Archaeozoic and Proterozoic: Formation of the Continents

Introduction: The Hadean, summary

In the last chapter we dealt with the formation of the earth and the moon. This falls in the time of the Hadean, which made the first half billion years of the earth history. In the Hadean the earth core and mantle, as well as the earth crust and the oceans were formed. In this time epoch the earth was also constantly bombarded by meteorites, because the debris of the early solar system was constantly attracted by the gravity of the earth. The bombardment may have even accelerated the process of continental crust formation. Geochemical data suggest that the crust of the Earth Age was extremely thin and simple, without the geologic complexity we find in modern oceanic or continental crust. Several lines of evidence suggest that it was only about 20 km thick, compared to modern continental crust, which is about 30 to 50 km thick (Fig. 1).

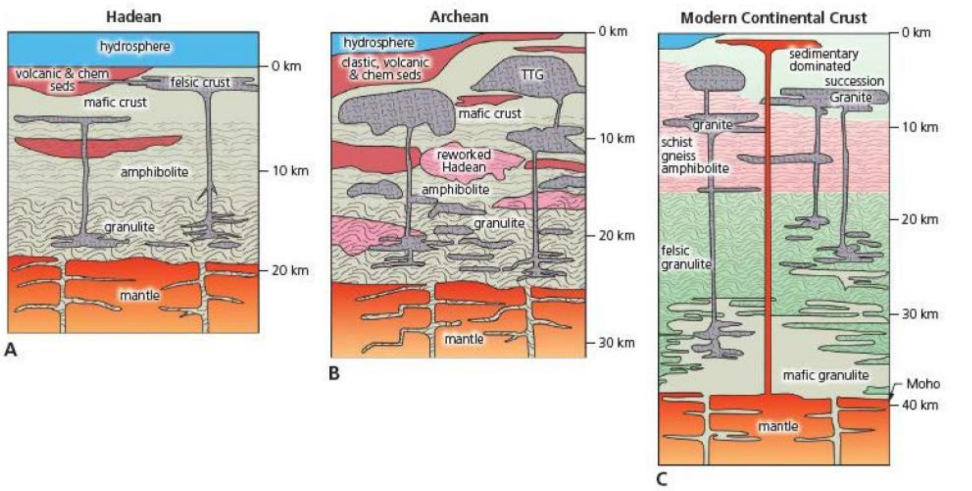

Figure 8.4 Cartoon cross sections of how the crust has changed through time. **A.** Hadean crust was very thin (only 20 km, or 12 miles maximum) and hot and consisted mainly of ultramafic volcanics like komatiite (tan color) made of pure olivine lavas erupting directly from the mantle with little or no differentiation. **B.** Archean crust was slightly thicker and still made of komatiites, but there were more metamorphosed rocks, more differentiation of magmas into granites, and a thicker sedimentary pile on top. **C.** Modern continental crust is 40 km (24 miles) thick or thicker with multiple layers of high-grade metamorphic rocks full of silica intruded by diorites, granodiorites, and granites. The mantle material only rarely erupts at the surface from volcanic vents of deep origin.

Fig. 1: The earth crust in earth history

Hardly any crustal rocks are preserved from the Hadean. Among the oldest are the 4.32 billion year old Nuvvuagittuq greenstones on the east coast of Hudson Bay or the 4.03 billion year old Acasta gneisses near Great Slave Lake in Canada.

Geologists are constantly searching for even older rocks and dating more and more samples. In fact, in 2018, they found rocks from the Earth's mantle that were churned up by volcanoes dating back to the Earth's formation 4.5 billion years ago.

In this paper, we want to turn our attention to how the Earth's crust continued to change and how the first continents and plate tectonics formed. In addition, we want to take a closer look at the earth's magnetic field.

Earth's magnetic field

The separation of the Earth's layers into an iron-nickel core and a silicate-rich mantle leads to the formation of the Earth's magnetic field (Fig.2). We cannot feel the Earth's magnetic field, so it is not surprising that for a long time no one suspected its existence. It was not until around 1600 that scholars came to the conclusion that the Earth behaves like a giant magnet with its two poles located near the geographic poles. They were able to show that compass needles point north because they align themselves along a magnetic field that extends between the poles. But where this field gets its energy from, how it is generated, and why it sometimes fluctuates dramatically remained mysterious for a long time.

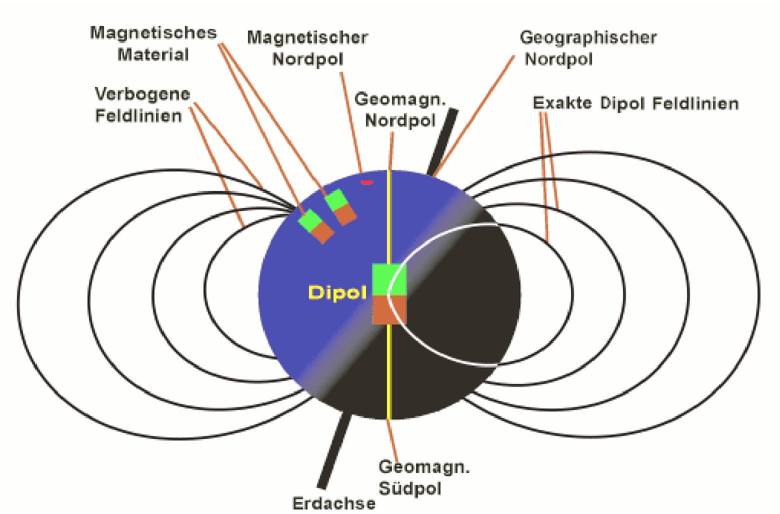

Fig. 2: Earth's magnetic field

Today we know: earth magnetism has its cause in enormous streams of liquid metal in certain zones of the earth's interior (fig. 3). In the interior of our young planet, as we have already learned, heavy elements such as iron and nickel had accumulated, from which a solid core was later formed. This inner core is still surrounded by a layer of molten metal, the outer core. Like the oceans on the surface of the earth, the liquid metals in the depths are permanently in motion. This is because the inner core, although solid due to high pressure, is 5,000 °C hot. The liquid iron of the outer core is therefore constantly circulated. The molten iron rises from the solid surface of the core in the direction of the Earth's mantle, spirals under the influence of the Earth's rotation, and cools as it sinks back into the depths in the direction of the inner core. These convection currents function like a kind of dynamo - that is, a machine that converts mechanical energy into electrical energy. Electric current flows and a magnetic field is formed. Researchers call this the Earth's geodynamo. The gigantic size of this geodynamo ensures that its magnetic field still has an effect far away from the Earth - and, among other things, effectively keeps out the particle stream from the sun and other cosmic particles. Only at the poles do particles that have to move along the field lines penetrate deep into the atmosphere and collide with the gas particles in the air. When this happens, oxygen atoms usually glow greenish, nitrogen atoms blue or red - we have the famous auroras.

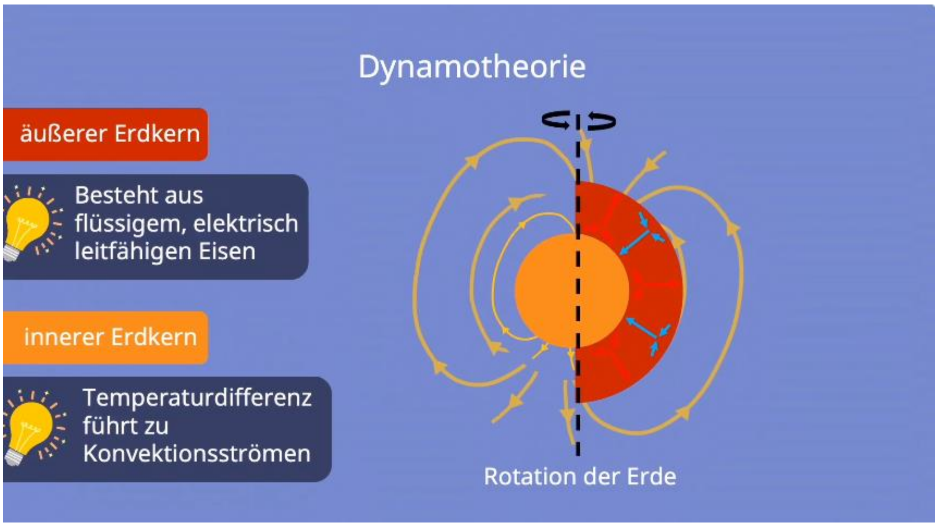

Fig. 3: Cause of the earth's magnetic field

If the Earth's magnetic field could not deflect the solar wind, the Earth would probably look like Mars: dry, cold and lifeless. Traces on the surface of Mars show that there were once seas there, as well as a dense atmosphere, protected by a magnetic field that existed at least for a time, as remains of magnetized rock show. But at some point the Martian magnetic field disappeared and the solar particles gradually carried away most of the Martian atmosphere and most of the water escaped. One thing is certain: without a magnetic field, there is no complex life (at least as we know it). However, our magnetic field is also an unsteady force. Since the earth's rotation pushes the turbulent streams of liquid metal only roughly in one direction, the magnetic field changes at any time. For example, the magnetic pole of the northern hemisphere recently changed so rapidly that it shifted an average of almost one kilometer per week from Canada toward Siberia. The Arctic magnetic pole has shifted northward by more than 15 degrees of latitude since the beginning of the 20th century (Fig. 4). For comparison, if the North African city of Tunis were to change its location by the same amount, it would be located next to Hanover.

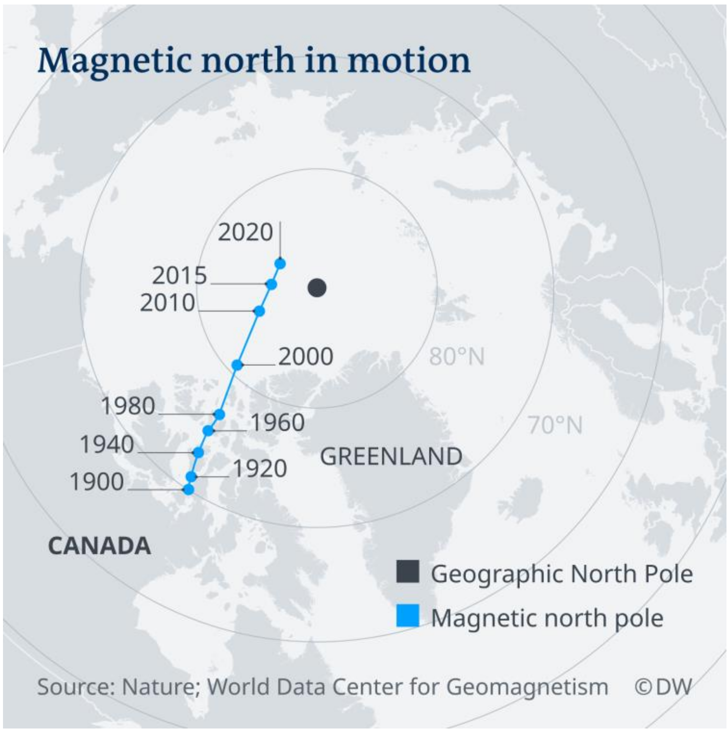

Fig. 4: Shift of the magnetic north pole

Researchers know from traces in the rocks that the magnetic field completely swapped its poles again and again in earlier times. In the last millions of years, such a field reversal occurred on average every 250,000 years, with individual intervals varying. The last pole reversal took place 780,000 years ago. Such reversals of the polarity of the Earth's magnetic field initially cause a certain amount of chaos - for example, the field strength would decrease so that more high-energy particles from the solar winds would reach the Earth, and many animals that orient themselves to the Earth's magnetic field, such as migratory birds, would have orientation problems. But life itself would survive such a pole reversal - and has, as we know, throughout Earth's history. Eventually, the magnetic field would stabilize again and life would adapt to it. But in the future, as the Earth's interior cools, the strength of the magnetic field will basically decrease and come to a halt - in a few billion years. So here we still have some time.

However, the convection currents did not only lead to the formation of the earth's magnetic field, but also for the movement of the earth's crust and the continents.

Archean - Formation of the first continents

The Archean covers 1.5 billion years, i.e. about one third of the Earth's history, and is subdivided into Eoarchaic, Paleoarchaic, Mesoarchaic and Neoarchaic (Fig. 5). The subdivision is somewhat arbitrary and difficult to correlate globally because it is based on only a limited number of radiometric datings, and stratigraphic correlation of ancient continental cores is limited.

	Äonothem/Äon	Ärathem/Ära	System/Periode	Alter [Ma]
Präkambrium	Proterozoikum	Neoproterozoikum	Ediacarium	630 - 542
			Cryogenium	850 - 630
			Tonium	1000 - 850
		Mesoproterozoikum	Stenium	1200 - 1000
			Ectasium	1400 - 1200
			Calymmium	1600 - 1400
		Paläoproterozoikum	Statherium	1800 - 1600
			Orosirium	2050 - 1800
			Rhyacium	2300 - 2050
			Siderium	2500 - 2300
	Archaikum	Neoarchaikum		2800 - 2500
		Mesoarchaikum		3200 - 2800
		Paläoarchaikum		3600 - 3200
		Eoarchaikum		4000 - 3600
	Hadaikum			4600 - 4000

Fig. 5: Precambrian

Archean rocks are widespread, but mostly strongly metamorphically overprinted. However, there are also many metasediments among them. Some of them still show primary sedimentary features. Some also contain stromatolites and tiny organism remains, which probably originate from bacteria. The sediments prove that sufficient continental crust was already formed or formed in this geological period.

What kind of rocks do we find from this period? Most of them are very different from the rocks found on Earth today. Some have no modern equivalents at all. They show us that the Archean crust was still very hot and very active, with thin, narrow microcontinents that formed, broke up, and collided with each other on an Earth with a much hotter, more active mantle than today. These ancient rocks are divided into four classes, all of which happen to begin with the letter "G": Gneisses, Greenstones, Graywackes, and Granites.

Gneisses (Fig. 6) are highly metamorphosed rocks, usually formed deep in the crust under high pressure and temperature. In many cases, they are so highly metamorphosed that nothing remains of the structure of the parent rock. They are usually rich in lighter silicate minerals such as quartz, potassium feldspar, and plagioclase, and darker minerals such as biotite and hornblende. Their most characteristic feature is that they have a banded structure that separates the light and dark minerals due to their intense heating. They are usually the oldest rocks of a crustal block, a so-called terrane. Their composition closely resembles that of modern continental crust, so geologists believe that they are metamorphosed protocontinental crust from the earliest microcontinents.

Abb. 10.22a,b Neu entdeckte Gesteine zeigen, dass bereits im Hadeum an der Erdoberfläche kontinentale Kruste vorhanden war. **a** Der Acasta-Gneis aus dem Archaikum der Slave-Provinz im Nordwesten Kanadas. Radiometrische Datierungen ergaben ein Alter von 4,0 Mrd. Jahren. **b** Amphibol führende Gesteine aus dem Nuvvuagittuq-Grünsteingürtel, Nord-Quebec (Kanada), besitzen ein Alter von 4,28 Mrd. Jahren und sind damit die ältesten Gesteine, die bisher gefunden wurden (Fotos: a mit frdl. Genehm. von Sam Bowring, Massachusetts Institute of Technology; b © Jonathan O'Neil)

Fig. 6: Gneisses

Between these gneissic protocontinents were very thin but broad areas of prooceanic crust. Today, when oceanic crust forms on the seafloor in a mid-ocean ridge, it erupts in the form of lava pillows emerging from a fracture in a submarine lava flow. Of course, almost all of the Archean proto-oceanic crust has similar lava pillows, proving that it once erupted underwater. But these ancient lava pillows and seafloor crust are very different from the modern basaltic lavas that erupt hourly at mid-ocean ridges. Instead, they are a strange form of lava known as komatiite (Fig. 7).

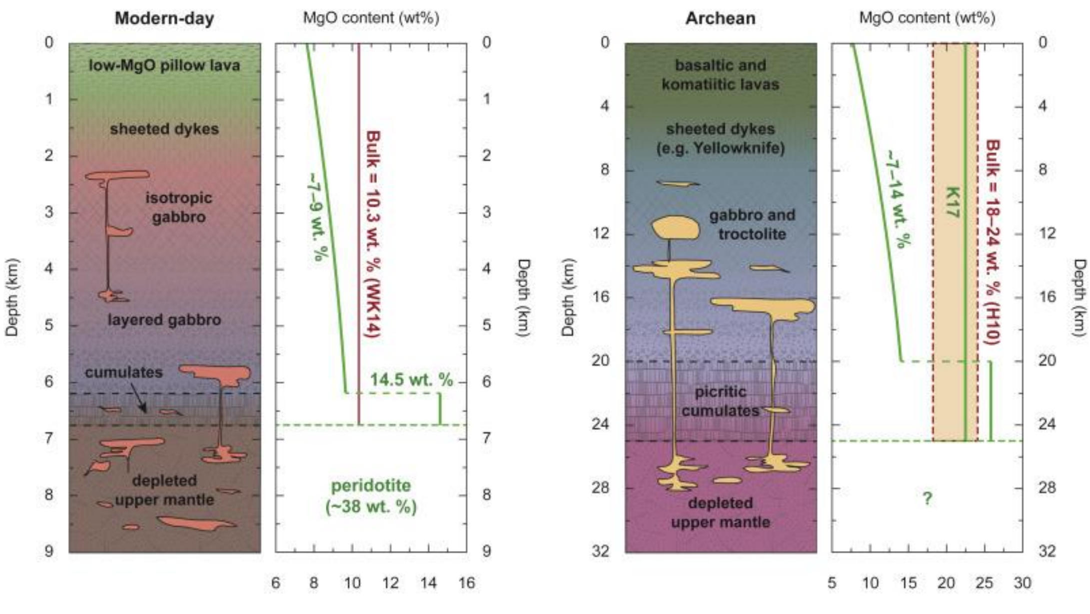

Fig. 7: Comparison archean and modern crust formation

It is extremely rich in magnesium and therefore rich in the mineral olivine. Modern basaltic lava, on the other hand, contains pryoxenes and calcium plagiocas. In fact, komatiites erupt almost nowhere on Earth, but formed when the Archean seafloor erupted in Earth's earliest oceans. Komatiites indicate a much hotter mantle, so magmas of pure olivine could have formed. Such magma would be more fluid than the basaltic lavas that flow from modern volcanoes. The presence of so much komatiite also suggests a much more active mantle, which very quickly poured out very thin, fluid, hot oceanic crust. All of these Archean komatiites found today have since been metamorphosed to consist of greenschist minerals such as chlorite and serpentine. For this reason, they are also called **greenstones** (Fig. 8).

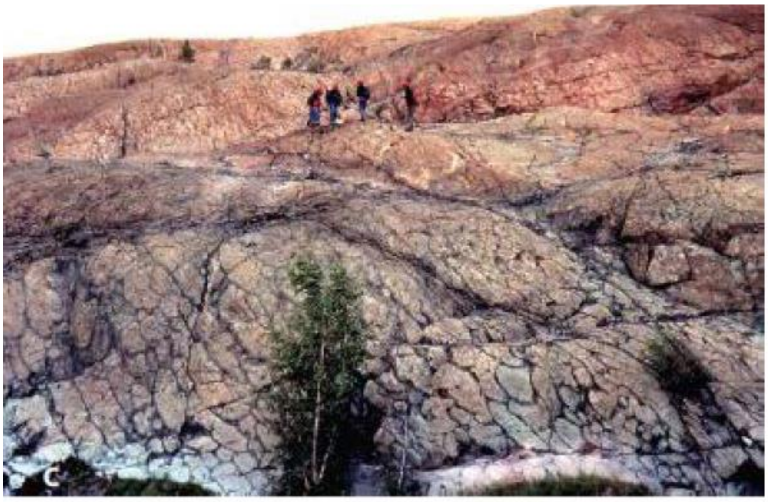

Fig. 8: Pillow lavas from the Yellowknife Group, northern Canada, metamorphosed to greenstone.

The komatiite pillow lavas of the earliest oceans were eventually covered by sediments that eroded from the protocontinents. However, the Archean sediments were very different from the typical marine sediments of today, which are normally composed of pure quartz sand and form normal sandstones. Instead, it is a mixture of sand and coarser material, with much silt between the grains, known as **graywacke** (Fig. 9). Instead of pure quartz sand, the sands in graywackes consist of a mixture of many different components, including unstable minerals such as feldspars. This indicates that graywackes were freshly eroded from the protocontinents and poured directly into the ocean basins without weathering. Even more interesting is that the graywackes are almost all overlain by deep marine shales, forming thick sequences of turbidites that repeat over and over, often over great distances. This shows that they were deposited from the continent without weathering or separation of the clays from the sands (as is usually the case today), and then deposited in huge submarine gravity currents called "turbidity currents" (Fig. 10).

Fig. 9: Graywacke

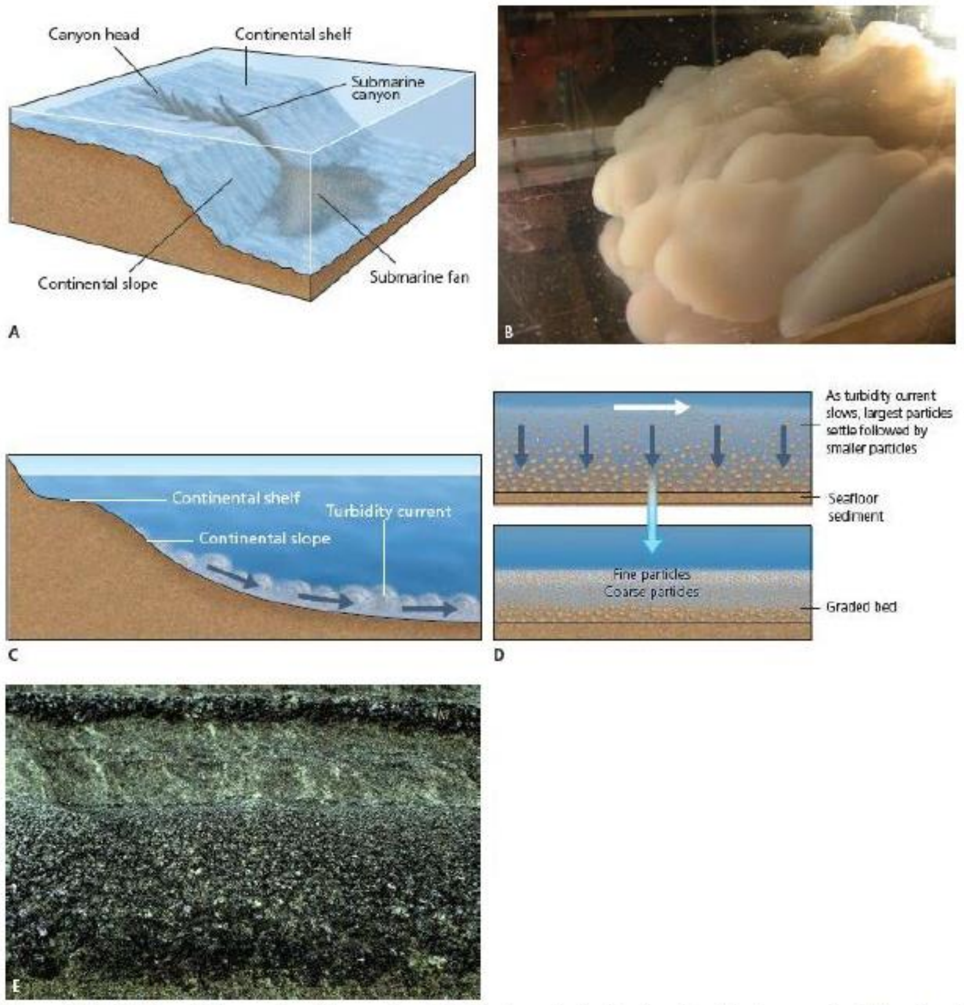

Figure 4.12 A–E. The offshore region of the continental shelf–slope–rise (top) is dominated by huge gravity slides of sand and mud (A–C), which funnel down through submarine canyons and then reach the submarine fan. There, turbidity currents (B) deposit thick sequences of graded beds (D–E), which coarsen upward from bottom (sandy) to top (muddy). (D–E) The graded beds are formed when the turbidity current slows down and stops, and the heaviest, coarsest sand and gravel settles out first, followed by the finer sands and then muds.

Fig. 10: turbidity currents

The true **granites** (Fig. 11) are often deep pink or even red in color, which is due to the high proportion of potassium feldspar. These granites usually occur as intrusions into older gneisses, graywackes and greenstones, indicating that they formed as the last of the "four Gs". They were formed by remelting of rocks from the floor of the gneissic protocontinental crust.

Fig. 11: Pink granite at Hiltaba, South Australia.

Even more characteristic of the Archean than the particular composition of the rocks is the way they were formed and distributed. In most Archean cores of today's continents, large masses of basement rocks known as greenstone belts were trapped between the gneissic protocontinents (Fig. 12).

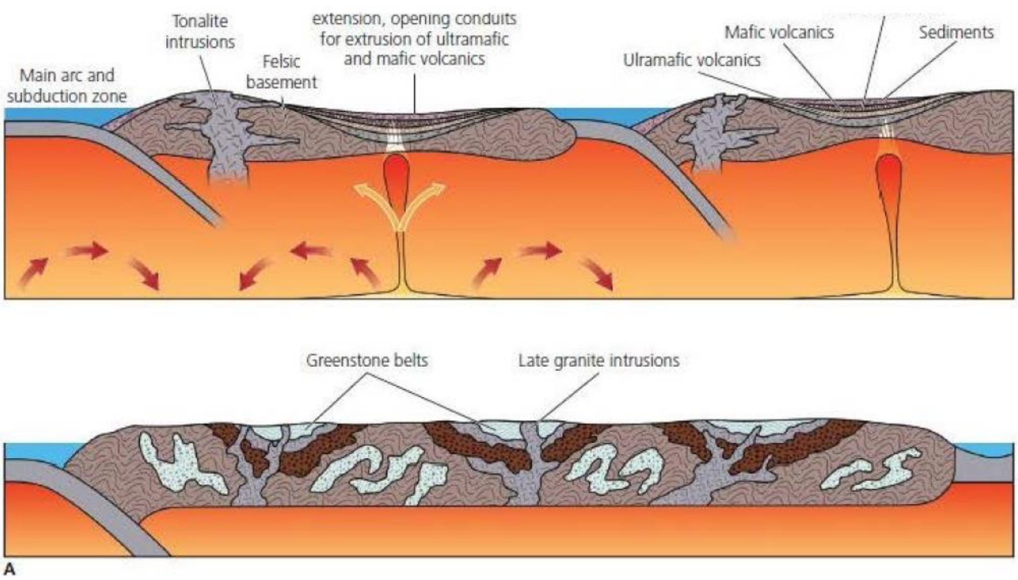

Fig. 12: Structure of the greenstone belts. When the gneissic protocontinents collided with each other, they tore into pieces of the proto-oceanic crust and crumpled it between blocks. These greenstone belts

(often covered by marine sediments such as graywackes and shales) are thus found around and between gneissic protocontinental cores. The final stage occurred when the blocks were joined together and the lower parts of this crustal material partially melted and formed granitic intrusions.

The ancient proto-oceanic crust of greenstone and the graywacke sands and silts that filled the ocean basin are typically crumpled and folded and deformed, presumably when the proto-continents collided and crushed the proto-oceanic crust between them. Thus, in map view, the greenstones form long, narrow belts of rock (Fig. 13), each of which was once a proto-ocean that has since been compressed into a narrow block by the proto-continents on either side. Presumably, the collision of several protocontinents and the proto-ocean formed a thicker crustal mass that began to melt at its base, producing magmas rich in silicon, potassium, sodium, and aluminum that penetrated the overlying rocks to form the typical Archean granites.

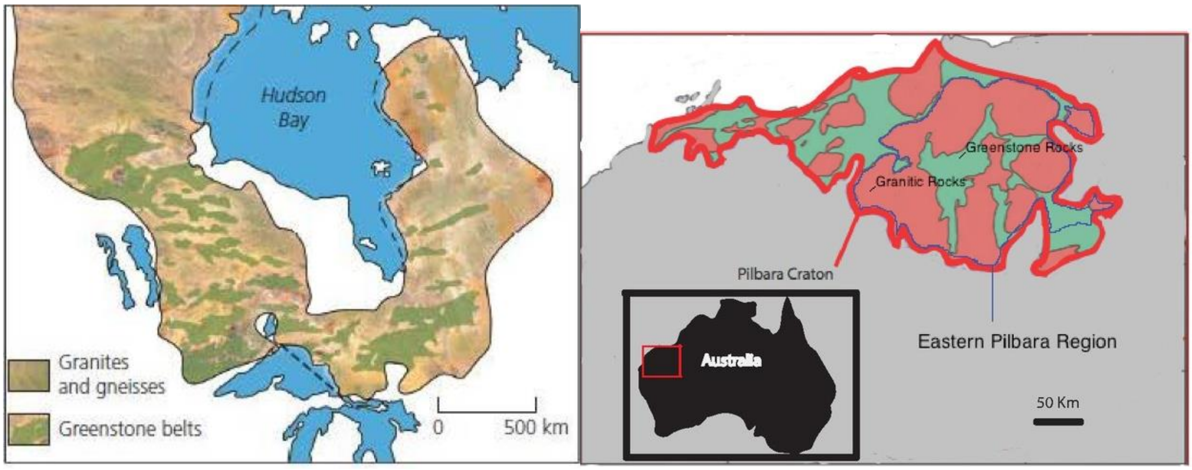

Fig. 13: Examples of greenstone belts in North America and Australia.

The protocontinents (Fig. 1B) were relatively thin, much smaller, and much hotter than today's true continents. The rocks at the surface came directly from the Earth's mantle (komatiites), and the rocks further down in the crust were under such high pressure and temperature that they underwent metamorphism.

These protoplates were not subject to plate tectonics in the modern sense, although they moved due to currents in the mantle. There may have been some small-scale versions of subduction zones, but the geochemical evidence suggests that they were not true subduction zones on the scale of those created by modern plate tectonics.

The proto-oceanic crust was much thinner and hotter and was formed from magmas erupting directly from the Earth's upper mantle, suggesting that the proto-plates moved much faster and were destroyed much more rapidly than plates today. The oceanic sediments were freshly eroded from the continents and dumped into the proto-oceanic basins as angular sands consisting of all sorts of unstable minerals and rock fragments and lots of mud, without being sorted out or recycled into younger sandstones. In addition, there were no limestones and almost no evaporites such as gypsum or halite, indicating conditions very unlike our modern sedimentary environments.

The Proterozoic and the origin of plate tectonics.

The Proterozoic is the third eon of the earth history and means translated "early time of the living beings". Strictly speaking, this term is no longer correct, because life already existed in the Archean, the origin of which we will deal with in another article.

The Proterozoic itself lasted about 2 billion years, almost half of the entire history of the Earth. Yet we cannot detail the entire 2-billion-year history of every continent during the Proterozoic, or record every complex event that occurred during that immense period. Instead, we will attempt to highlight some of the major trends that occurred between the Archean and the Cambrian.

In the Archean, we encounter unusual rocks such as the aforementioned greenstones and graywackes that formed in proto-oceans, and small gneissic continental crustal blocks that formed thin, hot protocontinents. In short, there were some similarities to modern plates and plate tectonics, but everything was hotter and thinner and moving much faster in a world of "proto-plate tectonics" (Fig. 1). However, as the Proterozoic transition began, we encounter rocks that could only be formed by the movement and collision of much thicker, cooler continental blocks and normal basaltic oceanic crust, so the transition to true plate tectonics began. At the end of the 2 billion years of the Proterozoic, the outcrops look like all other typical outcrops.

Due to intensive mantle circulation, plate tectonics and magma differentiation was very active and led to a rapid growth of the continental crust. The period from the younger Archean to the older Proterozoic is probably the main formation time for the crustal rocks. Due to rapid mantle convection, continental collisions formed large continents, possibly with pangaea phases, which subsequently disintegrated again. A major plate tectonic cycle, from the formation of a major continent, to its disintegration, to the re-formation of a major continent, is called a Wilson cycle and usually lasts about 500 million years (Fig. 14).

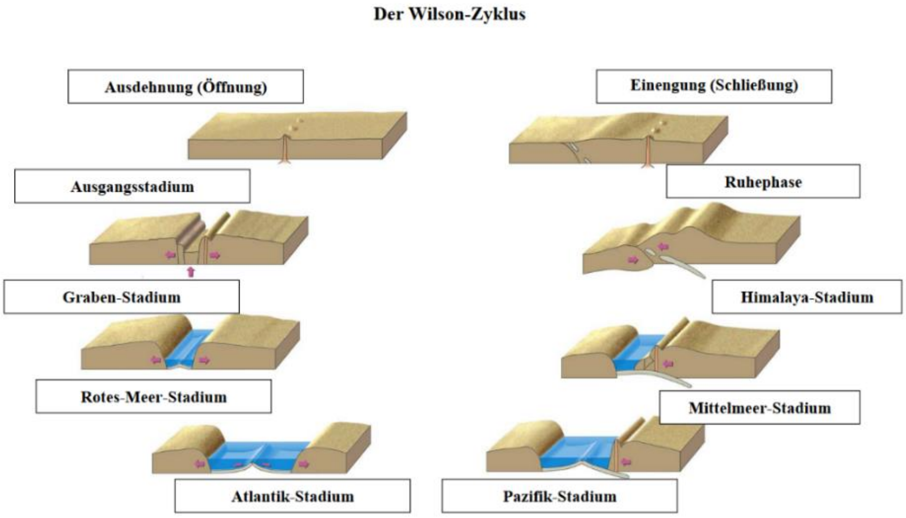

Fig. 14: Wilson cycle

The last major continent, Pangaea, which included all major continents and existed from the Late Carboniferous (325 million years before present) to the Jurassic (150 million years before present), is familiar to most and was verified by Alfred Wegener as an indication of continental movement. But also in the Archaic and Proterozoic large continents are postulated, but partly contradictory discussed. In view of the long duration of the Archean (1 .5 billion years) and the Proterozoic (2 billion years) it seems logical to assume multiple large continent formations with subsequent decay. These shall be presented briefly.

Examples of ancient cratons and first large continents

In today's continents numerous cores from the Eo- and Palaeoarchaic are preserved, the so-called cratons. They represent the oldest areas of continental crust, and are mostly present as highly metamorphic gneisses, e.g. the Acasta gneiss in northern Canada and the Amitsoq gneiss in Greenland. Some metasediments are intercalated in these gneisses, such as the Isua Gneiss with an age of about 3.8 billion years.

Large parts of North America were formed in the Archean and can be divided into four cratons, the Superior Craton, the Slave Craton, the Wyoming Craton, and the Nain Craton (Fig. 15). The four cratons were probably welded together by continent collisions with associated mountain building, orogeny, in the Neoarchaic. This led to the formation of the large continent Kenorland.

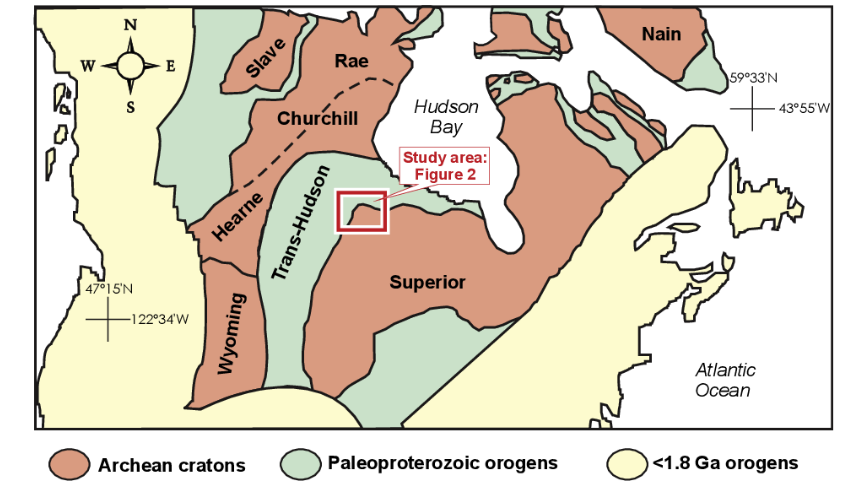

Fig. 15: Cratons of North America

Today's Africa is built up from several Archean cores, which were formed as small cratons in the Paleoarchaic to Mesoarchaic and were united only in the course of the late Proterozoic to a continent Africa within the large continent Gondwana (Fig. 16).

Fig. 16: Cratons of Africa

Australia also consists of very old cratons (Fig. 17). The best known are the Yilgarn craton in the southwest and the Pilbara craton in the northwest of the continent. The

Yilgarn craton consists of individual crustal blocks that grew together during the Neoarchaic. The Jack Hills zircons are from one of these crustal blocks. The Pilbara craton is about 3.5 Mia. years old and contains the oldest recorded life remains from the Warrawoona Group so far, in the form of stromatolites and silicified bacteria (Fig. 18).

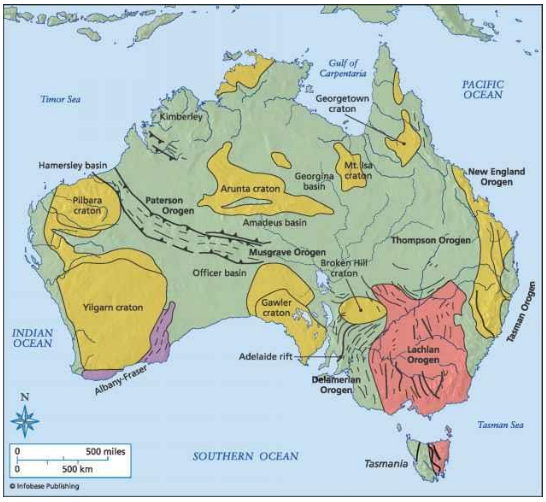

Fig. 17: Cratons of Australia

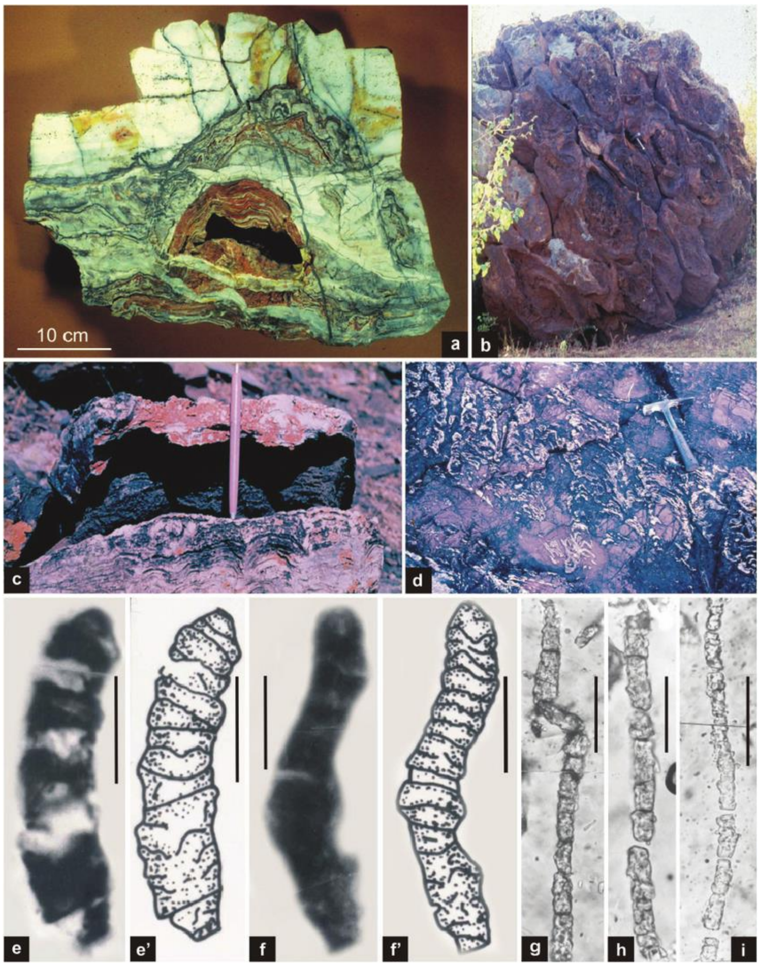

Fig. 18: The Pilbara craton is about 3.5 Mia. years old and contains the oldest recorded life remains from the Warrawoona Group so far.

Other areas with very old, archaic cratons are exposed in India, China, South America, Antarctica and northern Europe. As in North America, Africa and Australia, the ancient cores grew together to form larger continental areas only in the course of further Earth history.

Three major continents have been postulated for the Archean, but their existence is partly disputed:

Vaalbara (Fig. 19) is probably the oldest continent reconstructed so far. It is supposed to have existed about 3.2-2.8 Mia. years ago. Its existence is based on similarities of greenstone belts of this age from South Africa (Onverwacht Group of the Barberton Greenstone Belt) and Western Australia (Warrawoona Group in the Pilbara Greenstone Belt).

Fig. 19: The supercontinent Vaalbara is postulated based on the similarities of the greenstone belts from South Africa and Australia.

Ur (Fig. 20) is a large continent that may have existed 3-2.7 billion years ago. years ago. It consisted essentially of four major craton cores from South Africa (Kaapvaal craton), India (Singhbhum craton and Western Dharwar craton) and Australia (Pilbara craton).

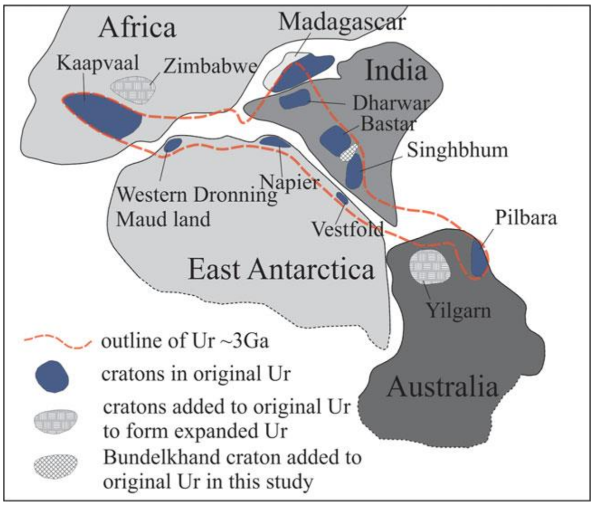

Fig. 20: The supercontinent Ur

Kenorland existed between 2.7-2.1 billion. years and possibly formed from the four Archean cratons of North America, which were welded together by the Kenora orogeny in the Neoarchean. Then Kenorland was probably merged with Siberia and Baltica, forming the large continent **Nena** (Northern Europe, Northern America) (Fig. 21).

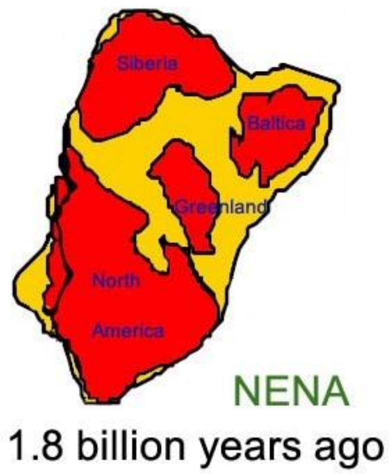

Abb. 21: The supercontinent Nena

At about the same time as the formation of Nena, the continent **Atlantica** was formed from West Africa and Amazonia (Fig. 22).

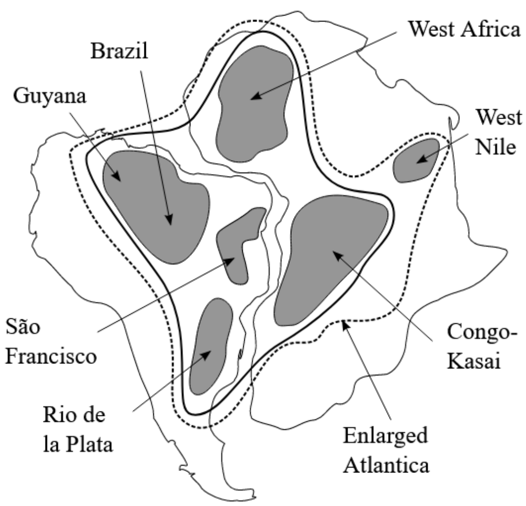

Fig. 22: Atlantica

Finally, the supercontinent **Columbia** or Nuna formed from Nena and Atlantica and other small continents in the younger Paleoproterozoic (Fig. 23). It existed about 1.8-1.5 billion years ago before it broke up again. Columbia broke up into several parts.

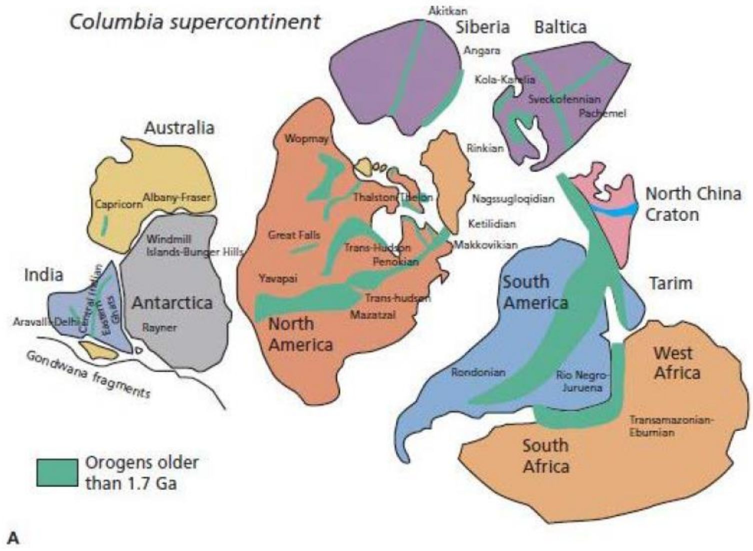

Fig. 23: Columbia

However, many of the continental blocks involved remained stable and merged again in a different configuration to form another supercontinent known as **Rodinia**, which was stable about 1.1-0.75 billion years ago (Fig. 24). Years ago was stable (Fig. 24). About 750 million years ago, the subsequent disintegration of Rodinia into several smaller continents began.

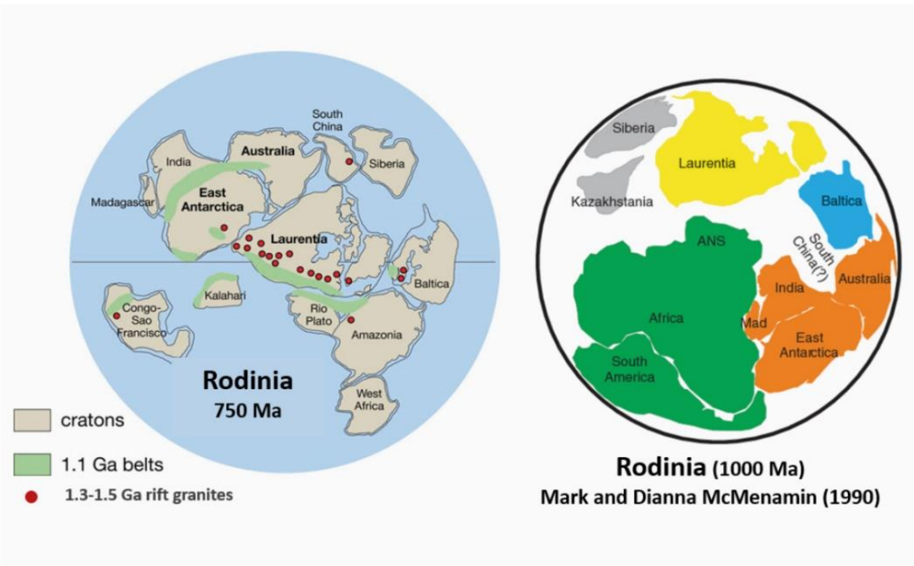

Fig. 24: Rodinia

About 600 million years ago, the short-lived supercontinent **Pannotia** formed (Fig. 25), which disintegrated again into the continents Gondwana, Laurentia, Baltica and Sibiria after only 50 million years. Alternatively, the fusion of East and West Gondwana is postulated, through which the large southern continent Gondwana was formed. It was composed of the continents South America, Africa, Australia, India and Antarctica.

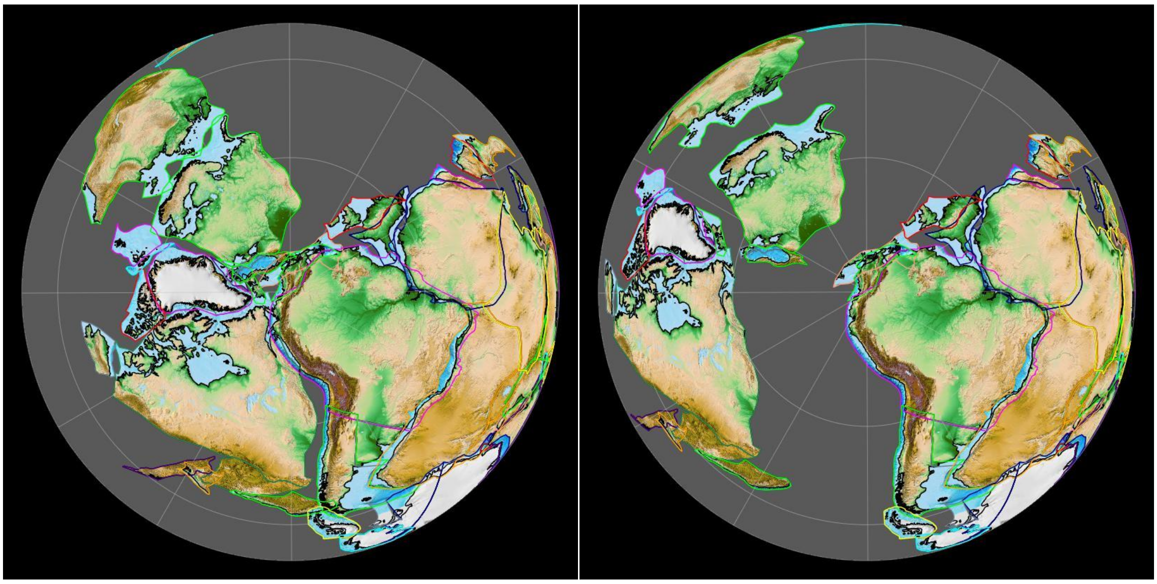

Fig. 25: Formation and breakup of the continent Pannotia

In the Carboniferous-Permian period, Gondwana then merged with the northern continents to form **Pangaea** (Fig. 26), whose breakup began in the Jurassic.

Fig. 26: Pangaea

The formation of the first continents had on the one hand influence on the development of life, but on the other hand also effects on the climate of the young earth. We will deal with these in the next article.

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