps and the Himalayas.

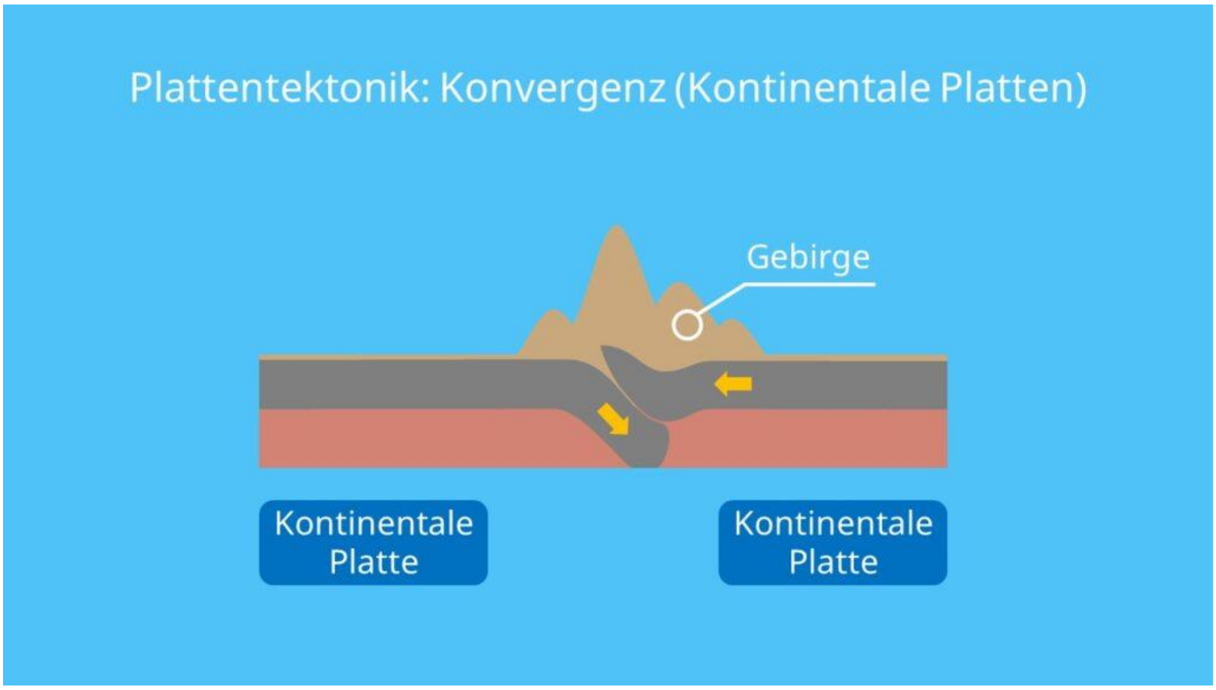

Abb. 14: Konvergence (continental plates)

When two oceanic plates meet, subduction also occurs (Fig. 15). This means that one of the plates sinks below the other. The subducted plate is the older of the two because it is usually heavier. Subduction results in the formation of volcanic island arcs, such as the Kuril Islands, a chain of islands near Japan. However, this type of convergence is rather rare.

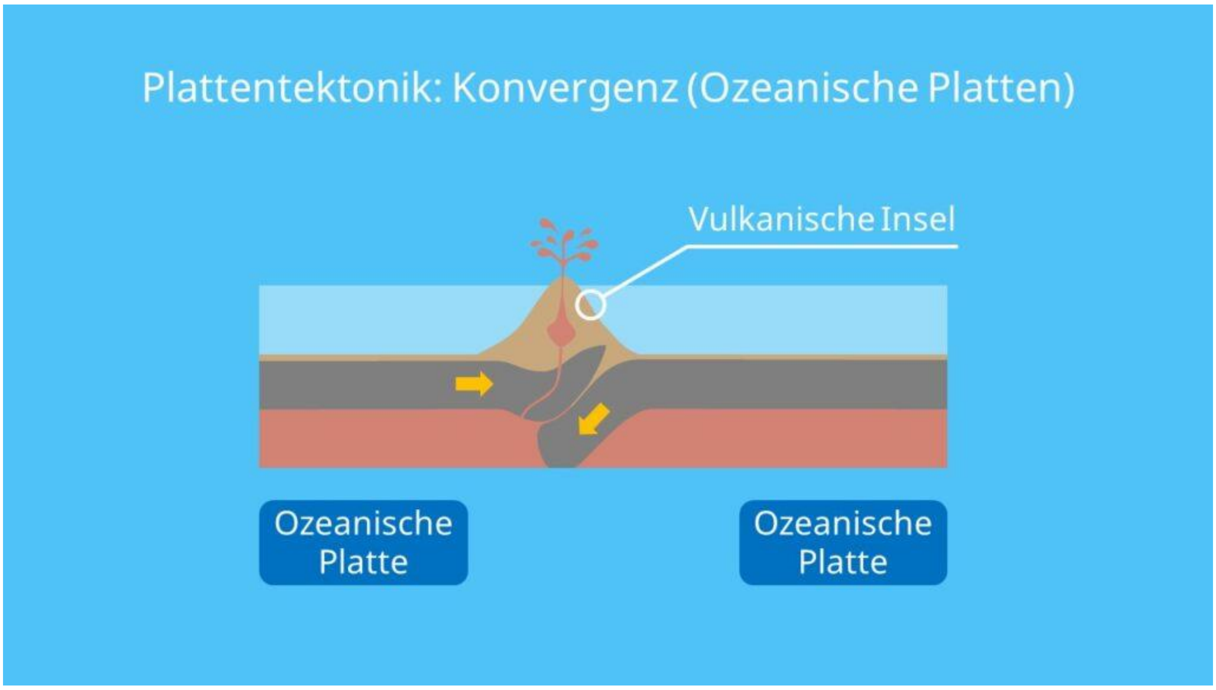

Abb. 15: Konvergence (oceanic plates)

Transform Fault:

The third type of plate boundary is the transform fault (Fig. 16). Here two earth plates slide past each other. In such a conservative plate boundary, fissures occur in the ground without destroying existing ground and forming new ground. Because of the friction, the occurrence of earthquakes is very frequent at these places.

Transform faults can occur between oceanic plates, but also between continental plates. An example of a fissure between continental plates is the San Andreas Fault in California.

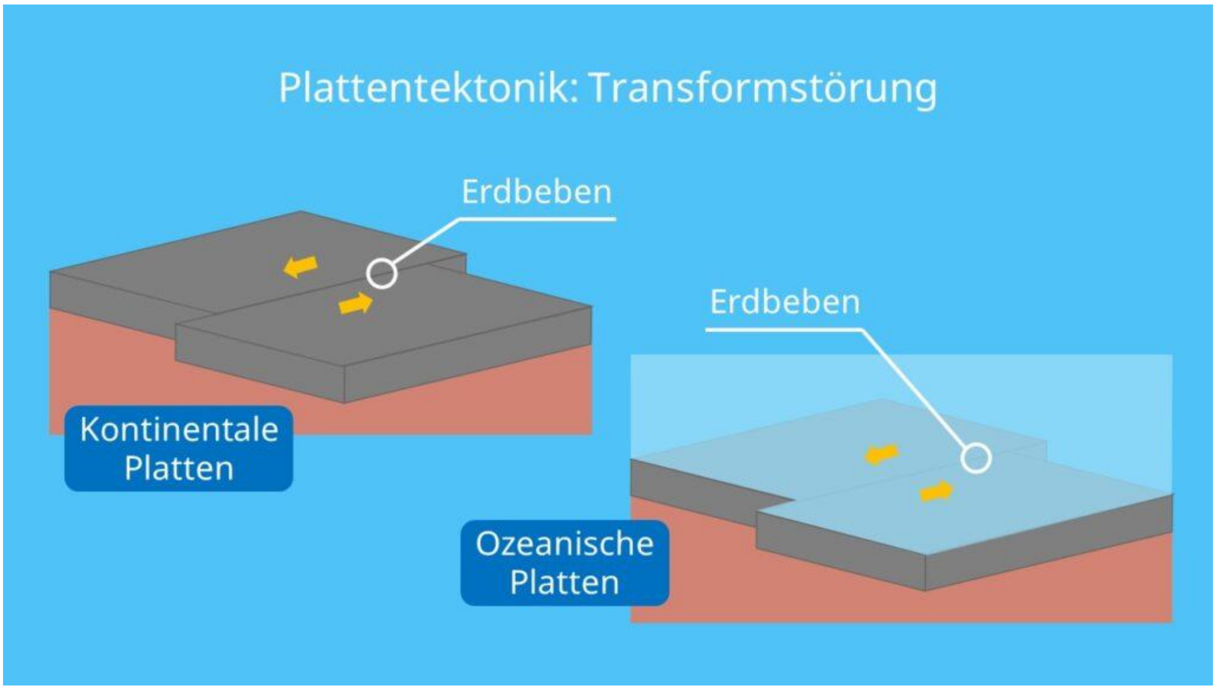

Abb. 16: Transform fault

Literature

Bahlburg, H. & Breitkreuz, C. (2017): Grundlagen der Geologie, 5.Auflage. Springer Verlag

Grotzinger, J. & Jordan, T. (2017): Press/Siever Allgemeine Geologie, 7. Auflage, Springer Verlag

Prothero, D. (2021): The Evolving Earth. Oxford University Press

Prothero, D. & Dott, (2004): Evolution of the Earth, Seventh edition.