Geological History of Earth

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Geological History of Earth

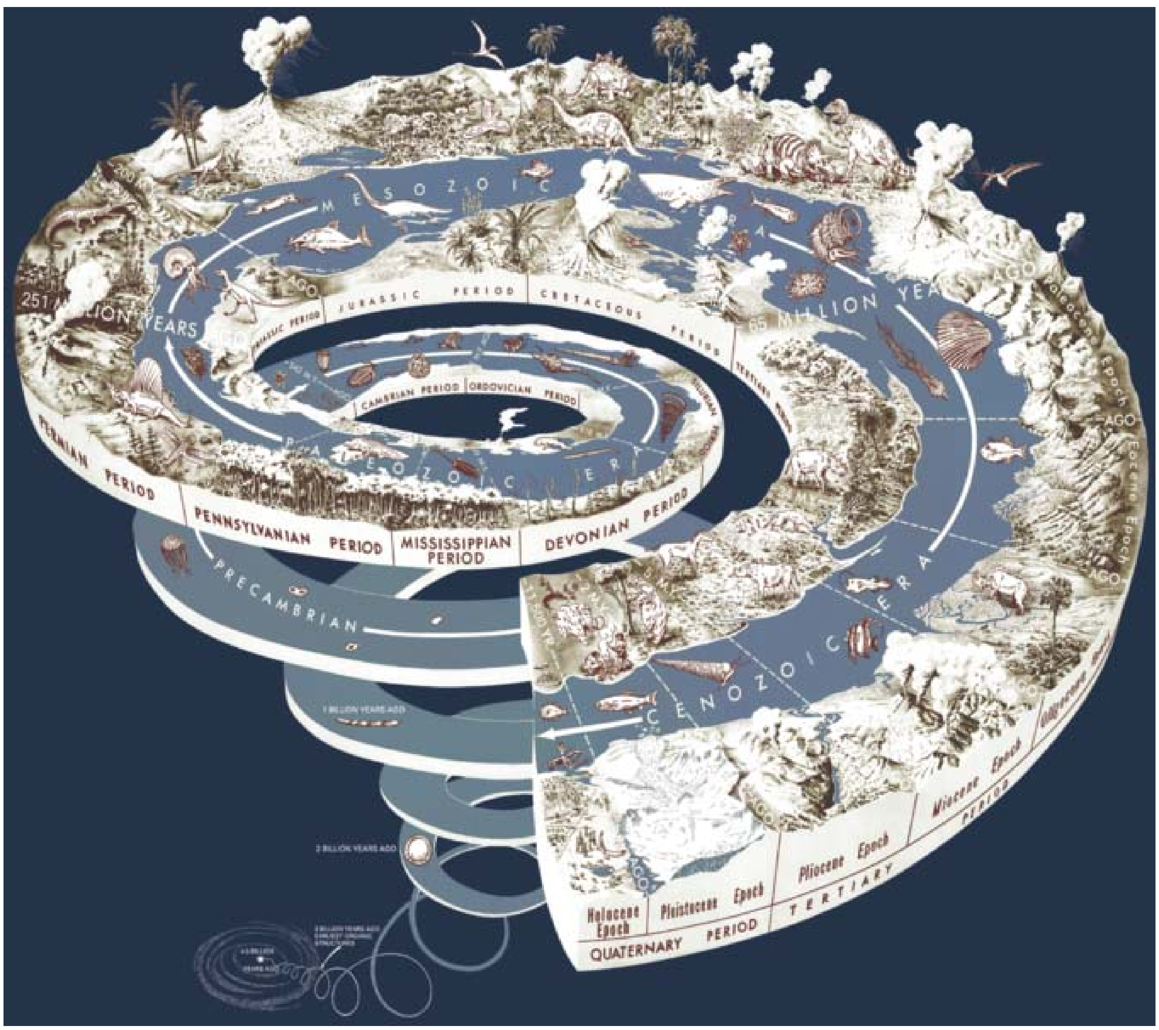


Diagram of geological time scale.

The **geological history of Earth** began 4.567 billion years ago when the planets of the Solar System were formed out of the solar nebula, a disk-shaped mass of dust and gas left over from the formation of the Sun. Initially molten, the outer layer of the planet Earth cooled to form a solid crust when water began accumulating in the atmosphere. The Moon formed soon afterwards, possibly as the result of a Mars-sized object with about 10% of the Earth's mass, known as Theia, impacting the Earth in a glancing blow. Some of this object's mass merged with the Earth and a portion was ejected into space, but enough material survived to form an orbiting moon.

Outgassing and volcanic activity produced the primordial atmosphere. Condensing water vapor, augmented by ice delivered by comets, produced the oceans.

As the surface continually reshaped itself over hundreds of millions of years, continents formed and broke up. The continents migrated across the surface, occasionally combining to form a supercontinent. Roughly 750 Ma (million years ago), the earliest-known supercontinent Rodinia, began to break apart. The continents later recombined to form Pannotia, 600–540 Ma, then finally Pangaea, which broke apart 180 Ma.

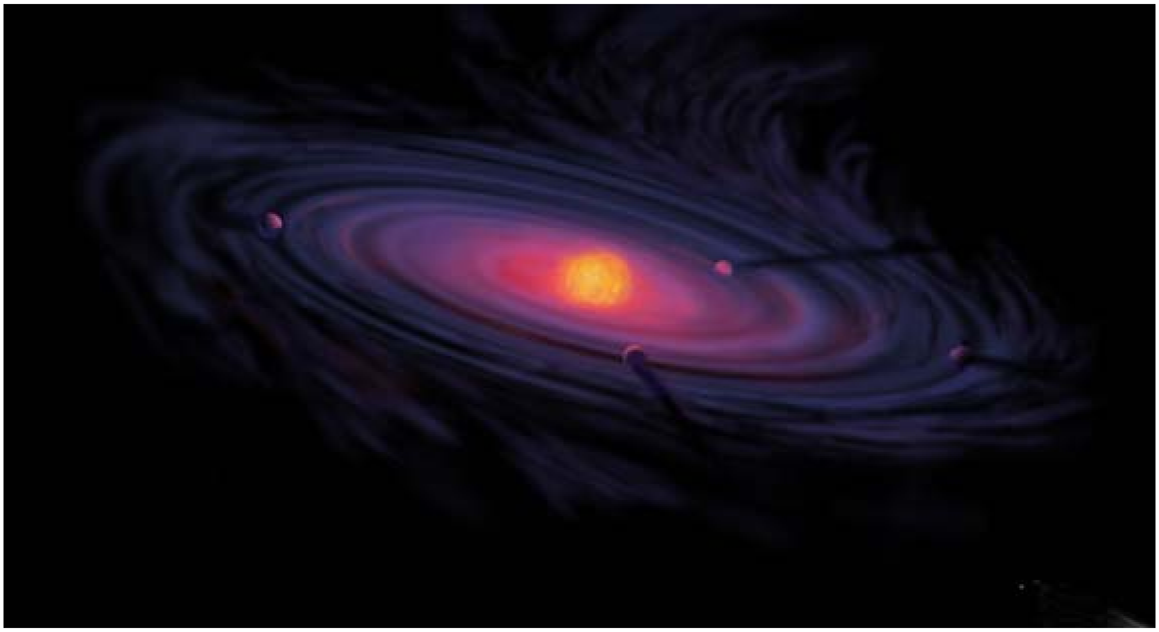
The present pattern of ice ages began about 40 Ma, then intensified during the Pleistocene about 3 Ma. The polar regions have since undergone repeated cycles of glaciation and thaw, repeating every 40,000–100,000 years. The last glacial period of the current ice age ended about 10,000 years ago.

The geological history of the Earth can be broadly classified into two periods: the Precambrian supereon and the Phanerozoic eon.

Precambrian

Precambrian includes approximately 90% of geologic time. It extends from 4.6 billion years ago to the beginning of the Cambrian Period (about 570 Ma). It includes three eons, the Hadean, Archean, and Proterozoic Eons.

Hadean Eon



Artist's conception of a protoplanetary disc.

During Hadean time (4.6–3.8 Ga), the Solar System was forming, probably within a large cloud of gas and dust around the sun, called an accretion disc. The Hadean Eon isn't formally recognized, but it essentially marks the era before there were any rocks. The oldest dated zircons date from about 4400 Ma (million years ago) - very close to the hypothesized time of the Earth's formation.

During the Hadean period the Late Heavy Bombardment occurred (approximately 3800 to 4100 Ma) during which a large number of impact craters are believed to have formed on the Moon, and by inference on Earth, Mercury, Venus and Mars as well.

Archean Eon

The Earth of the early Archean (3,800-2,500 Ma) may have had a different tectonic style. During this time, the Earth's crust cooled enough that rocks and continental plates began to form. Some scientists think because the Earth was hotter, that plate tectonic activity was more vigorous than it is today, resulting in a much greater rate of recycling of crustal material. This may have prevented cratonisation and continent formation until the mantle cooled and convection slowed down. Others argue that the subcontinental lithospheric mantle is too buoyant to subduct and that the lack of Archean rocks is a function of erosion and subsequent tectonic events.

In contrast to the Proterozoic, Archean rocks are often heavily-metamorphized deep-water sediments, such as graywackes, mudstones, volcanic sediments and banded iron formations. Greenstone belts are typical Archean formations, consisting of alternating high- and low-grade metamorphic rocks. The high-grade rocks were derived from volcanic island arcs, while the low-grade metamorphic rocks represent deep-sea sediments eroded from the neighboring island arcs and deposited in a forearc basin. In short, greenstone belts represent sutured protocontinents.

By 3.5 billion years ago, the Earth's magnetic field was established. The solar wind flux was about 100 times the value of the modern Sun, so the presence of the magnetic field helped prevent the planet's atmosphere from being stripped away, which is what likely happened to the atmosphere of Mars. However, the field strength was lower than at present and the magnetosphere was about half the modern radius.

Proterozoic Eon

The geologic record of the **Proterozoic** (2,500-570 Ma) is much better than that for the preceding Archean. In contrast to the deep-water deposits of the Archean, the Proterozoic features many strata that were laid down in extensive shallow epicontinental seas; furthermore, many of these rocks are less metamorphosed than Archean-age ones, and plenty are unaltered. Study of these rocks show that the eon featured massive, rapid continental accretion (unique to the Proterozoic), supercontinent cycles, and wholly-modern orogenic activity.

The first-known glaciations occurred during the Proterozoic, one began shortly after the beginning of the eon, while there were at least four during the Neoproterozoic, climaxing with the Snowball Earth of the Varangian glaciation.

Phanerozoic Eon

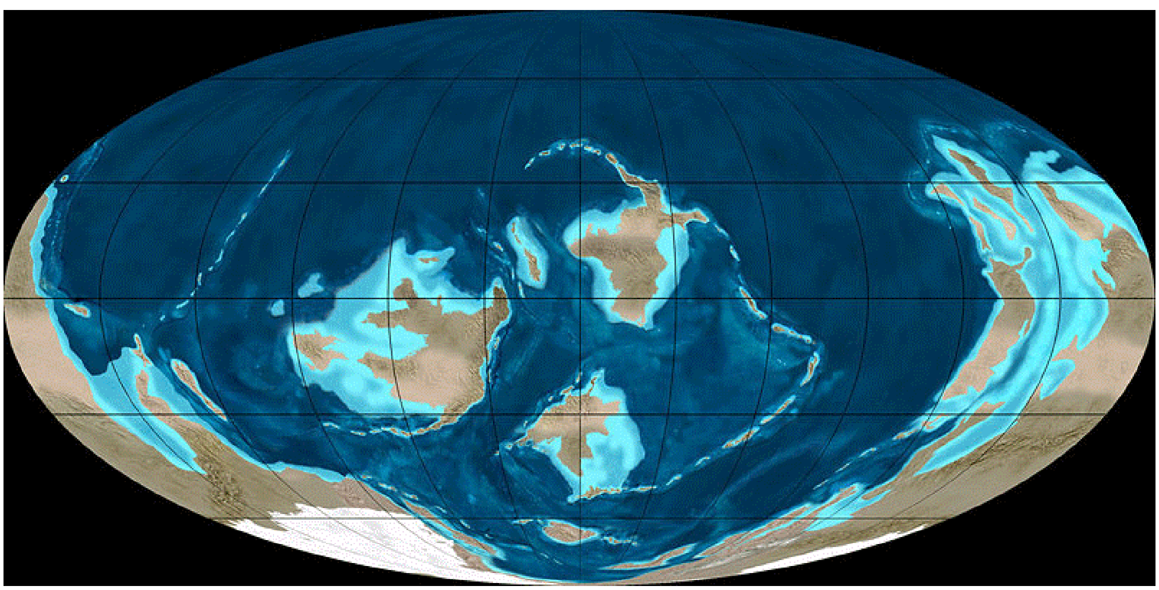


Image showing Earth's palaeogeographic reconstruction beginning from early Cambrian period.

The **Phanerozoic** Eon is the current eon in the geologic timescale. It covers roughly 545 million years. During this period continents drifted about, eventually collected into a single landmass known as Pangea and then split up into the current continental landmasses.

The Phanerozoic is divided into three eras — the Paleozoic, the Mesozoic and the Cenozoic.

Paleozoic Era

The **Paleozoic** spanned from roughly 542 Ma to roughly 251 Ma, and is subdivided into six geologic periods; from oldest to youngest they are the Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian. Geologically, the Paleozoic starts shortly after the breakup of a supercontinent called Pannotia and at the end of a global ice age. Throughout the early Paleozoic, the Earth's landmass was broken up into a substantial number of relatively small continents. Toward the end of the era the continents gathered together into a supercontinent called Pangaea, which included most of the Earth's land area.

Cambrian Period

The **Cambrian** is a major division of the geologic timescale that begins about 542 ± 1.0 Ma. Cambrian continents are thought to have resulted from the breakup of a Neoproterozoic supercontinent called Pannotia. The waters of the Cambrian period appear to have been widespread and shallow. Continental drift rates may have been anomalously high. Laurentia, Baltica and Siberia remained independent continents following the break-up of the supercontinent of Pannotia. Gondwana started to drift toward the South Pole. Panthalassa covered most of the southern hemisphere, and minor oceans included the Proto-Tethys Ocean, Iapetus Ocean and Khanty Ocean.

Ordovician Period

The **Ordovician** Period started at a major extinction event called the Cambrian-Ordovician extinction events some time about 488.3 ± 1.7 Ma. During the Ordovician the southern continents were collected into a single continent called Gondwana. Gondwana started the period in the equatorial latitudes and, as the period progressed, drifted toward the South Pole. Early in the Ordovician the continents Laurentia, Siberia and Baltica were still independent continents (since the break-up of the supercontinent Pannotia earlier), but Baltica began to move toward Laurentia later in the period, causing the Iapetus Ocean to shrink between them. Also, Avalonia broke free from Gondwana and began to head north toward Laurentia. The Rheic Ocean was formed as a result of this. By the end of the period, Gondwana had neared or approached the pole and was largely glaciated.

The Ordovician came to a close in a series of extinction events that, taken together, comprise the second-largest of the five major extinction events in Earth's history in terms of percentage of genera that went extinct. The only larger one was the Permian-Triassic extinction event. The extinctions occurred approximately 444-447 Ma and mark the boundary between the Ordovician and the following Silurian Period.

The most-commonly accepted theory is that these events were triggered by the onset of an ice age, in the Hirnantian faunal stage that ended the long, stable greenhouse conditions typical of the Ordovician. The ice age was probably not as long-lasting as once thought; study of oxygen isotopes in fossil brachiopods shows that it was probably no longer than 0.5 to 1.5 million years. The event was preceded by a fall in atmospheric carbon dioxide (from 7000ppm to 4400ppm) which selectively affected the shallow seas where most organisms lived. As the southern supercontinent Gondwana drifted over the South Pole, ice caps formed on it. Evidence of these ice caps have been detected in Upper Ordovician rock strata of North Africa and then-adjacent northeastern South America, which were south-polar locations at the time.

Silurian Period

The **Silurian** is a major division of the geologic timescale that started about 443.7 ± 1.5 Ma. During the Silurian, Gondwana continued a slow southward drift to high southern latitudes, but there is evidence that the Silurian ice caps were less extensive than those of the late Ordovician glaciation. The melting of ice caps and glaciers contributed to a rise in sea levels, recognizable from the fact that Silurian sediments overlie eroded Ordovician sediments, forming an unconformity. Other cratons and continent fragments drifted together near the equator, starting the formation of a second supercontinent known as Euramerica. The vast ocean of Panthalassa covered most of the northern hemisphere. Other minor oceans include Proto-Tethys, Paleo-Tethys, Rheic Ocean, a seaway of Iapetus Ocean (now in between Avalonia and Laurentia), and newly-formed Ural Ocean.

Devonian Period

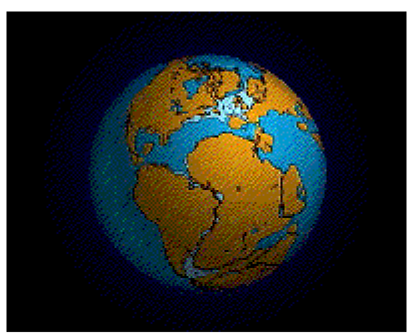
The **Devonian** spanned roughly from 416 to 359 Ma. The period was a time of great tectonic activity, as Laurasia and Gondwanaland drew closer together. The continent Euramerica (or Laurussia) was created in the early Devonian by the collision of Laurentia and Baltica, which rotated into the natural dry zone along the Tropic of Capricorn. In these near-deserts, the Old Red Sandstone sedimentary beds formed, made red by the oxidized iron (hematite) characteristic of drought conditions. Near the equator Pangaea began to consolidate from the plates containing North America and Europe, further raising the northern Appalachian Mountains and forming the Caledonian Mountains in Great Britain and Scandinavia. The southern continents remained tied together in the supercontinent of Gondwana. The remainder of modern Eurasia lay in the Northern Hemisphere. Sea levels were high worldwide, and much of the land lay submerged under shallow seas. The deep, enormous Panthalassa (the "universal ocean") covered the rest of the planet. Other minor oceans were Paleo-Tethys, Proto-Tethys, Rheic Ocean and Ural Ocean (which was closed during the collision with Siberia and Baltica).

Carboniferous Period

The **Carboniferous** extends from about 359.2 ± 2.5 Ma to about 299.0 ± 0.8 Ma.

A global drop in sea level at the end of the Devonian reversed early in the Carboniferous; this created the widespread epicontinental seas and carbonate deposition of the Mississippian. There was also a drop in south polar temperatures; southern Gondwanaland was glaciated throughout the period, though it is uncertain if the ice sheets were a holdover from the Devonian or not. These conditions apparently had little effect in the deep tropics, where lush coal swamps flourished within 30 degrees of the northernmost glaciers. A mid-Carboniferous drop in sea-level precipitated a major marine extinction, one that hit crinoids and ammonites especially hard. This sea-level drop and the associated unconformity in North America separate the Mississippian Period from the Pennsylvanian period.

The Carboniferous was a time of active mountain building, as the supercontinent Pangea came together. The southern continents remained tied together in the supercontinent Gondwana, which collided with North America-Europe (Laurussia) along the present line of eastern North America. This continental collision resulted in the Hercynian orogeny in Europe, and the Alleghenian orogeny in North America; it also extended the newly-uplifted Appalachians southwestward as the Ouachita Mountains. In the same time frame, much of present eastern Eurasian plate welded itself to Europe along the line of the Ural mountains. There were two major oceans in the Carboniferous the Panthalassa and Paleo-Tethys. Other minor oceans were shrinking and eventually closed the Rheic Ocean (closed by the assembly of South and North America), the small, shallow Ural Ocean (which was closed by the collision of Baltica, and Siberia continents, creating the Ural Mountains) and Proto-Tethys Ocean.



Pangaea separation animation.

Permian Period

The **Permian** extends from about 299.0 ± 0.8 Ma to 251.0 ± 0.4 Ma.

During the Permian all the Earth's major land masses, except portions of East Asia, were collected into a single supercontinent known as Pangaea. Pangaea straddled the equator and extended toward the poles, with a corresponding effect on ocean currents in the single great ocean (*Panthalassa*, the *universal sea*), and the Paleo-Tethys Ocean, a large ocean that was between Asia and Gondwana. The Cimmeria continent rifted away from

Gondwana and drifted north to Laurasia, causing the Paleo-Tethys to shrink. A new ocean was growing on its southern end, the Tethys Ocean, an ocean that would dominate much of the Mesozoic Era. Large continental landmasses create climates with extreme variations of heat and cold ("continental climate") and monsoon conditions with highly seasonal rainfall patterns. Deserts seem to have been widespread on Pangaea.

Mesozoic Era

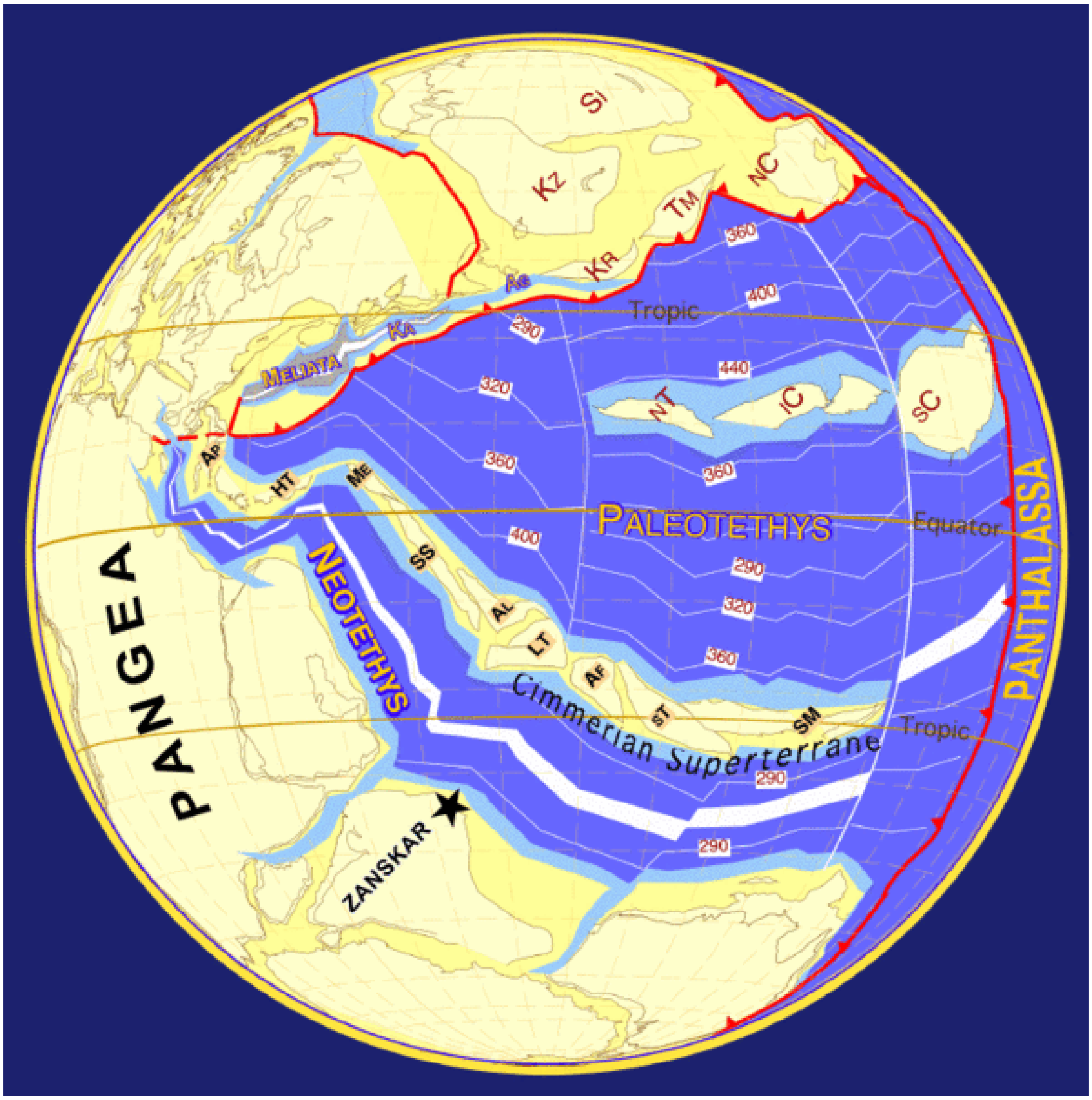


Plate tectonics- 249 MA (million years ago)

Plate tectonics- 290 MA (million years ago)

The **Mesozoic** extended roughly from 251 Ma to 65 Ma.

After the vigorous convergent plate mountain-building of the late Paleozoic, Mesozoic tectonic deformation was comparatively mild. Nevertheless, the era featured the dramatic rifting of the supercontinent Pangaea. Pangaea gradually split into a northern continent, Laurasia, and a southern continent, Gondwana. This created the passive continental margin that characterizes most of the Atlantic coastline (such as along the U.S. East Coast) today.

Triassic Period

The **Triassic** Period extends from about 251 ± 0.4 to 199.6 ± 0.6 Ma. During the Triassic, almost all the Earth's land mass was concentrated into a single supercontinent centered more or less on the equator, called Pangaea ("all the land"). This took the form of a giant "Pac-Man" with an east-facing "mouth" constituting the Tethys sea, a vast gulf that opened farther westward in the mid-Triassic, at the expense of the shrinking Paleo-Tethys Ocean, an ocean that existed during the Paleozoic.

The remainder was the world-ocean known as Panthalassa ("all the sea"). All the deep-ocean sediments laid down during the Triassic have disappeared through subduction of oceanic plates; thus, very little is known of the Triassic open ocean. The supercontinent Pangaea was rifting during the Triassic—especially late in the period—but had not yet separated. The first nonmarine sediments in the rift that marks the initial break-up of Pangea—which separated New Jersey from Morocco—are of Late Triassic age; in the U.S., these thick sediments comprise the Newark Supergroup. Because of the limited shoreline of one super-continental mass, Triassic marine deposits are globally relatively rare; despite their prominence in Western Europe, where the Triassic was first studied. In North America, for example, marine deposits are limited to a few exposures in the west. Thus Triassic stratigraphy is mostly based on organisms living in lagoons and hypersaline environments, such as *Estheria* crustaceans and terrestrial vertebrates.

Jurassic Period

The **Jurassic** Period extends from about 199.6 ± 0.6 Ma to 145.4 ± 4.0 Ma. During the early Jurassic, the supercontinent Pangaea broke up into the northern supercontinent Laurasia and the southern supercontinent Gondwana; the Gulf of Mexico opened in the new rift between North America and what is now Mexico's Yucatan Peninsula. The Jurassic North Atlantic Ocean was relatively narrow, while the South Atlantic did not open until the following Cretaceous Period, when Gondwana itself rifted apart. The Tethys Sea closed, and the Neotethys basin appeared. Climates were warm, with no evidence of glaciation. As in the Triassic, there was apparently no land near either pole, and no extensive ice caps existed. The Jurassic geological record is good in western Europe, where extensive marine sequences indicate a time when much of the continent was submerged under shallow tropical seas; famous locales include the Jurassic Coast World Heritage Site and the renowned late Jurassic *lagerstätten* of Holzmaden and Solnhofen. In contrast, the North American Jurassic record is the poorest of the Mesozoic, with few outcrops at the surface. Though the epicontinental Sundance Sea left marine deposits in parts of the northern plains of the United States and Canada during the late Jurassic, most exposed sediments from this period are continental, such as the alluvial deposits of the Morrison Formation. The first of several massive batholiths were emplaced in the northern Cordillera beginning in the mid-Jurassic, marking the Nevadan orogeny. Important Jurassic exposures are also found in Russia, India, South America, Japan, Australasia and the United Kingdom.

Cretaceous Period

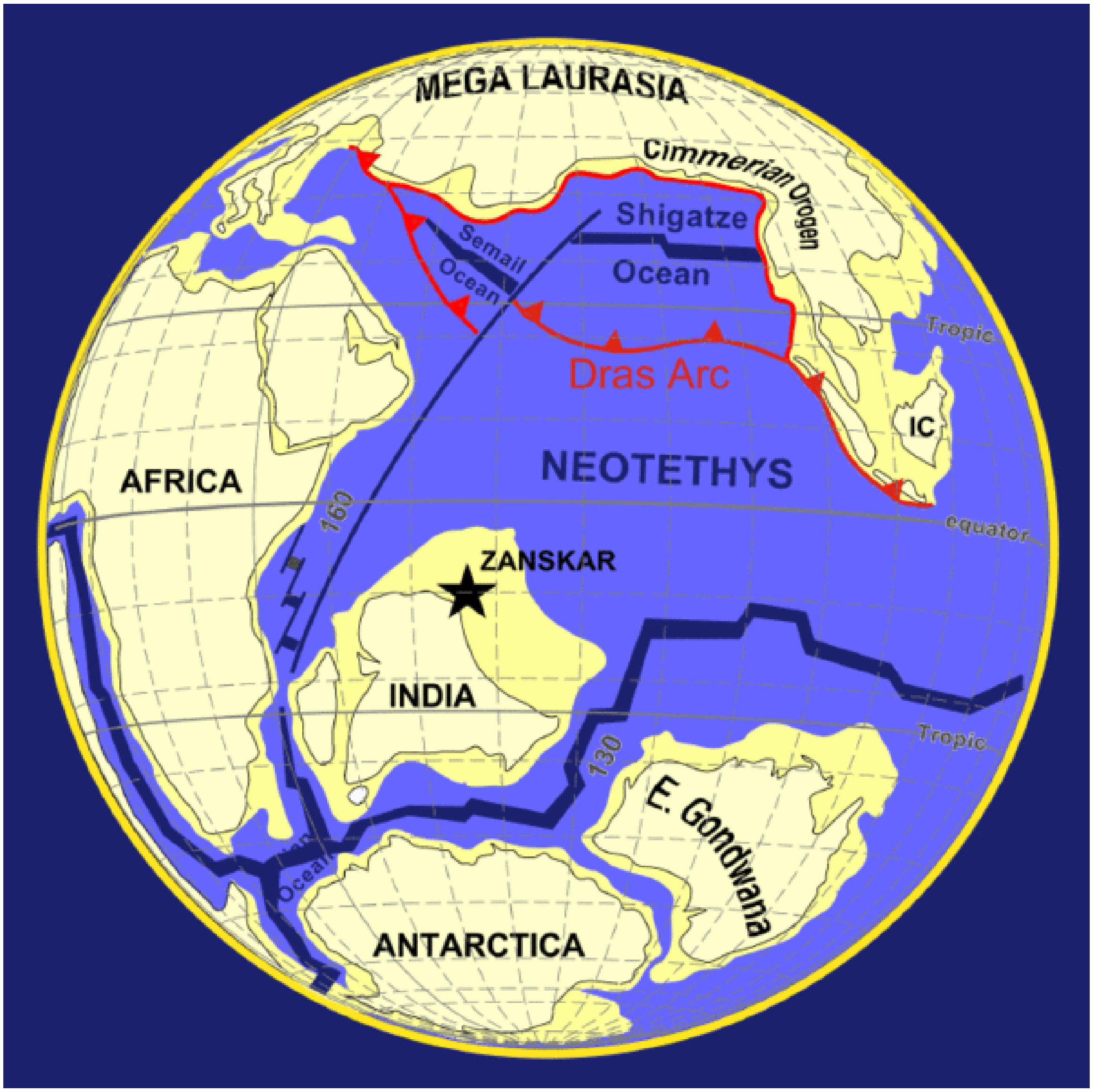


Plate tectonics- 100 Ma , Cretaceous period

The **Cretaceous** Period extends from about 145.5 ± 4.0 Ma to about 65.5 ± 0.3 Ma.

During the Cretaceous, the late Paleozoic-early Mesozoic supercontinent of Pangaea completed its breakup into present day continents, although their positions were substantially different at the time. As the Atlantic Ocean widened, the convergent-margin orogenies that had begun during the Jurassic continued in the North American Cordillera, as the Nevadan orogeny was followed by the Sevier and Laramide orogenies. Though Gondwana was still intact in the beginning of the Cretaceous, Gondwana itself broke up as South America, Antarctica and Australia rifted away from Africa (though India and Madagascar remained attached to each other); thus, the South Atlantic and Indian Oceans were newly formed. Such active rifting lifted great undersea mountain chains along the welts, raising eustatic sea levels worldwide.

To the north of Africa the Tethys Sea continued to narrow. Broad shallow seas advanced across central North America (the Western Interior Seaway) and Europe, then receded late in the period, leaving thick marine deposits sandwiched between coal beds. At the peak of the Cretaceous transgression, one-third of Earth's present land area was submerged. The Cretaceous is justly famous for its chalk; indeed, more chalk formed in the Cretaceous than in any other period in the Phanerozoic. Mid-ocean ridge activity—or rather, the circulation of seawater through the enlarged ridges—enriched the oceans in calcium; this made the oceans more saturated, as well as increased the bioavailability of the element for calcareous nanoplankton. These widespread carbonates and other sedimentary deposits make the Cretaceous rock record especially fine. Famous formations from North America include the rich marine fossils of Kansas's Smoky Hill Chalk Member and the terrestrial fauna of the late Cretaceous Hell Creek Formation. Other important Cretaceous exposures occur in Europe and China. In the area that is now India, massive lava beds called the Deccan Traps were laid down in the very late Cretaceous and early Paleocene.

Cenozoic Era

The **Cenozoic** Era covers the 65.5 million years since the Cretaceous-Tertiary extinction event. The Cenozoic era is ongoing. By the end of the Mesozoic era, the continents had rifted into nearly their present form. Laurasia became North America and Eurasia, while Gondwana split into South America, Africa, Australia, Antarctica and the Indian subcontinent, which collided with the Asian plate. This impact gave rise to the Himalayas. The Tethys Sea, which had separated the northern continents from Africa and India, began to close up, forming the Mediterranean sea.

Paleogene Period

The **Paleogene** (alternatively **Palaeogene**) Period is a unit of geologic time that began 65.5 ± 0.3 and ended 23.03 ± 0.05 Ma and comprises the first part of the Cenozoic Era. This period consists of the Paleocene, Eocene and Oligocene Epochs.

Paleocene Epoch

The **Paleocene**, lasted from 65.5 ± 0.3 Ma to 55.8 ± 0.2 Ma.

In many ways, the Paleocene continued processes that had begun during the late Cretaceous Period. During the Paleocene, the continents continued to drift toward their present positions. Supercontinent Laurasia had not yet separated into three continents. Europe and Greenland were still connected. North America and Asia were still intermittently joined by a land bridge, while Greenland and North America were beginning to separate. The Laramide orogeny of the late Cretaceous continued to uplift the Rocky Mountains in the American west, which ended in the succeeding epoch. South and North America remained separated by equatorial seas (they joined during the Neogene); the components of the former southern supercontinent Gondwanaland continued to split apart, with Africa, South America, Antarctica and Australia pulling away from each other. Africa was heading north toward Europe, slowly closing the Tethys Ocean, and India began its migration to Asia that would lead to a tectonic collision and the formation of the Himalayas.

Eocene Epoch

During the **Eocene** (55.8 ± 0.2 - 33.9 ± 0.1 Ma,) the continents continued to drift toward their present positions. At the beginning of the period, Australia and Antarctica remained connected, and warm equatorial currents mixed with colder Antarctic waters, distributing the heat around the world and keeping global temperatures high. But when Australia split from the southern continent around 45 Ma, the warm equatorial currents were deflected away from Antarctica, and an isolated cold water channel developed between the two continents. The Antarctic region cooled down, and the ocean surrounding Antarctica began to freeze, sending cold water and ice floes north, reinforcing the cooling. The northern supercontinent of Laurasia began to break up, as Europe, Greenland and North America drifted apart. In western North America, mountain building started in the Eocene, and huge lakes formed in the high flat basins among uplifts. In Europe, the Tethys Sea finally vanished, while the uplift of the Alps isolated its final remnant, the Mediterranean, and created another shallow sea with island archipelagos to the north. Though the North Atlantic was opening, a land connection appears to have remained between North America and Europe since the faunas of the two regions are very similar. India continued its journey away from Africa and began its collision with Asia, creating the Himalayan orogeny.

Oligocene Epoch

The **Oligocene** Epoch extends from about 34 Ma to 23 Ma. During the Oligocene the continents continued to drift toward their present positions.

Antarctica continued to become more isolated and finally developed a permanent ice cap. Mountain building in western North America continued, and the Alps started to rise in Europe as the African plate continued to push north into the Eurasian plate, isolating the remnants of Tethys Sea. A brief marine incursion marks the early Oligocene in Europe. There appears to have been a land bridge in the early Oligocene between North America and Europe since the faunas of the two regions are very similar. During the Oligocene, South America was finally detached from Antarctica and drifted north toward North America. It also allowed the Antarctic Circumpolar Current to flow, rapidly cooling the continent.

Neogene Period

Neogene Period is a unit of geologic time starting 23.03 ± 0.05 Ma. The Neogene Period follows the Paleogene Period. Under the current proposal of the International Commission on Stratigraphy (ICS), the Neogene would consist of the Miocene, Pliocene, Pleistocene and Holocene epochs and continue until the present.

Miocene Epoch

The **Miocene** extends from about 23.03 to 5.332 Ma.

During the Miocene continents continued to drift toward their present positions. Of the modern geologic features, only the land bridge between South America and North America was absent, the subduction zone along the Pacific Ocean margin of South America caused the rise of the Andes and the southward extension of the Meso-American peninsula. India continued to collide with Asia. The Tethys Seaway continued to shrink and then disappeared as Africa collided with Eurasia in the Turkish-Arabian region between 19 and 12 Ma (ICS 2004). Subsequent uplift of mountains in the western Mediterranean region and a global fall in sea levels combined to cause a temporary drying up of the Mediterranean Sea resulting in the Messinian salinity crisis near the end of the Miocene.

Pliocene Epoch

The **Pliocene** extends from 5.332 Ma to 2.588 Ma. During the Pliocene continents continued to drift toward their present positions, moving from positions possibly as far as 250 kilometres (155 mi) from their present locations to positions only 70 km from their current locations.

South America became linked to North America through the Isthmus of Panama during the Pliocene, bringing a nearly-complete end to South America's distinctive marsupial faunas. The formation of the Isthmus had major consequences on global temperatures, since warm equatorial ocean currents were cut off and an Atlantic cooling cycle began, with cold Arctic and Antarctic waters dropping temperatures in the now-isolated Atlantic Ocean. Africa's collision with Europe formed the Mediterranean Sea, cutting off the remnants of the Tethys Ocean. Sea level changes exposed the land-bridge between Alaska and Asia. Near the end of the Pliocene, about 2.58 Ma (the start the of the Quaternary Period), the current ice age began.

Pleistocene Epoch

The **Pleistocene** extends from 2.588 million to 11,700 years before present. The modern continents were essentially at their present positions during the Pleistocene, the plates upon which they sit probably having moved no more than 100 kilometres (62 mi) relative to each other since the beginning of the period.

Holocene Epoch

The **Holocene** Epoch began approximately 11,550 calendar years before present and continues to the present. During the Holocene, continental motions have been less than a kilometer.

However, ice melt caused world sea levels to rise about 35 metres (115 ft) in the early part of the Holocene. In addition, many areas above about 40 degrees north latitude had been depressed by the weight of the Pleistocene glaciers and rose as much as 180 metres (591 ft) over the late Pleistocene and Holocene, and are still rising today. The sea level rise and temporary land depression allowed temporary marine incursions into areas that are now far from the sea. Holocene marine fossils are known from Vermont, Quebec, Ontario and Michigan. Other than higher latitude temporary marine incursions associated with glacial depression, Holocene fossils are found primarily in lakebed, floodplain and cave deposits. Holocene marine deposits along low-latitude coastlines are rare because the rise in sea levels during the period exceeds any likely upthrusting of non-glacial origin. Post-glacial rebound in Scandinavia resulted in the emergence of coastal areas around the Baltic Sea, including much of Finland. The region continues to rise, still causing weak earthquakes across Northern Europe. The equivalent event in North America was the rebound of Hudson Bay, as it shrank from its larger, immediate post-glacial Tyrrell Sea phase, to near its present boundaries.

Chapter- 2

Precambrian

The **Precambrian** (Pre-Cambrian) is an informal name for the span of time before the current *Phanerozoic* Eon, and is divided into several eons of the geologic time scale. It spans from the formation of Earth around 4600 Ma (million years ago) to the beginning of the Cambrian Period, about 542 Ma, when macroscopic hard-shelled animals first appeared in abundance. The Precambrian is so named because it precedes the Cambrian, the first period of the Phanerozoic Eon, which is named after the classical name for Wales, *Cambria*, where rocks from this age were first studied. The Precambrian accounts for 85% of geologic time.

Overview

Very little is known about the Precambrian, despite it making up roughly seven-eighths of the Earth's history, and what little is known has largely been discovered in the past fifty years. The Precambrian fossil record is poor, and those fossils present (e.g. stromatolites) are of limited biostratigraphic use. Many Precambrian rocks are heavily metamorphosed, obscuring their origins, while others have either been destroyed by erosion, or remain deeply buried beneath Phanerozoic strata.

It is thought that the Earth itself coalesced from material in orbit around the Sun roughly 4500 Ma and may have been struck by a very large (Mars-sized) planetesimal shortly after it formed, splitting off material that came together to form the Moon. A stable crust was apparently in place by 4400 Ma, since zircon crystals from Western Australia have been dated at 4404 Ma.

The term *Precambrian* is somewhat out-moded, but is still in common use among geologists and paleontologists. It was briefly also called the **Cryptozoic** eon.

Life before the Cambrian

It is not known when life originated, but carbon in 3.8 billion year old rocks from islands off western Greenland may be of organic origin. Well-preserved bacteria older than 3.46 billion years have been found in Western Australia. Probable fossils 100 million years older have been found in the same area. There is a fairly solid record of bacterial life throughout the remainder of the Precambrian.

Excepting a few contested reports of much older forms from USA and India, the first complex multicelled life forms seem to have appeared roughly 600 Ma. A quite diverse collection of soft-bodied forms is known from a variety of locations worldwide between 542 and 600 Ma. These are referred to as *Ediacaran or Vendian biota*. Hard-shelled creatures appeared toward the end of that timespan.

A very diverse collection of forms appeared around 544 Ma, starting in the latest Precambrian with a poorly understood *small shelly fauna* and ending in the very early Cambrian with a very diverse, and quite modern *Burgess fauna*, the rapid radiation of forms called the *Cambrian explosion* of life.

Planetary environment and the oxygen catastrophe

Weathered Precambrian pillow lava in the Temagami greenstone belt of the Canadian Shield

Details of plate motions and other tectonic functions are only hazily known in the Precambrian. It is generally believed that small proto-continents existed prior to 3000

Ma, and that most of the Earth's landmasses collected into a single supercontinent around 1000 Ma. The supercontinent, known as Rodinia, broke up around 600 Ma. A number of glacial periods have been identified going as far back as the Huronian epoch, roughly 2200 Ma. The best studied is the Sturtian-Varangian glaciation, around 600 Ma, which may have brought glacial conditions all the way to the equator, resulting in a "Snowball Earth".

The atmosphere of the early Earth is poorly known, but it is thought to have been smothered in reducing gases, containing very little free oxygen. The oxygen free early atmosphere has been disputed with evidence supporting an oxygenic atmosphere since the early Archean.

When evolving life forms developed photosynthesis, molecular oxygen began to be produced in large quantities, causing an ecological crisis sometimes called the oxygen catastrophe. The oxygen was immediately tied up in chemical reactions, primarily with iron, until the supply of oxidizable surfaces ran out. After that the modern high-oxygen atmosphere developed. Older rocks contain massive banded iron formations that were apparently laid down as iron and oxygen first combined.

Subdivisions

An established terminology has evolved covering the early years of the Earth's existence, as radiometric dating allows plausible real dates to be assigned to specific formations and features. The Precambrian Supereon is divided into three Precambrian eons: the Hadean (4500-3950 Ma), Archean (3950-2500 Ma), and Proterozoic (2500-542 Ma).

- Proterozoic: this eon refers to the time from the lower Cambrian boundary, 542 Ma, back through 2500 Ma. The boundary has been placed at various times by various authors, but has now been settled at 542 Ma. As originally used, it was a synonym for "Precambrian" and hence included everything prior to the Cambrian boundary. The Proterozoic eon is divided into three eras: the Neoproterozoic, Mesoproterozoic, and Paleoproterozoic.
    - Neoproterozoic: The upper (i.e., youngest) geologic era of the Proterozoic eon, from the Cambrian period lower boundary (542 Ma) back to 1000 Ma. The Neoproterozoic corresponds to *Precambrian Z* rocks of older North American geology.
        - Ediacaran: The upper (youngest) geologic period within the Neoproterozoic Era. The "2009 GSA Geologic Time Scale" dates it from 630-542 Ma. (542 Ma is the beginning of the Cambrian period, the earliest period of the Paleozoic Era.) In this period the Ediacaran fauna appeared.
        - Cryogenian: The middle period in the Neoproterozoic Era: 950-630 Ma.
        - Tonian: the earliest period of the Neoproterozoic Era: 1000-950 Ma.

    - Mesoproterozoic: the middle era of the Proterozoic Eon, 1000-1600 Ma. Corresponds to "Precambrian Y" rocks of older North American geology.
    - Paleoproterozoic: oldest era of the Proterozoic Eon, 1600-2500 Ma. Corresponds to "Precambrian X" rocks of older North American geology.
- Archaean Eon: 2500-3800 Ma.
- Hadean Eon: 3950-4500 Ma. This term was intended originally to cover the time before any preserved rocks were deposited, although some zircon crystals from about 4400 Ma demonstrate the existence of crust in the Hadean Eon. Other records from Hadean time come from the moon and meteorites.

It has been proposed that the Precambrian should be divided into eons and eras that reflect stages of planetary evolution, rather than the current scheme based upon numerical ages. Such a system could rely on events in the stratigraphic record and be demarcated by GSSPs. The Precambrian could be divided into five "natural" eons, characterized as follows.

1. Accretion and differentiation: a period of planetary formation until giant Moon-forming impact event.
2. Hadean: dominated by heavy bombardment from about 4.51, (possibly including a Cool Early Earth period) to the end of the Late Heavy Bombardment period.
3. Archean: a period defined by the first crustal formations (the Isua greenstone belt) until the deposition of banded iron formations due to increasing atmospheric oxygen content.
4. Transition: a period of continued iron banded formation until the first continental red beds.
5. Proterozoic: a period of modern plate tectonics until the first animals.

Chapter- 3

Hadean

The **Hadean** is the geologic eon before the Archean. It started at Earth's formation about 4.6 billion years ago (4,600 Ma), and ended roughly 3.8 billion years ago, though the latter date varies according to different sources. The name "Hadean" derives from Hades, Greek for "Underworld", referring to the conditions on Earth at the time. The geologist Preston Cloud coined the term in 1972, originally to label the period before the earliest-known rocks. W. Brian Harland later coined an almost synonymous term: the "**Priscoan period**". Other older texts simply refer to the eon as the **Pre-Archean**.

Subdivisions

Since few geological traces of this period remain on Earth there are no official subdivisions. However, several major divisions of the Lunar geologic timescale occurred during the Hadean, and so these are sometimes used unofficially to refer to the same periods of time on Earth.

The Lunar divisions are:

- Pre-Nectarian, from the formation of the Moon's crust up to about 3920 Ma
- Nectarian ranging up to about 3850 Ma, in a time when the Late Heavy Bombardment, according to that theory, was in a stage of decline.

Hadean Eon			
The Hadean is not formally recognized by the International Commission on Stratigraphy. The following subdivisions represent one proposal that is loosely based on the lunar geologic time scale.			
Cryptic	**Basin Groups**	**Nectarian**	**Lower Imbrian**

Hadean rocks

In the last decades of the 20th century geologists identified a few Hadean rocks from Western Greenland, Northwestern Canada and Western Australia. Rock formations in Greenland comprise sediments dated around 3.8 billion years ago and are somewhat altered by a volcanic dike that penetrated the rocks after they were deposited. Individual zircon crystals redeposited in sediments in Western Canada and the Jack Hills region of Western Australia are much older. The oldest dated zircons date from about 4,400 Ma – very close to the hypothesized time of the Earth's formation.

The Greenland sediments include banded iron beds. They contain possibly organic carbon and imply some possibility that photosynthetic life had already emerged at that time. The oldest known fossils (from Australia) date from a few hundred million years later.

Atmosphere and oceans

A sizeable quantity of water would have been in the material which formed the Earth. Water molecules would have escaped Earth's gravity more easily when it was less massive during its formation. Hydrogen and helium are expected to continually leak from the atmosphere, but the lack of denser noble gases in the modern atmosphere suggests that something disastrous happened to the early atmosphere.

Part of the ancient planet is theorized to have been disrupted by the impact which created the Moon, which should have caused melting of one or two large areas. Present composition does not match complete melting and it is hard to completely melt and mix huge rock masses. However, a fair fraction of material should have been vaporized by this impact, creating a *rock vapor atmosphere* around the young planet. The rock vapor would have condensed within two thousand years, leaving behind hot volatiles which probably resulted in a heavy carbon dioxide atmosphere with hydrogen and water vapor. Liquid water oceans existed despite the surface temperature of 230 °C because of the atmospheric pressure of the heavy CO_2 atmosphere. As cooling continued, subduction and dissolving in ocean water removed most CO_2 from the atmosphere but levels oscillated wildly as new surface and mantle cycles appeared.

Study of zircons has found that liquid water must have existed as long ago as 4400 Ma, very soon after the formation of the Earth. This requires the presence of an atmosphere. The Cool Early Earth theory covers a range from about 4400 Ma to 4000 Ma.

A September 2008 study of zircons found that Australian Hadean rock holds minerals that point to the existence of plate tectonics as early as 4 billion years ago. If this holds true, the previous beliefs about the Hadean period are far from correct. That is, rather than a hot, molten surface and atmosphere full of carbon dioxide, the Earth's surface would be very much like it is today. The action of plate tectonics traps vast amounts of carbon dioxide, thereby eliminating the greenhouse effects and leading to a much cooler surface temperature and the formation of solid rock, and possibly even life.

Chapter- 4

Archean

The **Archean**, also spelled **Archaean**, formerly called the **Archaeozoic**, also spelled **Archeozoic** or **Archæozoic**) is a geologic eon before the Paleoproterozoic Era of the Proterozoic Eon, before 2.5 Ga (billion years ago, or 2,500 **Ma**). Instead of being based on stratigraphy, this date is defined chronometrically. The lower boundary (starting point) has not been officially recognized by the International Commission on Stratigraphy, but it is usually set to 3.8 Ga, at the end of the Hadean Eon. In older literature, the Hadean is included as part of the Archean. The name comes from the ancient Greek "Αρχή" (Arkhē), meaning "beginning, origin".

Archean Earth

The Archean is one of the four principal eons of Earth history. When the Archean began, the Earth's heat flow was nearly three times higher than it is today, and it was still twice the current level at the transition from the Archean to the Proterozoic (2,500 **Ma**). The extra heat was the result of a mix of remnant heat from planetary accretion, heat from the formation of the Earth's core, and heat produced by radioactive elements.

Most surviving Archean rocks are metamorphic or igneous. Volcanic activity was considerably higher than today, with numerous lava eruptions, including unusual types such as komatiite. Granitic rocks predominate throughout the crystalline remnants of the surviving Archean crust. Examples include great melt sheets and voluminous plutonic masses of granite, diorite, layered intrusions, anorthosites and monzonites known as sanukitoids.

The Earth of the early Archean may have supported a tectonic regime unlike that of the present. Some scientists argue that, because the Earth was much hotter, tectonic activity was more vigorous than it is today, resulting in a much faster rate of recycling of crustal material. This may have prevented cratonisation and continent formation until the mantle cooled and convection slowed down. Others argue that the oceanic lithosphere was too buoyant to subduct, and that the rarity of Archean rocks is a function of erosion by subsequent tectonic events. The question of whether or not plate tectonic activity existed in the Archean is an active area of modern research.

There are two schools of thought concerning the amount of continental crust that was present in the Archean. One school maintains that no large continents existed until late in the Archean: small *protocontinents* were the norm, prevented from coalescing into larger units by the high rate of geologic activity. The other school follows the teaching of Richard Armstrong, who argued that the continents grew to their present volume in the first 500 million years of Earth history and have maintained a near-constant ever since: throughout most of Earth history, recycling of continental material crust back to the mantle in subduction or collision zones balances crustal growth.

Opinion is also divided about the mechanism of continental crustal growth. Those scientists who doubt that plate tectonics operated in the Archean argue that the felsic protocontinents formed at hotspots rather than subduction zones. Through a process called "sagduction", which refers to partial melting in downward-directed diapirs, a variety of mafic magmas produce intermediate and felsic rocks. Others accept that granite formation in island arcs and convergent margins was part of the plate tectonic process, which has operated since at least the start of the Archean.

An explanation for the general lack of Hadean rocks (older than 3800 Ma) is the efficiency of the processes that either cycled these rocks back into the mantle or effaced any isotopic record of their antiquity. All rocks in the continental crust are subject to metamorphism, partial melting and tectonic erosion during multiple orogenic events and the chance of survival at the surface decreases with increasing age. In addition, a period of intense meteorite bombardment in the period 4.0-3.8 Ga pulverized all rocks at the Earth's surface during the period. The similar age of the oldest surviving rocks and the "late heavy bombardment" is probably not accidental.

Archean palaeoenvironment

The Archean atmosphere is thought to have lacked free oxygen. Astronomers think that the sun was about one-third dimmer than at present, yet temperatures appear to have been near modern levels even within 500 Ma of Earth's formation, which is puzzling (the faint young sun paradox). The presence of liquid water is evidenced by certain highly deformed gneisses produced by metamorphism of sedimentary protoliths. The equable temperatures may reflect the presence of larger amounts of greenhouse gases than later in the Earth's history. Alternatively, Earth's albedo may have been lower at the time, due to less land area and cloud cover.

By the end of the Archaean c. 2600 Mya, plate tectonic activity may have been similar to that of the modern Earth. There are well-preserved sedimentary basins, and evidence of volcanic arcs, intracontinental rifts, continent-continent collisions and widespread globe-spanning orogenic events suggesting the assembly and destruction of one and perhaps several supercontinents. Liquid water was prevalent, and deep oceanic basins are known to have existed by the presence of banded iron formations, chert beds, chemical sediments and pillow basalts.

Archean geology

Although a few mineral grains are known that are Hadean, the oldest rock formations exposed on the surface of the Earth are Archean or slightly older. Archean rocks are known from Greenland, the Canadian Shield, the Baltic Shield, Scotland, India, Brazil, western Australia, and southern Africa. Although the first continents formed during this eon, rock of this age makes up only 7% of the world's current cratons; even allowing for erosion and destruction of past formations, evidence suggests that continental crust equivalent to only 5-40% of the present amount formed during the Archean.

In contrast to Proterozoic rocks, Archean rocks are often heavily metamorphized deep-water sediments, such as graywackes, mudstones, volcanic sediments, and banded iron formations. Carbonate rocks are rare, indicating that the oceans were more acidic due to dissolved carbon dioxide than during the Proterozoic. Greenstone belts are typical Archean formations, consisting of alternating units of metamorphosed mafic igneous and sedimentary rocks. The meta-igneous rocks were derived from volcanic island arcs, while the metasediments represent deep-sea sediments eroded from the neighboring island arcs and deposited in a forearc basin. Greenstone belts represent sutures between protocontinents.

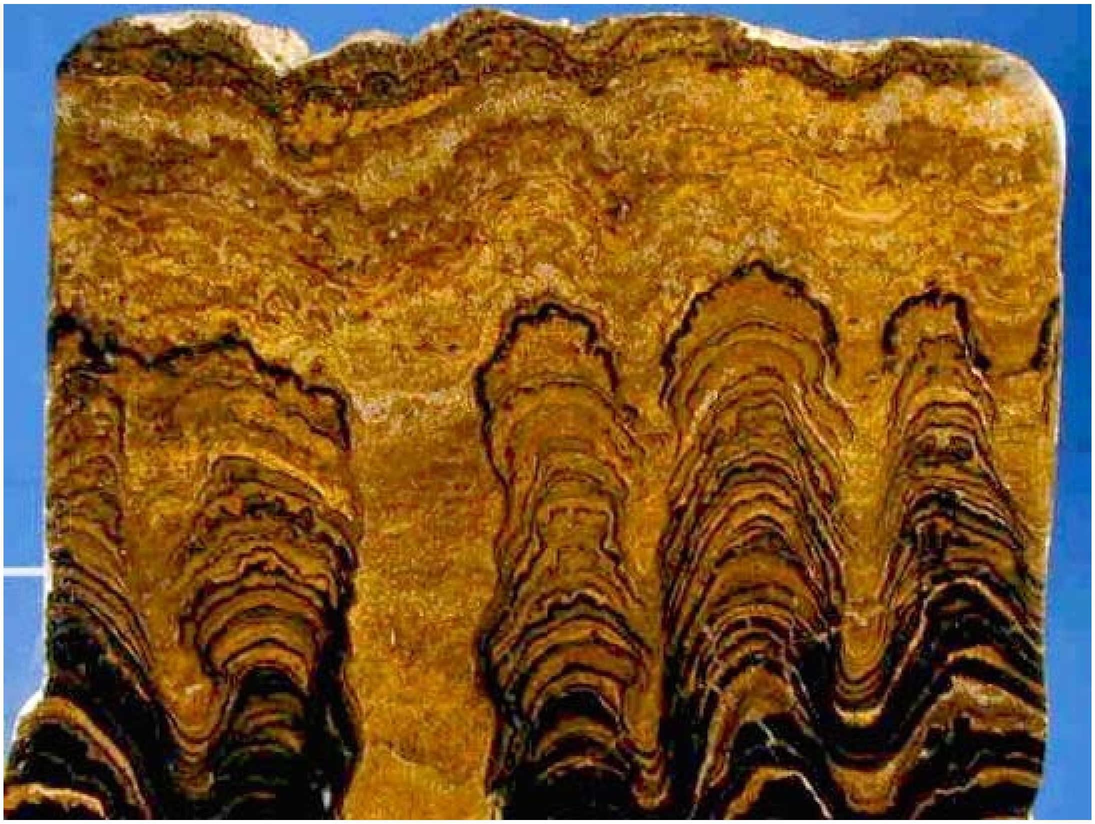
Archean life

Fossils of cyanobacterial mats (stromatolites, which were instrumental in creating the free oxygen in the atmosphere) are found throughout the Archean, becoming especially common late in the eon, while a few probable bacterial fossils are known from chert beds. In addition to the domain Bacteria (once known as Eubacteria), microfossils of the domain Archaea have also been identified.

Life was probably present throughout the Archean, but may have been limited to simple non-nucleated single-celled organisms, called Prokaryota (formerly known as Monera). There are no known eukaryotic fossils, though they might have evolved during the Archean without leaving any fossils. No fossil evidence yet exists for ultramicroscopic intracellular replicators such as viruses.

Chapter- 5

Proterozoic



Lower Proterozoic Stromatolites from Bolivia, South America

The **Proterozoic** is a geological eon representing a period before the first abundant complex life on Earth. The name Proterozoic comes from the Greek "earlier life". The Proterozoic Eon extended from 2500 Ma to 542.0 ± 1.0 Ma (million years ago), and is the most recent part of the old, informally named ‘Precambrian’ time.

The Proterozoic consists of 3 geologic eras, from oldest to youngest:

- Paleoproterozoic

- Mesoproterozoic
- Neoproterozoic

The well-identified events were:

- The transition to an oxygenated atmosphere during the Mesoproterozoic.
- Several glaciations, including the hypothesized Snowball Earth during the Cryogenian period in the late Neoproterozoic.
- The Ediacaran Period (635 to 542 Ma) which is characterized by the evolution of abundant soft-bodied multicellular organisms.

The Proterozoic record

The geologic record of the Proterozoic is much better than that for the preceding Archean. In contrast to the deep-water deposits of the Archean, the Proterozoic features many strata that were laid down in extensive shallow epicontinental seas; furthermore, many of these rocks are less metamorphosed than Archean-age ones, and plenty are unaltered. Study of these rocks shows that the eon featured massive, rapid continental accretion (unique to the Proterozoic), supercontinent cycles, and wholly-modern orogenic activity.

The first known glaciations occurred during the Proterozoic; one began shortly after the beginning of the eon, while there were at least four during the Neoproterozoic, climaxing with the Snowball Earth of the Varangian glaciation.

The buildup of oxygen

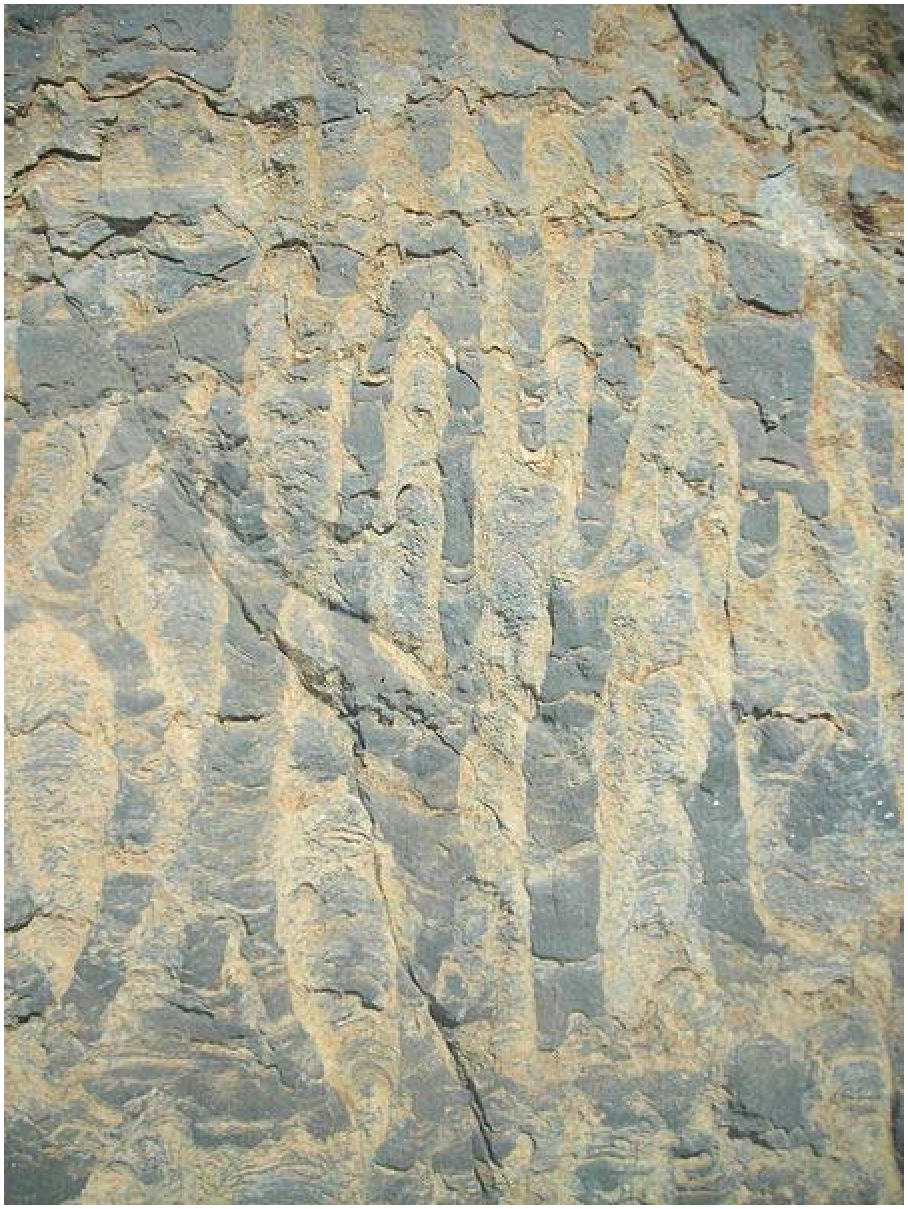
One of the most important events of the Proterozoic was the gathering up of oxygen in the Earth's atmosphere. Though oxygen was undoubtedly released by photosynthesis well back in Archean times, it could not build up to any significant degree until chemical sinks — unoxidized sulfur and iron — had been filled; until roughly 2.3 billion years ago, oxygen was probably only 1% to 2% of its current level. Banded iron formations, which provide most of the world's iron ore, were also a prominent chemical sink; most accumulation ceased after 1.9 billion years ago, either due to an increase in oxygen or a more thorough mixing of the oceanic water column.

Red beds, which are colored by hematite, indicate an increase in atmospheric oxygen after 2 billion years ago; they are not found in older rocks. The oxygen buildup was probably due to two factors: a filling of the chemical sinks, and an increase in carbon burial, which sequestered organic compounds that would have otherwise been oxidized by the atmosphere.

Paleogeography

The Mackenzie dike swarm in Canada's Canadian Shield is the largest known dike swarm on Earth, and was a source for significant massive flood basalt eruptions throughout the Proterozoic period. The source for the Mackenzie dike swarm is thought to have been a mantle plume center called the Mackenzie hotspot.

Proterozoic life



Stromatolites (Proterozoic) Zebra River Canyon, Western Namibia

The first advanced single-celled, eukaryotes and multi-cellular life, Francevillian Group Fossils, roughly coincides with the start of the accumulation of free oxygen. This may have been due to an increase in the oxidized nitrates that eukaryotes use, as opposed to cyanobacteria. It was also during the Proterozoic that the first symbiotic relationships between mitochondria (for nearly all eukaryotes) and chloroplasts (for plants and some protists only) and their hosts evolved.

The blossoming of eukaryotes such as acritarchs did not preclude the expansion of cyanobacteria; in fact, stromatolites reached their greatest abundance and diversity during the Proterozoic, peaking roughly 1.2 billion years ago.

Classically, the boundary between the Proterozoic and the Phanerozoic eons was set at the base of the Cambrian period when the first fossils of animals including trilobites and archeocyathids appeared. In the second half of the 20th century, a number of fossil forms have been found in Proterozoic rocks, but the upper boundary of the Proterozoic has remained fixed at the base of the Cambrian, which is currently placed at 542 Ma.

Proterozoic supercontinents

Throughout the history of the Earth, there have been times when the continental mass came together to form a supercontinent, followed by the break-up of the supercontinent and new continents moving apart again. This repetition of tectonic events is called a Wilson cycle. It is at least clear that, about 1000 to 830 Ma, most continental mass was united in the supercontinent Rodinia . Rodinia was not the first supercontinent; it formed at ~1.0 Ga by accretion and collision of fragments produced by breakup of the older supercontinent, called Nuna or Columbia, which was assembled by global-scale 2.0-1.8 Ga collisional events . This means plate tectonic processes similar to today's must have been active during the Proterozoic.

After the break-up of Rodinia about 800 Ma, it is possible the continents joined again around 550 Ma. The hypothetical supercontinent is sometimes referred to as Pannotia or Vendia. The evidence for it is a phase of continental collision known as the Pan-African orogeny, which joined the continental masses of current-day Africa, South-America, Antarctica and Australia. It is extremely likely, however, that the aggregation of continental masses was not completed, since a continent called Laurentia (roughly equivalent to current-day North America) had already started breaking off around 610 Ma. It is at least certain that by the end of the Proterozoic eon, most of the continental mass lay united in a position around the south pole.

Chapter- 6

Cambrian

The **Cambrian** is the first geological period of the Paleozoic Era, lasting from 542 ± 0.3 million years ago to 488.3 ± 1.7 million years ago (ICS, 2004, chart); it is succeeded by the Ordovician. Its subdivisions, and indeed its base, are somewhat in flux. The period was established by Adam Sedgwick, who named it after Cambria, the Latin name for Wales, where Britain's Cambrian rocks are best exposed.

The Cambrian is unique in its unusually high proportion of lagerstätten. These are sites of exceptional preservation, where 'soft' parts of organisms are preserved as well as their more resistant shells. This means that our understanding of the Cambrian biota surpasses that of some later periods.

The Cambrian Period marked a profound change in life on Earth. Before the Cambrian, life was on the whole small and simple. Complex organisms became gradually more common in the millions of years immediately preceding the Cambrian, but it wasn't until this period that mineralised — hence readily fossilised — organisms became common. This diversification of lifeforms was relatively rapid, and is termed the Cambrian explosion. This explosion produced the first representatives of most modern phyla, but on the whole, most Cambrian animals look alien to today's eyes, falling in the evolutionary stems of modern groups. While life prospered in the oceans, the land was barren — with nothing more than a microbial 'crud' known as soil crust gracing the soils. Apart from tentative evidence suggesting that some animals floundered around on land, most of the continents resembled deserts spanning from horizon to horizon. Shallow seas flanked the margins of several continents, which had resulted from the relatively recent breakup of the preceding supercontinent Pannotia. The seas were relatively warm, and polar ice was absent.

The United States Federal Geographic Data Committee uses a "crossed capital C" character similar to the capital letter Ukrainian Ye ‹Є› to represent the Cambrian Period.

Stratigraphy

Despite the long recognition of its distinction from younger Ordovician rocks and older Precambrian rocks it was not until 1994 that this time period was internationally ratified.

The base of the Cambrian is defined on a complex assemblage of trace fossils known as the *Treptichnus pedum* assemblage. Nevertheless, the usage of *Treptichnus pedum*, a reference ichnofossil for the lower boundary of the Cambrian, for the stratigraphic detection of this boundary is always risky because of occurrence of very similar trace fossils belonging to the Treptichnids group well below the *T. pedum* in Namibia, Spain and Newfoundland, and possibly, in the western USA. The stratigraphic range of *T. pedum* overlaps the range of the Ediacaran fossils in Namibia, and probably in Spain.

Subdivisions

The Cambrian period follows the Ediacaran and is followed by the Ordovician period. The Cambrian is divided into four epochs or series and ten ages or stages. Currently only two series and four stages are named and have a GSSP.

Since the international stratigraphic subdivision is not yet complete, many local subdivisions are still widely used. In some of these subdivisions the Cambrian is divided into three epochs with locally differing names — the Early Cambrian (Caerfai or Waucoban, 542 ± 0.3 million years ago to 513 ± 2 million years ago), Middle Cambrian (St Davids or Albertian, 513 ± 2 million years ago to 499 ± 2 million years ago) and Furongian (499 ± 2 million years ago to 488.3 million years ago million years ago ; also known as Late Cambrian, Merioneth or Croixan). Rocks of these epochs are referred to as belonging to the Lower, Middle, or Upper Cambrian.

Trilobite zones allow biostratigraphic correlation in the Cambrian.

Each of the local epochs are divided into several stages. The Cambrian is divided into several regional faunal stages of which the Russian-Kazakhian system is most used in international parlance:

*In Russian tradition the lower boundary of the Cambrian is suggested to be defined at the base of the Tommotian Stage which is characterized by diversification and global distribution of organisms with mineral skeletons and the appearance of the first Archaeocyath bioherms.

Cambrian dating

Archeocyathids from the Poleta formation in the Death Valley area

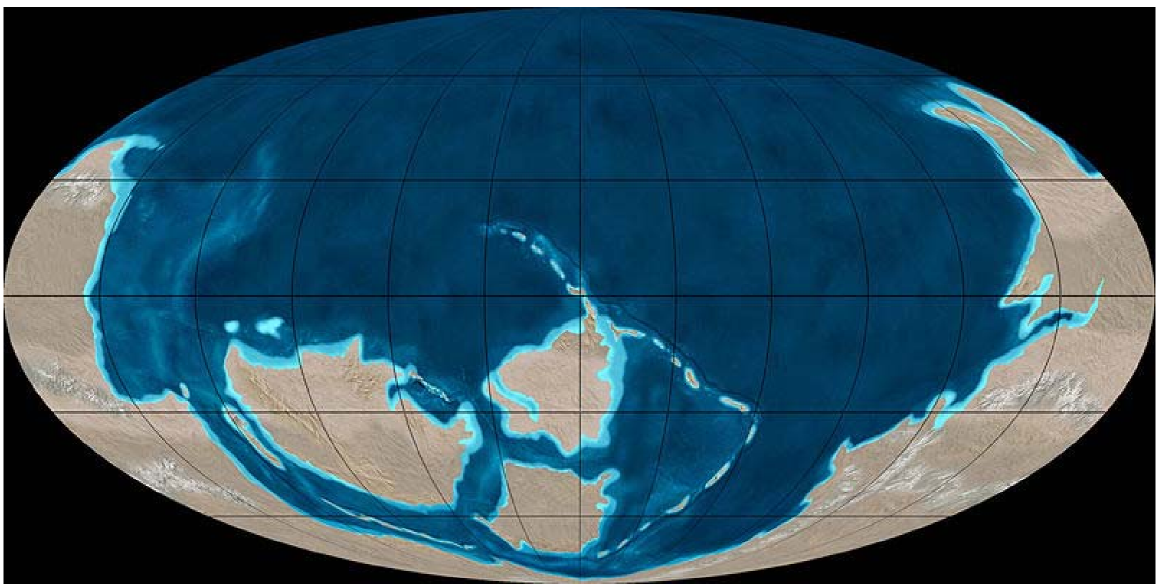
The time range for the Cambrian has classically been thought to have been from about 570 Mya to about 500 Mya. The lower boundary of the Cambrian was traditionally set at the earliest appearance of trilobites and also unusual forms known as archeocyathids (literally 'ancient cup') that are thought to be the earliest sponges and also the first non-microbial reef builders.

The end of the period was eventually set at a fairly definite faunal change now identified as an extinction event. Fossil discoveries and radiometric dating in the last quarter of the 20th century have called these dates into question. Date inconsistencies as large as 20 Mya are common between authors. Framing dates of *ca.* 545 to 490 Mya were proposed by the International Subcommission on Global Stratigraphy as recently as 2002.

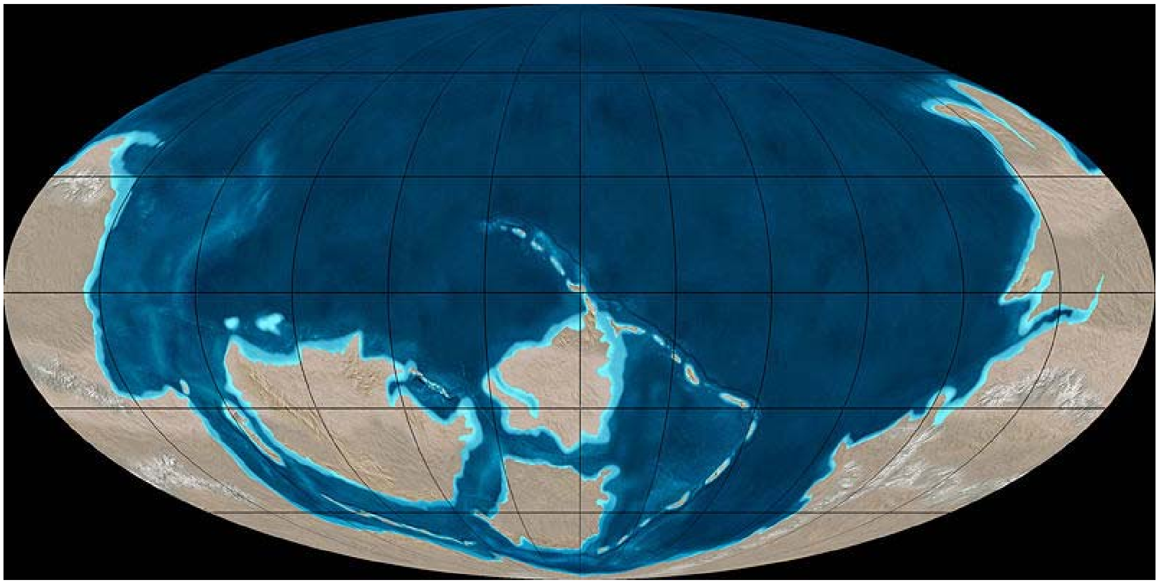
A radiometric date from New Brunswick puts the end of the Lower Cambrian around 511 Mya. This leaves 21 Mya for the other two series/epochs of the Cambrian.

A more precise date of 542 ± 0.3 Mya for the extinction event at the beginning of the Cambrian has recently been submitted. The rationale for this precise dating is interesting in itself as an example of paleological deductive reasoning. Exactly at the Cambrian boundary there is a marked fall in the abundance of carbon-13, a "reverse spike" that paleontologists call an *excursion*. It is so widespread that it is the best indicator of the position of the Precambrian-Cambrian boundary in stratigraphic sequences of roughly this age. One of the places that this well-established carbon-13 excursion occurs is in Oman. Amthor (2003) describes evidence from Oman that indicates the carbon-isotope excursion relates to a mass extinction: the disappearance of distinctive fossils from the Precambrian coincides exactly with the carbon-13 anomaly. Fortunately, in the Oman sequence, so too does a volcanic ash horizon from which zircons provide a very precise age of 542 ± 0.3 Mya (calculated on the decay rate of uranium to lead). This new and precise date tallies with the less precise dates for the carbon-13 anomaly, derived from sequences in Siberia and Namibia. It is presented here as likely to become accepted as the definitive age for the start of the Phanerozoic eon, and thus the start of the Paleozoic era and the Cambrian period.

Geography



Laurentia
Siberia
Baltica
Gondwana


Continental distribution in the Cambrian period

Reconstructions of Cambrian geography contain relatively large sources of error. They suggest that a global supercontinent, Pannotia, was in the process of breaking up, with Laurentia (North America) and Siberia having separated from the main mass of the Gondwana supercontinent to form isolated landmasses. Most continental land mass was clustered in the southern hemisphere. Large, high-velocity rotational movement of Gondwana appears to have occurred in the Early Cambrian.

With a lack of sea ice – the great glaciers of the Marinoan Snowball Earth were long melted – the sea level was high, which led to large areas of the continents being flooded in warm, shallow seas ideal for thriving life. The sea levels fluctuated somewhat, suggesting that there were 'ice ages', associated with pulses of expansion and contraction of a south polar ice cap.

Climate

While the Cambrian period was, on the whole, rather warm, it was not entirely without glaciation.

Fauna

The Cambrian marked a steep change in the diversity and composition of Earth's biosphere. The incumbent Ediacaran biota suffered a mass extinction at the base of the period, which corresponds to an increase in the abundance and complexity of burrowing behaviour. This behaviour had a profound and irreversible effect on the substrate which transformed the seabed ecosystems. Before Cambrian, the sea floor was covered by microbial mats. By the end of the period, burrowing animals had destroyed the mats through bioturbation, and gradually turned the seabeds into what they are today. As a consequence, many of those organisms who were dependent on the mats went extinct, while the other species adapted to the changed environment who now offered new ecological niches. Around the same time, the Cambrian explosion saw the seemingly rapid appearance of representatives of all the mineralized phyla. However, many of these phyla were represented only by stem-group forms; and since mineralized phyla generally have a benthic origin, they may not be a good proxy for (more abundant) non-mineralized phyla.

There are also suggestions that some Cambrian organisms ventured onto land, producing the trace fossils *Protichnites* and *Climactichnites*.

In contrast to later periods, the Cambrian fauna was somewhat restricted; free-floating organisms were rare, with the majority living on or close to the sea floor; and mineralizing animals were rarer than in future periods, in part due to the unfavourable ocean chemistry. (Most Cambrian carbonates were formed by microbial or non-biological processes.)

Flora

Generally it is accepted that there were no land plants at this time, although it is likely that a microbial "scum" comprising fungi, algae, and possibly lichens covered the land.

Chapter- 7

Ordovician

The **Ordovician** is a geologic period and system, the second of six of the Paleozoic Era, and covers the time between 488.3±1.7 to 443.7±1.5 million years ago (ICS, 2004, chart). It follows the Cambrian Period and is followed by the Silurian Period. The Ordovician, named after the Welsh tribe of the Ordovices, was defined by Charles Lapworth in 1879 to resolve a dispute between followers of Adam Sedgwick and Roderick Murchison, who were placing the same rock beds in northern Wales into the Cambrian and Silurian periods respectively. Lapworth, recognizing that the fossil fauna in the disputed strata were different from those of either the Cambrian or the Silurian periods, realized that they should be placed in a period of their own.

While recognition of the distinct Ordovician Period was slow in the United Kingdom, other areas of the world accepted it quickly. It received international sanction in 1906, when it was adopted as an official period of the Paleozoic Era by the International Geological Congress.

Dating

The Ordovician Period started at a major extinction event called the Cambrian-Ordovician extinction events some time about 488.3 ± 1.7 Mya (million years ago), and lasted for about 44.6 million years. It ended with the Ordovician–Silurian extinction event, about 443.7 ± 1.5 Mya (ICS, 2004) that wiped out 60% of marine genera.

The dates given are recent radiometric dates and vary slightly from those used in other sources. This second period of the Paleozoic era created abundant fossils and in some regions, major petroleum and gas reservoirs.

The boundary chosen for the beginning both of the Ordovician Period and the Tremadocian stage is highly useful. Since it correlates well with the occurrence of widespread graptolite, conodont, and trilobite species, the base of the Tremadocian allows scientists not only to relate these species to each other, but to species that occur with them in other areas as well. This makes it easier to place many more species in time relative to the beginning of the Ordovician Period.

Subdivisions

A number of regional terms have been used to refer to subdivisions of the Ordovician Period. In 2008, the ICS erected a formal international system of subdivisions, illustrated to the right.

The Ordovician Period in Britain was traditionally broken into Early (Tremadocian and Arenig), Middle (Llanvirn [subdivided into Abereiddian and Llandeilian] and Llandeilo) and Late (Caradoc and Ashgill) epochs. The corresponding rocks of the Ordovician System are referred to as coming from the Lower, Middle, or Upper part of the column. The faunal stages (subdivisions of epochs) from youngest to oldest are:

- Hirnantian/Gamach (Late Ordovician: Ashgill)
- Rawtheyan/Richmond (Late Ordovician: Ashgill)
- Cautleyan/Richmond (Late Ordovician: Ashgill)
- Pusgillian/Maysville/Richmond (Late Ordovician: Ashgill)

- Trenton (Middle Ordovician: Caradoc)
- Onnian/Maysville/Eden (Middle Ordovician: Caradoc)
- Actonian/Eden (Middle Ordovician: Caradoc)
- Marshbrookian/Sherman (Middle Ordovician: Caradoc)
- Longvillian/Sherman (Middle Ordovician: Caradoc)
- Soundleyan/Kirkfield (Middle Ordovician: Caradoc)
- Harnagian/Rockland (Middle Ordovician: Caradoc)
- Costonian/Black River (Middle Ordovician: Caradoc)
- Chazy (Middle Ordovician: Llandeilo)
- Llandeilo (Middle Ordovician: Llandeilo)
- Whiterock (Middle Ordovician: Llanvirn)
- Llanvirn (Middle Ordovician: Llanvirn)

- Cassinian (Early Ordovician: Arenig)
- Arenig/Jefferson/Castleman (Early Ordovician: Arenig)
- Tremadoc/Deming/Gaconadian (Early Ordovician: Tremadoc)

The Upper Ordovician edrioasteroid *Cystaster stellatus* on a cobble from the Kope Formation in northern Kentucky. In the background is the cyclostome bryozoan *Corynotrypa*.

Fossil Mountain, west-central Utah; Middle Ordovician fossiliferous shales and limestones in the lower half.

Outcrop of Upper Ordovician rubbly limestone and shale, southern Indiana; College of Wooster students.

Outcrop of Upper Ordovician limestone and minor shale, central Tennessee; College of Wooster students.

Paleogeography

Sea levels were high during the Ordovician; in fact during the Tremadocian, marine transgressions worldwide were the greatest for which evidence is preserved in the rocks.

During the Ordovician, the southern continents were collected into a single continent called Gondwana. Gondwana started the period in equatorial latitudes and, as the period progressed, drifted toward the South Pole. Early in the Ordovician, the continents Laurentia (present-day North America), Siberia, and Baltica (present-day northern

Europe) were still independent continents (since the break-up of the supercontinent Pannotia earlier), but Baltica began to move towards Laurentia later in the period, causing the Iapetus Ocean to shrink between them. The small continent Avalonia separated from Gondwana and began to head north towards Baltica and Laurentia. The Rheic Ocean between Gondwana and Avalonia was formed as a result.

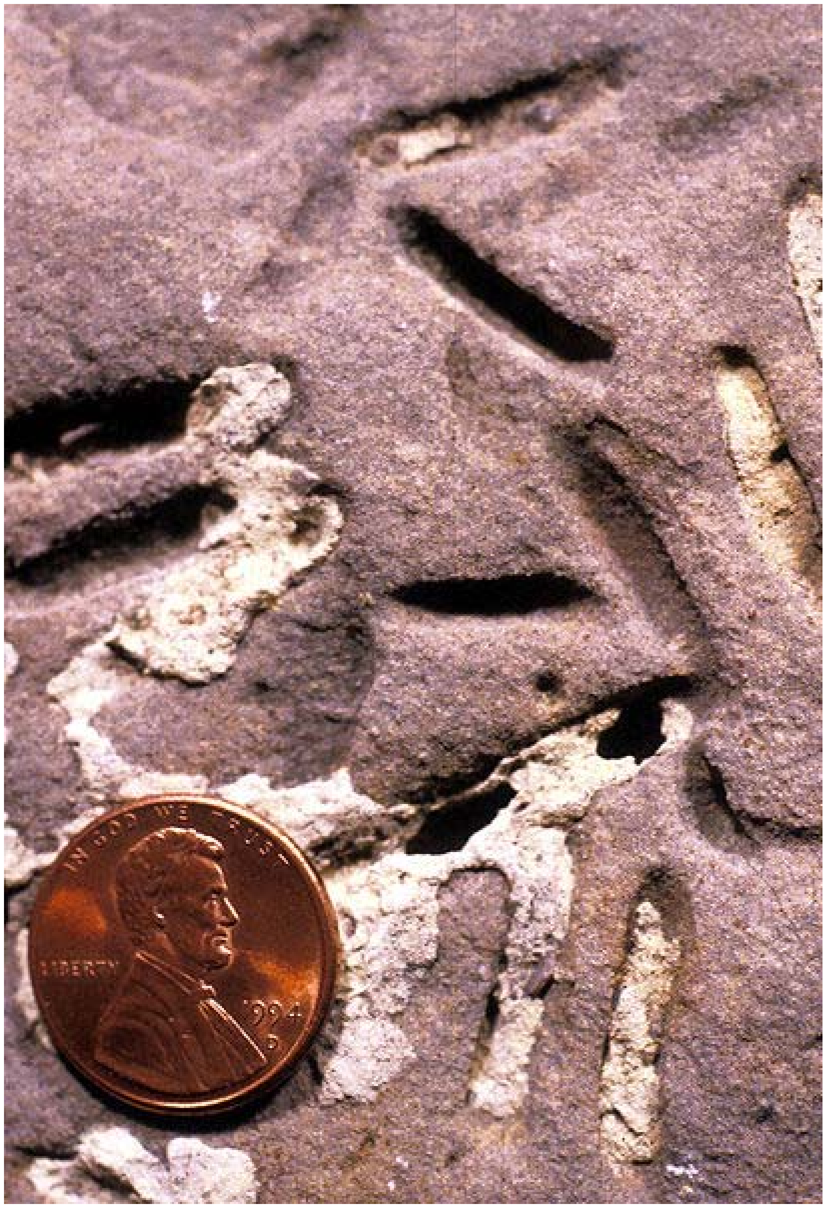
A major mountain-building episode was the Taconic orogeny that was well under way in Cambrian times. In the beginning of the Late Ordovician, from 460 to 450 Ma, volcanoes along the margin of the Iapetus Ocean spewed massive amounts of carbon dioxide into the atmosphere, turning the planet into a hothouse. These volcanic island arcs eventually collided with proto North America to form the Appalachian mountains. By the end of the Late Ordovician these volcanic emissions had stopped. Gondwana had by that time neared or approached the pole and was largely glaciated.

Geochemistry

The Ordovician was a time of calcite sea geochemistry in which low-magnesium calcite was the primary inorganic marine precipitate of calcium carbonate. Carbonate hardgrounds were thus very common, along with calcitic ooids, calcitic cements, and invertebrate faunas with dominantly calcitic skeletons.

Unlike Cambrian times, when calcite production was dominated by microbial and non-biological processes, animals (and macroalgae) became a dominant source of calcareous material in Ordovician deposits.

Trypanites borings in an Ordovician hardground, southeastern Indiana.



Petroxestes borings in an Ordovician hardground, southern Ohio.

Outcrop of Ordovician kukersite oil shale, northern Estonia.

Bryozoan fossils in Ordovician kukersite oil shale, northern Estonia.

Climate and sea level

The Ordovician saw the highest sea levels of the Palaeozoic, and the low relief of the continents led to many shelf deposits being formed under hundreds of metres of water. Sea level rose more or less continuously throughout the Early Ordovician, levelling off somewhat during the middle of the period. Locally, some regressions occurred, but sea level rise continued in the beginning of the Late Ordovician. A change was soon on the cards, however, and sea levels fell steadily in accord with the cooling temperatures for the ~30 million years leading up to the Hirnantian glaciation. Within this icy stage, sea level seems to have upped and downed somewhat, but despite much study the details remain unresolved.

At the beginning of the period, around 480 million years ago, the climate was very hot due to high levels of CO_2, which gave a strong greenhouse effect. The marine waters are assumed to have been around 45°C, which restricted the diversification of complex multi-cellular organisms. But over time, the climate become cooler, and around 460 million years ago, the ocean temperatures became comparable to those of present day equatorial waters.

As with North America and Europe, Gondwana was largely covered with shallow seas during the Ordovician. Shallow clear waters over continental shelves encouraged the growth of organisms that deposit calcium carbonates in their shells and hard parts. The Panthalassic Ocean covered much of the northern hemisphere, and other minor oceans included Proto-Tethys, Paleo-Tethys, Khanty Ocean, which was closed off by the Late Ordovician, Iapetus Ocean, and the new Rheic Ocean.

As the Ordovician progressed, we see evidence of glaciers on the land we now know as Africa and South America. At the time these land masses were sitting at the South Pole, and covered by ice caps.

Life

Nautiloids like *Orthoceras* were among the largest predators in the Ordovician.

A diorama depicting Ordovician flora and fauna.

For most of the Late Ordovician, life continued to flourish, but at and near the end of the period there were mass-extinction events that seriously affected planktonic forms like conodonts, graptolites, and some groups of trilobites (Agnostida and Ptychopariida, which completely died out, and the Asaphida, which were much reduced). Brachiopods, bryozoans and echinoderms were also heavily affected, and the endocerid cephalopods died out completely, except for possible rare Silurian forms. The Ordovician-Silurian Extinction Events may have been caused by an ice age that occurred at the end of the Ordovician period as the end of the Late Ordovician was one of the coldest times in the last 600 million years of earth history.

Fauna

On the whole, the fauna that emerged in the Ordovician set the template for the remainder of the Palaeozoic. The fauna was dominated by tiered communities of suspension feeders, mainly with short food chains; this said, the ecological system reached a new grade of complexity far beyond that of the Cambrian fauna, which has persisted until the present day.

Though less famous than the Cambrian explosion, the Ordovician featured an adaptive radiation, the Ordovician radiation, that was no less remarkable; marine faunal genera increased fourfold, resulting in 12% of all known Phanerozoic marine fauna. Another change in the fauna was the strong increase in filter feeding organisms. The trilobite, inarticulate brachiopod, archaeocyathid, and eocrinoid faunas of the Cambrian were succeeded by those that dominated the rest of the Paleozoic, such as articulate brachiopods, cephalopods, and crinoids. Articulate brachiopods, in particular, largely replaced trilobites in shelf communities. Their success epitomizes the greatly increased diversity of carbonate shell-secreting organisms in the Ordovician compared to the Cambrian.

In North America and Europe, the Ordovician was a time of shallow continental seas rich in life. Trilobites and brachiopods in particular were rich and diverse. Although solitary corals date back to at least the Cambrian, reef-forming corals appeared in the early Ordovician, corresponding to an increase in the stability of carbonate and thus a new abundance of calcifying animals.

Molluscs, which appeared during the Cambrian or even the Ediacaran, became common and varied, especially bivalves, gastropods, and nautiloid cephalopods.

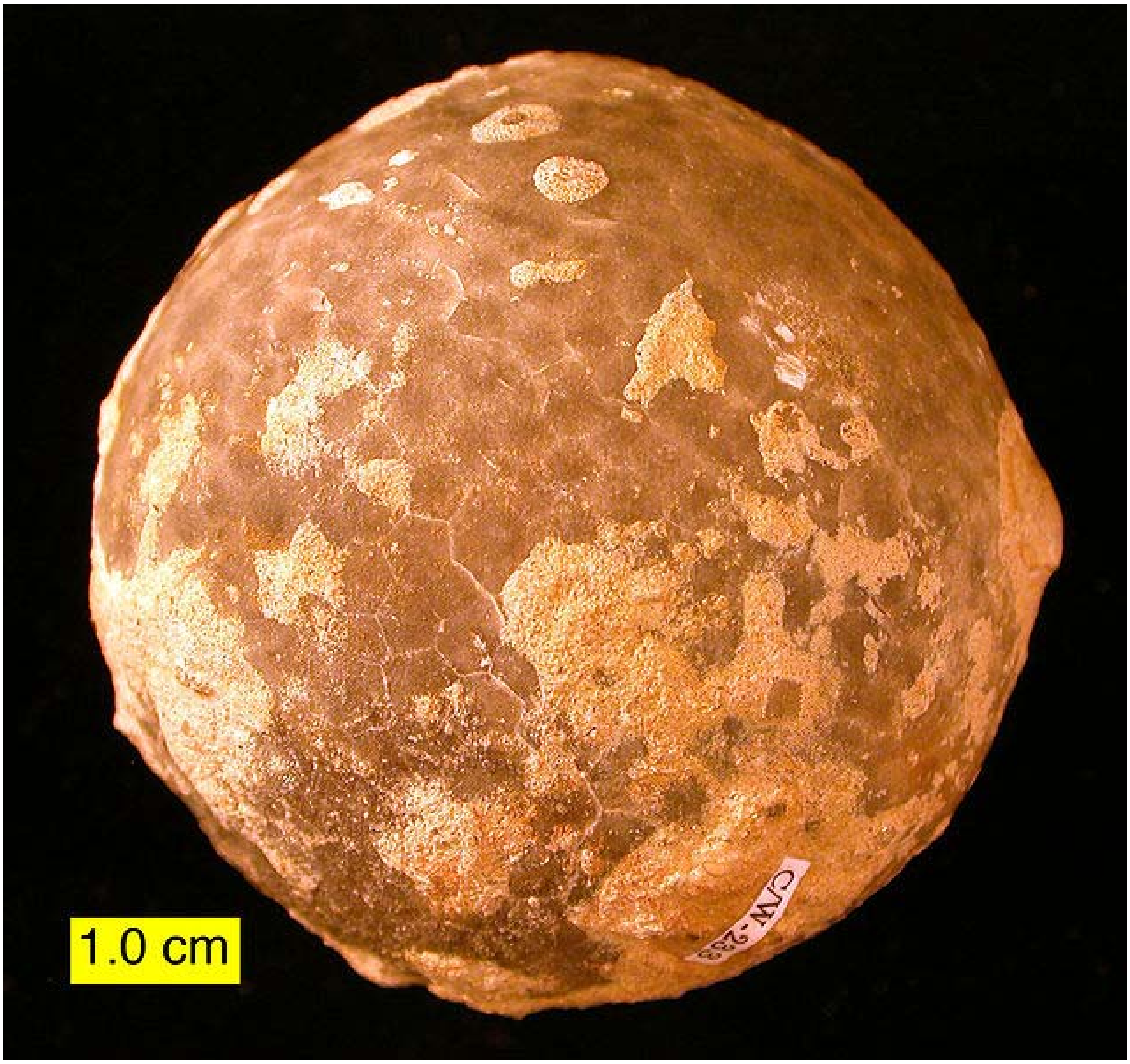
Now-extinct marine animals called graptolites thrived in the oceans. Some new cystoids and crinoids appeared.

It was long thought that the first true vertebrates (fish — Ostracoderms) appeared in the Ordovician, but recent discoveries in China reveal that they probably originated in the Early Cambrian. The very first gnathostome (jawed fish) appeared in the Late Ordovician epoch.

During the Middle Ordovician there was a large increase in the intensity and diversity of bioeroding organisms. This is known as the Ordovician Bioerosion Revolution. It is marked by a sudden abundance of hard substrate trace fossils such as *Trypanites*, *Palaeosabella* and *Petroxestes*.

Brachiopods and bryozoans in an Ordovician limestone, southern Minnesota.

Platystrophia ponderosa, Maysvillian (Upper Ordovician) near Madison, Indiana. Scale bar is 5.0 mm.



The Ordovician cystoid *Echinosphaerites* (an extinct echinoderm) from northeastern Estonia; approximately 5 cm in diameter.

Prasopora, a trepostome bryozoan from the Ordovician of Iowa.

In the Early Ordovician, trilobites were joined by many new types of organisms, including tabulate corals, strophomenid, rhynchonellid, and many new orthid brachiopods, bryozoans, planktonic graptolites and conodonts, and many types of molluscs and echinoderms, including the ophiuroids ("brittle stars") and the first sea stars. Nevertheless the trilobites remained abundant, with all the Late Cambrian orders continuing, and being joined by the new group Phacopida. The first evidence of land plants also appeared.

In the Middle Ordovician, the trilobite-dominated Early Ordovician communities were replaced by generally more mixed ecosystems, in which brachiopods, bryozoans, molluscs, cornulitids, tentaculitids and echinoderms all flourished, tabulate corals diversified and the first rugose corals appeared; trilobites were no longer predominant. The planktonic graptolites remained diverse, with the Diplograptina making their appearance. Bioerosion became an important process, particularly in the thick calcitic skeletons of corals, bryozoans and brachiopods, and on the extensive carbonate hardgrounds that appear in abundance at this time. One of the earliest known armoured agnathan ("ostracoderm") vertebrate, *Arandaspis*, dates from the Middle Ordovician.

Trilobites in the Ordovician were very different than their predecessors in the Cambrian. Many trilobites developed bizarre spines and nodules to defend against predators such as primitive sharks and nautiloids while other trilobites such as *Aeglina prisca* evolved to become swimming forms. Some trilobites even developed shovel-like snouts for ploughing through muddy sea bottoms. Another unusual clade of trilobites known as the trinucleids developed a broad pitted margin around their head shields. Some trilobites such as *Asaphus kowalewski* evolved long eyestalks to assist in detecting predators whereas other trilobite eyes in contrast disappeared completely.

Flora

Green algae were common in the Late Cambrian (perhaps earlier) and in the Ordovician. Terrestrial plants probably evolved from green algae, first appearing in the form of tiny non-vascular mosses resembling liverworts. Fossil spores from land plants have been identified in uppermost Ordovician sediments.

Among the first land fungi may have been arbuscular mycorrhiza fungi (Glomerales), playing a crucial role in facilitating the colonization of land by plants through mycorrhizal symbiosis, which makes mineral nutrients available to plant cells; such fossilized fungal hyphae and spores from the Ordovician of Wisconsin have been found with an age of about 460 million years ago, a time when the land flora most likely only consisted of plants similar to non-vascular bryophytes.

End of the period

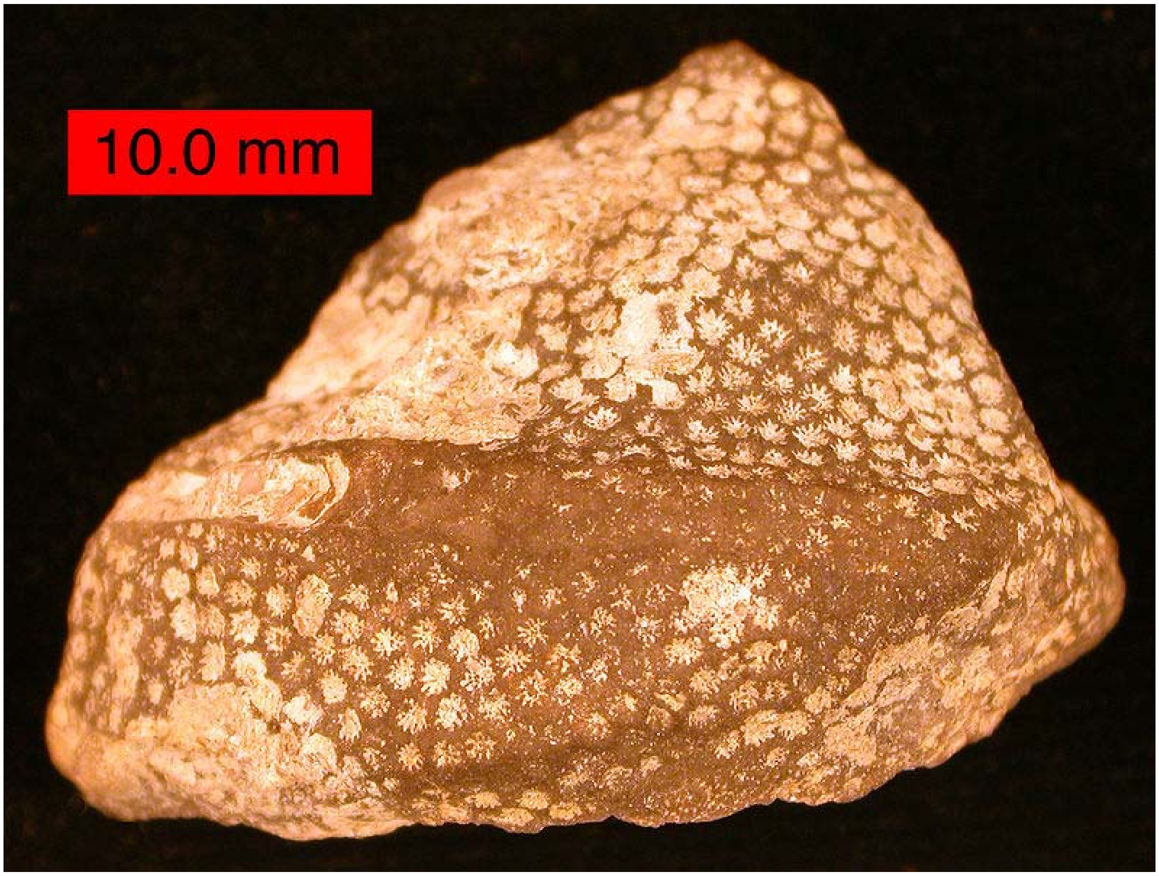
The Ordovician came to a close in a series of extinction events that, taken together, comprise the second largest of the five major extinction events in Earth's history in terms of percentage of genera that went extinct. The only larger one was the Permian-Triassic extinction event.

The extinctions occurred approximately 447–444 million years ago and mark the boundary between the Ordovician and the following Silurian Period. At that time all complex multicellular organisms lived in the sea, and about 49% of genera of fauna disappeared forever; brachiopods and bryozoans were greatly reduced, along with many trilobite, conodont and graptolite families.

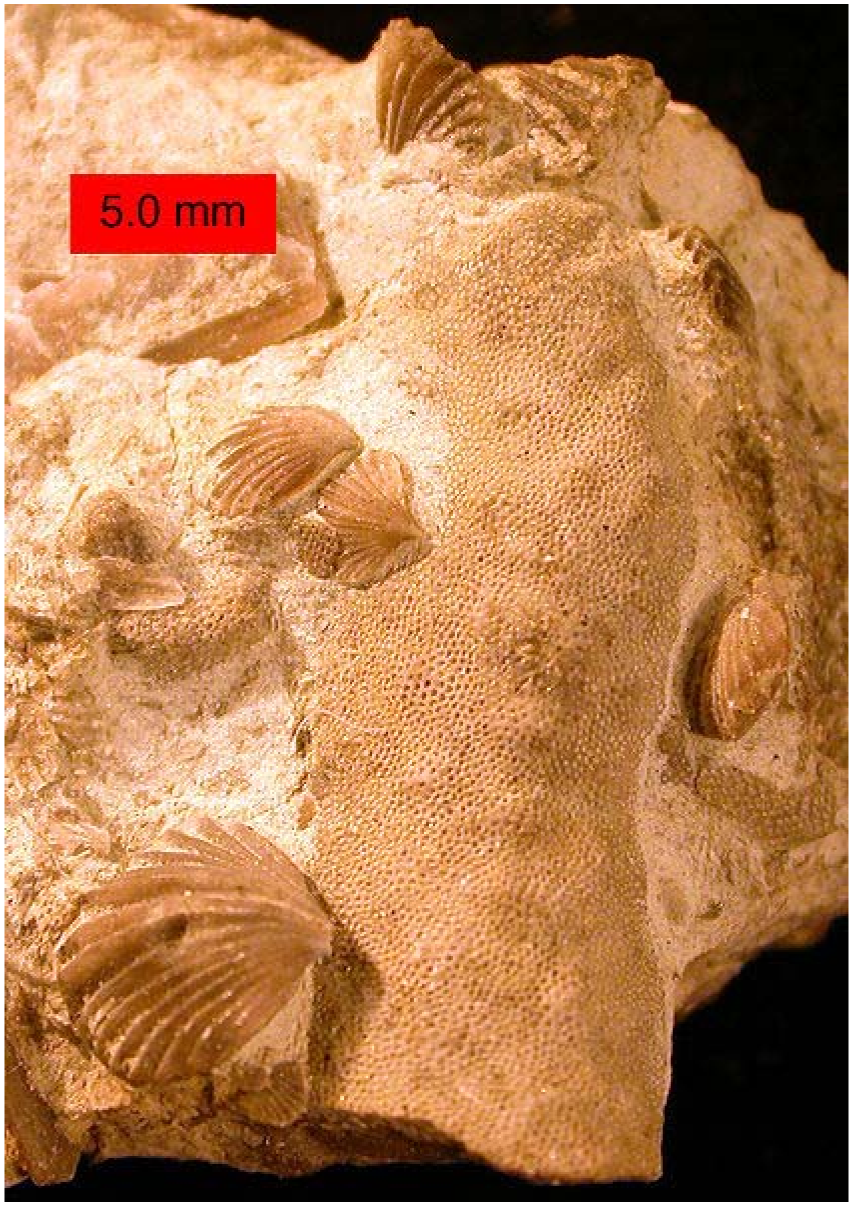
The most commonly accepted theory is that these events were triggered by the onset of most cold conditions in the late Katian, followed by an ice age, in the Hirnantian faunal stage, that ended the long, stable greenhouse conditions typical of the Ordovician.

The ice age was possibly not long-lasting, study of oxygen isotopes in fossil brachiopods showing that its duration could have been only 0.5 to 1.5 million years. Other researchers (Page et al.) estimate more temperate conditions did not return until the late Silurian.

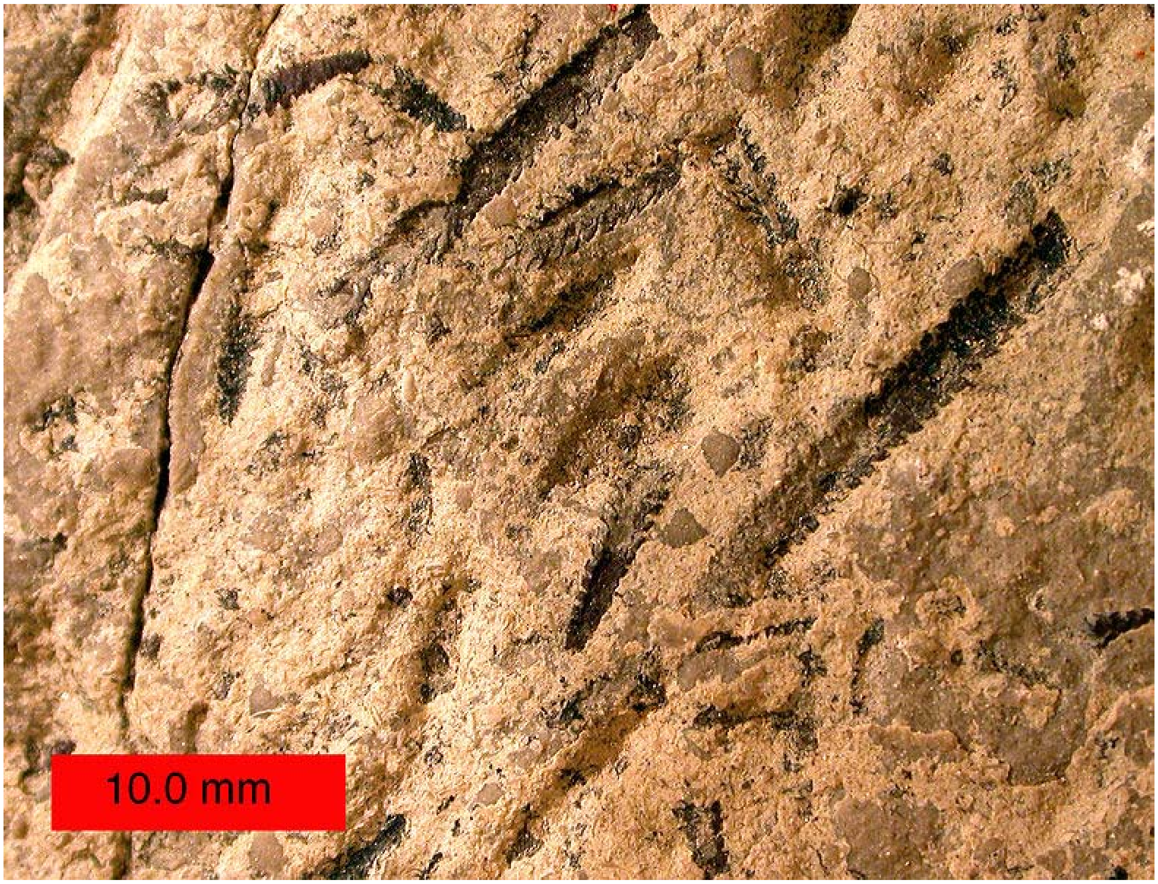
An Ordovician strophomenid brachiopod with encrusting inarticulate brachiopods and a bryozoan.



The heliolitid coral *Protaraea richmondensis* encrusting a gastropod; Cincinnatian (Upper Ordovician) of southeastern Indiana.



Zygospira modesta, spiriferid brachiopods, preserved in their original positions on a trepostome bryozoan; Cincinnatian (Upper Ordovician) of southeastern Indiana.



Graptolites (*Amplexograptus*) from the Ordovician near Caney Springs, Tennessee.

The late Ordovician glaciation event was preceded by a fall in atmospheric carbon dioxide (from 7000 ppm to 4400 ppm), which selectively affected the shallow seas where most organisms lived. As the southern supercontinent Gondwana drifted over the South Pole, ice caps formed on it, which have been detected in Upper Ordovician rock strata of North Africa and then-adjacent northeastern South America, which were south-polar locations at the time.

Glaciation locks up water from the world-ocean, and the interglacials free it, causing sea levels repeatedly to drop and rise; the vast shallow intra-continental Ordovician seas withdrew, which eliminated many ecological niches, then returned carrying diminished founder populations lacking many whole families of organisms, then withdrew again with the next pulse of glaciation, eliminating biological diversity at each change. Species limited to a single epicontinental sea on a given landmass were severely affected. Tropical lifeforms were hit particularly hard in the first wave of extinction, while cool-water species were hit worst in the second pulse.

Surviving species were those that coped with the changed conditions and filled the ecological niches left by the extinctions.

At the end of the second event, melting glaciers caused the sea level to rise and stabilise once more. The rebound of life's diversity with the permanent re-flooding of continental shelves at the onset of the Silurian saw increased biodiversity within the surviving Orders.

Melott *et al.* (2006) suggested a ten-second gamma ray burst could have destroyed the ozone layer and exposed terrestrial and marine surface-dwelling life to deadly radiation and initiated global cooling.

Chapter- 8

Silurian

The **Silurian** is a geologic period and system that extends from the end of the Ordovician Period, about 443.7 ± 1.5 Mya (million years ago), to the beginning of the Devonian Period, about 416.0 ± 2.8 Mya (ICS, 2004, chart). As with other geologic periods, the rock beds that define the period's start and end are well identified, but the exact dates are uncertain by several million years. The base of the Silurian is set at a major extinction event when 60% of marine species were wiped out.

History

The Silurian system was first identified by British geologist Sir Roderick Impey Murchison, who was examining fossil-bearing sedimentary rock strata in south Wales in the early 1830s. He named the sequences for a Celtic tribe of Wales, the Silures, following the convention his friend Adam Sedgwick had established for the Cambrian. In 1835 the two men presented a joint paper, under the title *On the Silurian and Cambrian Systems, Exhibiting the Order in which the Older Sedimentary Strata Succeed each other in England and Wales,* which was the germ of the modern geological time scale. As it was first identified, the "Silurian" series when traced farther afield quickly came to overlap Sedgwick's "Cambrian" sequence, however, provoking furious disagreements that ended the friendship. Charles Lapworth resolved the conflict by defining a new Ordovician system including the contested beds. An early alternative name for the Silurian was *"Gotlandian"* after the strata of the Baltic island of Gotland.

The French geologist Joachim Barrande, building on Murchison's work, used the term *Silurian* in a more comprehensive sense than was justified by subsequent knowledge. He divided the Silurian rocks of Bohemia into eight stages. His interpretation was questioned in 1854 by Edward Forbes, and the later stages of Barrande, F, G and H, have since been shown to be Devonian. Despite these modifications in the original groupings of the strata, it is recognized that Barrande established Bohemia as a classic ground for the study of the earliest fossils.

Subdivisions

Llandovery

The Llandovery epoch lasted from 443.7 ± 1.5 million years ago to 428.2 ± 2.3 million years ago, and is subdivided into three stages: the Rhuddanian, lasting until 439 million years ago, the Aeronian, lasting to 436 million years ago, and the Telychian. The epoch is named for the town of Llandovery in Carmarthenshire, Wales.

Wenlock

The Wenlock, which lasted from 428.2 ± 2.3 million years ago to 422.9 ± 2.5 million years ago, is subdivided into the Sheinwoodian (to 426.2 million years ago) and Homerian ages. It is named after the Wenlock Edge in Shropshire, England. During the Wenlock, the oldest known tracheophytes of the genus *Cooksonia*, appear. The complexity of slightly younger Gondwana plants like *Baragwanathia* indicates either a much longer history for vascular plants, perhaps extending into the early Silurian or even Ordovician.

Ludlow

The Ludlow, lasting from 422.9 ± 2.5 million years ago to 418.7 ± 2.7 million years ago, comprises the Gorstian stage, lasting until 421.3 million years ago, and the Ludfordian stage. It is named for the town of Ludlow in Shropshire, England.

Přídolí

The Pridoli, lasting from 418.7 ± 2.7 million years ago to 416 ± 2.8 million years ago, is the final and shortest epoch of the Silurian. It is named after one locality at natural reserve *Homolka a Přídolí* near the Prague suburb Slivenec in the Czech Republic. *Přídolí* is the old name of a cadastral field area.

Regional stages

In North America a different suite of regional stages is sometimes used:

- Cayugan (Late Silurian - Ludlow)
- Lockportian (middle Silurian: late Wenlock)
- Tonawandan (middle Silurian: early Wenlock)
- Ontarian (Early Silurian: late Llandovery)
- Alexandrian (earliest Silurian: early Llandovery)

Geography

Ordovician-Silurian boundary exposed on Hovedøya, Norway, showing the very marked difference between the light gray Ordovician calcareous sandstone and brown Silurian mudstone. The layers have been inverted (overturned) by the Caledonian orogeny.

With the supercontinent Gondwana covering the equator and much of the southern hemisphere, a large ocean occupied most of the northern half of the globe. The high sea levels of the Silurian and the relatively flat land (with few significant mountain belts) resulted in a number of island chains, and thus a rich diversity of environmental settings.

During the Silurian, Gondwana continued a slow southward drift to high southern latitudes, but there is evidence that the Silurian icecaps were less extensive than those of the late Ordovician glaciation. The southern continents remained united during this period. The melting of icecaps and glaciers contributed to a rise in sea level, recognizable from the fact that Silurian sediments overlie eroded Ordovician sediments, forming an unconformity. The continents of Avalonia, Baltica, and Laurentia drifted together near the equator, starting the formation of a second supercontinent known as Euramerica.

Fossilised Late Silurian shallow sea floor, on display in Bristol City Museum, Bristol, England. From the Wenlock epoch, in the Wenlock limestone, Dudley, West Midlands, England.

When the proto-Europe collided with North America, the collision folded coastal sediments that had been accumulating since the Cambrian off the east coast of North America and the west coast of Europe. This event is the Caledonian orogeny, a spate of mountain building that stretched from New York State through conjoined Europe and Greenland to Norway. At the end of the Silurian, sea levels dropped again, leaving telltale basins of evaporites in a basin extending from Michigan to West Virginia, and the new mountain ranges were rapidly eroded. The Teays River, flowing into the shallow mid-continental sea, eroded Ordovician strata, leaving traces in the Silurian strata of northern Ohio and Indiana.

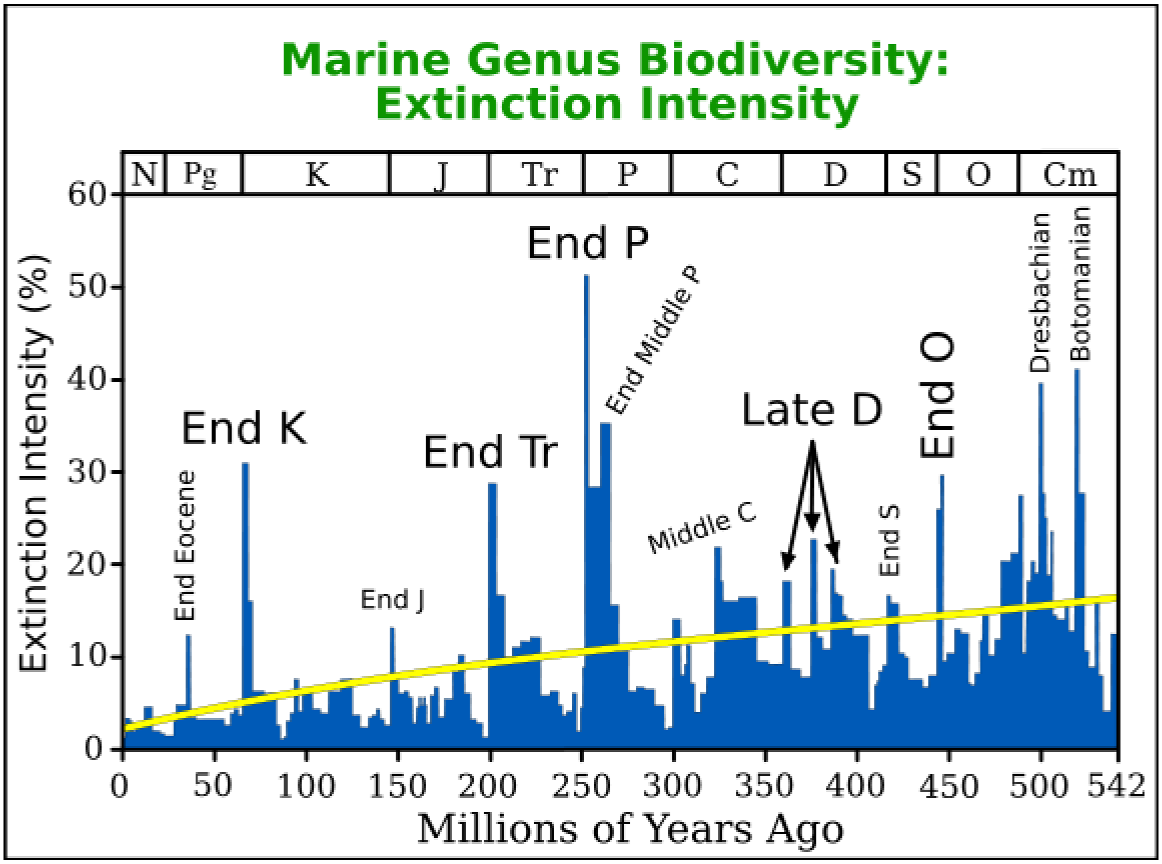
The vast ocean of Panthalassa covered most of the northern hemisphere. Other minor oceans include two phases of the Tethys— the Proto-Tethys and Paleo-Tethys— the Rheic Ocean, a seaway of the Iapetus Ocean (now in between Avalonia and Laurentia), and the newly formed Ural Ocean.

Climate and sea level

The Silurian period enjoyed relatively stable and warm temperatures, in contrast the extreme glaciations of the Ordovician before it, and the extreme heat of the ensuing Devonian. Sea levels rose from their Hirnantian low throughout the first half of the Silurian; they subsequently fell throughout the rest of the period, although smaller scale patterns are superimposed on this general trend; fifteen high-stands can be identified, and the highest Silurian sea level was probably around 140 m higher than the lowest level reached.

During this period, the Earth entered a long warm greenhouse phase, and warm shallow seas covered much of the equatorial land masses. Early in the Silurian, glaciers retreated back into the South Pole until they almost disappeared in the middle of Silurian. The period witnessed a relative stabilization of the Earth's general climate, ending the previous pattern of erratic climatic fluctuations. Layers of broken shells (called coquina) provide strong evidence of a climate dominated by violent storms generated then as now by warm sea surfaces. Later in the Silurian, the climate cooled slightly, but in the Silurian-Devonian boundary, the climate became warmer.

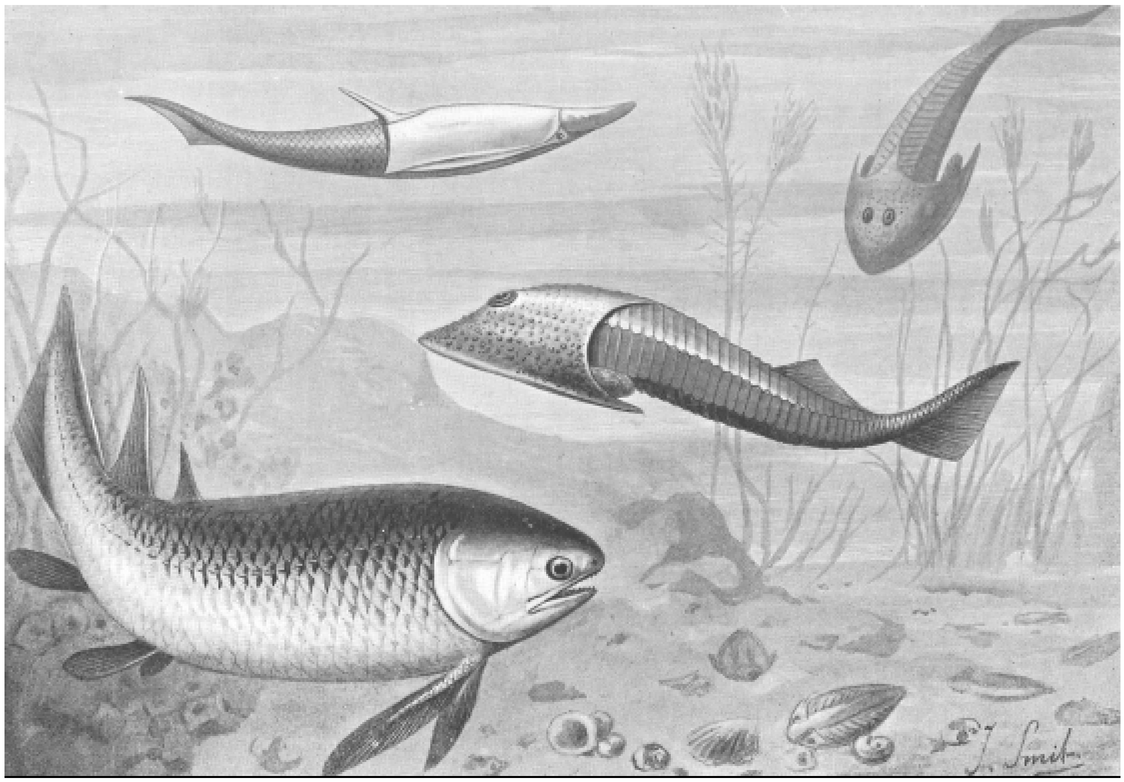
Perturbations



End of Silurian extinction.

The climate and carbon cycle appears to be rather unsettled during the Silurian, which has a higher concentration of isotopic excursions than any other period. The Ireviken event, Mulde event and Lau event each represent isotopic excursions following a minor mass extinction and associated with rapid sea-level change, in addition to the larger extinction at the end of the Silurian. Each home leaves a similar signature in the geological record, both geochemically and biologically; pelagic (free-swimming) organisms were particularly hard hit, as were brachiopods, corals and trilobites, and extinctions rarely occur in a rapid series of fast bursts.

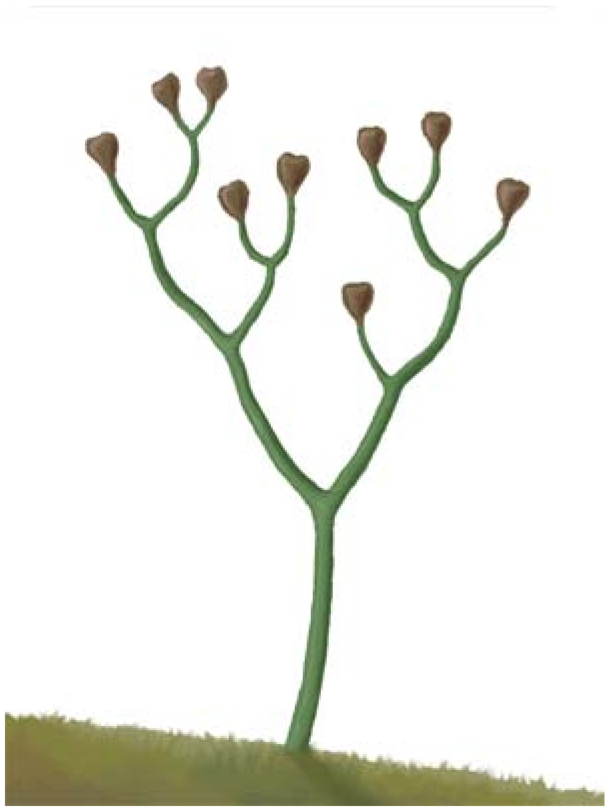
Fauna and flora



Artist's impression of Silurian fish

The first bony fish, the Osteichthyes, appeared, represented by the Acanthodians covered with bony scales; fish reached considerable diversity and developed movable jaws, adapted from the supports of the front two or three gill arches. A diverse fauna of Eurypterids (Sea Scorpions) -- some of them several meters in length—prowled the shallow Silurian seas of North America; many of their fossils have been found in New York State. Leeches also made their appearance during the Silurian Period. Brachiopods, bryozoa, molluscs, hederelloids and trilobites were abundant and diverse.

Reef abundance was patchy; sometimes they were everywhere, but at other points they are virtually absent from the rock record.



Cooksonia, the earliest vascular plant, middle Silurian

The Silurian was the first period to see macrofossils of extensive terrestrial biota, in the form of moss forests along lakes and streams. However, the land fauna did not have a major impact on the Earth until it diversified in the Devonian.

The first fossil records of vascular plants, that is, land plants with tissues that carry food, appeared in the second half of the Silurian period. The earliest known representatives of this group are the *Cooksonia* (mostly from the northern hemisphere) and *Baragwanathia* (from Australia). A primitive Silurian land plant with xylem and phloem but no differentiation in root, stem or leaf, was much-branched *Psilophyton*, reproducing by spores and breathing through stomata on every surface, and probably photosynthesizing in every tissue exposed to light. Rhyniophyta and primitive lycopods were other land plants that first appear during this period. Neither mosses nor the earliest vascular plants had deep roots. Silurian rocks often have a brownish tints, possibly a result of extensive erosion of the early soils.

Some evidence suggests the presence of predatory trigonotarbid arachnoids and myriapods in Late Silurian facies. Predatory invertebrates would indicate that simple food webs were in place that included non-predatory prey animals. Extrapolating back from Early Devonian biota, Andrew Jeram *et al.* in 1990 suggested a food web based on as yet undiscovered detritivores and grazers on microorganisms.

Chapter- 9

Devonian

The **Devonian** is a geologic period and system of the Paleozoic Era spanning from 416 to 359.2 million years ago (ICS, 2004, chart). It is named after Devon, England, where rocks from this period were first studied.

During the Devonian Period the pectoral and pelvic fins of lobe-finned fish evolved into legs as they started to walk on land as tetrapods around 397 Ma. Various terrestrial arthropods also became well-established.

The first seed-bearing plants spread across dry land, forming huge forests. In the oceans, primitive sharks became more numerous than in the Silurian and the late Ordovician, and the first ray finned and lobe-finned bony fish evolved. The first ammonite mollusks appeared, and trilobites, the mollusc-like brachiopods, as well as great coral reefs were still common. The Late Devonian extinction severely affected marine life.

The paleogeography was dominated by the supercontinent of Gondwana to the south, the continent of Siberia to the north, and the early formation of the small supercontinent of Euramerica in between.

History

The period is named after Devon, a county in southwestern England, where Devonian outcrops are common. While the rock beds that define the start and end of the period are well identified, the exact dates are uncertain. According to the International Commission on Stratigraphy (Ogg, 2004), the Devonian extends from the end of the Silurian Period 416.0 ± 2.8 Mya, to the beginning of the Carboniferous Period 359.9 ± 2.5 Mya (in North America, the beginning of the Mississippian subperiod of the Carboniferous) (ICS 2004).

In nineteenth-century texts the Devonian has been called the "Old Red Age", after the red and brown terrestrial deposits known in the United Kingdom as the Old Red Sandstone in which early fossil discoveries were found. Another common term is "Age of the Fishes", referring to the evolution of several major groups of fish that took place during the period. Older literature on the Anglo-Welsh basin divides it into the Downtonian, Dittonian, Breconian and Farlovian stages, the latter three of which are place in the Devonian.

The Devonian has also erroneously been characterized as a "greenhouse age", due to sampling bias: most of the early Devonian-age discoveries came from the strata of western Europe and eastern North America, which at the time straddled the Equator as part of the supercontinent of Euramerica where fossil signatures of widespread reefs indicate tropical climates that were warm and moderately humid but in fact the climate in the Devonian differed greatly between epochs and geographic regions. For example, during the Early Devonian, arid conditions were prevalent through much of the world including Siberia, Australia, North America, and China, but Africa and South America had a warm temperate climate. In the Late Devonian, by contrast, arid conditions were less prevalent across the world and temperate climates were more common.

Subdivisions

The Devonian Period is formally broken into Early, Middle, and Late subdivisions. The rocks corresponding to these epochs are referred to as belonging to the Lower, Middle and Upper parts of the Devonian System.

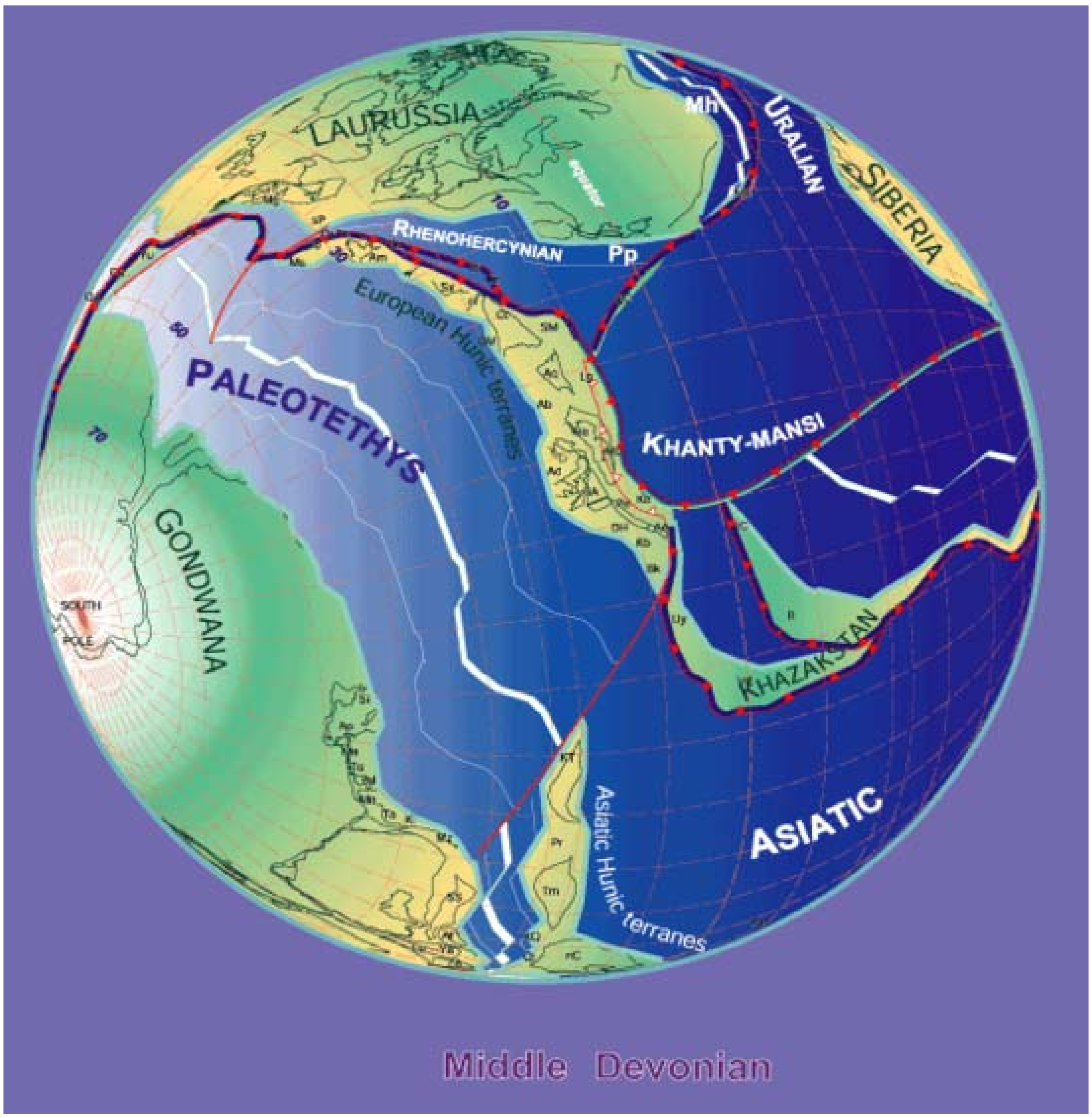
The Early Devonian lasts from 416 ± 2.8 million years ago to 397.5 ± 2.7 million years ago and begins with the Lochkovian stage, which lasts until the Pragian. This spans from 411.2 million years ago million years ago to 407 ± 2.8 million years ago, and is followed by the Emsian, which lasts until the Middle Devonian begins, 397.5± 2.7 million years ago. The Middle Devonian comprises two subdivisions, the Eifelian giving way to the Givetian 391.8± 2.7 million years ago. During this time the armoured jawless ostracoderm fish were declining in diversity; the jawed fish were thriving and increasing in diversity in both the oceans and freshwater. The shallow, warm, oxygen-depleted waters of Devonian inland lakes, surrounded by primitive plants, provided the environment necessary for certain early fish to develop essential characteristics such as well developed lungs, and the ability to crawl out of the water and onto the land for short periods of time.

Finally, the Late Devonian starts with the Frasnian, 385.3 ± 2.6 million years ago to 374.5 ± 2.6 million years ago, during which the first forests were taking shape on land. The first tetrapods appear in the fossil record in the ensuing Famennian subdivision, the beginning and end of which are marked with extinction events. This lasted until the end of the Devonian, 359.2± 2.5 million years ago.

Climate

The Devonian was a relatively warm period, and probably lacked any glaciers. Reconstruction of tropical sea surface temperature from conodont apatite implies an average value of 30 °C (86 °F) in the Early Devonian. CO_2 levels dropped steeply throughout the Devonian period as the burial of the newly-evolved forests drew carbon out of the atmosphere into sediments; this may be reflected by a Mid-Devonian cooling of around 5 °C (9 °F). The Late Devonian warmed to levels equivalent to the Early Devonian; while there is no corresponding increase in CO_2 concentrations, continental weathering increases (as predicted by warmer temperatures); further, a range of evidence, such as plant distribution, points to Late Devonian warming. The climate would have affected the dominant organisms in reefs; microbes would have been the main reef-forming organisms in warm periods, with corals and stromatoporoid sponges taking the dominant role in cooler times. The warming at the end of the Devonian may even have contributed to the extinction of the stromatoporoids.

Paleogeography



The Paleo-Tethys Ocean opened during the Devonian

The Devonian period was a time of great tectonic activity, as Euramerica and Gondwanaland drew closer together.

The continent Euramerica (or Laurussia) was created in the early Devonian by the collision of Laurentia and Baltica, which rotated into the natural dry zone along the Tropic of Capricorn, which is formed as much in Paleozoic times as nowadays by the convergence of two great air-masses, the Hadley cell and the Ferrel cell. In these near-deserts, the Old Red Sandstone sedimentary beds formed, made red by the oxidized iron (hematite) characteristic of drought conditions.

Near the equator, the plate of Euramerica and Gondwana were starting to meet, beginning the early stages of assembling Pangaea. This activity further raised the northern Appalachian Mountains and formed the Caledonian Mountains in Great Britain and Scandinavia.

The west coast of Devonian North America, by contrast, was a passive margin with deep silty embayments, river deltas and estuaries, in today's Idaho and Nevada; an approaching volcanic island arc reached the steep slope of the continental shelf in Late Devonian times and began to uplift deep water deposits, a collision that was the prelude to the mountain-building episode of Mississippian times called the Antler orogeny.

Sea levels were high worldwide, and much of the land lay submerged under shallow seas, where tropical reef organisms lived. The deep, enormous Panthalassa (the "universal ocean") covered the rest of the planet. Other minor oceans were Paleo-Tethys, Proto-Tethys, Rheic Ocean, and Ural Ocean (which was closed during the collision with Siberia and Baltica).

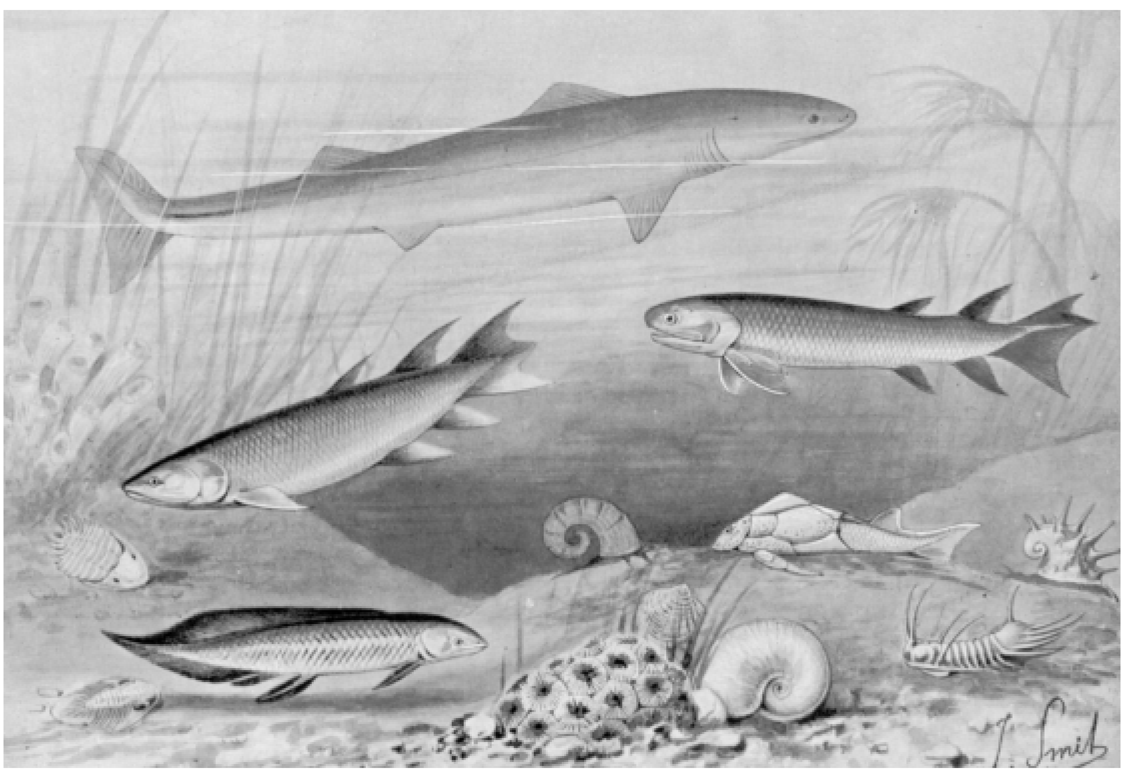
Biota

Marine biota

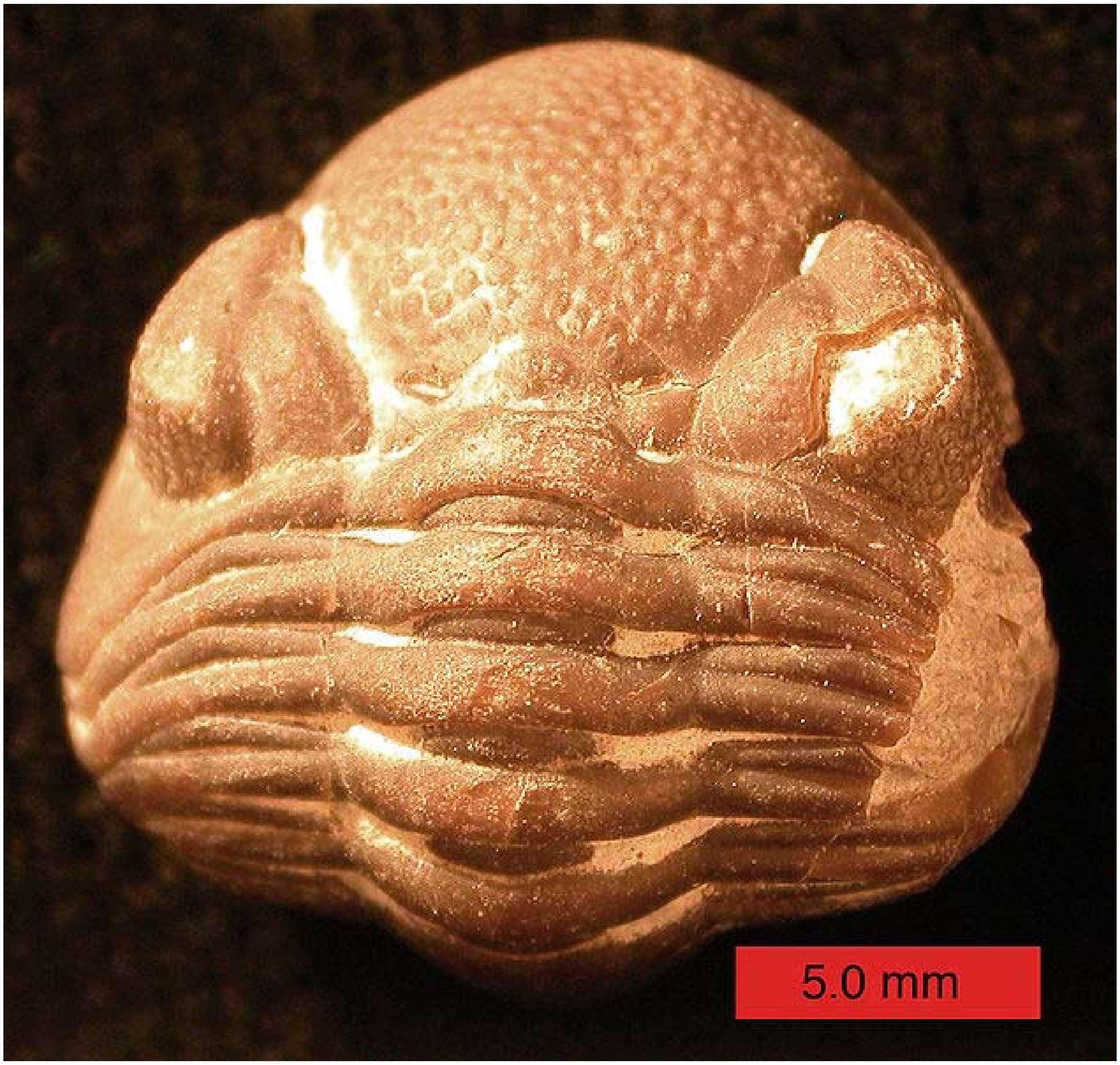
Sea levels in the Devonian were generally high. Marine faunas continued to be dominated by bryozoa, diverse and abundant brachiopods, the enigmatic hederelloids, microconchids and corals. Lily-like crinoids were abundant, and trilobites were still fairly common. Among vertebrates, jaw-less armored fish (ostracoderms) declined in diversity, while the jawed fish (gnathostomes) simultaneously increased in both the sea and fresh water. Armored placoderms were numerous during the lower stages of the Devonian Period and became extinct in the Late Devonian, perhaps because of competition for food against the other fish species. Early cartilaginous (Chondrichthyes) and bony fishes (Osteichthyes) also become diverse and played a large role within the Devonian seas. The first abundant genus of shark, *Cladoselache*, appeared in the oceans during the Devonian period. The great diversity of fish around at the time, have led to the Devonian being given the name "The Age of Fish" in popular culture.

The first ammonites also appeared during or slightly before the early Devonian period around 400 Mya.

Dunkleosteus, one of the largest armoured fishes to ever roam the planet, lived during the late Devonian.



Early shark Cladoselache, several lobe-finned fishes, including *Eusthenopteron* , and the placoderm *Bothriolepis* on a painting from 1905.

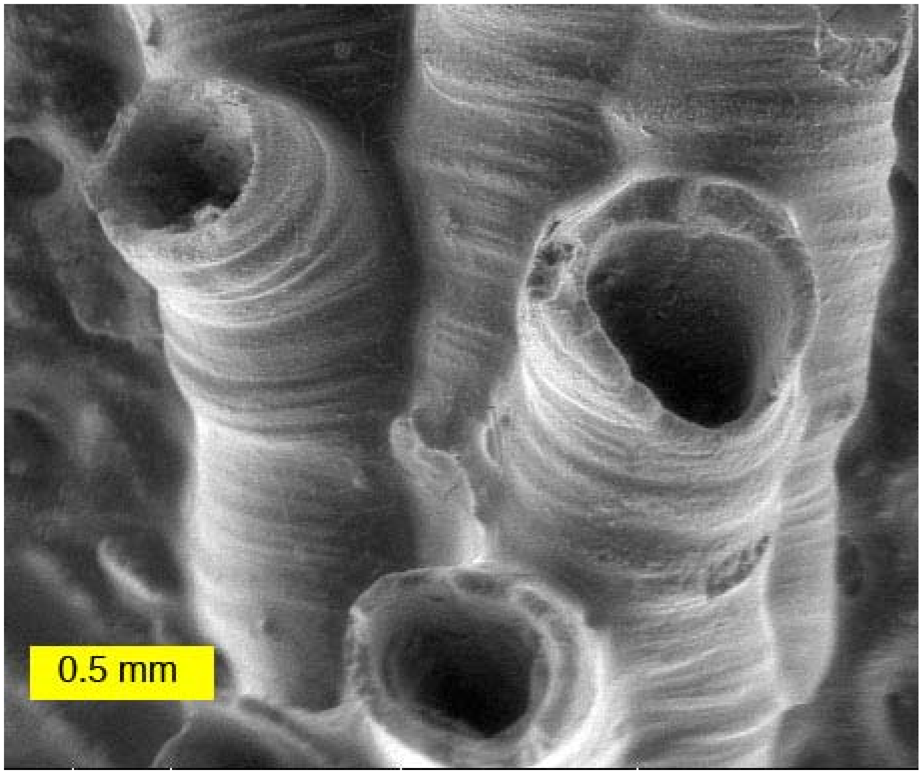


Phacopid trilobite from the Devonian of Ohio. Scale bar is 5.0 mm.

The common tabulate coral *Aulopora* from the Middle Devonian of Ohio; view of colony origin encrusting a brachiopod valve.

Reefs

A now dry barrier reef, located in present day Kimberley Basin of northwest Australia, once extended a thousand kilometers, fringing a Devonian continent. Reefs in general are built by various carbonate-secreting organisms that have the ability to erect wave-resistant frameworks close to sea level. The main contributors of the Devonian reefs were unlike modern reefs, which are constructed mainly by corals and calcareous algae. They were composed of calcareous algae and coral-like stromatoporoids, and tabulate and rugose corals, in that order of importance.



SEM image of a hederelloid from the Devonian of Michigan (largest tube diameter is 0.75 mm).

A Devonian spiriferid brachiopod from Ohio which served as a host substrate for a colony of hederelloids. The specimen is 5 cm wide.

Terrestrial biota

By the Devonian Period, life was well underway in its colonization of the land. The moss forests and bacterial and algal mats of the Silurian were joined early in the period by primitive rooted plants that created the first stable soils and harbored arthropods like mites, scorpions and myriapods (although arthropods appeared on land much earlier than in the Early Devonian and the existence of fossils such as *Climactichnites* suggest that land arthropods may have appeared as early as the Cambrian period). Also the first possible fossils of insects appeared around 416 Mya in the Early Devonian. The first tetrapods evolving from lobe-finned fish, appeared in the coastal water no later than middle Devonian, and give rise to the first Amphibians.

The greening of land

The Devonian period marks the beginning of extensive land colonization by plants. With large herbivorous land-animals not yet being present, large forests could grow and shape the landscape.

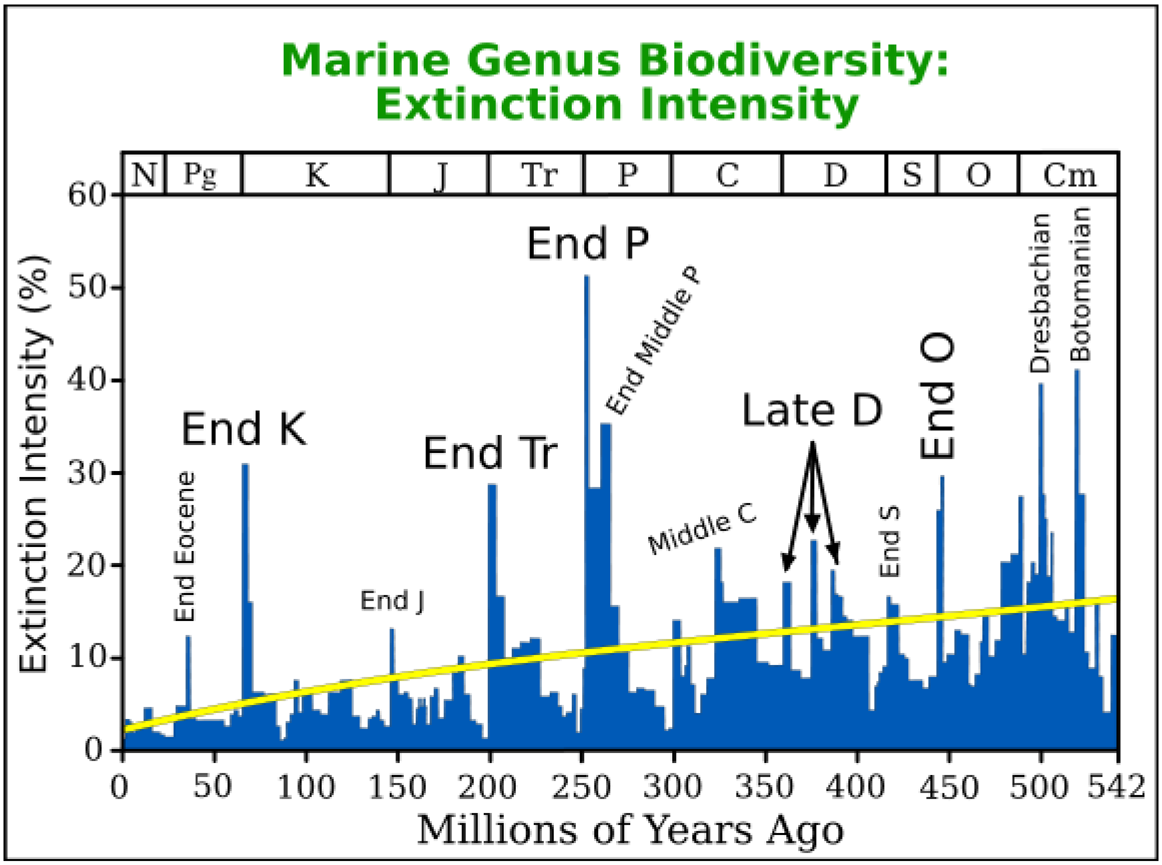
Early Devonian plants did not have roots or leaves like the plants most common today, and many had no vascular tissue at all. They probably spread largely by vegetative growth, and did not grow much more than a few centimeters tall. By far the greatest land organism was *Prototaxites*, the fruiting body of an enormous fungus that stood more than 8 meters tall, towering over the low, carpet-like vegetation. By Middle Devonian, shrub-like forests of primitive plants existed: lycophytes, horsetails, ferns, and progymnosperms had evolved. Most of these plants had true roots and leaves, and many were quite tall. The earliest known trees, from the genus *Wattieza*, appeared in the Late Devonian around 380 Ma. In the Late Devonian, the tree-like ancestral fern *Archaeopteris* and the giant cladoxylopsid trees grew with true wood. These are the oldest known trees of the world's first forests. By the end of the Devonian, the first seed-forming plants had appeared. This rapid appearance of so many plant groups and growth forms has been called the "Devonian Explosion".

The 'greening' of the continents acted as a carbon dioxide sink, and atmospheric levels of this greenhouse gas may have dropped. This may have cooled the climate and led to a massive extinction event.

Animals and the first soils

Primitive arthropods co-evolved with this diversified terrestrial vegetation structure. The evolving co-dependence of insects and seed-plants that characterizes a recognizably modern world had its genesis in the Late Devonian. The development of soils and plant root systems probably led to changes in the speed and pattern of erosion and sediment deposition. The rapid evolution of a terrestrial ecosystem containing copious animals opened the way for the first vertebrates to seek out a terrestrial living. By the end of the Devonian, arthropods were solidly established on the land.

Late Devonian extinction



The Late Devonian is characterised by three episodes of extinction ("Late D")

A major extinction occurred at the beginning of the last phase of the Devonian period, the Famennian faunal stage, (the Frasnian-Famennian boundary), about 364 Mya, when all the fossil agnathan fishes, save for the psammosteid heterostracans, suddenly disappeared. A second strong pulse closed the Devonian period. The Late Devonian extinction was one of five major extinction events in the history of the Earth's biota, more drastic than the familiar extinction event that closed the Cretaceous.

The Devonian extinction crisis primarily affected the marine community, and selectively affected shallow warm-water organisms rather than cool-water organisms. The most important group to be affected by this extinction event were the reef-builders of the great Devonian reef-systems .

Amongst the severely affected marine groups were the brachiopods, trilobites, ammonites, conodonts, and acritarchs, as well as jawless fish, and all placoderms. Land plants as well as freshwater species, such as our tetrapod ancestors, were relatively unaffected by the Late Devonian extinction event.

The reasons for the Late Devonian extinctions are still unknown, and all explanations remain speculative. Canadian paleontologist Digby McLaren suggested in 1969 that the Devonian extinction events were caused by an asteroid impact. However, while there were Late Devonian collision events, little evidence supports the existence of a Devonian crater large enough.

Chapter- 10

Carboniferous

The **Carboniferous** is a geologic period and system that extends from the end of the Devonian Period, about 359.2 ± 2.5 Mya (million years ago), to the beginning of the Permian Period, about 299.0 ± 0.8 Mya (ICS, 2004, chart).

The Carboniferous was a time of glaciation, low sea level and mountain building, diversification and extinction; a minor marine and terrestrial extinction event among animals and plants (Carboniferous Rainforest Collapse) occurred in the middle of the period caused by climate change.

The name comes from the Latin word for coal, *carbo*. Carboniferous means "coal-bearing". Many coal beds were laid down globally during this period, hence the name.

Subdivisions

In the USA the Carboniferous is usually broken into Mississippian (earlier) and Pennsylvanian (later) Epochs. The Mississippian is about twice as long as the Pennsylvanian, but due to the large thickness of coal bearing deposits with Pennsylvanian ages in Europe and North America, the two subperiods were long thought to have been more or less equal. The faunal stages from youngest to oldest, together with some of their subdivisions, are:

Late Pennsylvanian: Gzhelian (most recent)

- Noginskian / Virgilian *(part)*

Late Pennsylvanian: Kasimovian

- Klazminskian
- Dorogomilovksian / Virgilian *(part)*
- Chamovnicheskian / Cantabrian / Missourian
- Krevyakinskian / Cantabrian / Missourian

Middle Pennsylvanian: Moscovian

- Myachkovskian / Bolsovian / Desmoinesian
- Podolskian / Desmoinesian
- Kashirskian / Atokan
- Vereiskian / Bolsovian / Atokan

Early Pennsylvanian: Bashkirian / Morrowan

- Melekesskian / Duckmantian
- Cheremshanskian / Langsettian
- Yeadonian
- Marsdenian
- Kinderscoutian

Late Mississippian: Serpukhovian

- Alportian
- Chokierian / Chesterian / Elvirian
- Arnsbergian / Elvirian
- Pendleian

Middle Mississippian: Visean

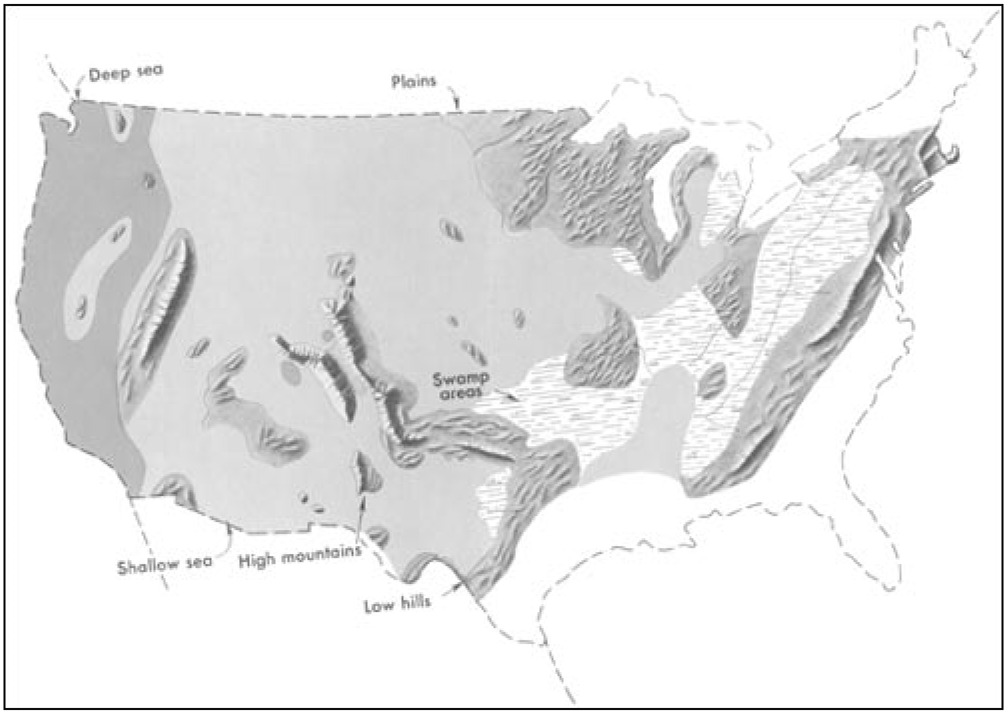
- Brigantian / St Genevieve / Gasperian / Chesterian
- Asbian / Meramecian
- Holkerian / Salem
- Arundian / Warsaw / Meramecian
- Chadian / Keokuk / Osagean *(part)* / Osage *(part)*

Early Mississippian: Tournaisian (oldest)

- Ivorian / *(part)* / Osage *(part)*
- Hastarian / Kinderhookian / Chouteau

Paleogeography

A global drop in sea level at the end of the Devonian reversed early in the Carboniferous; this created the widespread epicontinental seas and carbonate deposition of the Mississippian. . There was also a drop in south polar temperatures; southern Gondwanaland was glaciated throughout the period, though it is uncertain if the ice sheets were a holdover from the Devonian or not. . These conditions apparently had little effect in the deep tropics, where lush coal swamps flourished within 30 degrees of the northernmost glaciers. .



Generalized geographic map of the United States in Middle Pennsylvanian time.

A mid-Carboniferous drop in sea level precipitated a major marine extinction, one that hit crinoids and ammonites especially hard. . This sea level drop and the associated unconformity in North America separate the Mississippian subperiod from the Pennsylvanian subperiod. . This happened about 318 million years ago, at the onset of the Permo-Carboniferous Glaciation.

The Carboniferous was a time of active mountain-building, as the supercontinent Pangaea came together. The southern continents remained tied together in the supercontinent Gondwana, which collided with North America–Europe (Laurussia) along the present line of eastern North America. This continental collision resulted in the Hercynian orogeny in Europe, and the Alleghenian orogeny in North America; it also extended the newly-uplifted Appalachians southwestward as the Ouachita Mountains. . In the same time frame, much of present eastern Eurasian plate welded itself to Europe along the line of the Ural mountains. Most of the Mesozoic supercontinent of Pangea was now assembled, although North China (which would collide in the Latest Carboniferous), and South China continents were still separated from Laurasia. The Late Carboniferous Pangaea was shaped like an "O."

There were two major oceans in the Carboniferous—Panthalassa and Paleo-Tethys, which was inside the "O" in the Carboniferous Pangaea. Other minor oceans were shrinking and eventually closed - Rheic Ocean (closed by the assembly of South and North America), the small, shallow Ural Ocean (which was closed by the collision of Baltica and Siberia continents, creating the Ural Mountains) and Proto-Tethys Ocean (closed by North China collision with Siberia/Kazakhstania).

Climate

The early part of the Carboniferous was mostly warm; in the later part of the Carboniferous, the climate cooled. Glaciations in Gondwana, triggered by Gondwana's southward movement, continued into the Permian and because of the lack of clear markers and breaks, the deposits of this glacial period are often referred to as Permo-Carboniferous in age.

The cooling and drying of the climate led to the Carboniferous Rainforest Collapse (CRC). Tropical rainforests fragmented and then were eventually devastated by climate change.

Rocks and coal

Lower Carboniferous marble in Big Cottonwood Canyon, Wasatch Mountains, Utah.

Carboniferous rocks in Europe and eastern North America largely consist of a repeated sequence of limestone, sandstone, shale and coal beds. In North America, the early Carboniferous is largely marine limestone, which accounts for the division of the Carboniferous into two periods in North American schemes. The Carboniferous coal beds provided much of the fuel for power generation during the Industrial Revolution and are still of great economic importance.

The large coal deposits of the Carboniferous primarily owe their existence to two factors. The first of these is the appearance of bark-bearing trees (and in particular the evolution of the bark fiber lignin). The second is the lower sea levels that occurred during the Carboniferous as compared to the Devonian period. This allowed for the development of extensive lowland swamps and forests in North America and Europe. Some hypothesize that large quantities of wood were buried during this period because animals and decomposing bacteria had not yet evolved that could effectively digest the new lignin. Those early plants made extensive use of lignin. They had bark to wood ratios of 8 to 1, and even as high as 20 to 1. This compares to modern values less than 1 to 4. This bark, which must have been used as support as well as protection, probably had 38% to 58% lignin. Lignin is insoluble, too large to pass through cell walls, too heterogeneous for specific enzymes, and toxic, so that few organisms other than Basidiomycetes fungi can degrade it. It can not be oxidized in an atmosphere of less than 5% oxygen. It can linger in soil for thousands of years and inhibits decay of other substances. Probably the reason for its high percentages is protection from insect herbivory in a world containing very effective insect herbivores, but nothing remotely as effective as modern insectivores and probably many fewer poisons than currently. In any case coal measures could easily have made thick deposits on well drained soils as well as swamps. The extensive burial of biologically-produced carbon led to a buildup of surplus oxygen in the atmosphere; estimates place the peak oxygen content as high as 35%, compared to 21% today. This oxygen level probably increased wildfire activity, as well as resulted in insect and amphibian gigantism--creatures whose size is constrained by respiratory systems that are limited in their ability to diffuse oxygen.

In eastern North America, marine beds are more common in the older part of the period than the later part and are almost entirely absent by the late Carboniferous. More diverse geology existed elsewhere, of course. Marine life is especially rich in crinoids and other echinoderms. Brachiopods were abundant. Trilobites became quite uncommon. On land, large and diverse plant populations existed. Land vertebrates included large amphibians.

Life

Plants

Etching depicting some of the most significant plants of the Carboniferous.

Early Carboniferous land plants were very similar to those of the preceding Late Devonian, but new groups also appeared at this time.

The main Early Carboniferous plants were the Equisetales (horse-tails), Sphenophyllales (vine-like plants), Lycopodiales (club mosses), Lepidodendrales (scale trees), Filicales (ferns), Medullosales (informally included in the "seed ferns", an artificial assemblage of a number of early gymnosperm groups) and the Cordaitales. These continued to dominate throughout the period, but during late Carboniferous, several other groups, Cycadophyta (cycads), the Callistophytales (another group of "seed ferns"), and the Voltziales (related to and sometimes included under the conifers), appeared.

The Carboniferous lycophytes of the order Lepidodendrales, which are cousins (but not ancestors) of the tiny club-moss of today, were huge trees with trunks 30 meters high and up to 1.5 meters in diameter. These included *Lepidodendron* (with its fruit cone called Lepidostrobus), *Halonia*, *Lepidophloios* and *Sigillaria*. The roots of several of these forms are known as Stigmaria. The Cladoxylopsids were large trees, that were ancestors of ferns, first arising in the Carboniferous.

The fronds of some Carboniferous ferns are almost identical with those of living species. Probably many species were epiphytic. Fossil ferns and "seed ferns" include *Pecopteris*, *Cyclopteris*, *Neuropteris*, *Alethopteris*, and *Sphenopteris*; *Megaphyton* and *Caulopteris* were tree ferns.

The Equisetales included the common giant form *Calamites*, with a trunk diameter of 30 to 60 cm (24 in) and a height of up to 20 m (66 ft). *Sphenophyllum* was a slender climbing plant with whorls of leaves, which was probably related both to the calamites and the lycopods.

Cordaites, a tall plant (6 to over 30 meters) with strap-like leaves, was related to the cycads and conifers; the catkin-like inflorescence, which bore yew-like berries, is called *Cardiocarpus*. These plants were thought to live in swamps and mangroves. True coniferous trees (*Walchia*, of the order Voltziales) appear later in the Carboniferous, and preferred higher drier ground.

Marine invertebrates

In the oceans the most important marine invertebrate groups are the foraminifera, corals, bryozoa, brachiopods, ammonoids, hederelloids, microconchids and echinoderms (especially crinoids).

For the first time foraminifera take a prominent part in the marine faunas. The large spindle-shaped genus *Fusulina* and its relatives were abundant in what is now Russia, China, Japan, North America; other important genera include *Valvulina*, *Endothyra*, *Archaediscus*, and *Saccammina* (the latter common in Britain and Belgium). Some Carboniferous genera are still extant.

The microscopic shells of radiolarians are found in cherts of this age in the Culm of Devon and Cornwall, and in Russia, Germany and elsewhere.

Sponges are known from spicules and anchor ropes, and include various forms such as the Calcispongea *Cotyliscus* and *Girtycoelia*, the demosponge *Chaetetes*, and the genus of unusual colonial glass sponges *Titusvillia*.

Both reef-building and solitary corals diversify and flourish; these include both rugose (e.g. *Canina*, *Corwenia*, *Neozaphrentis*), heterocorals, and tabulate (e.g. *Chladochonus*, *Michelinia*) forms.

Conularids were well represented by *Conularia*

Bryozoa are abundant in some regions; the fenestellids including *Fenestella*, *Polypora*, and the remarkable *Archimedes*, so named because it is in the shape of an Archimedean screw.

Brachiopods are also abundant; they include productids, some of which (e.g. *Gigantoproductus*) reached very large (for brachiopods) size and had very thick shells, while others like *Chonetes* were more conservative in form. Athyridids, spiriferids, rhynchonellids, and terebratulids are also very common. Inarticulate forms include *Discina* and *Crania*. Some species and genera had a very wide distribution with only minor variations.

Annelids such as *Serpulites* are common fossils in some horizons.

Among the mollusca, the bivalves continue to increase in numbers and importance. Typical genera include *Aviculopecten*, *Posidonomya*, *Nucula*, *Carbonicola*, *Edmondia*, and *Modiola*

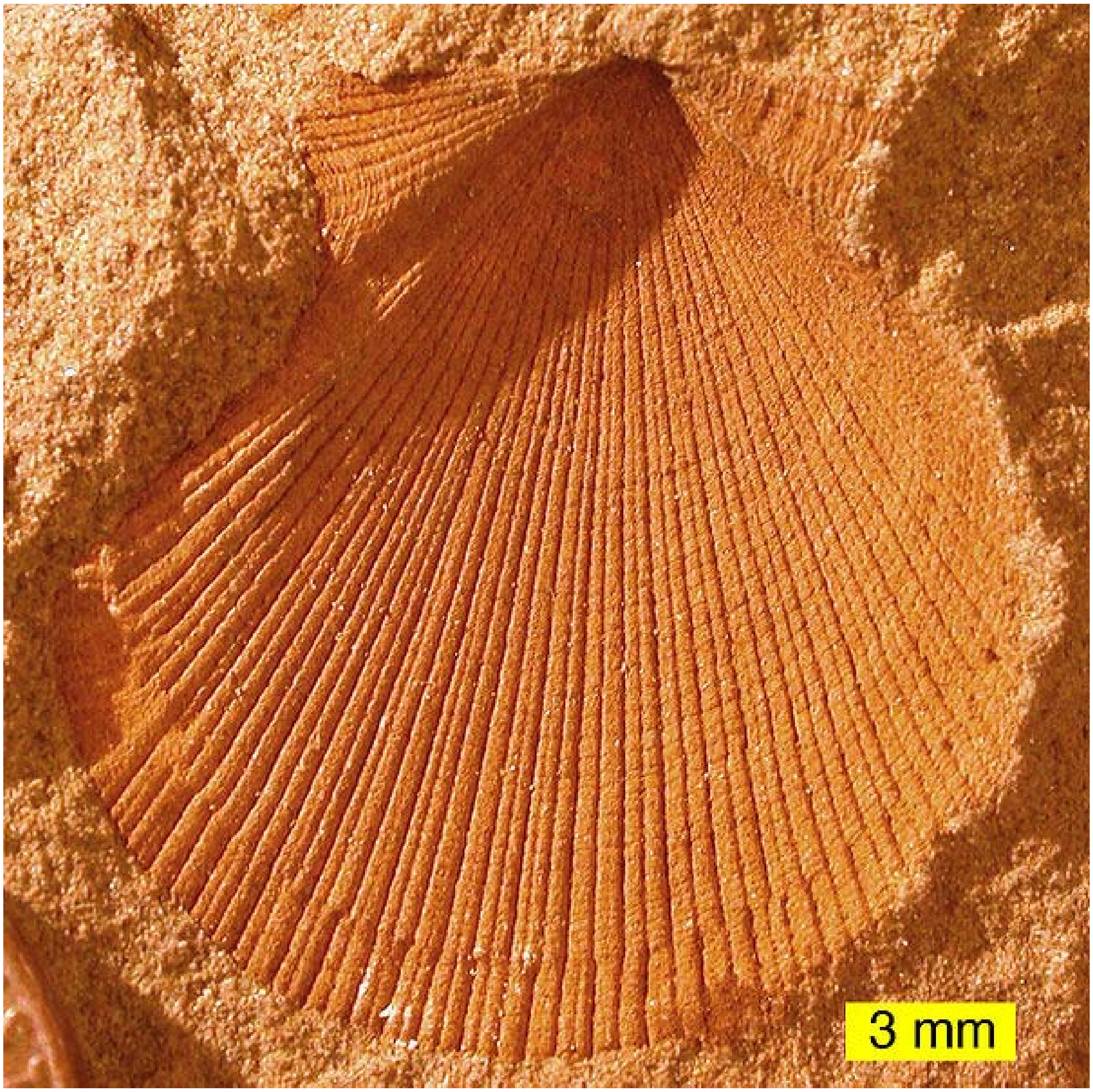
Conocardium is a common rostroconch.

Gastropods are also numerous, including the genera *Murchisonia*, *Euomphalus*, *Naticopsis*.

Nautiloid cephalopods are represented by tightly coiled nautilids, with straight-shelled and curved-shelled forms becoming increasingly rare. Goniatite ammonoids are common.

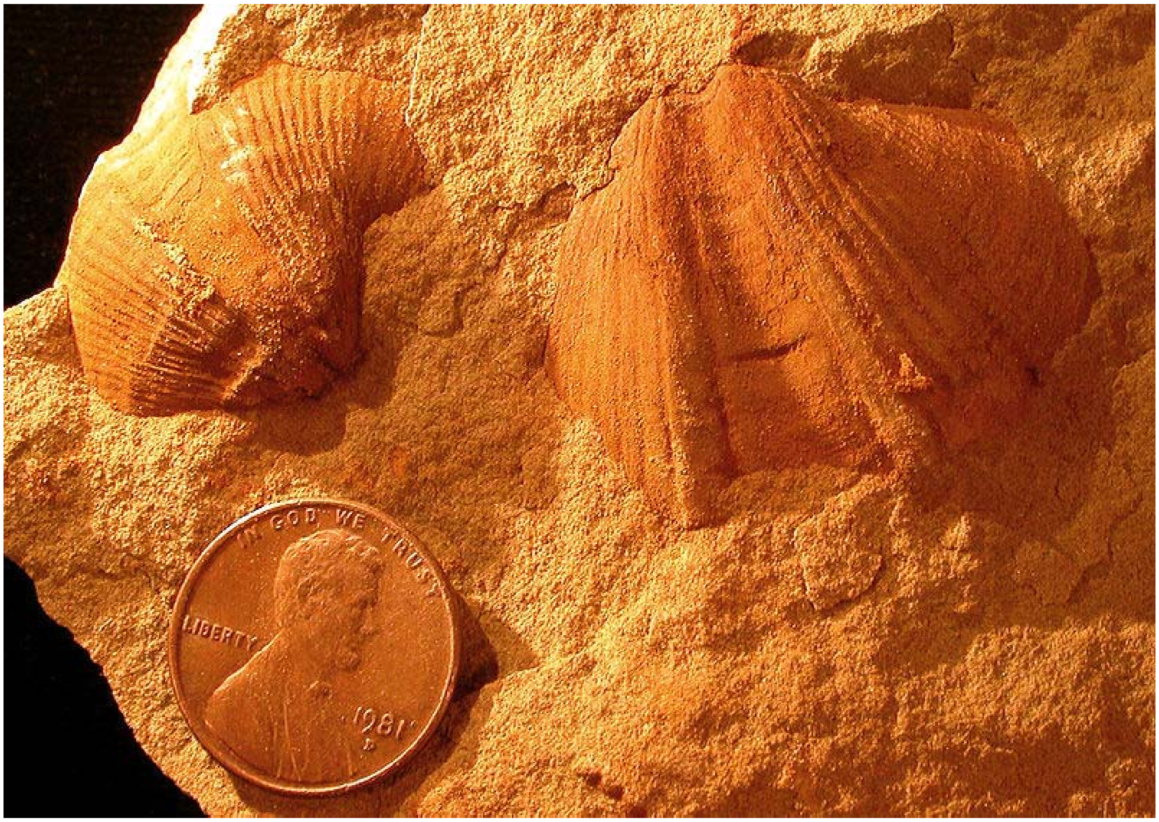
Trilobites are rarer than in previous periods, represented only by the proetid group. Ostracods, a class of crustacean zooplankton, were abundant; genera included *Cythere*, *Kirkbya*, and *Beyrichia*.

Amongst the echinoderms, the crinoids were the most numerous. Dense submarine thickets of long-stemmed crinoids appear to have flourished in shallow seas, and their remains were consolidated into thick beds of rock. Prominent genera include *Cyathocrinus*, *Woodocrinus*, and *Actinocrinus*. Echinoids such as *Archaeocidaris* and *Palaeechinus* were also present. The blastoids, which included the Pentreinitidae and Codasteridae and superficially resembled crinoids in the possession of long stalks attached to the seabed, attain their maximum development at this time.



Aviculopecten subcardiformis; a bivalve from the Logan Formation (Lower Carboniferous) of Wooster, Ohio (external mold).

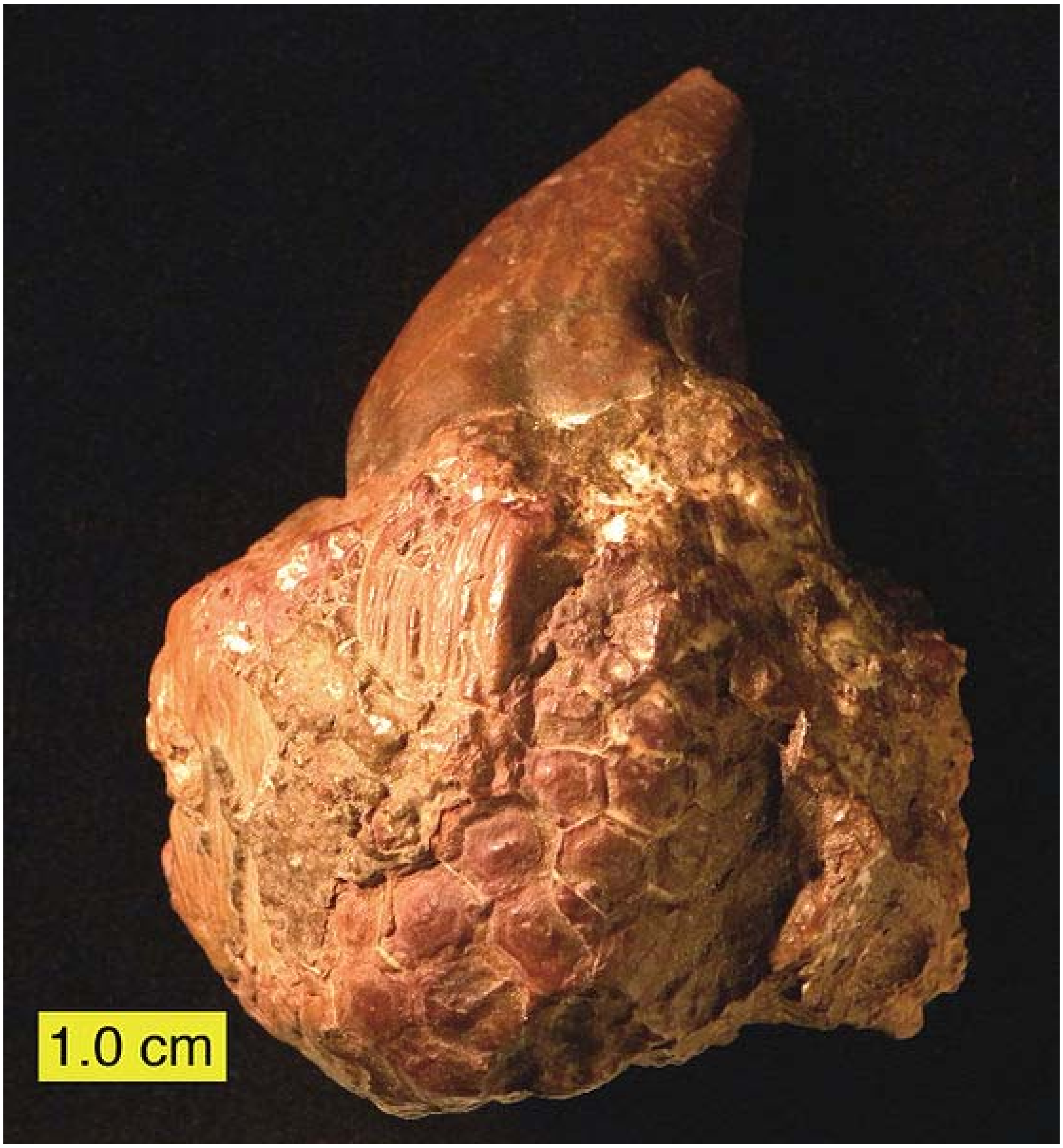
Schizodus medinaensis; a bivalve from the Logan Formation (Lower Carboniferous) of Wooster, Ohio (internal mold).



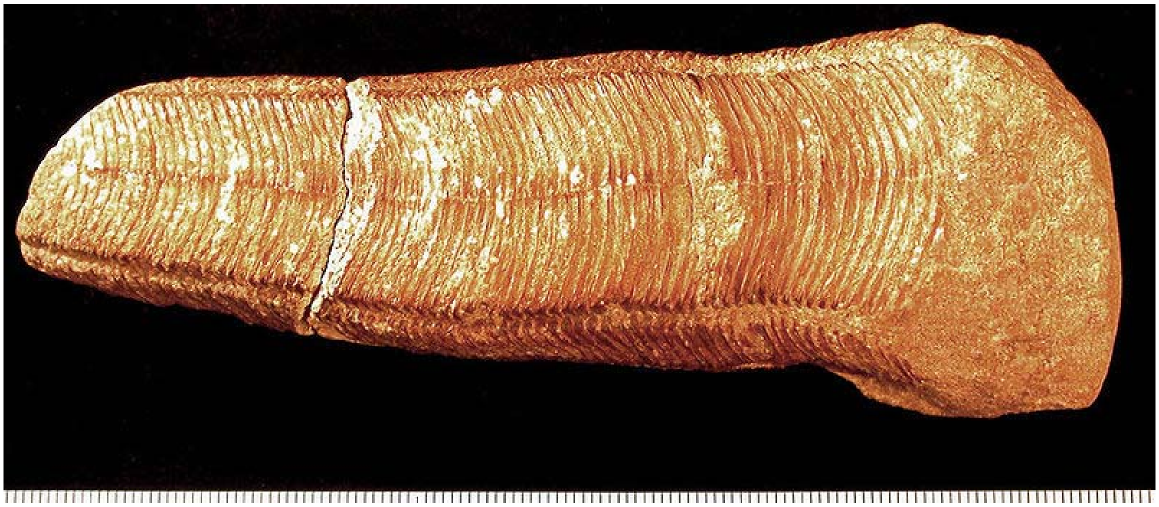
Syringothyris sp.; a spiriferid brachiopod from the Logan Formation (Lower Carboniferous) of Wooster, Ohio (internal mold).

Palaeophycus ichnosp.; a trace fossil from the Logan Formation (Lower Carboniferous) of Wooster, Ohio.

Helminthopsis ichnosp.; a trace fossil from the Logan Formation (Lower Carboniferous) of Wooster, Ohio.



Crinoid calyx from the Lower Carboniferous of Ohio with a conical platyceratid gastropod (*Palaeocapulus acutirostre*) attached.



Conulariid from the Lower Carboniferous of Indiana; scale in mm.

Tabulate coral (a syringoporid); Boone Limestone (Lower Carboniferous) near Hiwasse, Arkansas. Scale bar is 2.0 cm (1 in).

Fish

Many fish inhabited the Carboniferous seas; predominantly Elasmobranchs (sharks and their relatives). These included some, like *Psammodus*, with crushing pavement-like teeth adapted for grinding the shells of brachiopods, crustaceans, and other marine organisms. Other sharks had piercing teeth, such as the Symmoriida; some, the petalodonts, had peculiar cycloid cutting teeth. Most of the sharks were marine, but the Xenacanthida invaded fresh waters of the coal swamps. Among the bony fish, the Palaeonisciformes found in coastal waters also appear to have migrated to rivers. Sarcopterygian fish were also prominent, and one group, the Rhizodonts, reached very large size.

Most species of Carboniferous marine fish have been described largely from teeth, fin spines and dermal ossicles, with smaller freshwater fish preserved whole.

Freshwater fish were abundant, and include the genera *Ctenodus*, *Uronemus*, *Acanthodes*, *Cheirodus*, and *Gyracanthus*.

Sharks (especially the *Stethacanthids*) underwent a major evolutionary radiation during the Carboniferous. It is believed that this evolutionary radiation occurred because the decline of the placoderms at the end of the Devonian period caused many environmental niches to become unoccupied and allowed new organisms to evolve and fill these niches. As a result of the evolutionary radiation carboniferous sharks assumed a wide variety of bizarre shapes including *Stethacanthus* who possessed a flat brush-like dorsal fin with a patch of denticles on its top. *Stethacanthus* unusual fin may have been used in mating rituals.

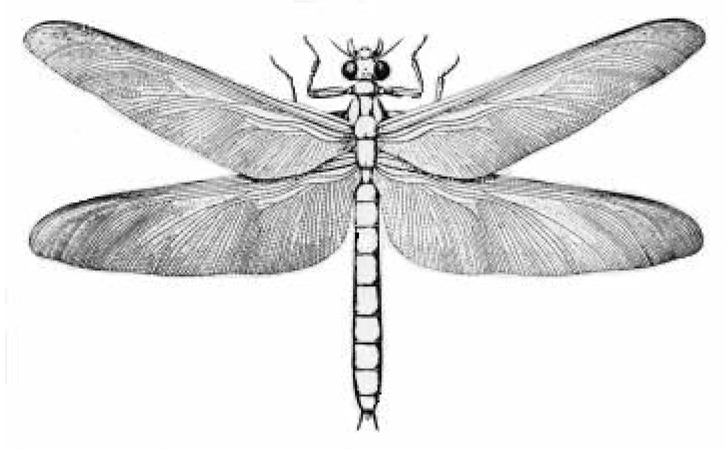
Freshwater and lagoonal invertebrates

Freshwater Carboniferous invertebrates include various bivalve molluscs that lived in brackish or fresh water, such as *Anthracomya*, *Naiadiles*, and *Carbonicola*; diverse crustaceans such as *Bairdia*, *Carbonita*, *Estheria*, *Acanthocaris*, *Dithyrocaris*, and *Anthrapalaemon*.

The Eurypterids were also diverse, and are represented by such genera as *Eurypterus*, *Glyptoscorpius*, *Anthraconectes*, *Megarachne* (originally misinterpreted as a giant spider) and the specialised very large *Hibbertopterus*. Many of these were amphibious.

Frequently a temporary return of marine conditions resulted in marine or brackish water genera such as *Lingula*, Orbiculoidea, and *Productus* being found in the thin beds known as marine bands.

Terrestrial Invertebrates



Late Carboniferous giant dragonfly-like insect Meganeura grew to wingspans of 75 cm (30 in).

Gigantic Pulmonoscorpius from the early Carboniferous reached a length of up to one metre.

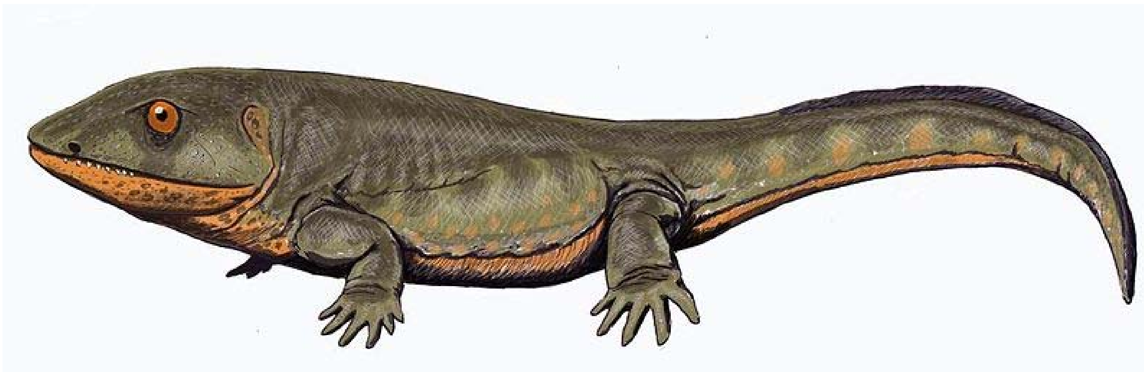
Fossil remains of air-breathing insects, myriapods and arachnids are known from the late Carboniferous, but so far not from the early Carboniferous. Their diversity when they do appear, however, shows that these arthropods were both well developed and numerous. Their large size can be attributed to the moistness of the environment (mostly swampy fern forests) and the fact that the oxygen concentration in the Earth's atmosphere in the Carboniferous was much higher than today. (The oxygen concentration in the Earth's atmosphere during the Carboniferous was 35% whereas the oxygen concentration in earth's current atmosphere is 21%.) This required less effort for respiration and allowed arthropods to grow larger with the up to 2.6 metres long millipede-like Arthropleura being the largest known land invertebrate of all time. Among the insect groups are the huge predatory Protodonata (griffinflies), among which was Meganeura, a giant dragonfly-like insect and with a wingspan of ca. 75 cm (30 in) — the largest flying insect ever to roam the planet. Further groups are the Syntonopterodea (relatives of present-day mayflies), the abundant and often large sap-sucking Palaeodictyopteroidea, the diverse herbivorous "Protorthoptera", and numerous basal Dictyoptera (ancestors of cockroaches). Many insects have been obtained from the coalfields of Saarbrücken and Commentry, and from the hollow trunks of fossil trees in Nova Scotia. Some British coalfields have yielded good specimens: *Archaeoptitus*, from the Derbyshire coalfield, had a spread of wing extending to more than 35 cm; some specimens (*Brodia*) still exhibit traces of brilliant wing colors. In the Nova Scotian tree trunks land snails (*Archaeozonites*, *Dendropupa*) have been found.

Tetrapods

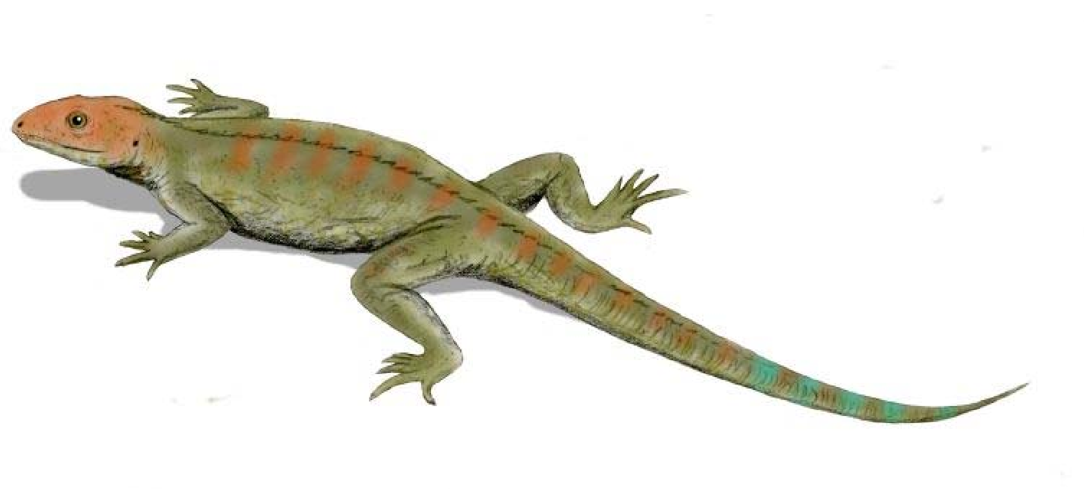
Carboniferous amphibians were diverse and common by the middle of the period, more so than they are today; some were as long as 6 meters, and those fully terrestrial as adults had scaly skin. They included a number of basal tetrapod groups classified in early books under the Labyrinthodontia. These had long bodies, a head covered with bony plates and generally weak or undeveloped limbs. The largest were over 2 meters long. They were accompanied by an assemblage of smaller amphibians included under the Lepospondyli, often only about 15 cm (6 in) long. Some Carboniferous amphibians were aquatic and lived in rivers (*Loxomma*, *Eogyrinus*, *Proterogyrinus*); others may have been semi-aquatic (*Ophiderpeton*, *Amphibamus*, *Hyloplesion*) or terrestrial (*Dendrerpeton*, *Tuditanus*, *Anthracosaurus*).

The Carboniferous Rainforest Collapse slowed the evolution of amphibians who could not survive as well in the cooler, drier conditions. Reptiles, however prospered due to specific key adaptations. One of the greatest evolutionary innovations of the Carboniferous was the amniote egg, which allowed for the further exploitation of the land by certain tetrapods. These included the earliest sauropsid reptiles (*Hylonomus*), and the earliest known synapsid (*Archaeothyris*). These small lizard-like animals quickly gave rise to many descendants. The amniote egg allowed these ancestors of all later birds, mammals, and reptiles to reproduce on land by preventing the desiccation, or drying-out, of the embryo inside.

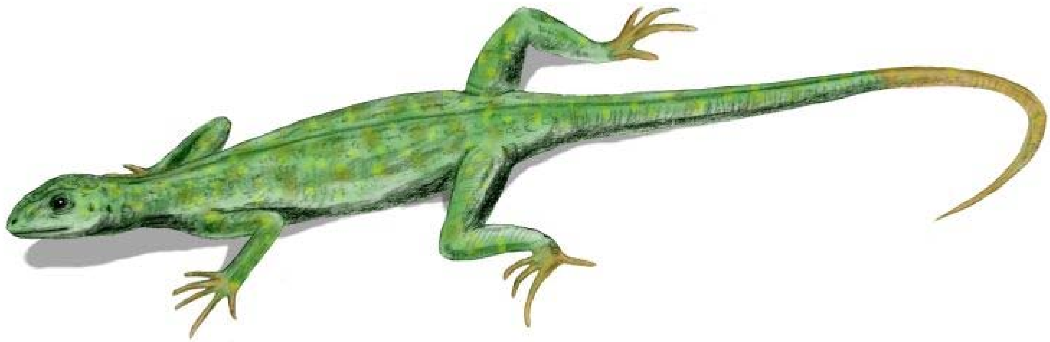
Reptiles underwent a major evolutionary radiation, in response to the drier climate that proceeded the rainforest collapse. By the end of the Carboniferous period, amniotes had already diversified into a number of groups, including protorothyridids, captorhinids, aeroscelids, and several families of pelycosaurs.



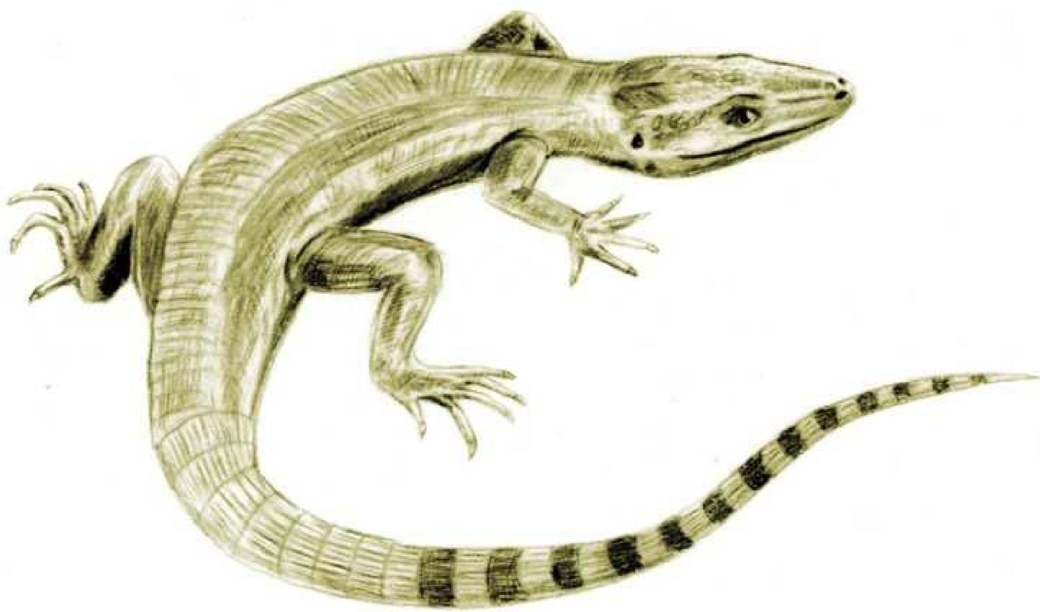
The amphibian-like *Pederpes*, the most primitive Mississippian tetrapod



Hylonomus, the earliest sauropsid reptile, appeared in the Pennsylvanian.



Petrolacosaurus, the first diapsid reptile known, lived during the late Carboniferous.



Archaeothyris was a very early mammal-like reptile and is the oldest undisputed synapsid known.

Fungal life

Because plants and animals were growing in size and abundance in this time (e.g., *Lepidodendron*), land fungi diversified further. Marine fungi still occupied the oceans.

All modern classes of fungi were present in the Late Carboniferous (Pennsylvanian Epoch).

Extinction events

In the middle Carboniferous, an extinction event occurred. On land this event is referred to as the Carboniferous Rainforest Collapse (CRC) . Vast tropical rainforests collapsed suddenly as the climate changed from hot and humid to cool and arid. This was likely caused by intense glaciation and a drop in sea levels .

The new climatic conditions were not favorable to the growth of rainforest and the animals within them. Rainforests shrank into isolated islands, surrounded by seasonally dry habitats. Towering lycopsid forests with a heterogenus mixture of vegetation were replaced by much less diverse treefrens dominated flora.

Amphibians, the dominant vertebrates at the time fared poorly through this event with large losses in biodiversity; reptiles continued to diversify due to key adaptations that let them survive in the drier habitat, specifically the hard-shelled egg and scales both of which retain water better then their amphibian counterparts .

Chapter- 11

Permian

The **Permian** is a geologic period and system characterized among land vertebrates by the diversification of the early amniotes into the ancestral groups of the mammals, turtles, lepidosaurs and archosaurs. The Permian Period follows the Carboniferous and extends from 299.0 ± 0.8 to 251.0 ± 0.4 Mya (million years before the present). It is the last period of the Paleozoic Era and famous for its ending epoch event, the largest mass extinction known to science. The Permian Period was named after the kingdom of Permia in modern-day Russia by Scottish geologist Roderick Murchison in 1841.

ICS Subdivisions

Official (ICS, 2004, chart) Subdivisions of the Permian System, from most recent to most ancient rock layers are:

Upper Permian (Late Permian) or Lopingian, Tatarian, or Zechstein, epoch [260.4 ± 0.7 Mya - 251.0 ± 0.4 Mya]

- Changhsingian (Changxingian) [253.8 ± 0.7 Mya - 251.0 ± 0.4 Mya]
- Wuchiapingian (Wujiapingian) [260.4 ± 0.7 Mya - 253.8 ± 0.7 Mya]
- Others:
  - Waiitian (New Zealand) [260.4 ± 0.7 Mya - 253.8 ± 0.7 Mya]
  - Makabewan (New Zealand) [253.8 - 251.0 ± 0.4 Mya]
  - Ochoan (North American) [260.4 ± 0.7 Mya - 251.0 ± 0.4 Mya]

Middle Permian, or Guadalupian epoch [270.6 ± 0.7 - 260.4 ± 0.7 Mya]

- Capitanian stage [265.8 ± 0.7 - 260.4 ± 0.7 Mya]
- Wordian stage [268.0 ± 0.7 - 265.8 ± 0.7 Mya]
- Roadian stage [270.6 ± 0.7 - 268.0 ± 0.7 Mya]
- Others:
  - Kazanian or Maokovian (European) [270.6 ± 0.7 - 260.4 ± 0.7 Mya]
  - Braxtonian stage (New Zealand) [270.6 ± 0.7 - 260.4 ± 0.7 Mya]

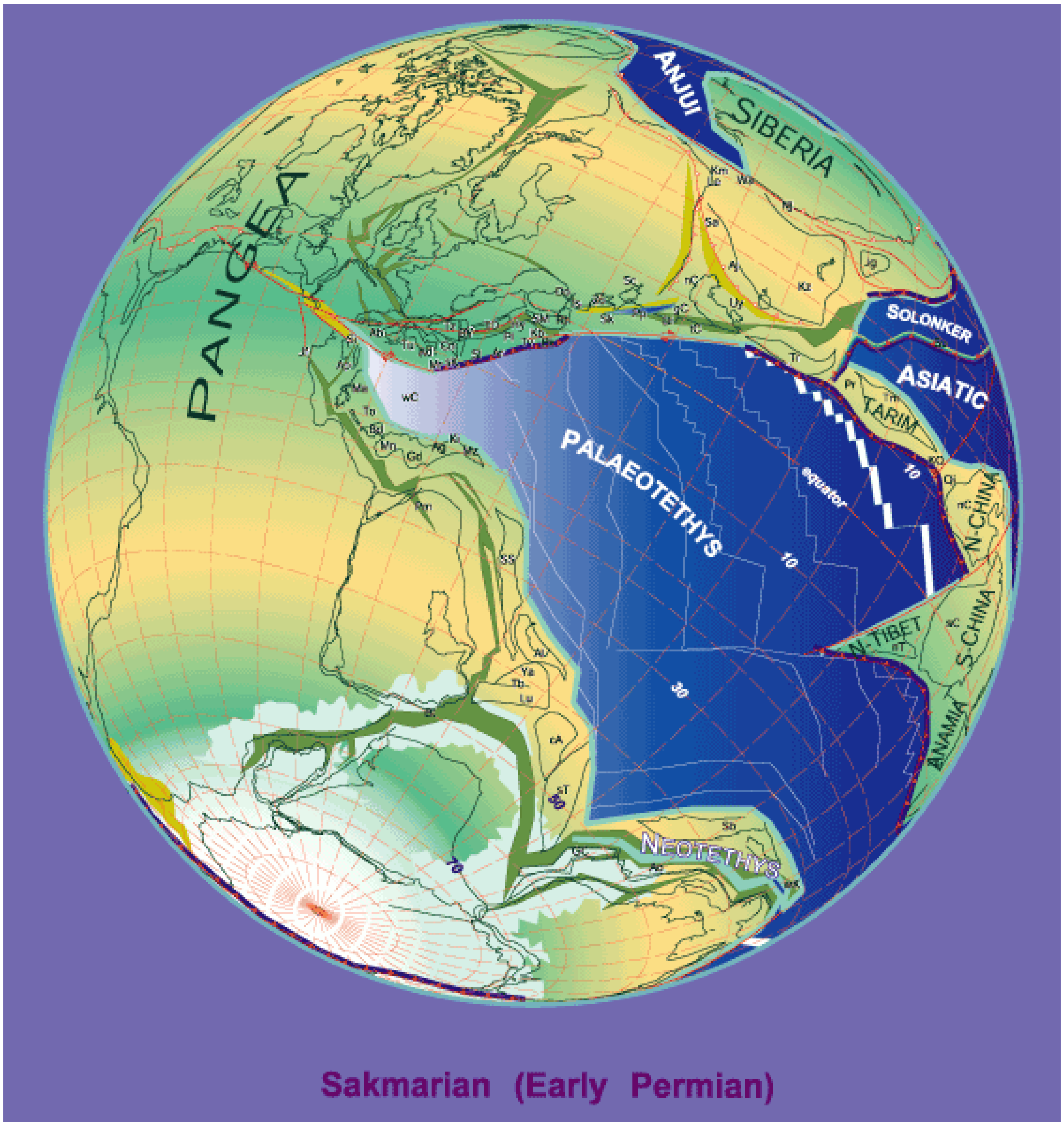
Lower / Early Permian or Cisuralian epoch [299.0 ± 0.8 - 270.6 ± 0.7 Mya]

- Kungurian (Irenian / Filippovian / Leonard) stage [275.6 ± 0.7 - 270.6 ± 0.7 Mya]
- Artinskian (Baigendzinian / Aktastinian) stage [284.4 ± 0.7 - 275.6 ± 0.7 Mya]
- Sakmarian (Sterlitamakian / Tastubian / Leonard / Wolfcamp) stage [294.6 ± 0.8 - 284.4 ± 0.7 Mya]
- Asselian (Krumaian / Uskalikian / Surenian / Wolfcamp) stage [299.0 ± 0.8 - 294.6 ± 0.8 Mya]
- Others:
    - Telfordian (New Zealand) [289 - 278]
    - Mangapirian (New Zealand) [278 - 270.6]

Oceans

Sea levels in the Permian remained generally low, and near-shore environments were limited by the collection of almost all major landmasses into a single continent -- Pangaea. This could have in part caused the widespread extinctions of marine species at the end of the period by severely reducing shallow coastal areas preferred by many marine organisms.

Paleogeography



Sakmarian (Early Permian)

Geography of the Permian world

During the Permian, all the Earth's major land masses were collected into a single supercontinent known as Pangaea. Pangaea straddled the equator and extended toward the poles, with a corresponding effect on ocean currents in the single great ocean ("Panthalassa", the "universal sea"), and the Paleo-Tethys Ocean, a large ocean that was between Asia and Gondwana. The Cimmeria continent rifted away from Gondwana and drifted north to Laurasia, causing the Paleo-Tethys to shrink. A new ocean was growing on its southern end, the Tethys Ocean, an ocean that would dominate much of the Mesozoic Era. Large continental landmasses create climates with extreme variations of heat and cold ("continental climate") and monsoon conditions with highly seasonal rainfall patterns. Deserts seem to have been widespread on Pangaea. Such dry conditions favored gymnosperms, plants with seeds enclosed in a protective cover, over plants such as ferns that disperse spores. The first modern trees (conifers, ginkgos and cycads) appeared in the Permian.

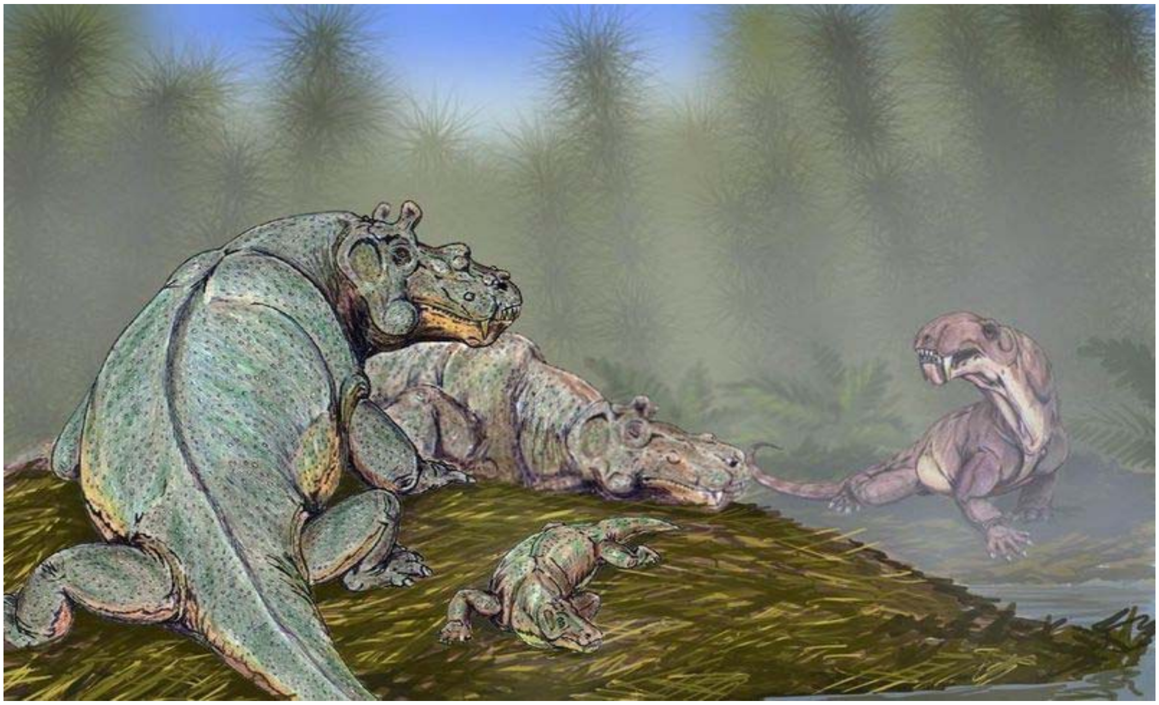
Three general areas are especially noted for their extensive Permian deposits - the Ural Mountains (where Perm itself is located), China, and the southwest of North America, where the Permian Basin in the U.S. state of Texas is so named because it has one of the thickest deposits of Permian rocks in the world.

Climate

The climate in the Permian was quite varied. At the start of the Permian, the Earth was still at the grip of an Ice Age from the Carboniferous. Glaciers receded around the mid-Permian period as the climate gradually warmed, drying the continent's interiors. In the late Permian period, the drying continued although the temperature cycled between warm and cool cycles.

Life

Dimetrodon and *Eryops*- Early Permian, North America



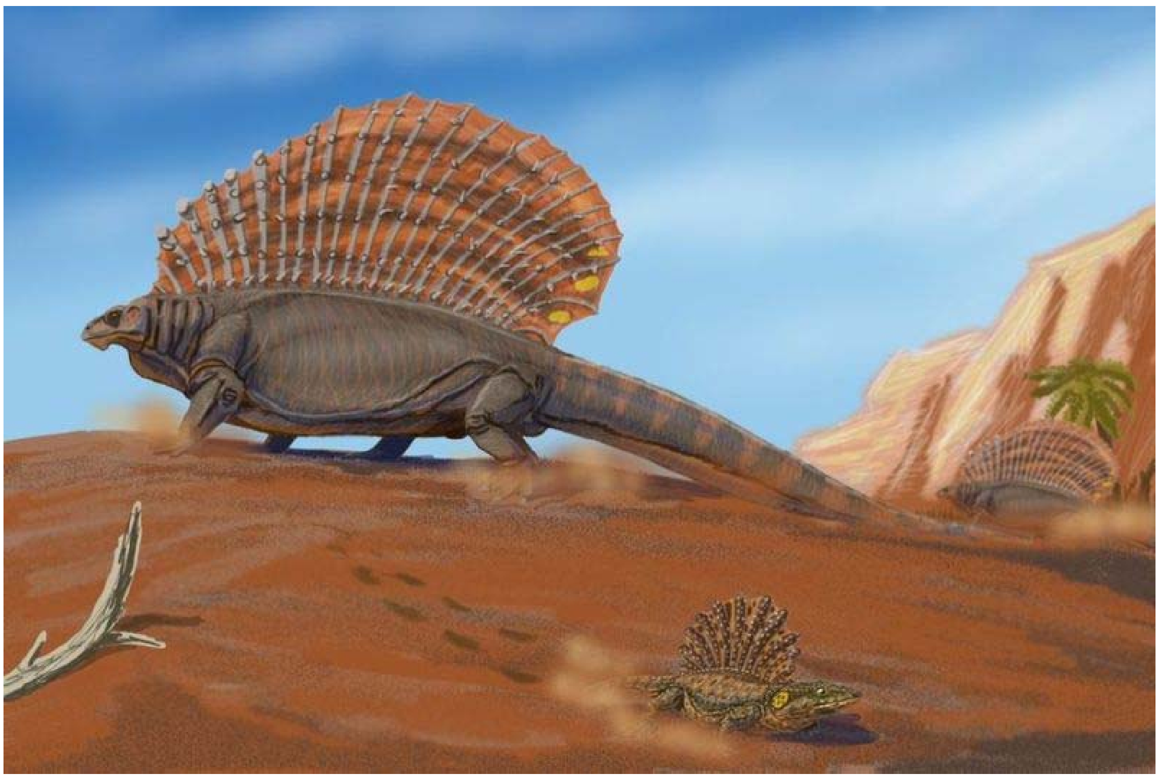
Ocher fauna - Early Middle Permian, Ural Region

Titanophoneus and *Ulemosaurus* - Ural Region

Marine biota

Permian marine deposits are rich in fossil mollusks, echinoderms, and brachiopods. Fossilized shells of two kinds of invertebrates are widely used to identify Permian strata and correlate them between sites: fusulinids, a kind of shelled amoeba-like protist that is one of the foraminiferans, and ammonoids, shelled cephalopods that are distant relatives of the modern nautilus. By the close of the Permian, trilobites and a host of other marine groups became extinct.

Terrestrial biota



Edaphosaurus pogonias and *Platyhystrix* - Early Permian

Terrestrial life in the Permian included diverse plants, fungi, arthropods, and various types of tetrapods. The period saw a massive desert covering the interior of the Pangaea. The warm zone spread in the northern hemisphere, where extensive dry desert appeared. The rocks formed at that time were stained red by iron oxides, the result of intense heating by the sun of a surface devoid of vegetation cover. A number of older types of plants and animals died out or became marginal elements.

The Permian began with the Carboniferous flora still flourishing. About the middle of the Permian a major transition in vegetation began. The swamp-loving lycopod trees of the Carboniferous, such as *Lepidodendron* and *Sigillaria*, were progressively replaced in the continental interior by the more advanced seed ferns and early conifers. At the close of the Permian, lycopod and equicete swamps reminiscent of Carboniferous flora was relegated to a series of equatorial islands in the Paleotethys Sea that later would become the South China.

The Permian saw the radiation of many important conifer groups, including the ancestors of many present-day families. Rich forests were present in many areas, with a diverse mix of plant groups. The southern continent saw extensive seed fern forests of the *Glossopteris* flora. Oxygen levels were probably high there. The ginkgos and cycads also appeared during this period.

Insects of the Permian

By the Pennsylvanian and well into the Permian, by far the most successful were primitive relatives of cockroaches. Six fast legs, two well developed folding wings, fairly good eyes, long, well developed antennae (olfactory), an omnivorous digestive system, a receptacle for storing sperm, a chitin skeleton that could support and protect, as well as form of gizzard and efficient mouth parts, gave it formidable advantages over other herbivorous animals. About 90% of insects were cockroach-like insects ("Blattopterans").

The dragonflies *Odonata* were the dominant aerial predator and probably dominated terrestrial insect predation as well. True Odonata appeared in the Permian and all are amphibious. Their prototypes are the oldest winged fossils, go back to the Devonian, and are different from other wings in every way. Their prototypes may have had the beginnings of many modern attributes even by late Carboniferous and it is possible that they even captured small vertebrates, for some species had a wing span of 71 cm. A number of important new insect groups appeared at this time, including the Coleoptera (beetles) and Diptera (flies).

Reptile and amphibian fauna

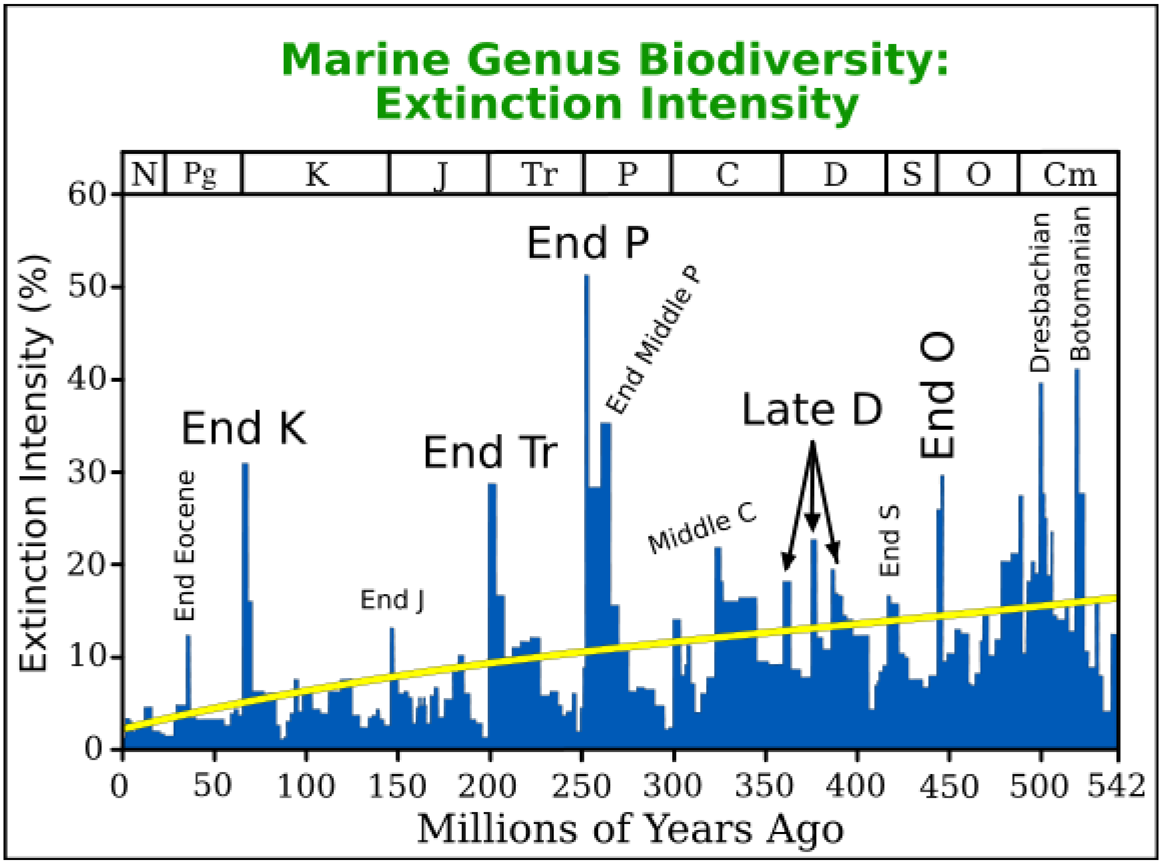
Early Permian terrestrial faunas were dominated by pelycosaurs and amphibians, the middle Permian by primitive therapsids such as the dinocephalia, and the late Permian by more advanced therapsids such as gorgonopsians and dicynodonts. Towards the very end of the Permian the first archosaurs appeared, a group that would give rise to the dinosaurs in the following period. Also appearing at the end of the Permian were the first cynodonts, which would go on to evolve into mammals during the Triassic. Another group of therapsids, the therocephalians (such as *Trochosaurus*), arose in the Middle Permian. There were no aerial vertebrates.

The Permian period saw the development of a fully terrestrial fauna and the appearance of the first large herbivores and carnivores. It was the high tide of the anapsides in the form of the massive Pareiasaurs and host of smaller, generally lizard-like groups. A group of small reptiles, the diapsids started to abound. These were the ancestors to most modern reptiles and the ruling dinosaurs as well as pterosaurs and crocodiles.

Thriving also, were the early ancestors to mammals, the synapsida, which included some large reptiles such as *Dimetrodon*. Reptiles grew to dominance among vertebrates, because their special adaptations enabled them to flourish in the drier climate.

Permian amphibians consisted of temnospondyli, lepospondyli and batrachosaurs.

Permian–Triassic extinction event



The Permian–Triassic extinction event, labeled "End P" here, is the most significant extinction event in this plot for marine genera which produce large numbers of fossils.

The Permian ended with the most extensive extinction event recorded in paleontology: the Permian-Triassic extinction event. 90% to 95% of marine species became extinct, as well as 70% of all land organisms. It is also the only known mass extinction of insects. On an individual level, perhaps as many as 99.5% of separate organisms died as a result of the event. Recovery from the Permian-Triassic extinction event was protracted; on land ecosystems took 30M years to recover.

There is also significant evidence that massive flood basalt eruptions from magma output lasting thousands of years in what is now the Siberian Traps contributed to environmental stress leading to mass extinction. The reduced coastal habitat and highly increased aridity probably also contributed. Based on the amount of lava estimated to have been produced during this period, the worst-case scenario is an expulsion of enough carbon dioxide from the eruptions to raise world temperatures five degrees Celsius.

Another hypothesis involves ocean venting of hydrogen sulfide gas. Portions of deep ocean will periodically lose all of their dissolved oxygen allowing bacteria that live without oxygen to flourish and produce hydrogen sulfide gas. If enough hydrogen sulfide accumulates in an anoxic zone, the gas can rise into the atmosphere.

Oxidizing gases in the atmosphere would destroy the toxic gas, but the hydrogen sulfide would soon consume all of the atmospheric gas available to change it. Hydrogen sulfide levels would increase dramatically over a few hundred years.

Modeling of such an event indicates that the gas would destroy ozone in the upper atmosphere allowing ultraviolet radiation to kill off species that had survived the toxic gas. Of course, there are species that can metabolize hydrogen sulfide.

Another hypothesis builds on the flood basalt eruption theory. Five degrees Celsius would not be enough increase in world temperatures to explain the death of 95% of life. But such warming could slowly raise ocean temperatures until frozen methane reservoirs below the ocean floor near coastlines (a current target for a new energy source) melted, expelling enough methane, among the most potent greenhouse gases, into the atmosphere to raise world temperatures an additional five degrees Celsius. The frozen methane hypothesis helps explain the increase in carbon-12 levels midway into the Permian-Triassic boundary layer. It also helps explain why the first phase of the layer's extinctions was land-based, the second was marine-based (and starting right after the increase in C-12 levels), and the third land-based again.

An even more speculative hypothesis is that intense radiation from a nearby supernova was responsible for the extinctions.

Trilobites, which had thrived since Cambrian times, finally became extinct before the end of the Permian.

Nautiluses, a species of cephalopods, surprisingly survived this occurrence.

In 2006, a group of American scientists from Ohio State University reported evidence for a possible huge meteorite crater (Wilkes Land crater) with a diameter of around 500 kilometers in Antarctica. The crater is located at a depth of 1.6 kilometers beneath the ice of Wilkes Land in eastern Antarctica. The scientists speculate that this impact may have caused the Permian–Triassic extinction event, although its age is bracketed only between 100 million and 500 million years ago. They also speculate that it may have contributed in some way to the separation of Australia from the Antarctic landmass, which were both part of a supercontinent called Gondwana. Levels of iridium and quartz fracturing in the Permian-Triassic layer do not approach those of the Cretaceous-Tertiary boundary layer. Given that a far greater proportion of species and individual organisms became extinct during the former, doubt is cast on the significance of a meteor impact in creating the latter. Further doubt has been cast on this theory based on fossils in Greenland showing the extinction to have been gradual, lasting about eighty thousand years, with three distinct phases.

Many scientists believe that the Permian-Triassic extinction event was caused by a combination of some or all of the hypotheses above and other factors; the formation of Pangaea decreased the number of coastal habitats and may have contributed to the extinction of many clades.

Chapter- 12

Mesozoic

The **Mesozoic Era** is an interval of geological time from about 250 million years ago to about 65 million years ago. It is called the Age of Dinosaurs because most dinosaurs developed, and went extinct, during that time. The Chicxulub impact and other events ended the era when a majority of species on earth went extinct.

It is one of three geologic eras of the Phanerozoic eon. The division of time into eras dates back to Giovanni Arduino, in the 18th century, although his original name for the era now called the "Mesozoic" was "Secondary" (making everything after, including the modern era, the "Tertiary"; the current term Quaternary was later proposed for the modern era, following the same numbering principle). Lying between the Paleozoic and the Cenozoic, "Mesozoic" means "middle life", deriving from the Greek prefix *meso-*/*μεσο-* for "between" and *zoon*/*ζωον* meaning "animal" or "living being". It is often called the "Age of the Reptiles", after the dominant fauna of the era.

The Mesozoic was a time of tectonic, climatic and evolutionary activity. The continents gradually shifted from a state of connectedness into their present configuration; the drifting provided for speciation and other important evolutionary developments. The climate was exceptionally warm throughout the period, also playing an important role in the evolution and diversification of new animal species. By the end of the era, the basis of modern life was in place.

Geologic periods

Following the Paleozoic, the Mesozoic extended roughly 180 million years: from 251 million years ago (Mya) to when the Cenozoic era began 65 Mya. This time frame is separated into three geologic periods. From oldest to youngest:

- Triassic (251.0 Ma to 199.6 Mya)
- Jurassic (199.6 Ma to 145.5 Mya)
- Cretaceous (145.5 Ma to 65.5 Mya)

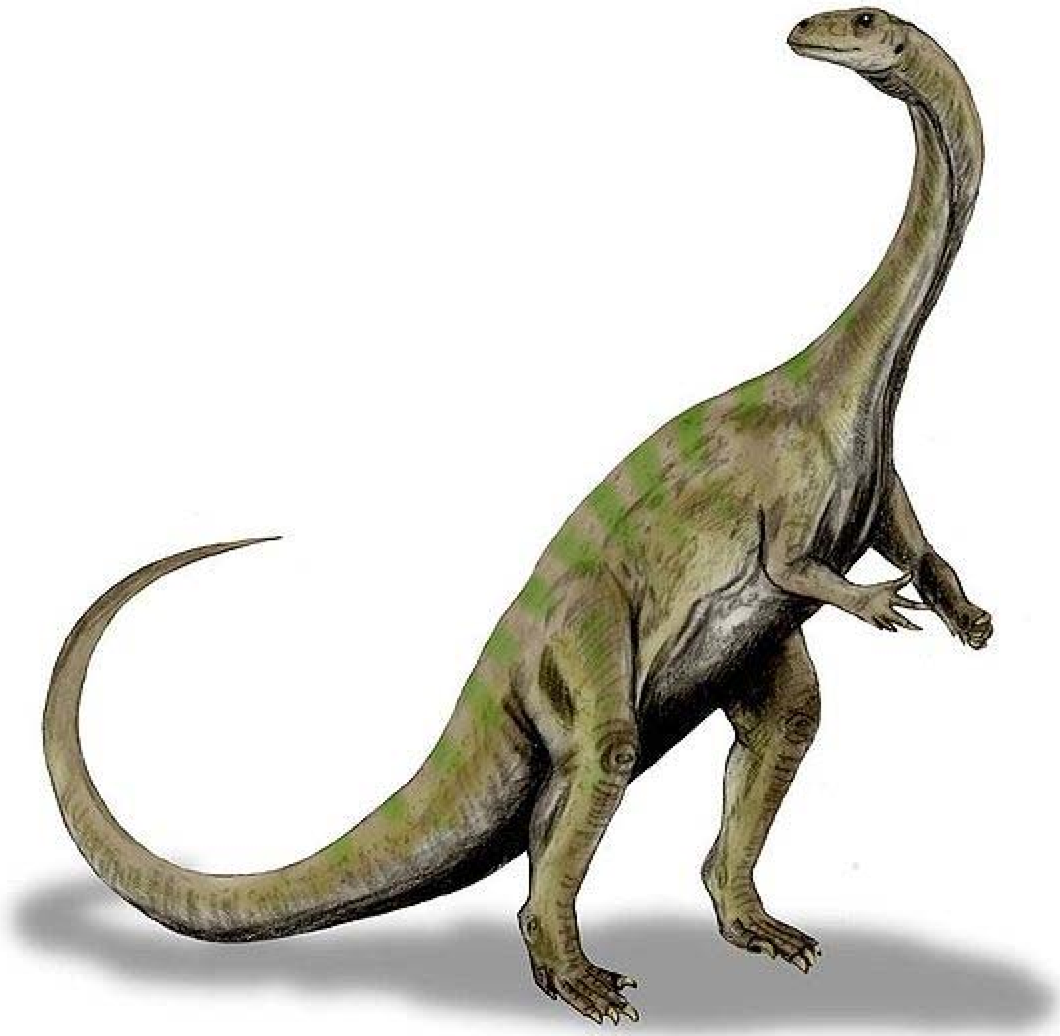
The lower (Triassic) boundary is set by the Permian-Triassic extinction event, during which approximately 90% to 96% of marine species and 70% of terrestrial vertebrates became extinct. It is also known as the "Great Dying" because it is considered the largest mass extinction in the Earth's history. The upper (Cretaceous) boundary is set at the Cretaceous-Tertiary (KT) extinction event (now more accurately called the Cretaceous–Paleogene (or K–Pg) extinction event), which may have been caused by the impactor that created Chicxulub Crater on the Yucatán Peninsula. Approximately 50% of all genera became extinct, including all of the non-avian dinosaurs.

Paleogeography and tectonics

Compared to the vigorous convergent plate mountain-building of the late Paleozoic, Mesozoic tectonic deformation was comparatively mild. Nevertheless, the era featured the dramatic rifting of the supercontinent Pangaea. Pangaea gradually split into a northern continent, Laurasia, and a southern continent, Gondwana. This created the passive continental margin that characterizes most of the Atlantic coastline (such as along the U.S. East Coast) today.

By the end of the era, the continents had rifted into nearly their present form. Laurasia became North America and Eurasia, while Gondwana split into South America, Africa, Australia, Antarctica and the Indian subcontinent, which collided with the Asian plate during the Cenozoic, the impact giving rise to the Himalayas.

Africa

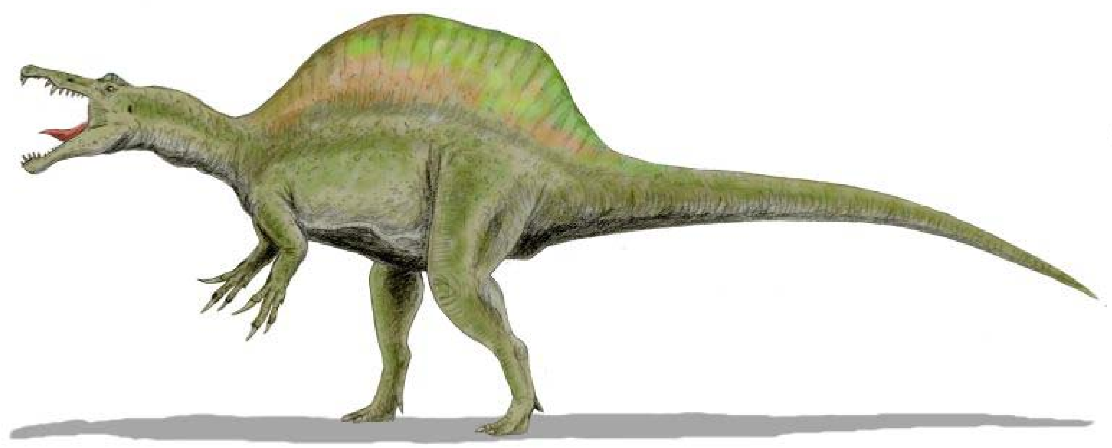


The African prosauropod *Massospondylus*.

At the beginning of the Mesozoic Era, Africa was joined with Earth's other continents in Pangaea. Africa shared the supercontinent's relatively uniform fauna which was dominated by theropods, prosauropods and primitive ornithischians by the close of the Triassic period. Late Triassic fossils are found throughout Africa, but are more common in the south than north. The boundary separating the Triassic and Jurassic marks the advent of an extinction event with global impact, although African strata from this time period have not been thoroughly studied.

Early Jurassic strata are distributed in a similar fashion to Late Triassic beds, with more common outcrops in the south and less common fossil beds which are predominated by tracks to the north. As the Jurassic proceeded, larger and more iconic groups of dinosaurs like sauropods and ornithopods proliferated in Africa. Middle Jurassic strata are neither well represented nor well studied in Africa. Late Jurassic strata are also poorly represented apart from the spectacular Tendeguru fauna in Tanzania. The Late Jurassic life of Tendeguru is very similar to that found in western North America's Morrison Formation.

Midway through the Mesozoic, about 150-160 million years ago, Madagascar separated from Africa, although it remained connected to India and the rest of the Gondwanan landmasses. Fossils from Madagascar include abelisaurs and titanosaurs.



The African theropod *Spinosaurus*, the largest known predatory land animal of all time.

Later into the Early Cretaceous epoch, the India-Madagascar landmass separated from the rest of Gondwana. By the Late Cretaceous, Madagascar and India had permanently split ways and continued until later reaching their modern configurations.

By contrast to Madagascar, mainland Africa was relatively stable in position through-out the Mesozoic. Despite the stable position, major changes occurred to its relation to other landmasses as the remains of Pangaea continued to break apart. By the beginning of the Late Cretaceous epoch South America had split off from Africa, completing the southern half of the Atlantic Ocean. This event had a profound effect on global climate by altering ocean currents.

During the Cretaceous, Africa was populated by allosauroids and spinosaurids, including the largest known carnivorous dinosaurs. Titanosaurs were significant herbivores in its ancient ecosystems. Cretaceous sites are more common than Jurassic ones, but are often unable to be dated radiometrically making it difficult to know their exact ages. Paleontologist Louis Jacobs, who spent time doing field work in Malawi, says that

African beds are "in need of more field work" and will prove to be a "fertile ground...for discovery."

Climate

The Triassic was generally dry, a trend that began in the late Carboniferous, and highly seasonal, especially in the interior of Pangaea. Low sea levels may have also exacerbated temperature extremes. With its high specific heat capacity, water acts as a temperature-stabilizing heat reservoir, and land areas near large bodies of water—especially the oceans—experience less variation in temperature. Because much of the land that constituted Pangaea was distant from the oceans, temperatures fluctuated greatly, and the interior of Pangaea probably included expansive areas of desert. Abundant evidence of red beds and evaporites such as salt support these conclusions.

Sea levels began to rise during the Jurassic, which was probably caused by an increase in seafloor spreading. The formation of new crust beneath the surface displaced ocean waters by as much as 200 m (656 ft) more than today, which flooded coastal areas. Furthermore, Pangaea began to rift into smaller divisions, bringing more land area in contact with the ocean by forming the Tethys Sea. Temperatures continued to increase and began to stabilize. Humidity also increased with the proximity of water, and deserts retreated.

The climate of the Cretaceous is less certain and more widely disputed. Higher levels of carbon dioxide in the atmosphere are thought to have caused the world temperature gradient from north to south to become almost flat: temperatures were about the same across the planet. Average temperatures were also higher than today by about 10°C. In fact, by the middle Cretaceous, equatorial ocean waters (perhaps as warm as 20°C in the deep ocean) may have been too warm for sea life, and land areas near the equator may have been deserts despite their proximity to water. The circulation of oxygen to the deep ocean may also have been disrupted. For this reason, large volumes of organic matter that was unable to decompose accumulated, eventually being deposited as "black shale".

Not all of the data support these hypotheses, however. Even with the overall warmth, temperature fluctuations should have been sufficient for the presence of polar ice caps and glaciers, but there is no evidence of either. Quantitative models have also been unable to recreate the flatness of the Cretaceous temperature gradient.

Oxygen levels in the Mesozoic atmosphere were probably lower (12 to 15%) than today's level (20 to 21%). Some researchers have postulated levels of 12% because that was assumed to be the lowest concentration at which natural combustion could occur. However, a 2008 study concludes that at least 15 % is necessary.

Life

The extinction of nearly all animal species at the end of the Permian period allowed for the radiation of many new lifeforms. In particular, the extinction of the large herbivorous and carnivorous dinocephalia left those ecological niches empty. Some were filled by the surviving cynodonts and dicynodonts, the latter of which subsequently became extinct. Some plant species had distributions that were markedly different from succeeding periods; for example, the Schizeales, a fern order, were skewed to the Northern Hemisphere in the Mesozoic, but are now better represented in the Southern Hemisphere.

Recent research indicates that the specialized animals that formed complex ecosystems, with high biodiversity, complex food webs and a variety of niches, took much longer to reestablish, recovery did not begin until the start of the mid-Triassic, 4M to 6M years after the extinction and was not complete until 30M years after the P-Tr extinction. Animal life was then dominated, by large archosaurian reptiles: dinosaurs, pterosaurs, and aquatic reptiles such as ichthyosaurs, plesiosaurs, and mosasaurs.

The climatic changes of the late Jurassic and Cretaceous provided for further adaptive radiation. The Jurassic was the height of archosaur diversity, and the first birds and placental mammals also appeared. Angiosperms radiated sometime in the early Cretaceous, first in the tropics, but the even temperature gradient allowed them to spread toward the poles throughout the period. By the end of the Cretaceous, angiosperms dominated tree floras in many areas, although some evidence suggests that biomass was still dominated by cycad and ferns until after the KT extinction.

Some have argued that insects diversified with angiosperms because insect anatomy, especially the mouth parts, seems particularly well-suited for flowering plants. However, all major insect mouth parts preceded angiosperms and insect diversification actually slowed when they arrived, so their anatomy originally must have been suited for some other purpose.

As the temperatures in the seas increased, the larger animals of the early Mesozoic gradually began to disappear while smaller animals of all kinds, including lizards, snakes, and perhaps the ancestor mammals to primates, evolved. The KT extinction exacerbated this trend. The large archosaurs became extinct, while birds and mammals thrived, as they do today.

Chapter- 13

Triassic

The **Triassic** is a geologic period that extended from about 250 to 200 Mya (million years ago). As the first period of the Mesozoic Era, the Triassic follows the Permian and is followed by the Jurassic. Both the start and end of the Triassic are marked by major extinction events. The extinction event that closed the Triassic Period has recently been more accurately dated, but as with most older geologic periods, the rock beds that define the start and end are well identified, but the exact dates of the start and end of the period are uncertain by a few million years.

During the Triassic, both marine and continental life show an adaptive radiation beginning from the starkly impoverished biosphere that followed the Permian-Triassic extinction. Corals of the hexacorallia group made their first appearance. The first flying vertebrates, the pterosaurs, evolved during the Triassic.

Dating and subdivisions

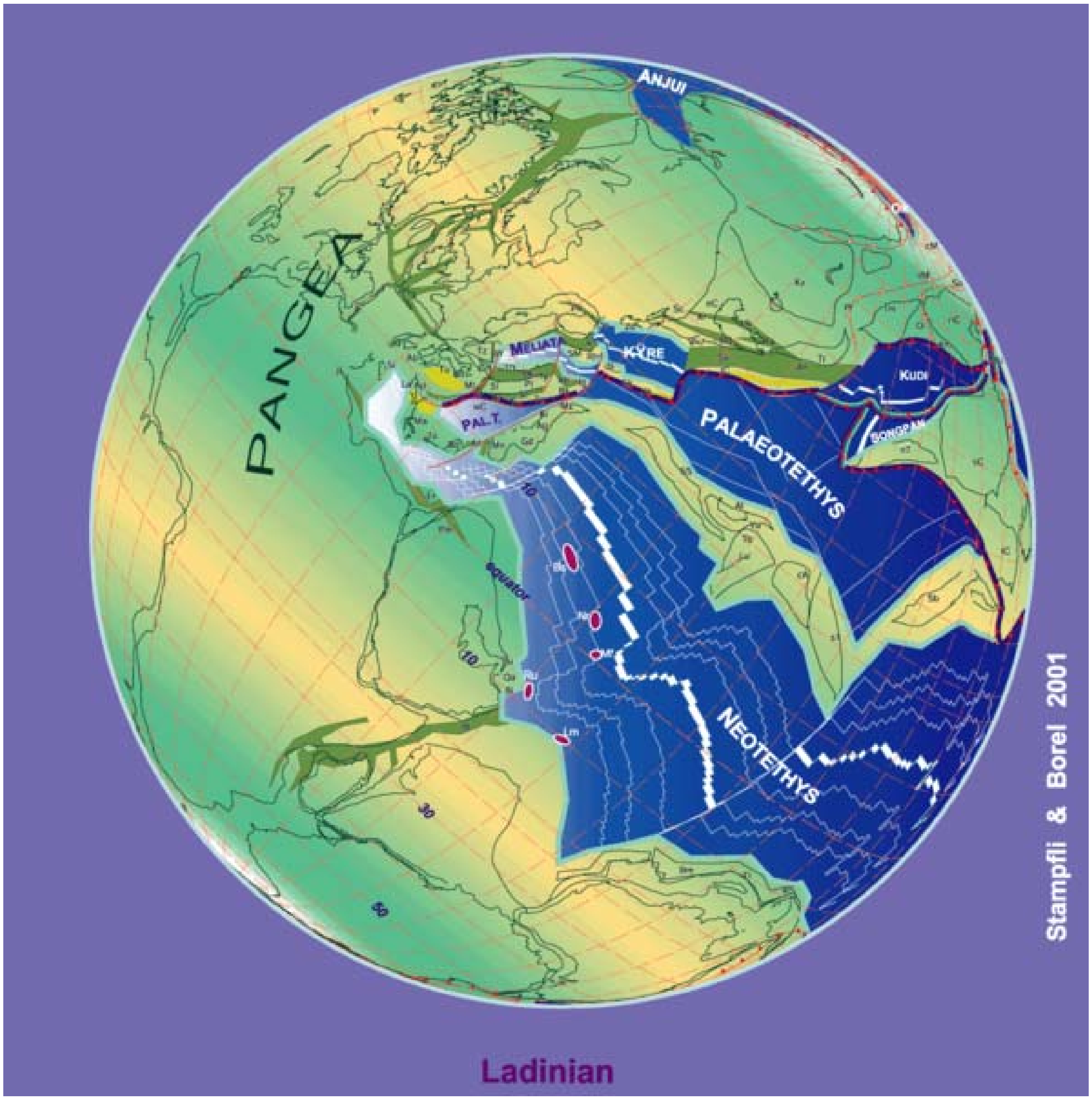
The Triassic was named in 1834 by Friedrich Von Alberti from the three distinct layers (Latin *trias* meaning triad)—red beds, capped by chalk, followed by black shales—that are found throughout Germany and northwest Europe, called the 'Trias'.

The Triassic is usually separated into Early, Middle, and Late Triassic Epochs, and the corresponding rocks are referred to as Lower, Middle, or Upper Triassic. The faunal stages from the youngest to oldest are:

Upper/Late Triassic (Tr3)	
Rhaetian	(203.6 ± 1.5 – 199.6 ± 0.6 Mya)
Norian	(216.5 ± 2.0 – 203.6 ± 1.5 Mya)
Carnian	(228.0 ± 2.0 – 216.5 ± 2.0 Mya)
Middle Triassic (Tr2)	
Ladinian	(237.0 ± 2.0 – 228.0 ± 2.0 Mya)
Anisian	(245.0 ± 1.5 – 237.0 ± 2.0 Mya)
Lower/Early Triassic (Scythian)	

Olenekian	(249.7 ± 0.7 – 245.0 ± 1.5 Mya)
Induan	(251.0 ± 0.4 – 249.7 ± 0.7 Mya)

Paleogeography



230 Ma plate tectonic reconstruction

During the Triassic, almost all the Earth's land mass was concentrated into a single supercontinent centered more or less on the equator, called Pangaea ("all the land"). From the east a vast gulf entered Pangaea, the Tethys sea. It opened farther westward in the mid-Triassic, at the expense of the shrinking Paleo-Tethys Ocean, an ocean that existed during the Paleozoic. The remaining shores were surrounded by the world-ocean known as Panthalassa ("all the sea"). All the deep-ocean sediments laid down during the Triassic have disappeared through subduction of oceanic plates; thus, very little is known of the Triassic open ocean. The supercontinent Pangaea was rifting during the Triassic—especially late in the period—but had not yet separated. The first nonmarine sediments in the rift that marks the initial break-up of Pangaea—which separated New Jersey from Morocco—are of Late Triassic age; in the U.S., these thick sediments comprise the Newark Group. Because of the limited shoreline of one super-continental mass, Triassic marine deposits are globally relatively rare, despite their prominence in Western Europe, where the Triassic was first studied. In North America, for example, marine deposits are limited to a few exposures in the west. Thus Triassic stratigraphy is mostly based on organisms living in lagoons and hypersaline environments, such as Estheria crustaceans.

Africa

At the beginning of the Mesozoic Era, Africa was joined with Earth's other continents in Pangaea. Africa shared the supercontinent's relatively uniform fauna which was dominated by theropods, prosauropods and primitive ornithischians by the close of the Triassic period. Late Triassic fossils are found through-out Africa, but are more common in the south than north. The boundary separating the Triassic and Jurassic marks the advent of an extinction event with global impact, although African strata from this time period have not been thoroughly studied.

Climate

Middle Triassic marginal marine sequence, southwestern Utah

The Triassic climate was generally hot and dry, forming typical red bed sandstones and evaporites. There is no evidence of glaciation at or near either pole; in fact, the polar regions were apparently moist and temperate, a climate suitable for reptile-like creatures. Pangaea's large size limited the moderating effect of the global ocean; its continental climate was highly seasonal, with very hot summers and cold winters. It probably had strong, cross-equatorial monsoons.

Life

Triassic flora as depicted in Meyers Konversations-Lexikon (1885-90)

Three categories of organisms can be distinguished in the Triassic record: holdovers from the Permian-Triassic extinction, new groups which flourished briefly, and other new groups which went on to dominate the Mesozoic world.

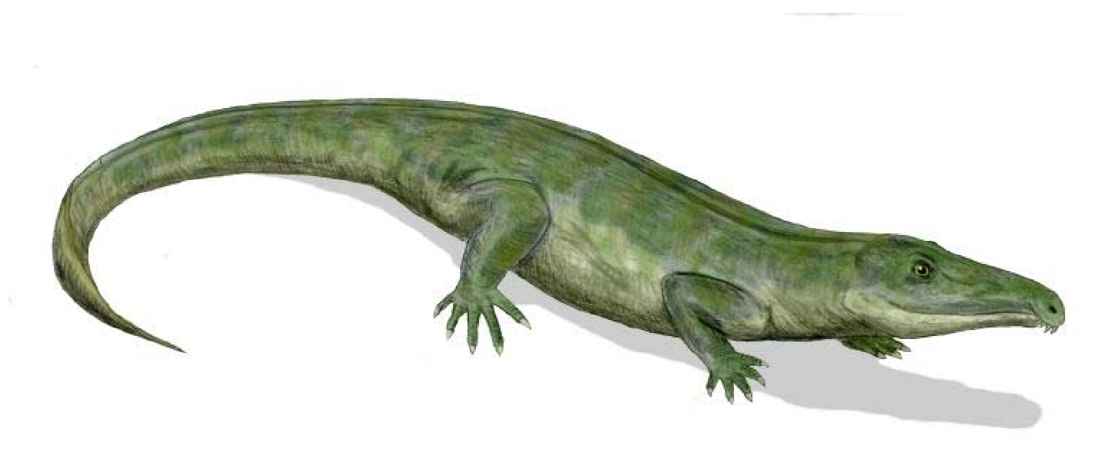
Flora

On land, the holdover plants included the lycophytes, the dominant cycads, ginkgophyta (represented in modern times by *Ginkgo biloba*) and glossopterids. The spermatophytes, or seed plants came to dominate the terrestrial flora: in the northern hemisphere, conifers flourished. *Glossopteris* (a seed fern) was the dominant southern hemisphere tree during the Early Triassic period.

Marine fauna

In marine environments, new modern types of corals appeared in the Early Triassic, forming small patches of reefs of modest extent compared to the great reef systems of Devonian times or modern reefs. The shelled cephalopods called ammonites recovered, diversifying from a single line that survived the Permian extinction. The fish fauna was remarkably uniform, reflecting the fact that very few families survived the Permian extinction. There were also many types of marine reptiles. These included the Sauropterygia, which featured pachypleurosaurs and nothosaurs (both common during the Middle Triassic, especially in the Tethys region), placodonts, and the first plesiosaurs; the first of the lizardlike Thalattosauria (askeptosaurs); and the highly successful ichthyosaurs, which appeared in Early Triassic seas and soon diversified, some eventually developing to huge size during the late Triassic.

Terrestrial fauna



Reconstruction of *Proterosuchus*, a genus of carnivorous reptile, classified under Archosauromorpha, that existed in the Early Triassic period.

Coelophysis, one of the first Dinosaurs, appeared in the mid-Triassic.

The Permian-Triassic extinction devastated terrestrial life. Biodiversity rebounded with the influx of disaster taxa, however these were short lived. Diverse communities with complex trophic structures took 30 million years to reestablish.

Temnospondyl amphibians were among those groups that survived the Permian-Triassic extinction, some lineages (e.g. Trematosaurs) flourishing briefly in the Early Triassic, while others (e.g. capitosaurs) remained successful throughout the whole period, or only came to prominence in the Late Triassic (e.g. plagiosaurs, metoposaurs). As for other amphibians, the first Lissamphibia, characterized by the first frogs, are known from the Early Triassic, but the group as a whole did not become common until the Jurassic, when the temnospondyls had become very rare.

Archosauromorph reptiles—especially archosaurs—progressively replaced the synapsids that had dominated the Permian. Although *Cynognathus* was a characteristic top predator in earlier Triassic (Olenekian and Anisian) Gondwana, and both kannemeyeriid dicynodonts and gomphodont cynodonts remained important herbivores during much of the period. By the end of the Triassic, synapsids played only bit parts. During the Carnian (early part of the Late Triassic), some advanced cynodont gave rise to the first mammals. At the same time the Ornithodira, which until then had been small and insignificant, evolved into pterosaurs and a variety of dinosaurs. The Crurotarsi were the other important archosaur clade, and during the Late Triassic these also reached the height of their diversity, with various groups including the phytosaurs, aetosaurs, several distinct lineages of Rauisuchia, and the first crocodylians (the Sphenosuchia). Meanwhile the stocky herbivorous rhynchosaurs and the small to medium-sized insectivorous or piscivorous Prolacertiformes were important basal archosauromorph groups throughout most of the Triassic.

Among other reptiles, the earliest turtles, like *Proganochelys* and Proterochersis, appeared during the Norian (middle of the Late Triassic). The Lepidosauromorpha—specifically the Sphenodontia—are first known in the fossil record a little earlier (during the Carnian). The Procolophonidae were an important group of small lizard-like herbivores.

Archosaurs were initially rarer than the therapsids which had dominated Permian terrestrial ecosystems, but they began to displace therapsids in the mid-Triassic. This "Triassic Takeover" may have contributed to the evolution of mammals by forcing the surviving therapsids and their mammaliform successors to live as small, mainly nocturnal insectivores; nocturnal life probably forced at least the mammaliforms to develop fur and higher metabolic rates.

Coal

At the start of the Triassic period coal is noticeable by geologists today as being absent throughout the world. This is known as the "coal gap" and can be seen as part of the Permian–Triassic extinction event. Sharp drops in sea level across the Permo Triassic boundary may be the proper explanation for the coal gap. However, theories are still speculative as to why it is missing. During the preceding Permian period the arid desert conditions contributed to the evaporation of many inland seas and the inundation of these seas, perhaps by a number of tsunami events that may have been responsible for the drop in sea level. This due to the finding of large salt basins in the southwest United States and a very large basin in central Canada.

Immediately above the boundary the glossopteris flora was suddenly largely displaced by an Australia wide coniferous flora containing few species and containing a lycopod herbaceous under story. Conifers also became common in Eurasia. These groups of conifers arose from endemic species because of the ocean barriers that prevented seed crossing for over one hundred million years. For instance, Podocarpis was located south and Pines, Junipers, and Sequoias were located north. The dividing line ran through the Amazon Valley, across the Sahara, and north of Arabia, India, Thailand, and Australia. It has been suggested that there was a climate barrier for the conifers. although water barriers are more plausible. If so, something that can cross at least short water barriers must have been involved in producing the coal hiatus. Hot climate could have been an important auxiliary factor across Antarctica or the Bering Strait, however. There was a spike of fern and lycopod spores immediately after the close of the Permian. In addition there was also a spike of fungal spores immediately after the Permian-Triassic boundary. This spike may have lasted 50,000 years in Italy and 200,000 years in China and must have contributed to the climate warmth.

An event excluding a catastrophe must have been involved to cause the coal hiatus due to the fact that fungi would have removed all dead vegetation and coal forming detritus in a few decades in most tropical places. In addition, fungal spores rose gradually and declined similarly along with a prevalence of woody debris. Each phenomenon would hint at widespread vegetative death. Whatever the cause of the coal hiatus must have started in North America approximately 25 million years sooner.

Lagerstätten

Triassic sandstone near Stadtroda, Germany

The Monte San Giorgio lagerstätte, now in the Lake Lugano region of northern Italy and Switzerland, was in Triassic times a lagoon behind reefs with an anoxic bottom layer, so there were no scavengers and little turbulence to disturb fossilization, a situation that can be compared to the better-known Jurassic Solnhofen limestone lagerstätte. The remains of fish and various marine reptiles (including the common pachypleurosaur Neusticosaurus, and the bizarre long-necked archosauromorph *Tanystropheus*), along with some terrestrial forms like *Ticinosuchus* and *Macrocnemus*, have been recovered from this locality. All these fossils date from the Anisian/Ladinian transition (about 237 million years ago).

Late Triassic extinction event

The Triassic period ended with a mass extinction, which was particularly severe in the oceans; the conodonts disappeared, and all the marine reptiles except ichthyosaurs and plesiosaurs. Invertebrates like brachiopods, gastropods, and molluscs were severely affected. In the oceans, 22% of marine families and possibly about half of marine genera went missing according to University of Chicago paleontologist Jack Sepkoski.

Though the end-Triassic extinction event was not equally devastating everywhere in terrestrial ecosystems, several important clades of crurotarsans (large archosaurian reptiles previously grouped together as the thecodonts) disappeared, as did most of the large labyrinthodont amphibians, groups of small reptiles, and some synapsids (except for the proto-mammals). Some of the early, primitive dinosaurs also went extinct, but other more adaptive dinosaurs survived to evolve in the Jurassic. Surviving plants that went on to dominate the Mesozoic world included modern conifers and cycadeoids.

What caused this Late Triassic extinction is not known with certainty. It was accompanied by huge volcanic eruptions that occurred as the supercontinent Pangaea began to break apart about 202 to 191 million years ago [(40Ar/39Ar dates)], forming the Central Atlantic Magmatic Province [(CAMP)], one of the largest known inland volcanic events since the planet cooled and stabilized. Other possible but less likely causes for the extinction events include global cooling or even a bolide impact, for which an impact crater containing Manicouagan Reservoir in Quebec, Canada, has been singled out. At the Manicouagan impact crater, however, recent research has shown that the impact melt within the crater has an age of 214±1 Mya. The date of the Triassic-Jurassic boundary has also been more accurately fixed recently, at 201.58±0.28 Mya. Both dates are gaining accuracy by using more accurate forms of radiometric dating, in particular the decay of uranium to lead in zircons formed at the impact. So the evidence suggests the Manicouagan impact preceded the end of the Triassic by approximately 10±2 Ma. Therefore it could not be the immediate cause of the observed mass extinction.

The number of Late Triassic extinctions is disputed. Some studies suggest that there are at least two periods of extinction towards the end of the Triassic, between 12 and 17 million years apart. But arguing against this is a recent study of North American faunas. In the Petrified Forest of northeast Arizona there is a unique sequence of latest Carnian-early Norian terrestrial sediments. An analysis in 2002 found no significant change in the paleoenvironment. Phytosaurs, the most common fossils there, experienced a change-over only at the genus level, and the number of species remained the same. Some aetosaurs, the next most common tetrapods, and early dinosaurs, passed through unchanged. However, both phytosaurs and aetosaurs were among the groups of archosaur reptiles completely wiped out by the end-Triassic extinction event.

It seems likely then that there was some sort of end-Carnian extinction, when several herbivorous archosauromorph groups died out, while the large herbivorous therapsids—the kannemeyeriid dicynodonts and the traversodont cynodonts— were much reduced in the northern half of Pangaea (Laurasia).

These extinctions within the Triassic and at its end allowed the dinosaurs to expand into many niches that had become unoccupied. Dinosaurs became increasingly dominant, abundant and diverse, and remained that way for the next 150 million years. The true "Age of Dinosaurs" is the Jurassic and Cretaceous, rather than the Triassic.

Chapter- 14

Jurassic

The **Jurassic** is a geologic period and system that extends from about 199.6± 0.6 Mya (million years ago) to 145.5± 4 Mya, that is, from the end of the Triassic to the beginning of the Cretaceous. The Jurassic constitutes the middle period of the Mesozoic Era, also known as the Age of Reptiles. The start of the period is marked by the major Triassic–Jurassic extinction event. However, the end of the Jurassic Period did not witness any major extinction event. The start and end of the period are defined by carefully selected locations; the uncertainty in dating arises from trying to date these horizons.

The chronostratigraphic term "Jurassic" is directly linked to the Swiss Jura Mountains. Alexander von Humboldt (*1769, † 1859) recognized the mainly limestone dominated mountain range of the Swiss Jura Mountains as a separate formation that was not at the time included in the established stratigraphic system defined by Abraham Gottlob Werner (* 1749, † 1817) and named it "Jurakalk" in 1795. The name "Jura" is derived from the celtic root "jor" which was Latinised into "juria", meaning forest (i.e. "Jura" is forest mountains).

Divisions

The Jurassic Period is divided into Early Jurassic, Middle, and Late Jurassic epochs. The Jurassic System, in stratigraphy, is divided into Lower Jurassic, Middle, and Upper Jurassic series of rock formations, also known as *Lias*, *Dogger* and *Malm* in Europe. The separation of the term **Jurassic** into three sections goes back to Leopold von Buch (* 1774, † 1853). The faunal stages from youngest to oldest are:

Upper/Late Jurassic	
Tithonian	(150.8 ± 4.0 – 145.5 ± 4.0 Mya)
Kimmeridgian	(155.7 ± 4.0 – 150.8 ± 4.0 Mya)
Oxfordian	(161.2 ± 4.0 – 155.7 ± 4.0 Mya)
Middle Jurassic	
Callovian	(164.7 ± 4.0 – 161.2 ± 4.0 Mya)
Bathonian	(167.7 ± 3.5 – 164.7 ± 4.0 Mya)

Bajocian	(171.6 ± 3.0 – 167.7 ± 3.5 Mya)
Aalenian	(175.6 ± 2.0 – 171.6 ± 3.0 Mya)
Lower/Early Jurassic	
Toarcian	(183.0 ± 1.5 – 175.6 ± 2.0 Mya)
Pliensbachian	(189.6 ± 1.5 – 183.0 ± 1.5 Mya)
Sinemurian	(196.5 ± 1.0 – 189.6 ± 1.5 Mya)
Hettangian	(199.6 ± 0.6 – 196.5 ± 1.0 Mya)

Paleogeography and tectonics

During the early Jurassic period, the supercontinent Pangaea broke up into the northern supercontinent Laurasia and the southern supercontinent Gondwana; the Gulf of Mexico opened in the new rift between North America and what is now Mexico's Yucatan Peninsula. The Jurassic North Atlantic Ocean was relatively narrow, while the South Atlantic did not open until the following Cretaceous Period, when Gondwana itself rifted apart. The Tethys Sea closed, and the Neotethys basin appeared. Climates were warm, with no evidence of glaciation. As in the Triassic, there was apparently no land near either pole, and no extensive ice caps existed.

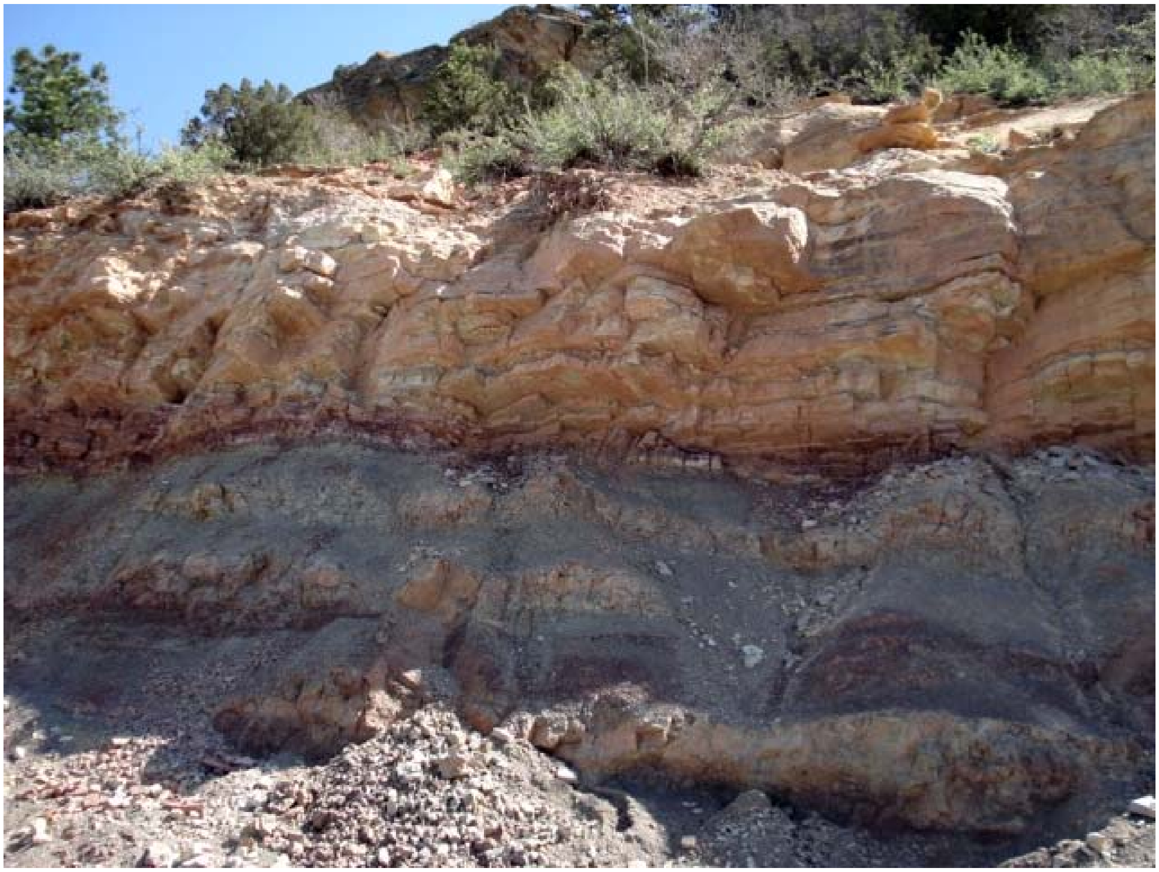
The Jurassic geological record is good in western Europe, where extensive marine sequences indicate a time when much of the continent was submerged under shallow tropical seas; famous locales include the Jurassic Coast World Heritage Site and the renowned late Jurassic *lagerstätten* of Holzmaden and Solnhofen. In contrast, the North American Jurassic record is the poorest of the Mesozoic, with few outcrops at the surface. Though the epicontinental Sundance Sea left marine deposits in parts of the northern plains of the United States and Canada during the late Jurassic, most exposed sediments from this period are continental, such as the alluvial deposits of the Morrison Formation.

The Jurassic was a time of calcite sea geochemistry in which low-magnesium calcite was the primary inorganic marine precipitate of calcium carbonate. Carbonate hardgrounds were thus very common, along with calcitic ooids, calcitic cements, and invertebrate faunas with dominantly calcitic skeletons (Stanley and Hardie, 1998, 1999).

The first of several massive batholiths were emplaced in the northern Cordillera beginning in the mid-Jurassic, marking the Nevadan orogeny. Important Jurassic exposures are also found in Russia, India, South America, Japan, Australasia and the United Kingdom.

Early Jurassic strata are distributed in a similar fashion to Late Triassic beds, with more common outcrops in the south and less common fossil beds which are predominated by tracks to the north. As the Jurassic proceeded, larger and more iconic groups of dinosaurs like sauropods and ornithopods proliferated in Africa. Middle Jurassic strata are neither well represented nor well studied in Africa. Late Jurassic strata are also poorly represented apart from the spectacular Tendeguru fauna in Tanzania. The Late Jurassic life of Tendeguru is very similar to that found in western North America's Morrison Formation.

Jurassic limestones and marls (the Matmor Formation) in southern Israel.



The late Jurassic Morrison Formation in Colorado is the most fertile source of dinosaur fossils in North America.

Gigandipus, a dinosaur footprint in the Lower Jurassic Moenave Formation at the St. George Dinosaur Discovery Site at Johnson Farm, southwestern Utah.

Fauna

Aquatic and marine

During the Jurassic period, the primary vertebrates living in the seas were fish and marine reptiles. The latter include ichthyosaurs who were at the peak of their diversity, plesiosaurs, pliosaurs, and marine crocodiles of the families Teleosauridae and Metriorhynchidae.

In the invertebrate world, several new groups appeared, including rudists (a reef-forming variety of bivalves) and belemnites. The Jurassic also had diverse encrusting and boring (sclerobiont) communities, and it saw a significant rise in the bioerosion of carbonate shells and hardgrounds. Especially common is the ichnogenus (trace fossil) *Gastrochaenolites*.

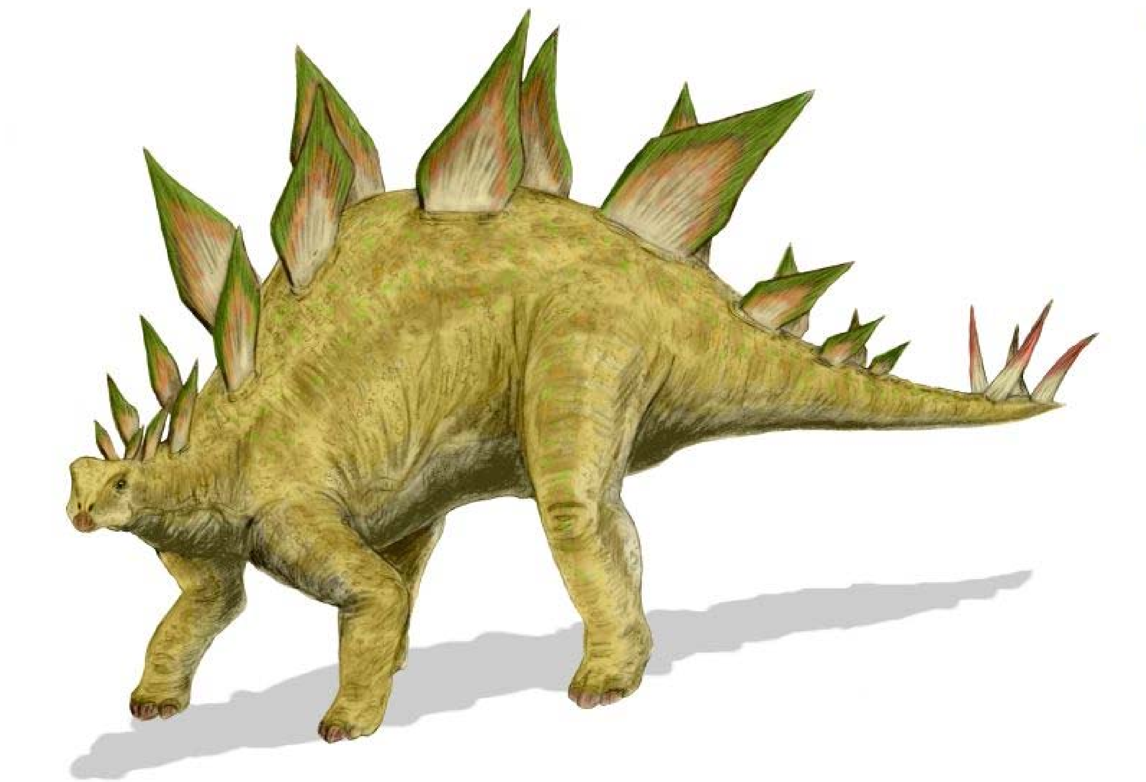
During the Jurassic period about four or five of the twelve clades of planktonic organisms that exist in the fossil record either experienced a massive evolutionary radiation or appeared for the first time.

Terrestrial

On land, large archosaurian reptiles remained dominant. The Jurassic was a golden age for the large herbivorous dinosaurs known as the sauropods—*Camarasaurus*, *Apatosaurus*, *Diplodocus*, *Brachiosaurus*, and many others—that roamed the land late in the period; their mainstays were either the prairies of ferns, palm-like cycads and bennettitales, or the higher coniferous growth, according to their adaptations. They were preyed upon by large theropods as for example *Ceratosaurus*, *Megalosaurus*, *Torvosaurus* and *Allosaurus*. All these belong to the 'lizard hipped' or saurischian branch of the dinosaurs. During the Late Jurassic, the first birds, like Archaeopteryx, evolved from small coelurosaurian dinosaurs. Ornithischian dinosaurs were less predominant than saurischian dinosaurs, although some like stegosaurs and small ornithopods played important roles as small and medium-to-large (but not sauropod-sized) herbivores. In the air, pterosaurs were common; they ruled the skies, filling many ecological roles now taken by birds. Within the undergrowth were various types of early mammals, as well as tritylodont mammal-like reptiles, lizard-like sphenodonts, and early lissamphibians.

The rest of the Lissamphibia evolved in this period, introducing the first salamanders and caecilians.

Large dinosaurs roamed forests of similarly large conifers during the Jurassic Period.



Stegosaurus is one of the most recognizable genera of dinosaurs and lived during the mid to late Jurassic.

In the late Jurassic, the emergence of *Archaeopteryx* marks the start of the evolution of birds.

Flora

Conifers were common in the Jurassic period.

The arid, continental conditions characteristic of the Triassic steadily eased during the Jurassic period, especially at higher latitudes; the warm, humid climate allowed lush jungles to cover much of the landscape. Gymnosperms were relatively diverse during the Jurassic period. The Conifers in particular dominated the flora, as during the Triassic; they were the most diverse group and constituted the majority of large trees. Extant conifer families that flourished during the Jurassic included the Araucariaceae, Cephalotaxaceae, Pinaceae, Podocarpaceae, Taxaceae and Taxodiaceae. The extinct Mesozoic conifer family Cheirolepidiaceae dominated low latitude vegetation, as did the shrubby Bennettitales. Cycads were also common, as were ginkgos and Dicksoniaceous tree ferns in the forest. Smaller ferns were probably the dominant undergrowth. Caytoniaceous seed ferns were another group of important plants during this time and are thought to have been shrub to small-tree sized. Ginkgo plants were particularly common in the mid- to high northern latitudes. In the Southern Hemisphere, podocarps were especially successful, while Ginkgos and Czekanowskiales were rare.

In the oceans modern coralline algae appeared for the first time.

Chapter- 15

Cretaceous

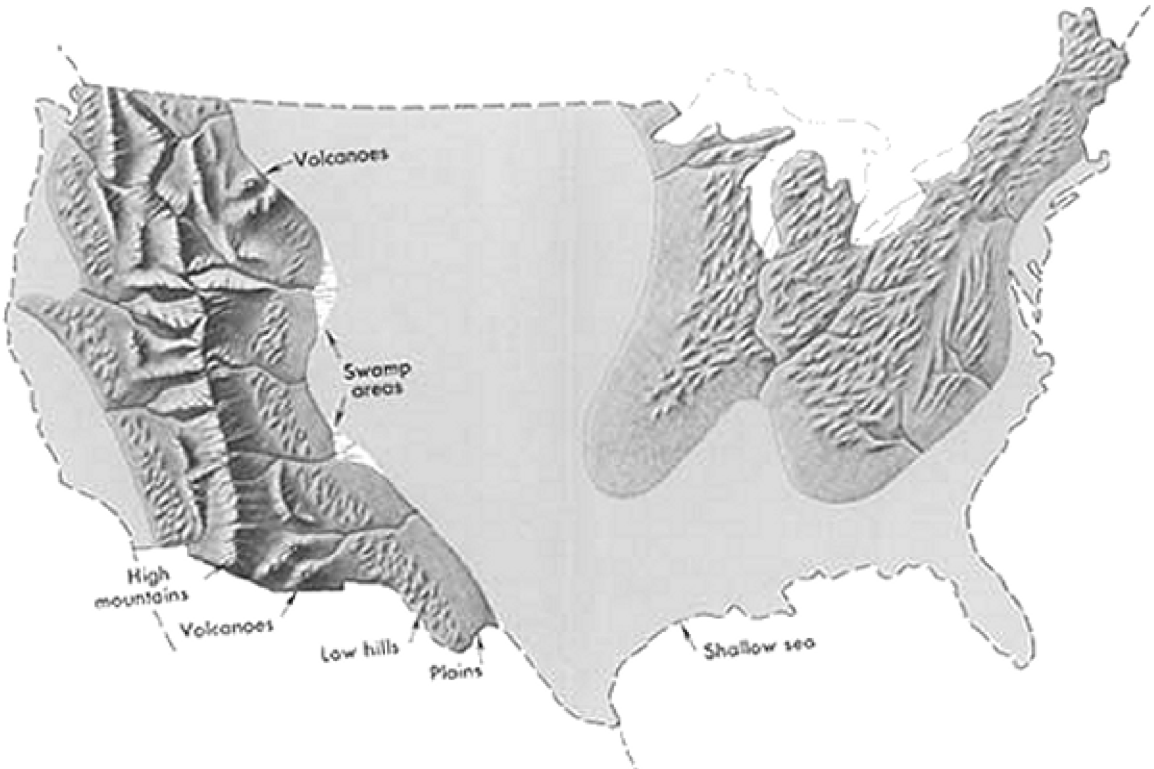
The **Cretaceous**, Latin for "chalky", usually abbreviated **K** for its German translation *Kreide* (chalk), is a geologic period and system from circa 145.5 ± 4 to 65.5 ± 0.3 million years (Ma) ago. In the geologic timescale, the Cretaceous follows on the Jurassic Period and is followed by the Paleogene Period of the Cenozoic Era. It is the youngest period of the Mesozoic Era, and at 80 million years long, the longest period of the Phanerozoic Eon. The end of the Cretaceous defines the boundary between the Mesozoic and Cenozoic eras. In many languages this period is known as "chalk period".

The Cretaceous was a period with a relatively warm climate and high eustatic sea level. The oceans and seas were populated with now extinct marine reptiles, ammonites and rudists; and the land by dinosaurs. At the same time, new groups of mammals and birds as well as flowering plants appeared. The Cretaceous ended with one of the largest mass extinctions in Earth history, the K-T extinction, when many species, including non-avian dinosaurs, pterosaurs, and large marine reptiles, disappeared.

The Cretaceous world

Paleogeography

During the Cretaceous, the late-Paleozoic-to-early-Mesozoic supercontinent of Pangaea completed its tectonic breakup into present day continents, although their positions were substantially different at the time. As the Atlantic Ocean widened, the convergent-margin orogenies that had begun during the Jurassic continued in the North American Cordillera, as the Nevadan orogeny was followed by the Sevier and Laramide orogenies.



Geography of the US in the Late Cretaceous Period

Though Gondwana was still intact in the beginning of the Cretaceous, it broke up as South America, Antarctica and Australia rifted away from Africa (though India and Madagascar remained attached to each other); thus, the South Atlantic and Indian Oceans were newly formed. Such active rifting lifted great undersea mountain chains along the welts, raising eustatic sea levels worldwide. To the north of Africa the Tethys Sea continued to narrow. Broad shallow seas advanced across central North America (the Western Interior Seaway) and Europe, then receded late in the period, leaving thick marine deposits sandwiched between coal beds. At the peak of the Cretaceous transgression, one-third of Earth's present land area was submerged.

The Cretaceous is justly famous for its chalk; indeed, more chalk formed in the Cretaceous than in any other period in the Phanerozoic. Mid-ocean ridge activity—or rather, the circulation of seawater through the enlarged ridges—enriched the oceans in calcium; this made the oceans more saturated, as well as increased the bioavailability of the element for calcareous nanoplankton. These widespread carbonates and other sedimentary deposits make the Cretaceous rock record especially fine. Famous formations from North America include the rich marine fossils of Kansas's Smoky Hill Chalk Member and the terrestrial fauna of the late Cretaceous Hell Creek Formation. Other important Cretaceous exposures occur in Europe (e.g., the Weald) and China (the Yixian Formation). In the area that is now India, massive lava beds called the Deccan Traps were erupted in the very late Cretaceous and early Paleocene.

Climate

The Berriasian epoch showed a cooling trend that had been seen in the last epoch of the Jurassic. There is evidence that snowfalls were common in the higher latitudes and the tropics became wetter than during the Triassic and Jurassic. Glaciation was however restricted to alpine glaciers on some high-latitude mountains, though seasonal snow may have existed farther south. Rafting by ice of stones into marine environments occurred during much of the Cretaceous but evidence of deposition directly from glaciers is limited to the Early Cretaceous of the Eromanga Basin in southern Australia.

After the end of the Berriasian, however, temperatures increased again, and these conditions were almost constant until the end of the period. This trend was due to intense volcanic activity which produced large quantities of carbon dioxide. The development of a number of mantle plumes across the widening mid-ocean ridges further pushed sea levels up, so that large areas of the continental crust were covered with shallow seas. The Tethys Sea connecting the tropical oceans east to west also helped in warming the global climate. Warm-adapted plant fossils are known from localities as far north as Alaska and Greenland, while dinosaur fossils have been found within 15 degrees of the Cretaceous south pole.

A very gentle temperature gradient from the equator to the poles meant weaker global winds, contributing to less upwelling and more stagnant oceans than today. This is evidenced by widespread black shale deposition and frequent anoxic events. Sediment cores show that tropical sea surface temperatures may have briefly been as warm as 42 °C (107 °F), 17 °C (31 °F) warmer than at present, and that they averaged around 37 °C (99 °F). Meanwhile deep ocean temperatures were as much as 15 to 20 °C (27 to 36 °F) higher than today's.

Geology

Research history

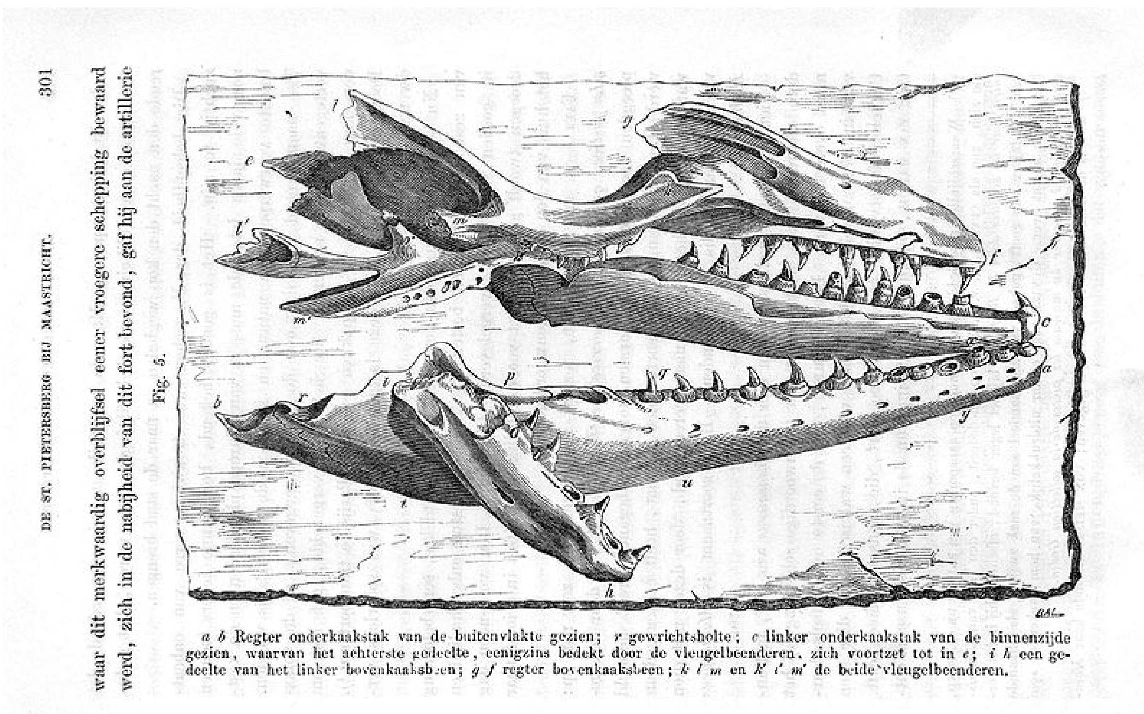
The Cretaceous as a separate period was first defined by a Belgian geologist Jean d'Omalius d'Halloy in 1822, using strata in the Paris Basin and named for the extensive beds of chalk (calcium carbonate deposited by the shells of marine invertebrates, principally coccoliths), found in the upper Cretaceous of western Europe. The name Cretaceous was derived from Latin *creta*, meaning *chalk*. The name of the island Crete has the same origin.

Stratigraphic subdivisions

The Cretaceous is divided into Early and Late Cretaceous epochs or Lower and Upper Cretaceous series. In older literature the Cretaceous is sometimes divided into three series: Neocomian (lower/early), Gallic (middle) and Senonian (upper/late). A subdivision in eleven stages, all origining from European stratigraphy, is now used worldwide. In many parts of the world, alternative local subdivisions are still in use.

As with other older geologic periods, the rock beds of the Cretaceous are well identified but the exact ages of the system's top and base are uncertain by a few million years. No great extinction or burst of diversity separates the Cretaceous from the Jurassic. However, the top of the system is sharply defined, being placed at an iridium-rich layer found worldwide that is believed to be associated with the Chicxulub impact crater in Yucatan and the Gulf of Mexico. This layer has been tightly dated at 65.5 Ma.

Rock formations



Drawing of fossil jaws of *Mosasaurus hoffmanni*, from the Maastrichtian of Dutch Limburg, by Dutch geologist Pieter Harting (1866).

The high eustatic sea level and warm climate of the Cretaceous meant a large area of the continents was covered by warm shallow seas. The Cretaceous was named for the extensive chalk deposits of this age in Europe, but in many parts of the world, the Cretaceous system consists for a major part of marine limestone, a rock type that is formed under warm, shallow marine circumstances. Due to the high sea level there was extensive accommodation space for sedimentation so that thick deposits could form. Because of the relatively young age and great thickness of the system, Cretaceous rocks crop out in many areas worldwide.

Chalk is a rock type characteristic for (but not restricted to) the Cretaceous. It consists of coccoliths, microscopically small calcite skeletons of coccolithophores, a type of algae that prospered in the Cretaceous seas.

In northwestern Europe, chalk deposits from the Upper Cretaceous are characteristic for the Chalk Group, which forms the white cliffs of Dover on the south coast of England and similar cliffs on the French Normandian coast. The group is found in England, northern France, the low countries, northern Germany, Denmark and in the subsurface of the southern part of the North Sea. Chalk is not easily consolidated and the Chalk Group still consists of loose sediments in many places. The group also has other limestones and arenites. Among the fossils it contains are sea urchins, belemnites, ammonites and sea reptiles such as *Mosasaurus*.

In southern Europe, the Cretaceous is usually a marine system consisting of competent limestone beds or incompetent marls. Because the Alpine mountain chains did not yet exist in the Cretaceous, these deposits formed on the southern edge of the European continental shelf, at the margin of the Tethys Ocean.

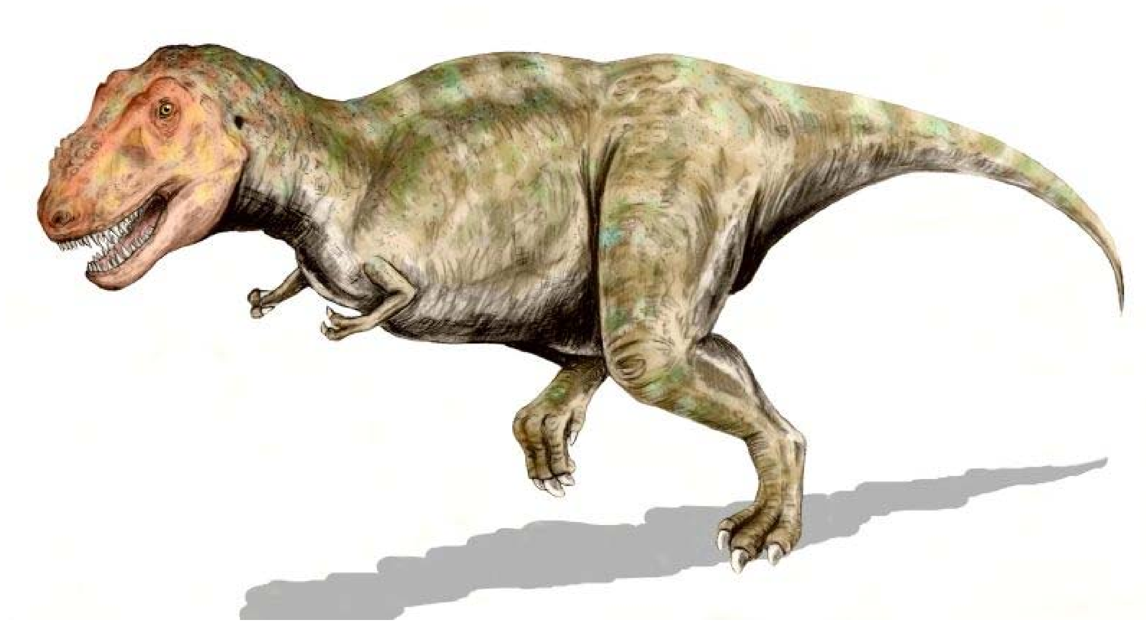
Stagnation of deep sea currents in middle Cretaceous times caused anoxic circumstances in the sea water. In many places around the world, dark anoxic shales were formed during this interval. These shales are an important source rock for oil and gas, for example in the subsurface of the North Sea.

Life

Plants

Flowering plants (angiosperms) spread during this period, although they did not become predominant until the Campanian stage near the end of the epoch. Their evolution was aided by the appearance of bees; in fact angiosperms and insects are a good example of coevolution. The first representatives of many leafy trees, including figs, planes and magnolias, appeared in the Cretaceous. At the same time, some earlier Mesozoic gymnosperms like Conifers continued to thrive; pehuéns (Monkey Puzzle trees, *Araucaria*) and other conifers being notably plentiful and widespread. Some fern orders such as Gleicheniales appeared as early in the fossil record as the Cretaceous, and achieved an early broad distribution. Gymnosperm taxa like Bennettitales died out before the end of the period.

Terrestrial fauna



Tyrannosaurus rex, one of the largest land predators of all time, lived during the late Cretaceous.

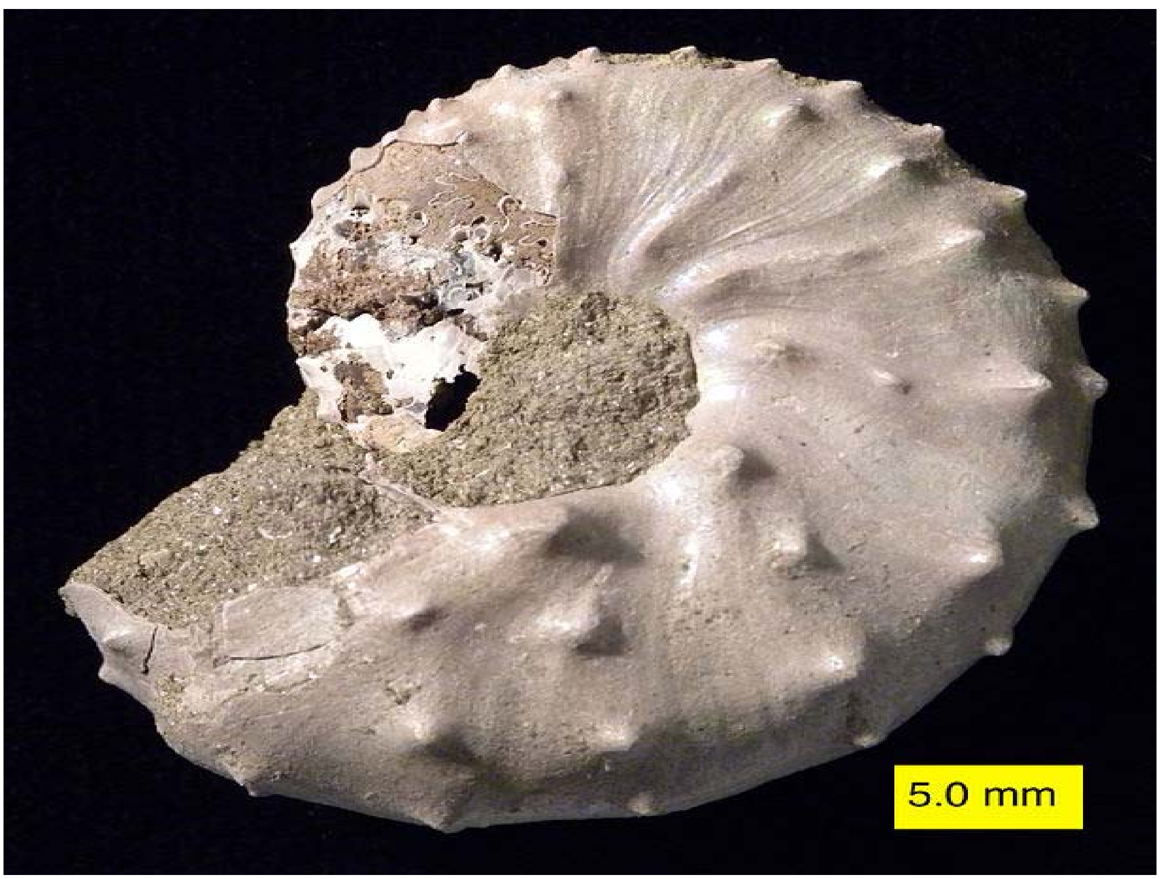
A pterosaur, *Anhanguera piscator*

On land, mammals were a small and still relatively minor component of the fauna. Early marsupial mammals evolved in the Early Cretaceous, with true placentals emerging in the Late Cretaceous period. The fauna was dominated by archosaurian reptiles, especially dinosaurs, which were at their most diverse stage. Pterosaurs were common in the early and middle Cretaceous, but as the Cretaceous proceeded they faced growing competition from the adaptive radiation of birds, and by the end of the period only two highly specialized families remained.

The Liaoning lagerstätte (Chaomidianzi formation) in China provides a glimpse of life in the Early Cretaceous, where preserved remains of numerous types of small dinosaurs, birds, and mammals have been found. The coelurosaur dinosaurs found there represent types of the group Maniraptora, which is transitional between dinosaurs and birds, and are notable for the presence of hair-like feathers.

During the Cretaceous, insects began to diversify, and the oldest known ants, termites and some lepidopterans, akin to butterflies and moths, appeared. Aphids, grasshoppers, and gall wasps appeared.

Marine fauna



Discoscaphites iris, Owl Creek Formation (Upper Cretaceous), Ripley, Mississippi.

In the seas, rays, modern sharks and teleosts became common. Marine reptiles included ichthyosaurs in the early and middle of the Cretaceous, becoming extinct during the late Cretaceous, plesiosaurs throughout the entire period, and mosasaurs appearing in the Late Cretaceous.

Baculites, an ammonite genus with a straight shell, flourished in the seas along with reef-building rudist clams. The Hesperornithiformes were flightless, marine diving birds that swam like grebes. Globotruncanid Foraminifera and echinoderms such as sea urchins and starfish (sea stars) thrived. The first radiation of the diatoms (generally siliceous, rather than calcareous) in the oceans occurred during the Cretaceous; freshwater diatoms did not appear until the Miocene. The Cretaceous was also an important interval in the evolution of bioerosion, the production of borings and scrapings in rocks, hardgrounds and shells (Taylor and Wilson, 2003).

Extinction

There was a progressive decline in biodiversity during the Maastrichtian stage of the Cretaceous Period prior to the suggested ecological crisis induced by events at the K-T boundary. Furthermore, biodiversity required a substantial amount of time to recover from the K-T event, despite the probable existence of an abundance of vacant ecological niches.

Despite the severity of this boundary event, there was significant variability in the rate of extinction between and within different clades. Species which depended on photosynthesis declined or became extinct because of the reduction in solar energy reaching the Earth's surface due to atmospheric particles blocking the sunlight. As is the case today, photosynthesizing organisms, such as phytoplankton and land plants, formed the primary part of the food chain in the late Cretaceous. Evidence suggests that herbivorous animals, which depended on plants and plankton as their food, died out as their food sources became scarce; consequently, top predators such as *Tyrannosaurus rex* also perished.

Coccolithophorids and molluscs, including ammonites, rudists, freshwater snails and mussels, as well as organisms whose food chain included these shell builders, became extinct or suffered heavy losses. For example, it is thought that ammonites were the principal food of mosasaurs, a group of giant marine reptiles that became extinct at the boundary.

Omnivores, insectivores and carrion-eaters survived the extinction event, perhaps because of the increased availability of their food sources. At the end of the Cretaceous there seem to have been no purely herbivorous or carnivorous mammals. Mammals and birds which survived the extinction fed on insects, larvae, worms, and snails, which in turn fed on dead plant and animal matter. Scientists theorise that these organisms survived the collapse of plant-based food chains because they fed on detritus.

In stream communities, few groups of animals became extinct. Stream communities rely less on food from living plants and more on detritus that washes in from land. This particular ecological niche buffered them from extinction. Similar, but more complex patterns have been found in the oceans. Extinction was more severe among animals living in the water column, than among animals living on or in the sea floor. Animals in the water column are almost entirely dependent on primary production from living phytoplankton, while animals living on or in the ocean floor feed on detritus or can switch to detritus feeding.

The largest air-breathing survivors of the event, crocodilians and champsosaurs, were semi-aquatic and had access to detritus. Modern crocodilians can live as scavengers and can survive for months without food, and their young are small, grow slowly, and feed largely on invertebrates and dead organisms or fragments of organisms for their first few years. These characteristics have been linked to crocodilian survival at the end of the Cretaceous.