3. Explosion of Life

The long, slow decline of sedentary species such as *Charina* and *Cloudina* that had dominated Neoproterozoic life for many millions of years is a trademark of the transition to the Phanerozoic Eon, "modern times." Although it has all disappeared, Neoproterozoic life left the legacy of sexual reproduction that was the foundation for what has been called "The Cambrian Explosion." It's called an explosion because fossils suddenly became numerous during the Cambrian. But by the end of the twentieth Century, paleontologists realized that fossils had only seemed to become more numerous during the Cambrian because Precambrian fossils were very fragile and, until recently, we didn't have the knowledge of where to look for them or the technology to recognize them if we had found them. Cambrian life was simply more durable. Moreover, the environment is hostile to fossils, and the further back in time, the less likely fossils can survive. Perhaps, it's a wonder any evidence of fragile ancient life has survived at all.

During the 3.2 billion years before the Cambrian, life slowly evolved from mere molecules to worms, sponges, and jellyfish, but life diversified from those worms and jellyfish to all its present various and complex forms during the short 542 million years of the Phanerozoic Eon. So you could say that we are actually part of the "Phanerozoic Explosion." The rapid diversification of life during our Phanerozoic Eon was made possible by the evolution of sexual reproduction during the Mesoproterozoic and Neoproterozoic Eras. The jumbling of genes during the meiosis phase of sexual reproduction opens up a greater possibility of mistakes (mutations) than simple mitosis of non-sexual reproduction, and enough mutations were sufficiently favorable for the mutants to flourish and occupy a wider range of ecological niches than simply floating in the ocean or anchored to its bottom. This is a strong evolutionary advantage.

This evolutionary advantage was critical for coping with environmental changes and escaping predation. As mentioned previously, all life is divided into producers (forms such as plants that use only chemicals from the environment and energy from some source such as the Sun to produce biomass) and consumers (forms such as animals that either directly or indirectly consume biomass that producers create). Ever since animals evolved during the Mesoproterozoic and Neoproterozoic Eras, predation has been their (our) sole means of accumulating biomass. At first animals dined only on the photosynthesizing producers, but as boreholes in *Cloudina* suggest, they eventually expanded their menu to include each other, creating the predator-prey arms race that continues today. Moving to a new ecological niche is an excellent strategy for escaping predation and has been used endlessly, but it's only a temporary solution because the predators soon follow. One of the constant themes of the Phanerozoic Eon, is the escape of prey into new ecological spaces closely followed by predators.

The Neoproterozoic was a time of significant environmental changes that forced life to adapt or perish. Around 750 million years ago, Rodinia began to rift apart and the glaciers that covered it began to melt, causing a rise in sea level. As Rodinia broke apart and sea level rose, vast new stretches of shallow coastline were created, and scores of millions of years of weathering the land had provided these shallow coastal regions with a muddy sea floor for new life forms to burrow into. Oxygen levels rose and carbon dioxide levels fell as algae continued to remake the atmosphere. As the land masses that had been Rodinia rifted apart, the rift valleys sank below sea level, becoming centers of sea floor spreading, and the associated volcanic activity modified ocean chemistry.

Geologists have compared the geology of 500 million year old rock formations from around the globe and pieced together the jigsaw puzzle of what the Earth looked like during the Cambrian. There were seven continents: Avalonia (parts of eastern Canada, New England, and England), Baltica (Scandinavia, the Baltic countries, and eastern Russia), Gondwana (the southern continents, Middle East, and India), Kazakhstania (Kazakhstan and adjacent areas), Laurentia (Scotland and most of North America), north China, and Siberia. No land was more than 60 degrees away from the equator, and the poles were free of ice. Rodinia's breakup created significantly more continental shelf area for seafloor life than when the great continent was whole. Natural processes had prepared Earth for an explosion of life during the Phanerozoic Eon.

The Phanerozoic Eon is divided into the Paleozoic, Mesozoic, and Cenozoic Eras. The Paleozoic Era, the earliest of modern times, is the time when life came out of the sea onto the land. It extended from about 542 to about 251 million years ago and is divided into Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian periods. Many of these names for geologic periods refer to Wales, where fossils were first found. For example, Cambria is an old name for Wales; the Ordovices were a tribe that lived in northern Wales; and the Silures were a Celtic tribe that lived in Wales during Roman times. Devonian is derived from the British region of Devonshire.

For over three billion years, life consisted of a small variety of simple, "soft" forms that merely floated in the ocean or collected into mats on its bottom, but during the relatively brief 54 million years of the Cambrian period (542 to 488 million years ago), life diversified into many, many forms, perhaps 10,000 species of trilobites alone. Life mutated into forms that filled ecological niches other than floating in the ocean. It moved onto the sea floor and burrowed into it. Although there were still soft bodied worms (and there always will be), this was the time of the development of hard, protective shells, which is the development that made finding such "small shelly fossils" easy and led to the somewhat simplistic belief that the Cambrian brought an explosion of life: Cambrian life, though numerous, was simply more durable.

Cambrian Period (542 to 488 million years ago)

The explosion of life began during the Cambrian Period, during which ten modern major animal groups first appeared, joining the cnidarians (jellyfish, anemone, and other stinging sea creatures) and sponges, both of which had first appeared during the Neoproterozoic. The ten groups are molluscs (clams, squids), brachiopods (clam-like critters), velvet worms (found mostly in South American forests), tardigrada (water bears), arthropods (insects, spiders), aschelminths (nematodes, etc.), echinoderms (starfish, sea cucumbers), annelids (segmented worms), hemichordats (acorn worms, etc.), and chordata (critters with a backbone). Of course, the "founding fathers" of these ten modern groups died out hundreds of millions of years ago, but their DNA lives on in their modern descendants, which is what life is all about from a biological perspective. Other animal groups evolved at the same time but died out, leaving no modern descendants. All life existed in the ocean just as it had for the previous three billion years.

Cambrian life was marked by an ecology whose members developed increasingly complex behavior patterns. It began with simple worms like *Trichophycus pedum*, which left burrow traces that are found almost worldwide. *Trichophycus* produced a fairly complicated and distinctive burrow pattern that had a central burrow with upward probes through the sediment in search of nutrients, generating a trace pattern similar to a fan or twisted rope.

Around 531 million years ago, some molluscs, brachiopods, arthropods, and archaeocyaths began to appear. Archaeocyaths were a type of calcified sponge that diversified into maybe hundreds of species during their geologically short and, if the University of California at Berkeley can be believed, spectacular history. For 10 to 15 million years, they were the first widespread reef builders before a mid-Cambrian mass extinction brought about by oxygen depletion in the oceans did them in. Although reef ecosystems tend to support a wide variety of life and the Cambrian ecology was increasingly complex compared with the Neoproterozoic, it was still not diverse enough to withstand an extended period of low oxygen levels in the oceans, which is what killed off the archaeocyaths. Many call that time a mass extinction because around 83% of the animal genera (a genus is a group of species that share a set of characteristics) didn't survive it, although not all that many genera died off in absolute numbers because there weren't a great many genera yet. Still, it was one of the first of the great Phanerozoic extinction events that intermittently plagues life.

In the 1990s, many fossils of the 2.5 centimeter (1 inch) primitive fish *Haikouichthys ercaicunensis* were discovered in the Chengjiang formation in China, joining *Pikaia* as the first chordates and our most ancient ancestors. *Pikaia* was discovered in 1911 at the famous Burgess Shale site in British Columbia, Canada, by Charles Walcott. *Haikouichthys* and *Pikaia* were not vertebrates because they had a notocord instead of a true skeleton. Notochords are sort of primitive backbones that serve as support structures in chordates that lacked a bony skeleton. All vertebrates such as you and I are derived from these ancient chordates. This is the reason that embryos of modern vertebrates have notochords before they develop their backbone; embryonic development often happens to follow a pattern similar to the ancestral development of the modern animal's traits. Notochords were advantageous to our primitive fish ancestors because they were a structure rigid enough for muscle attachment, yet flexible enough to allow more movement than, for example, the exoskeleton of the dominant animals of that time, such as trilobites.

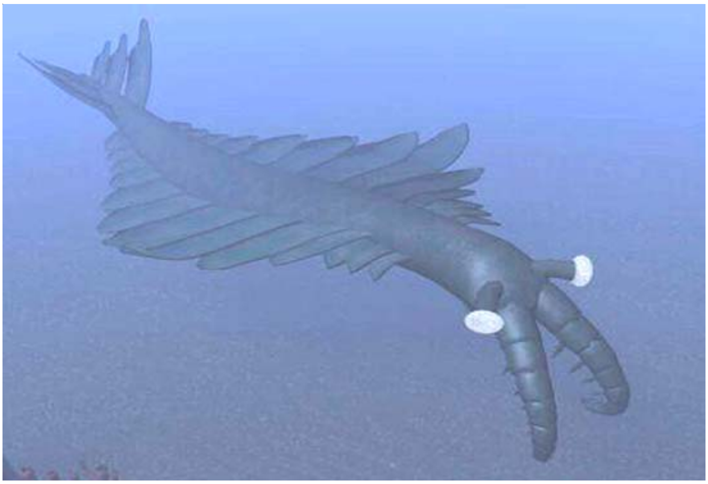
The most numerous Cambrian animals were the trilobites, arthropods that evolved over 15,000 species during their more than 270 million year existence. They got their name, trilobite, from their three part body plan. Most animals have only a right side and a left side and are symmetrical around a central axis that runs its length. Trilobites have a left side, a right side, and a middle section. Trilobites ranged in size from a few millimeters (1/4 of an inch) to over 70 cm (2 feet) long. They were so successful because, along with *Haikouichthys* and *Pikaia*, they were one of the first animals to have efficient eyes. Eyesight required a larger brain to process visual cues and to initiate some sort of action based on the processed information. The first great predator in history, *Anomalocaris*, which showed up during the Cambrian also had vision. At a size of one meter (three feet) or so, it was large for animals of the time and has been called the T-Rex of the Cambrian.

Ordovician Period (488 to 444 million years ago)

Around 488 million years ago, the Cambrian Period ended with another extensive extinction event, giving way to the Ordovician Period, but all major animal groups survived. The ecology of the Ordovician seas must have been relatively complete because only one new major animal group (the Bryozoa, or moss animals) evolved. Bryozoa are colony-type animals,

Cambrian Trilobites

The specimen on the left is *Elrathia kingi* from the 505 million year old Wheeler Shale formation in Western Utah. *Elrathia* is one of the most common trilobites in the world. The specimen on the right is *Bergeroniellus asiaticus* from the Sinsk Formation, Lena River, Russia, dating to 520–525 million years ago. This was the time and place that was the focus of the Middle Cambrian mass extinction. *Bergeroniellus* is of the order Redlichiida, which are the first trilobites to appear in history.



Anomalocarid

An artist conception of an anomalocarid hunting a trilobite. Anomalocarids were the first large predators in history, growing up to 2 m (6 feet) in length. They were free swimming, and their fossils have been found all over the world.

and they first appeared early in the Ordovician. The number of minor animal groups more than doubled during the 44 million year Ordovician Period, and the total animal population increased significantly.

One of the recurring themes in the history of life is that an extinction event makes room for minor animal groups to diversify, and previously minor players often proliferate after a mass extinction, becoming major players in the recovery. So it was with the stemmed crinoids (Sea Lilies). Rare during the Cambrian, they diversified to large numbers during the Ordovician and became an important part of the Paleozoic ecology for almost 200 million years. Crinoids feed by filtering small particles such as microscopic plants, animals, bacteria, and larvae out of the water.

Another animal group that found the end-Cambrian extinction beneficial was the cephalopods (squid-like critters) with an external shell (which makes them nautiloid). They could become very large; *Endoceras* and *Cameroceras* could reach a length of as much as 10 meters (33 feet). They replaced the Anomalocarids of the Cambrian as the ocean's top predator. Their tentacles added a complex sense of touch to their sensory repertoire, requiring an increase in brain power over their less gifted contemporaries and probably making them the Einsteins of the Ordovician.

Fortunately for us, since they're our earliest ancestors, the small, jawless fish of the Cambrian, such as *Haikouichthys*, also survived the extinction and began to diversify. Some species, such as *Arandaspis prionotolepis*, developed armor plate, a defense mechanism that would often recur throughout evolution. Others, such as *Promissum*, developed both a primitive mouth with mineralized teeth and a primitive backbone that evolved from *Haikouichthys'* notochord. *Promissum* looked like a small eel or large worm because the only fin it had was a small one on the tail. But these were still

Ordovician Scene

This is a NASA artist's depiction of Ordovician life. The cephalopod *Endoceras* is capturing a trilobite among a scattering of Sea Lilies. Two other cephalopods with distinctive long conical shells, *Orthoceras regulare*, float nearby.

jawless fish that fed by sucking organic debris from the ocean floor. There's some tantalizing hints from close analysis of the many Ordovician fish fossils that primitive fish brains had begun to develop the three parts (forebrain, midbrain, and hindbrain) that all of us with a backbone have. Corals and rudimentary sharks appeared in small numbers.

The ocean's plant and animal population increased during the Ordovician to the point that it created the first important source for our oil. There is some oil in Cambrian formations, but Ordovician oil is much more extensive, being found throughout the middle of the United States, from Maryland to Montana.

Probably the most important Ordovician development was the first tentative move toward the land. For hundreds of millions of years, green algae had been washing ashore, and eventually genetic mutations slowly gave some of them both a waxy outer coating (cuticle), which enabled them to survive exposure to drying air and direct sunlight, and a new way to reproduce (spores). The result was a stemless, rootless land plant similar to liverworts; in fact, analyses of mitochondrial DNA suggests that liverworts were the first plants to evolve from green algae. The ability to survive on land was a great evolutionary advantage because it allowed the new plants to escape their ocean predators. Fossils of spores suggest this happened at least 480 million years ago.

When the Ordovician Period began, a large continent called Gondwana contained a significant portion of dry landmass. The rest was spread over three smaller continents and some minor landmasses and island arcs. No land was far from the equator, and sea level was rather high. Thus it was that the Ordovician began with idyllic, extensive, warm, shallow continental shelves. The Ordovician came in like a lamb, but it went out like a lion with the second worst mass extinction in the history of life. As the period progressed, sea floor spreading pushed Gondwana toward the South Pole. At the end of the period, Gondwana was over the pole and covered with massive glaciers, removing a great amount of water from the oceans and dropping sea level over 50 meters (160 feet). The glaciated supercontinent at the pole created a strong deep-ocean circulation and cooled ocean surface temperatures. The warm, shallow-water continental shelves on which all life depended nearly disappeared, and almost half of the genera living at the time didn't survive into the Silurian Period.

Silurian Period (444 to 416 million years ago)

The Silurian Period began at the end of the Ordovician's great mass extinction. It's the shortest Period in the entire Phanerozoic Eon except for our current one, which hasn't ended yet, and it was a time of recovery and expansion onto the land. The Ordovician extinction was so devastating primarily because life had existed solely in the sea and had not yet established a broadly diverse ecological basis, leaving it vulnerable. That began to change during the Silurian. But first the climate had to get warmer.

The warm ocean temperatures throughout most of the Ordovician had encouraged extensive algae growth, which increased the removal of atmospheric carbon dioxide. This lower greenhouse gas concentration coupled with the glaciation of Gondwana cooled the oceans and killed a large portion of the algae during the great Ordovician mass extinction (probably the source of Ordovician oil). With less algae available to remove carbon dioxide that volcanic activity put into the atmosphere, greenhouse conditions returned during the Silurian, warming the planet back up. As the Earth warmed, the glaciers melted, and sea levels rose again, stimulating recovery.

Trilobites again survived a mass extinction as did some Orthoceras species with their long, conical shells. Quite a number of Silurian Orthoceras fossil shells are for sale on the open market. Although the Orthocerans survived, their larger cousins and the Ordovician's top predators, the endocerids, did not. Their place as top predator was taken during the Silurian by *Pterygotus*, popularly called a sea scorpion. *Pterygotus* had four pair of walking legs, a pair of swimming paddles, and a pair of large pincers in front that it used to subdue its prey. Corals, which were not common during the Ordovician, also survived and became the dominant reef-building organism.

The jawless fishes also survived and expanded their number of species, but their time as an important member of the undersea life was coming to an end. The front gill slits of some fish species were slowly evolving into jaws, and the older, jawless fishes would not be able to compete with the jawed fishes that joined the ocean community at the end of the Silurian. By the late Silurian, fish also had begun to move into fresh water.

Without a doubt, the most important development during the Silurian was the permanent habitation of the land, and it had to begin with plants, the producers. It's impossible to overemphasize the importance of the movement of plants onto the land because plants are the source of all biomass, and opening up this vast, new ecological frontier was crucial to the evolution of life. Of course, you could argue that the movement onto land was

The Sea Scorpion, *Pterygotus*

Pterygotus, a dominant Silurian predator, could reach a length of 2.3 m (about 7 feet). It had a pair of very large compound eyes and a pair of smaller eyes in the center of its head.

inevitable because anything that **can** happen, **will** happen if given enough time (Murphy's Law). But its inevitability doesn't diminish its importance once it does happen.

The transition of plants from a strictly water habitat onto the land probably happened in shallow tidal pools or freshwater ponds when some plants developed the ability to get minerals necessary for building cells from the mud at the bottom of the pools in addition to their usual source, which was water. Because sunlight unfiltered by water enables more efficient photosynthesis, it was beneficial to protrude above the water a little. Once these two new sources were tapped, the race was on to use them to their fullest.

The winner of that competition was *Cooksonia*, the first land plant, a two to three centimeter (1 inch) plant with a spoor packet at the end of each branch. It was a vascular plant, which means it had a capillary system to move water and nutrients around in it like all modern plants have. It had no leaves; the entire plant surface was photosynthetically active. It was connected to the soil by horizontal runners (rhizomes) and small root hairs. It has been found in Europe, the British Isles, and Bolivia, but it had become extinct by the middle of the Devonian Period. Before the Silurian ended, *Cooksonia* was joined by *Baragwanathia*, which was also a spoor-bearing, vascular plant, but it had needle-like structures similar to leaves. *Baragwanathia* has been found primarily in Australia, but some species have been found in China and Canada. At up to one meter (three feet) high, it was larger than *Cooksonia* and had evolved independently to fill the same ecological niche as *Cooksonia,* which was tidal flats.

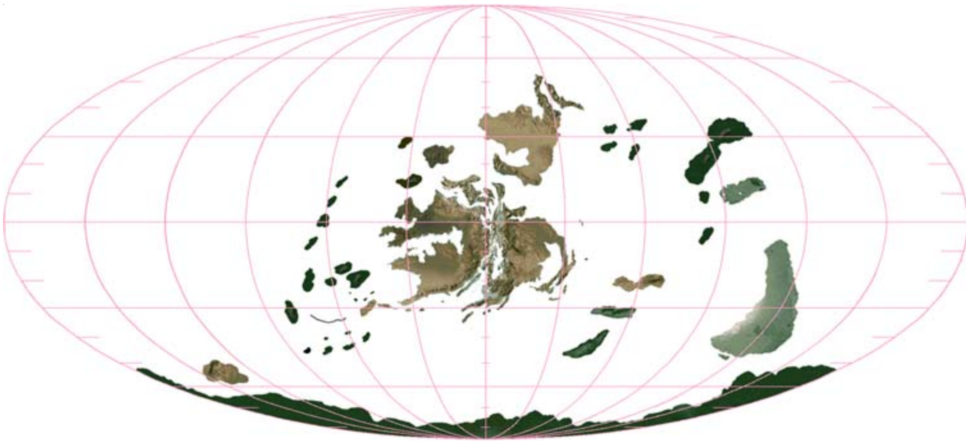
Of course, *Cooksonia* and *Baragwanathia* didn't just suddenly appear out of thin air. Paleontologists have found spoors characteristic of land plants dating back to the mid Ordovician, but fossils of the plants themselves have not yet been found. This is not unexpected because the conditions necessary for making fossils are pretty strict; the life form has to be preserved before it has a chance to decay, which is an uncommon situation. But they might be out there in rocks buried somewhere in this big world.

Paramvir Dehal of the Lawrence Berkeley National Laboratory and Jeffrey L. Boore of the University of California, Berkeley, have detected evidence in the genomes of the sea squirt, Japanese puffer fish, mouse, and human that sometime during the Silurian, or even as early as the late Ordovician, our ancestor duplicated its entire genome during reproduction. Several million years later, another ancestor did it again. Duplications in the genome often cause disease such as Down syndrome and can even be fatal. So in the past 400 million years, the entire genome might have been duplicated during reproduction several times, but we wouldn't know it because it led to the death of the individual. Our two ancestors who were successful at it were fortunate enough that their genome control system (the epigenome) was able to adapt to the duplication because the evidence is that the whole genome was successfully duplicated at least twice in our ancestors. This gave our ancestors a copy to carry on with normal protein manufacturing while providing extra copies that could undergo mutation without damaging the individual. These mutating copies paved the way for our ancestors' adaptation to the land during the Devonian Period.

Devonian Period (416 to 359 million years ago)

Throughout the millions of years between the Neoproterozoic and the Devonian Periods, the continents were continuing their slow, majestic dance to the music of magma in Earth's mantle; they would pull apart, then come together again with different partners. They were being carried along by convection currents in the molten rock mantle on which they dance. Sometimes these convection currents break through a relatively weak point in the crust and form spreading centers like those currently along the mid-ocean ridge shown on page 121. These convection plume spreading centers push apart whatever happens to be on opposite sides of them. If a convection plume wells up underneath a continent, it will slowly split the continent apart like happened to Rodinia and is currently happening along the 6,000 kilometer long Great Rift Valley that stretches from northern Syria in Southwest Asia to central Mozambique in East Africa. The plume making this rift is probably centered under the Afar Depression in the Horn of Africa. This dance of the continents is so much slower than the pace of life that entire species can rise, flourish, and fall during one minor step of the dance.

As continents come together, they slide up over the ocean floor that had been separating them because continents are lighter than the ocean floor. As the ocean floor dives under a continent (is subducted), there is extensive volcanic activity in the area where the ocean floor is subducted (subduction zone) like is happening now around the rim of the Pacific Ocean in the so-called Ring of Fire. It's this volcanic activity that enables scientists to recreate the events of so long ago. Radioactive dating of zircon in



Earth 400 Million Years Ago

This paleomap, composed from data accumulated by Ron Blakey of Northern Arizona University and Christopher Scotese of the University of Texas at Arlington, shows Laurasia and Baltica beginning to join, forming the minor supercontinent of Euramerica, which was on the equator. Later, Siberia, Gondwanaland, and Euramerica joined to make Pangea. Most of the Earth's surface was covered by a vast, unbroken ocean.

the lava flows gives accurate dates of events, and residual magnetism frozen in magnetic minerals (like magnetite) of the lava when it cooled gives orientation and latitude information.

As ocean floor is subducted, continents scrape off some of the surface mud of the ocean floor (and the remains of dead animals buried in it), which is called an accretionary wedge and which then becomes part of the continent. This former ocean floor material is often lifted up into mountains as the two continents are rammed together, as is now happening in the Himalayas, where fossils of ancient ocean life are found high in the mountains.

During the end of the Ordovician and beginning of the Silurian Periods, the eastern tip of the microcontinent of Avalonia had been pushed into Baltica, forming an extended peninsula. During the Devonian, Baltica/Avalonia and Laurentia were pushed together, creating the minor supercontinent Euramerica. This collision started around 375 million years ago as the Avalon Peninsula of Baltica began to push into the part of Laurentia that is now New England, creating some of the northern part of the Appalachian mountains.

This ongoing dance of the continents has some effect on life because species tend to evolve together when continents are joined, but diverge when the continents pull apart. Though species tend to diverge when isolated from one another, they tend to evolve along similar, though not identical, lines in response to similar ecological opportunities. For example, Australia has been isolated for a long time and has evolved a collection of animals that raise their young in pouches, but these pouched animals fill similar ecological niches as their counterparts on other continents.

Although the Devonian is often called "The Age of Fishes" (there were so many of them; the first member of the shark family appeared during the Devonian), it was the scene in which two major developments important for the evolution of life on land were played out. The most fundamental, because it's the source of all land-based biomass, was the expansion of plant life on land. Once *Cooksonia* made its appearance, mutations began to diversify the plant into new species, each trying to use the new habitat to the best advantage, growing larger and burrowing deeper into the soil.

When *Cooksonia* and *Baragwanathia* appeared in the late Silurian, they had the basic characteristics necessary for survival on land: a means to prevent dehydration (cuticle), a way to get water and nutrients from soil (rhizomes and root hairs), a system for moving water and nutrients throughout the plant (vascular system), a means to get carbon dioxide into, and oxygen out of, the plant (stomata), and a method of reproduction (spores). But to proliferate rather then merely survive, plants needed to increase their efficiency at creating biomass and to use more of the available land space in terms of growing both farther from the water's edge and higher up in the air. This involved improvements in photosynthesis, reproduction, and structure.

For the first few million years on land, plants such as *Rhynia gwynne-vaughanii* (410 to 400 million years ago) were basically stems that grew horizontally along the ground as rhizomes that then curved upward as shoots, and nutrients were drawn up from the ground by small root hairs that grew out of the rhizomes. Some plants, like *Nothia aphylla*, had rhizomes that grew underground. All these plants grew to be around 18 centimeters (7 inches) tall. *Asteroxylon mackiei* had branching underground rhizomes (sort of like roots) that penetrated as much as 20 centimeters (7½ inches) into the soil, enabling it to grow over twice as tall as its contemporaries, *Rhynia* and *Nothia*. The competition for sunlight and nutrients drove the shoots higher and the roots deeper as millennia passed until roots of *Archaeopteris* (not to be confused with the bird fossil, *Archaeopteryx*) reached down 100 centimeters (over 3 feet) and the plant height reached to 30 meters (100 feet) by 380 million years ago (36 million years after the beginning of the Devonian). To enable them to grow to such great heights, plants grew more sturdy by developing the capacity for what is called secondary growth, which is what makes wood. *Archaeopteris* was the first modern tree, and it made wood the same way modern trees do.

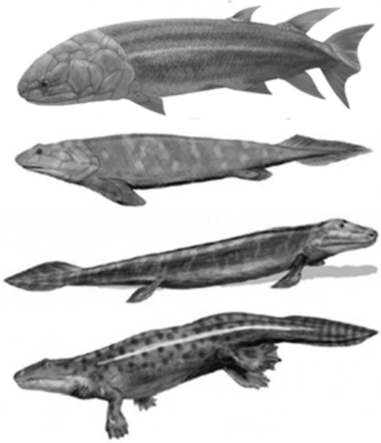
As plants grew larger during the 57 million years of the Devonian Period and their roots dug deeper into the soil and rock crevasses, carbon dioxide was increasingly sequestered from the atmosphere by both accumulation of plant biomass and increased chemical weathering of rock brought about by roots. Weathering sequesters carbon dioxide (CO_2) as dolomite, $MgCa(CO_3)_2$, and calcite, $CaCO_3$, and was probably the primary way carbon dioxide was removed from the Devonian atmosphere. The net effect was that atmospheric carbon dioxide at the end of the Devonian was only ten percent of what it was at the beginning. What this meant to plants was that photosynthesis in the stems alone, as in *Rhynia* and *Nothia*, could not supply the carbon dioxide needs of the increasingly larger plants from a diminishing supply, and those that developed a more efficient method for photosynthesis (leaves) survived. Some early Devonian plants like *Baragwanathia* and *Nothia aphylla* had stems with scales (like modern clubmosses) that somewhat resembled leaves, but true leaves with veins to move the products of photosynthesis throughout the plant (absent in *Baragwanathia* and *Nothia*) developed gradually and weren't widespread until the Devonian was more than half over. *Archaeopteris* had true leaves.

The most striking improvement in plants was the development of seeds, which involved a number of developments in spores that are too technical to talk about here. The first land plants like *Cooksonia*, *Baragwanathia*, and *Rhynia* had to have their feet wet to reproduce because they dropped their spores packets in water and the male sperm had to swim through the water to the female spore. Botanists don't generally use "male" and "female" terms, preferring "microspore" and "megaspore," respectively, but we'll stay with "male" and "female." Eventually, the male spore developed a durable coat so it could be carried on the wind, and the female spore was retained and nourished by the plant, so plants could reproduce without water and could therefore increase their range to dry land. By 385 million years ago, *Runcaria* was well on the way to developing a full-fledged seed habit. Finally, the first true seed plant *Elkinsia polymorpha*, a "seed fern" found in West Virginia and dated at about 365 million years ago, appeared.

Along with plants, the land became home to some small centipede-like and spider-like arthropods (bugs). Once plants gained a foothold onto dry land, the second major development occurred in the animal kingdom: the evolution of fish into four-limbed, land animals (tetrapods, which all land animals are at heart; snakes are tetrapods that have lost their limbs). This evolution took place in the river deltas and fresh water marshes of Euramerica and involved the development of a bone structure for limbs, a heavy duty structure for support, and a means to get oxygen from the increasingly oxygenated atmosphere. The two drivers for these developments, as in all evolution, were survival (to eat and avoid being eaten) and reproduction (survival of the young). The development of the skeleton, lungs, and the five senses all supported these two imperatives.

All tetrapods share similar features. All have backbones, a pelvis attached to the backbone to support their weight, lungs, a ribcage to protect the heart and lungs, and nostrils for breathing. Their front limbs invariably consist of a single bone nearest the body that's called the humerus, then a pair of bones called the radius and ulna leading to "hands." Their back limbs are similarly constructed with a single bone nearest the body that's called the femur, then a pair of bones called the tibia and fibula leading to "feet." It doesn't matter whether you're a dinosaur, whale, or human; the construction of all limbs follows the same plan.

Eusthenopteron, a 1.2 meter long (4 feet) fish that lived 385 million years ago, was the first known ancestor to have all these features; it lived in the ocean rather than near shore or in tidal pools. The first *Eusthenopteron* fossil was found in Canada in the 1880s. In the open ocean, *Eusthenopteron* probably suffered extensive predation by much larger predators like whale-



Devonian Tetrapods

Eusthenopteron (top), *Panderichthys* (second from top), *Tiktaalik* (second from bottom), and *Acanthostega* (bottom) illustrate the evolution of fish into amphibians. A form like *Tiktaalik* was predicted to exist based on the characteristics of *Panderichthys* and *Acanthostega,* and the discovery expedition to Ellesmere Island was conducted specifically to find it. Such prediction of previously unknown form or function followed by its discovery is the essence of science.

sized *Dunkleosteus*, but some developed mutations that enabled them to escape predation and survive. One set of mutations led to a more bottom-feeding pattern like coelacanth, which is a "living fossil" that has survived to the present day.

The other set of mutations led to a shallow water life-style like *Panderichthys* (380 million years ago), a transitional form about the same size as *Eusthenopteron* and whose fossils were found the Baltic region of Europe. Unlike *Eusthenopteron*, *Panderichthys* had a flattened skull with eyes on top of its head and no dorsal or anal fins. It was still a fish because it had scales and both gills and lungs. It probably spent most of the time perched on its stubby leg-like fins on the bottom of shallow tidal pools and river deltas in Euramerica, which was then along the equator. Warm water has a lower oxygen content than cool water (If you set a pan of cool water in the sun, you'll see bubbles slowly forming on the bottom as the sun's warmth drives the oxygen from the cool water.), so *Panderichthys* probably raised its head out of the water occasionally for a gulp of air. *Panderichthys* wasn't strong enough to support itself on land to feed, which wasn't a big problem because the food necessary to support such a large fish was in the water anyway; the only land-based food were bugs. But its young might have been able to scramble briefly onto dry land after the small creatures that lived there.

Around 375 million years ago *Panderichthys* gave way to *Tiktaalik*, discovered early in the twenty-first century north of Canada at Ellesmere Island, which was near the equator 375 million years ago. *Tiktaalik* had all the characteristics of *Panderichthys* but had shoulders disconnected from its skull, giving it a functional neck, and ribs more like tetrapods although its ribs weren't strong enough to support its lungs against the full pull of gravity. Although its fins were more like arms and legs than those of *Panderichthys,* it still wasn't strong enough to support itself out of water.

Fins of the next generation tetrapod, *Acanthostega*, looked a little more like arms and legs because they had "hands" and "feet" with webbed "fingers" and "toes", but they were not significantly stronger than those of *Tiktaalik*. Those fingers and toes were not well constructed for use on land. *Acanthostega* probably spent most of its time in the water because, although it had lungs, it also had gills that were internal like a fish has, not external like modern amphibians that are primarily aquatic. It also had a finned tail that was more like that of a fish than a crocodile. It was flexible from side to side and probably used its tail and webbed toes to maneuver through swamps like a crocodile does today. *Acanthostega* was discovered in Greenland in rock layers dated at 365 million years ago.

Ichthyostega was a somewhat stronger tetrapod that was also discovered in Greenland and possibly lived at about the same time as *Acanthostega*. *Ichthyostega* had a life-style different from *Acanthostega* because it had no gills and its rib cage and forelimbs (also with hands and feet and fingers and toes) were strong enough to support the animal out of water. Nevertheless, it wasn't a full-fledged amphibian because it wasn't able to move freely when out of water, probably pulling itself along like an elephant seal.

The end of the Devonian saw other tetrapods like *Tulerpeton*, *Hynerpeton*, and *Sinostega*, but less is known about them at this time. Finding fossils is difficult because so much of the ancient rock is under forests or fields or the works of civilized man. Fossils are usually found in remote places like Ellesmere Island and Greenland where ancient rock is exposed.

Carboniferous Period (359 to 299 million years ago)

The Carboniferous Period began at the close of the Devonian Period, around 359 million years ago, and ended around 299 million years ago. Geologically, Siberia and Euramerica joined during this Period, creating the Ural Mountains and completing the formation the supercontinent Laurasia. The large supercontinent, Gondwanaland, which was composed of what is now Africa, South America, Australia, India, and Antarctica, was at the South pole, where much of it was covered with massive glaciers that intermittently grew and retreated, probably under the influence of the same astronomical processes (Milankovitch cycles) that have caused the cycles of glaciation during the past half million years. Ancient bedrock in Africa, Australia, India, and South America show scratches and gouges from this Carboniferous glaciation.

According to a paper published by the National Academy of Sciences, the atmospheric carbon dioxide level at the beginning of the Carboniferous was around 1500 parts per million (1500 cubic feet of carbon dioxide in each million cubic feet of air), which was much more than the 300 parts per million in 1900, and the average world temperature was approximately 20^{o} C (68^{o} F), which also was more than the 15^{o} C (59^{o} F) average of today. The world was warmer than today, and Laurasia (North America, Greenland, Europe, and Asia) were more humid. By the end of the Period, atmospheric carbon dioxide level was around 350 parts per million, and the average world temperature was about 12^{o} C (54^{o} F).

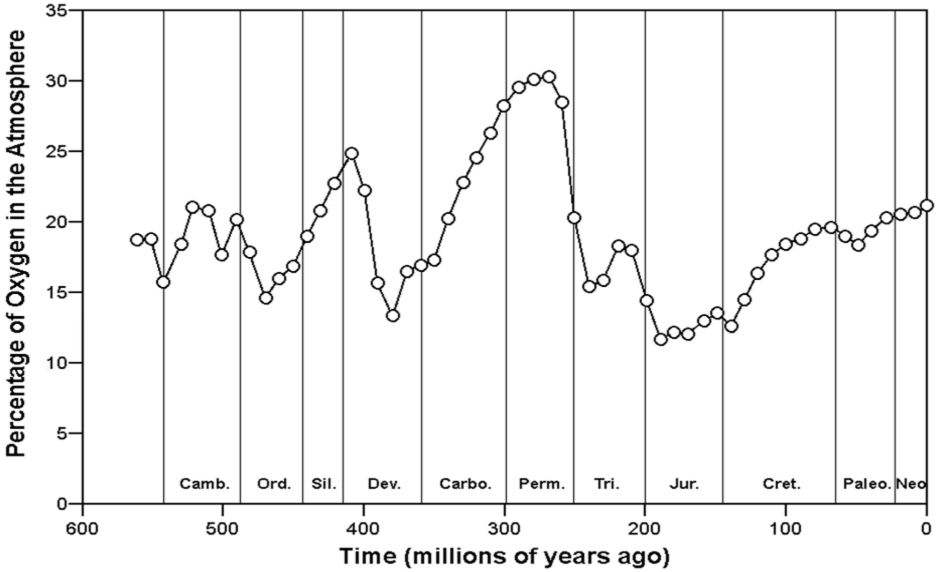
This early Carboniferous carbon dioxide was removed from the atmosphere by vast forests of shrubs, such as club mosses and ferns, and large trees like horse-tails and the newly evolved conifers. These forests grew in lowlands of what is now the eastern United States, England, Europe, and parts of Russia. This extensive forestation had been made possible by the evolution of seeds during the Devonian. Trees had also developed a protective bark made of lignin, which is a complex chemical that provides strong, chemically resistant, lightweight structural support; wood is mainly composed of lignin and structural carbohydrates.

As the glaciers in Gondwanaland grew and retreated, these lowland forests were intermittently drowned by rising seawater as glaciers melted, only to grow back again as sea level fell during the next Gondwanaland glacial period. No microorganisms had evolved at that time that were capable of breaking down the lignin in the protective bark and causing decay, so the drowned forests formed vast peat bogs, which were then covered by sediments. This process was repeated several times to form layers of buried peat bogs and sediments, storing atmospheric carbon dioxide from the Carboniferous Period in layers of buried peat.

Since then, hundreds of millions of years of heat and pressure from overlying deposits converted the buried peat bogs to coal seams that are now found throughout the eastern United States, England, Europe, and parts of Russia. When we burn coal today, we release back into the atmosphere some of that 1200 parts per million carbon dioxide that had been removed from the atmosphere during the Carboniferous Period. Some of the carbon dioxide removed during the Period was returned to the atmosphere right away by forest fires that probably burned unchecked over large areas of forest, and charcoal from those ancient forest fires is sometimes found embedded in the coal seams of today.

Photosynthesis in the great Carboniferous forests put a lot of oxygen into the atmosphere. Atmospheric oxygen late in the Devonian was about 13% to 17% (compared with about 21.5% today), but had climbed to approximately 17.5% by the start of the Carboniferous thanks largely to forests of Devonian *Archaeopteris*. The evolution of new tree species and growth of vast forests during the Carboniferous led atmospheric oxygen to steadily rise to approximately 28.5% by the close of the Period. Insects, which are limited in size by their inefficient way of breathing, took advantage of the high oxygen level to grow large, like the foot-long cockroach, *Dictyomylacris*. Many of these insects had developed mouth parts that enabled them to bore into plants and suck nourishment from them, making them the first land-based herbivores. The most famous Carboniferous insect is *Meganeura monyi*, which looked like a modern dragonfly but had a wingspan up to 75 cm (2 feet).

One of the reasons that atmospheric oxygen increased was because evolution of animal life on the land, which consumes the oxygen plants produce, lagged behind that of plant life. Throughout the Devonian, animals were still tied to the sea for food and reproduction. Eggs of all amphibians are enclosed only in a cellular membrane; so, like the eggs of modern frogs, they’re laid in water, fertilized by a cloud of sperm that the male releases to drift over them, and then need to remain in water until the young emerge.



Oxygen Content of the Atmosphere during Phanerozoic Time

This figure (adapted from an article by Berner, VandenBrooks, and Ward in the American Association for the Advancement of Science publication *Science*) shows the increase of atmospheric oxygen during the Carboniferous and Permian Periods.

Exposing the eggs to the elements and predation with only a weak cellular membrane for protection is a weakness of all amphibians. Carboniferous amphibian predators were also wedded to the water for food because there was no complete land-based food chain to draw them from a primarily aquatic lifestyle. What was missing from the land-based food chain was a herbivore, other than insects, that could convert plant biomass to animal biomass for amphibians, carnivores all, to prey on. For hundreds of millions of years, aquatic herbivores had converted plant biomass to animal biomass by dining on algae or seaweeds. But in order to survive on land, plants had evolved a complex array of chemical characteristics that were far different from their sea-borne ancestors and that made them difficult for animals to digest. Some were even toxic. Nature needed a long time to solve these puzzles and take advantage of the ecological opportunity for a land-based animal herbivore.

Animal herbivores evolved during the same time as did a method of reproduction somewhat safer than that of amphibians. This new method of reproduction is centered around what is called the amniotic egg, which is similar to a human egg. The amniotic egg encloses all the nutrients necessary to develop the young in a tough, protective membrane that can be enclosed in some sort of shell, either hard like a chicken's egg or leathery like a crocodile's egg, and laid on land. This was an evolutionary advantage over amphibians, and the rise of amniotes marked the fall of amphibians as the dominant life form. This evolutionary advance required a change from the external method of fertilization that had been around since the advent of sex; the amniotic egg required that the female be fertilized internally, and the sex act was born.

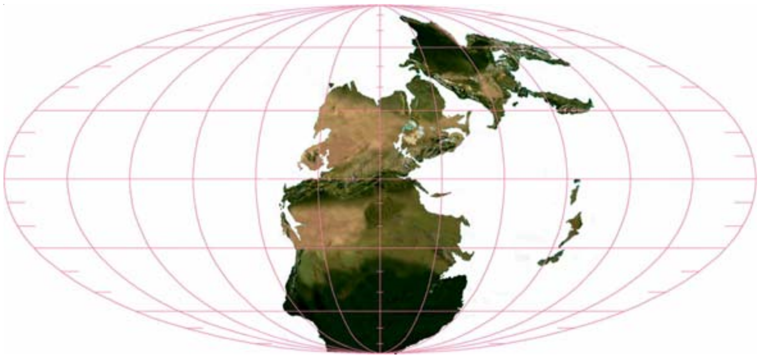
The reproductive style of the *Seymouria* was probably typical of the intermediate phase between amphibians and amniotes. The female *Seymouria* was internally fertilized, but returned to the water to lay her eggs. The young were aquatic until they were strong enough to live on land. The *Seymouria* itself lived after the end of the Carboniferous, but its ancestors probably provided the transition between amphibians and amniotes.

During the Devonian, plants had evolved a tough skin to prevent them from drying out and a method of reproduction that didn't depend on water, so they could grow far from water during the Carboniferous Period. An effective animal land herbivore had to solve the same two problems in order to go where the food was. The evolution of the amniotic egg solved the reproduction problem. The desiccation problem was solved during the Carboniferous by the evolution of a tough, scaly hide that allowed the animal to preserve its water. The result was the early reptile.

The first known reptile, called *Hylonomus*, lived around 315 million years ago and probably looked like a modern lizard. Early reptiles were small like *Hylonomus*, which was about 20 to 30 centimeters (8 to 12 inches) long including its tail, and *Petrolacosaurus*, which lived a little later than *Hylonomus* and was about 40 centimeters (16 inches) long. They probably fed on insects, and *Meganeura monyi* might have also fed on them. Another late Carboniferous reptile was *Mesosaurus*, which was perhaps the first reptile to revert (during the Permian Period) from a land dweller back to living in the water, where its amphibian ancestors originally came from. It was the distribution of *Mesosaurus* (Africa and South America) that helped lead to the conclusion in the early twentieth Century that Africa and South America were once joined.

Nearly all the life forms described by only one word, like *Mesosaurus*, are actually a related group (called a genus) having two or more species, so *Mesosaurus* is not really only one kind of critter but is several that are closely related. The exact number of species (which is always written with two words as in *Meganeura monyi*, for example) in a genus is seldom known. What's more, there are ancient (and modern) genera that are yet unknown and might always remain hidden in rocks deep under forests, fields, and cities. Far, far more kinds of life forms populated Earth in ancient times than can be inferred from the brief descriptions in these few pages.

Over the last of the second millennium of our time and the beginning of the third, there was a small controversy among palaeontologists over what constituted a reptile. Unlike Protestants and Catholics in Northern Ireland, Muslims and anyone anywhere, or Sikhs and Hindus in India, scientists are always able to resolve these sorts of disagreements without resorting to clubs, AK-47s, or bombs, which is one of many things religion can learn from science. For technical reasons, early herbivores are not classed as true reptiles by most scientists but are called mammal-like reptiles because their



Permian Geography

This is approximately what Earth's Geography looked like 260 million years ago, near the end of the Permian Period. Most of Earth's land was fused together in one supercontinent called Pangea which was surrounded by one ocean called Panthalassa. The remaining small land masses east of Pangea were separated from the great continent by the Tethys Sea.

line eventually evolved into mammals. Regardless of these minor disagreements, the important roll of converting plant biomass to animal biomass was filled by the end of the Carboniferous by several herbivores that were mammal-like reptiles such as *Edaphosaurus*, which ranged in size from 50 centimeters (20 inches) to over 3 meters (10 feet) long and had a large fin along its back, which is thought to be a temperature regulating appendage, quickly warming the critter on cool mornings and cooling it in the shade during the heat of the day.

By the end of the Carboniferous Period, there was a complete, though rudimentary, ecological system on the land: shrubs, such as club mosses and ferns, and large trees like horse-tails and the newly evolved conifers used solar energy to convert carbon dioxide, water, and minerals to biomass; herbivores like *Edaphosaurus* and *Diadectes* converted plant biomass to animal biomass; and carnivores like *Haptodus* and the amphibian *Cochleosaurus* controlled the herbivore population.

Permian Period (299 to 251 million years ago)

As the Permian began, conditions on the land were very much like those of the Carboniferous. The climate was generally cool, and tropical areas were covered in lowland forests and swamps. Some of the Gondwanaland (southern) part of Pangea was on the South Pole, just as it had been for several hundred million years, and covered with glaciers.

The Permian could be thought of as a time of consolidation. Plants and animals consolidated their move onto the land and began to fully exploit this new ecological opportunity. During most of the Carboniferous, tetrapods were slowly losing their bonds to water, and their legs gradually became stronger as they relied less on water's buoyancy. Only during the last few million years of the Carboniferous had tetrapods become strong enough to completely support themselves on land. From the Permian on, tetrapods were at last prepared to fully exploit life on dry land.

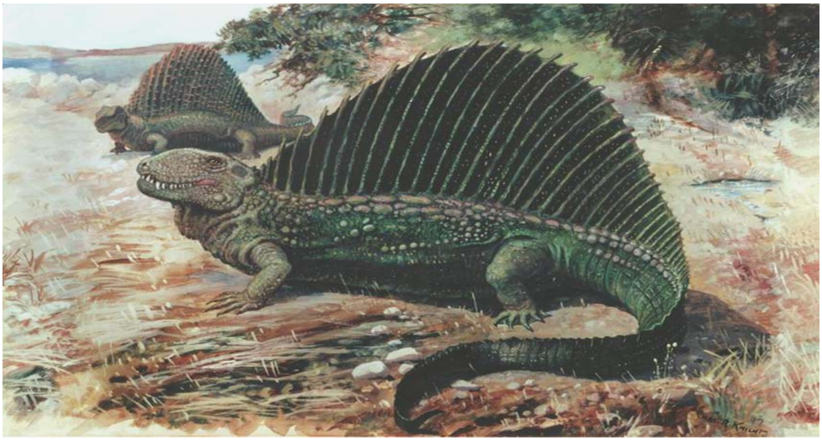
The land itself (except for a small part of what is now China) was consolidated into one supercontinent called Pangea. It was the first time since the breakup of Rodinia almost half a billion years earlier that all land was gathered into one, giant continent. The landmass that's now Siberia/ North China was separated from northeastern Pangea by a shallow sea, which was slowly closing as Siberia/North China was being pushed into the rest of the existing land to finalize the formation of Pangea. These conditions were relatively stable for around 20 million years.

The consolidation of land had a profound effect on life. It reduced the amount of shallow continental shelf area to perhaps one sixth of its area when the continents were separate long ago during the Cambrian when life was exclusively marine. Correspondingly, the population of marine species that lived in those shallow continental shelf waters suffered during the time of Pangea. However, corals still built reefs around the giant continent for the new breeds of sponges, fish, molluscs, and the few species of trilobites that had evolved from Cambrian forms to carry on for their kind.

Consolidation also increased the land area that was far enough from the moderating influence of the ocean to have a continental climate, which is characterized by hot, often dry, summers and cold winters. By 270 million years ago, the large, coal producing forests typical of the Carboniferous were gone. Plants had changed from those that favored moist-to-swampy environments of the Carboniferous to those like conifers and ginkgoes that flourished in a dryer climate. The continent became increasing dry, which favor amniotes over amphibians. Because of its remoteness from the ocean, some of central Pangea eventually became one of the largest deserts that ever existed in the world.

As during the Carboniferous, early Permian herbivores were not yet very diverse and at first were limited primarily to the Carboniferous holdovers *Edaphosaurus*, which was widespread, and *Diadectes*. They primarily ate leaf litter and other loose plant debris. This leaf litter and loose plant debris had been partially broken down by bacteria and fungi and were easily digested.

Herbivores gradually began to diversify and grow larger until, by 270 million years ago, the group included such members as *Caseoides sanangelensis*, *Caseopsis agilis*, *Angelosaurus dolani* (all found in Texas), which were all up to 3 meters (10 feet) long and generally heavily built. Largest of them all was *Cotylorhynchus hancocki* (found in Texas), which was about 6 meters (20 feet) long and weighed around 2000 kilograms (4410 pounds). These are only a few of the many, many herbivores that were munching their way through early Permian foliage. The new herbivores moved away from a diet based on leaf litter and other loose plant debris to one in which living plants (primary producers) were the main item, which provided them with a wider menu and enabled them to push *Diadectes* and *Edaphosaurus* aside. But to digest plants rather than easily digested leaf litter and other loose plant debris, the new herbivores needed to improve their digestion by developing a larger gut than their predecessors, which led to the larger, bulkier body style.



Dimetrodon

Dimetrodon is often grouped with dinosaurs although its splayed legs means that it's not actually a dinosaur. It's often called a mammal-like reptile but is properly a classified as a pelycosaur. It was the top predator of its time. This painting was done by Charles R. Knight in 1897.

Although there were enough lakes and rivers at the beginning of the Period for amphibian predators like *Eryops*, which was 2 meters (6½ feet) long and weighing 130 kilograms (285 pounds), to persevere for millions of years, the vast inland areas of Pangea were best suited for amniote reptiles. The most prolific of the reptile predators during the first 20 million years of the Permian were the various species of *Dimetrodon*, some of which were contemporary with *Eryops*. Like the herbivores, carnivore species grew larger as the Permian progressed (the increase in size of the various species as time passed was to become a common characteristic of life); *Dimetrodon limbatus* (found in Texas) of around 290 million years ago was about 2.5 meters (8 feet) long and weighed 150 kilograms (330 pounds), but *Dimetrodon angelensis* (found in Texas) of 275 million years ago was bigger, at about 4 meters (13 feet) long and weighing 300 kg (660 pounds). *Dimetrodon* and its equally beefy contemporary cousins *Ctenospondylus* (found in Ohio) and *Secodontosaurus* (found in Texas) all had a large sail down their back like *Edaphosaurus*. Other contemporary predators, such as *Ophiacodon retroversus* (found in Texas) and *Spenacodon ferocior* (found in New Mexico), were about the same size as *Dimetrodon* but didn't have the large sail. These are only a few of the many, many carnivores that were chomping on early Permian herbivores and each other.

The variety of herbivores increased as the Permian wore on, and the newer species gradually replaced the older ones and were replaced in turn. By 270 million years ago, *Caseoides sanangelensis*, *Caseopsis agilis*, *Angelosaurus dolani*, and *Cotylorhynchus hancocki* had become extinct and were replaced with new herbivores that were more efficient and sometimes larger. Among the many, many new middle Permian herbivores were *Estemmenosuchus* (found in Russia), which was 4½ meters (14 feet) long and weighed 1500 kilograms (3300 pounds), *Tapinocephalus* (found in South

Africa), which was 3 meters (10 feet) long and weighed 1000 kilograms (2200 pounds), and *Moschops capiensis* (found in South Africa), which could have been as much as 5 meters (16 feet) long. Of course, there were also ecological niches for smaller herbivores such as diminutive *Nyctiphruretus acudens* (found in Russia), which was only 36 centimeters (14 inches) long. Small forms of life are always able to find a sometimes precarious existence by hiding in the shadows of the large.

New carnivores also appeared by 270 million years ago, pushing aside old *Dimetrodon* and its cousins. Skulls of these new predators tell us that each new species had a stronger bite than the old. Like the herbivores, many of the new carnivores like *Eotitanosuchus olsoni* (found in Russia), which was 5 meters (16 feet) long and weighing 500 kilograms (1100 pounds), were larger than their predecessors. *Anteosaurus magnificus* (found in South Africa) was the same size as *Eotitanosuchus*. There was also a place in the food chain for smaller predators like the dog-sized *Biarmosuchus tener* (found in Russia), which was about 1 meter long and weighed around 30 kilograms (65 pounds).

The trend toward larger animals during the first 40 million years of the Permian was reversed during the last 9 million years, probably because the drying climate that made the big Pangaean desert had reduced plant growth, upon which all life depends. The largest tetrapod of the late Permian was probably the herbivore *Scutosaurus karpinskii*, which was about 3 meters (10 feet) long and weighed around 600 kilograms (1300 pounds). Most animals at the end of the Permian were more the size of the herbivore *Lystrosaurus*, which was about the size of a modern pig. Carnivores were not large either as typified by the two dog-sized meat eaters *Lycaenops* and *Dvinia prima* and the bear-sized *Inostrancevia*.

The Permian Period was extremely important to we humans because that was the Period during which some basic architectural features of all mammals (among them, our skull, teeth, and parts of our skeleton) began to take shape in what are called "mammal-like reptiles." Of course, the defining characteristic of mammals is that we suckle our young, so these mammal-like reptiles were certainly not mammals. But all mammals also share features of our teeth and skull that first appeared during the Permian. Much of the early evolutionary change occurred in the teeth and jaw. At the beginning of the Period, the lower jaw of tetrapods was made of several bones, and the upper jaw was hinged like that of modern crocodiles. But by the end of the Period, the mammal-like line of tetrapod reptiles, like modern mammals, had a lower jaw of only one bone, and the upper jaw was immovable (*Biarmosuchia*, for example). At the beginning of the Period, tetrapods had a lot of teeth (which they continually replaced like modern sharks do) that were all simply points, so they ripped off chunks of their food and swallowed them whole like modern crocodiles do. But by the end of the Period, the mammal-like line of reptiles, such as *Dvinia*, had fewer teeth that were not replaced and were differentiated into incisors, canines, premolars, and molars to chew their food like we do, which aids in digestion.

Other evolutionary changes in tetrapods were made in the bones of the skull and skeleton. At the beginning of the Period, tetrapods had no secondary palate (part of roof of the mouth in humans that separates the oral cavity from the nasal cavity), which allows us to breathe while we chew; but by the end of the Period, the mammal-like line of reptiles such as *Dvinia* had a secondary palate. The evolution of both the secondary palate and differentiated teeth for chewing was roughly concurrent and was probably encouraged by the improvement in digestion that's derived from chewing food. At the beginning of the Period, tetrapods' limbs sprawled out from the body like modern crocodiles and lizards, but by the end of the Period, mammal-like reptiles' limbs were under the body, which allowed them to run. At the beginning of the Period, tetrapods had more toe bones than we do, but by the end of the Period, mammal-like reptiles had the same number of toe bones that we do. Mammal-like reptiles also incorporated other, more technical, changes to the skeleton as the Permian wore on so that, by the end of the Period, many basic structural features of mammals were in place in a group of mammal-like reptiles like *Dvinia*.

The Permian ended 251 million years ago with the most severe mass extinction of life in the history of Earth, sometimes referred to as the "Great Dying." Around 95 percent of all marine animal species, 70 percent of all land animal species, and nearly all trees became extinct. There is considerable disagreement among scientists about the cause, and several have been proposed, ranging from a nearby (within 32 light years) supernova to extensive volcanic activity. The currently most favored cause is massive volcanism in the area of Siberia called the Siberian Traps (the word "Traps" is derived from a Finnish word that describes this type of area) that led to a complicated chain of events; this cause is the most favored because it explains the extinction of everything that died. The Siberian Traps didn't explode like a lot of volcanoes (neither does the shield volcano Kilauea in Hawaii), but for up to a million years, released the common volcanic gas carbon dioxide and oozed lava in what's called a flood basalt flow. The eruption was so extensive that its lava covered an area about the size of the continental United States and was over a mile deep in some places. It wasn't the lava but the greenhouse gas carbon dioxide that was the ultimate cause of the catastrophe, though, by inducing extensive global warming. At the time of the extinction, high-latitude temperatures were 10° to 30° C (18° to 54° F) higher than today.

But carbon dioxide itself wasn't the killer. This is known because trees, which love carbon dioxide, also suffered a massive die-off, resulting in the global "coal gap" that began at the end of the Permian; no coal that dates from the end of the Permian to the middle of the Triassic is known anywhere in the world. The carbon dioxide increase touched off a series of events that began with global warming heating the oceans. Warmer water absorbs less gas, such as oxygen, than colder water as you can see by the gas that bubbles up in a champaign glass as it warms. Warmer oceans also reduce, or eliminate, the vertical circulation that brings oxygen to the ocean depths.

The reduction of oxygen in the deep ocean allowed the proliferation of bacteria that thrive in the absence of oxygen and that are always there in limited numbers. These bacteria produce hydrogen sulfide, which is toxic to all life, and it's this hydrogen sulfide that killed marine life as well as plants and animals as it bubbled out of the oceans. Although this scenario explains how trees as well as marine and terrestrial animals died off, some evidence of hydrogen sulfide in end-Permian rocks needs to be found, and some calculations on the amount of hydrogen sulfide needed for such an extensive kill must be made to determine if volcanism is the most likely scenario for the extinction.

Of course there are alternate explanations for the end Permian extinction, and the most favored of these is the impact hypothesis. Two possible impact craters have been found. One, called Bedout, is off the coast of Australia, and the other is in Antarctica, where signs of a possible impact have been found in rocks; a NASA satellite has also discovered a gravitational anomaly in Antarctica that could be a large impact crater. But the impact hypothesis has not yet been developed to the extent that it paints as complete a picture of the enormity of the end Permian extinction as the volcanism scenario does. Perhaps both volcanism and impact combined as a sort of one-two punch.

Whatever the cause, life teetered on the brink of total annihilation at the end of the Permian, and its future was held by some seeds and a few survivors like the herbivore *Lystrosaurus*, which came to dominate the early Triassic landscape, the carnivorous mammal-like reptile *Dvinia*, and a few aquatic reptiles decended from *Mesosaurus*-like ancestors. Trilobites, which had carried on for 300 million years, finally met their end.

Triassic Period (251 to 199.6 million years ago)

The Great Dying marked the end of the Permian Period and the beginning of the Triassic, the first of the three periods that make up the Mesozoic Age, The Age of Dinosaurs. It's been said that during the Great Dying "The world itself seems to have become toxic in some as yet uncertain way" and the oceans lost all their oxygen at depths below 20 meters (65 feet). This ocean anoxia is basically what killed 95% of Permian marine life, while the toxic atmosphere killed 70% of all land vertebrates and most plants, including nearly all large trees.

Thus, the Triassic Period began with a seriously depleted biosphere that was ripe for repopulation by plants and animals that were different from anything that had ever existed before. It was a time of change. But change had to begin with recovery, which took about 6 million years. The most successful survivor of the Great Dying was the pig-sized herbivore *Lystrosaurus*, which was the most numerous and widespread resident during the recovery. *Lystrosaurus* fossils in what appear to be burrows have been found in South Africa's Karroo basin, suggesting that they were able to survive the toxic air of the Great Dying partly because they could burrow into the ground.

Among the carnivores that joined *Lystrosaurus* in the recovery to feed on herbivores and one another was *Proterosuchus*, a medium-sized semi-aquatic predator that probably lived a crocodile-like lifestyle, ambushing its prey from the water. It also was likely one of the reptiles that formed the basis from which all subsequent reptiles evolved.

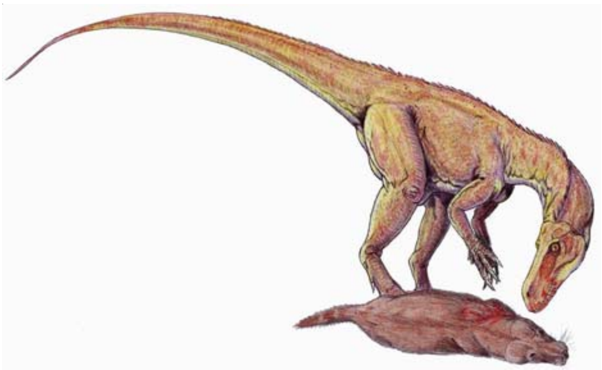
Another early Triassic carnivore was the mammal-like reptile *Thrinaxodon*, which might possibly have been a descendant of *Dvinia* and is possibly an ancestor of all mammals. According to the many skulls and bones it left behind, *Thrinaxodon* was about the size of a modern house cat. Some scientists interpret pits in its skull as housing concentrations of nerves and blood vessels that, in mammals, service whiskers; thus, it possibly had fur and was warm blooded. But a furry, warm blooded *Thrinaxodon* is speculation, though a good one, because there's no direct evidence to support such a conclusion.

Early Triassic creatures were not very large because the depleted food supply of the decimated biosphere favored small size. But as the Period wore on and the recovering biosphere made food supplies more plentiful, the new forms that appeared were larger. For example, pig-sized *Lystrosaurus* was replaced by bigger herbivores like ox-sized *Kannemeyeria*, and house-cat-sized *Thrinaxodon* was replaced by bigger carnivores like the wide-spread, wolf-sized *Cynognathus*.

By the time the Triassic was about half over, the land and sea were once again well populated, but many of the plants and animals were like nothing that had ever existed before. One new kind of herbivorous land dweller, which are called Aetosaurids after the quintessential example genus, *Aetosaurus*, had a skull resembling that of a bird and sported a pig's snout that they probably used the same way modern pigs use theirs. They were low, long, and broad like modern crocodiles, but they walked more upright and were more heavily armored than crocodiles. There were nearly 20 species of Aetosaurids that all generally looked alike with minor variations. Another new kind of low, long, broad animal, with perhaps 15 to 20 species such as *Leptosuchus crosbiensis*, that were spread among several genera, were semi-aquatic carnivores that probably had a lifestyle like modern crocodiles, ambushing their prey from the water like the earlier *Proterosuchus*, which was extinct by that time.

Although crocodile-like predators like *Aetosaurus* and *Leptosuschus* were abundant during the last half of the Triassic, two new reptiles made their entrance around 230 million years ago (about 20 million years into the Triassic Period). These new players were destined to rule the Earth for the next 165 million years: the dinosaurs (terrible lizards) and the ichthyosaurs (fish lizards). Reptiles were well on their way to taking over.

Some aquatic reptiles, whose ancestors such as *Mesosaurus* had left the land to return to the water as long ago as the late Carboniferous or early Permian, managed to survive the Great Dying. During the first 20 million years of the Triassic, these aquatic survivors evolved into a large family of ichthyosaurs that ruled the seas as top predators until replaced in the middle Cretaceous by more capable aquatic reptiles. Early ichthyosaurs



Herrerasaurus ischigualastensis

Herrerasaurus lived at a time when crocodile-like reptiles were the most common predators. Only 6% of the fossils are dinosaurs where *Herrerasaurus* was found, but by the end of the Triassic, dinosaurs were the most numerous. The place *Herrerasaurus* has in the dinosaur family tree is unclear as the third millennium opens. Some researchers put *Herrerasaurus* at the base of the dinosaur tree before they separated into ornithischians and saurischians, while others put it at the base of the saurischian branch before saurischians diverged into prosauropods and theropods. Dinosaurs are placed in their tree according to the characteristics of every bone and tooth, so there are a lot of combinations to compare and many ways to interpret them.

were rather crude, but by the middle of the Triassic, they had evolved into sleek, fast forms that very closely resembled modern dolphins. Being reptiles, they breathed air like modern dolphins. Adult ichthyosaur fossils have been found with baby ichthyosaur fossils inside them, suggesting that they gave birth to live young, though they probably didn't suckle their young like mammals do. The young were simply born with the ability to feed on flesh like their parents did.

Reptiles took over the land during the Triassic probably because Earth's climate favored them. Carbon dioxide levels were still rather high because the depleted plant life had not yet sequestered the carbon dioxide emissions from the Siberian Traps episode, so Earth was uniformly warm. There was no ice at the poles. Because nearly all the land was gathered up into Pangea, the interior was hot and rather dry because it was far from the ocean's source of moisture. Reptiles conserve their water because their skin had no sweat glands and they excreted urine as a paste like modern birds do. In the Triassic's hot, dry climate, the reptile's ability to conserve water was a decided advantage.

Thus about the same time that the first primitive ichthyosaur swam in the Triassic seas, around 228 million years ago, two bipedal carnivorous dinosaurs, *Herrerasaurus* (possibly the first dinosaur) and *Eoraptor*, appeared in northwest Patagonia of what is now Argentina. But what makes dinosaurs different from all other reptiles? Well, there are a number of differences between the skeletons of dinosaurs and those of other reptiles, but according to Dr. Paul Olsen, a professor at Columbia University, the most important one was that only dinosaurs, of all reptiles, had a hip socket structure that allowed them to extend their legs directly beneath their bodies instead of sprawling out to the sides like most other reptiles. This let dinosaurs, unlike most other reptiles, stand fully erect. And this erect posture let dinosaurs breathe more easily while moving, which likely enabled them to run faster and farther than other reptiles. Running on two legs probably made some of them more agile as well. Thus, greater agility and the ability to run faster and farther than their competition (such as the crocodile-like predators) gave dinosaurs a decided advantage in the daily struggle to eat and not be eaten.

Like all introductory genera of new forms, *Herrerasaurus* and *Eoraptor* were relatively small. *Herrerasaurus* was only 3 meters (10 feet) or so from the tip of its nose to the tip of its tail. They moved on their two hind legs, and their front legs had become shorter than their hind legs, essentially becoming "arms" and their front feet becoming grasping "hands" with claws. *Eoraptor* was the smaller of the two, standing about the height of our knee. *Herrerasaurus* and *Eoraptor* were both found at the same place in Argentina although *Eoraptor* was found in slightly younger rock (by a million years or so), which suggests that *Eoraptor* was a newer model. But further excavation in the area might reveal them to be contemporaries. Further excavation might also reveal entirely new animals similar to these two.

Around 8 million years later, a different bipedal carnivorous dinosaur, *Coelophysis bauri*, appeared in what is now New Mexico. Several *Coelophysis* fossils were found together along with the remains of other animals, suggesting they all died together in some catastrophe such as a flash flood. The interesting thing about *Coelophysis* is that its limb bones were hollow, which is where its name comes from (Greek for "hollow form"), like those of modern birds. It also had a wishbone, the first dinosaur to have one as far as we know. The obvious speculation is that it was the *Coelophysis* family tree that led to birds.

Perhaps the most radical new development among animals that occurred during the Triassic was conquest of the sky, and reptiles were the first to take flight. It probably began with the gliding reptiles such as *Sharovipteryx*, which lived 225 million years ago, that appeared during the middle years of the Period. Gliding was probably a strategy to escape predators because survival is the most basic driving force to evolution. It's natural to speculate that gliding flights grew longer and longer as predators grew accustomed to the strategy and learned to chase down their airborne prey. Gradually gliding developed into the ultimate escape: soaring. A mastery of soaring as an escape strategy probably led to finding the skill advantageous for finding their own prey, possibly first by accident, then eventually by intent. Sometime late in the Period, soaring reptiles learned to extend their flights by flapping their wings, and pterosaurs such as the diminutive *Peteinosaurus zambellii* were born.

As the Triassic drew to a close, reptiles continued to expand their kinds and numbers, interrupted only briefly by a mass extinction around 214 million years ago, called the Carnian-Norian extinction. This one was much, much less significant than the Great Dying at the end of the Permian or the mass extinction that closed the Triassic. The Carnian-Norian event was probably caused by the impact of an extraterrestrial object that formed the 60-mile-wide Manicouagan crater (which has been dated to about that time) in what is now Quebec.

Toward the end of the Triassic, mammal-like reptiles began to more closely resemble true mammals than before. It's impossible for mere bones to tell us whether or not an animal suckled its young (the classic definition of a mammal), so paleontologists use other methods to determine the classification of a fossil. Two characteristics that are preserved in fossils and that only mammals share are the bones of the inner ear and the multiple root structure of the molars. Triassic fossils with these two characteristics are generally called mammaliformes rather that true mammals to indicate the uncertainty about just how close to a true mammal a fossil is. One widespread (North America, Europe, China, and South Africa) mammaliforme that has been found in 204 million year old rocks is *Morganucodon*, a shrew-like animal about 10 centimeters (4 inches) long. Our tiny ancestors were furtively dining on insects in the shadow of late Triassic reptiles.

The Triassic Period ended in one of the five most severe mass extinctions to hit the planet; around 76% of species didn't survive into the Jurassic. None of the crocodile-like herbivores and carnivores survived as species, but the dinosaurs and ichthyosaurs survived to inherit the Earth. A few mammaliformes survived to continued living in the shadow of the great beasts. Like all mass extinctions except the one at the end of the Cretaceous, the cause of the end Triassic extinction is open to question. Some think a massive outpouring of lava called the Central Atlantic Magmatic Province (CAMP) was the cause. CAMP has a larger area than the Siberian Traps that might have ended the Permian, but the total volume of lava is much less. Others believe an asteroid impact might have been the culprit because clays in the Newark basin of eastern North America that date to about that time have an unusually high level of iridium, which was the telltale sign of the asteroid impact that killed off the dinosaurs. There's little iridium on the Earth's surface because it all sank along with iron to the core when it was formed billions of years ago. What iridium we have now comes from outer space. So where's the crater? Ohio State University researchers in conjunction with the NASA have found evidence of a crater under a mile of ice in Antarctica that's twice the size of the Chicxulub Crater that killed off the dinosaurs, but there's been no direct study of it yet. Therefore, whether it actually is an impact crater and when it hit is unknown. There's also a crater in western Australia that's 120 kilometers (75 miles) wide, but little is known about it either. No one knows the answer yet. But we do know some early forms of frogs and turtles, some mammaliformes, and most of all, some dinosaurs and ichthyosaurs survived to carry on their kinds.

Jurassic Period (199.6 to 145.5 million years ago)

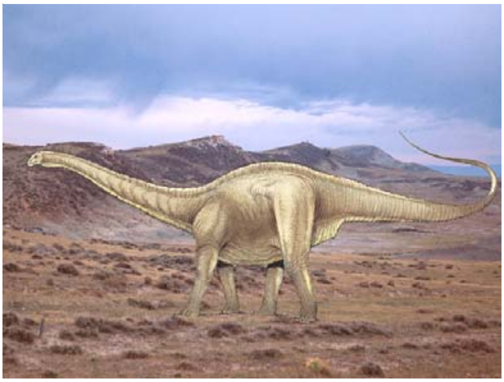
The mass extinction at the end of the Triassic marked the beginning of the Jurassic Period. Though the end-Triassic extinction was one of the five worst in the history of life on Earth, it was not as severe as the Great Dying.

Nevertheless, there were winners and losers. Generally, any life that was too specialized or too in-tune with the environment that existed at the end of the Triassic didn't survive. The survivors were those that were adaptable enough to cope with the rapidly changing environment that causes a mass extinction. Dinosaurs were the great survivors on land while ichthyosaurs and plesiosaurs were the big survivors in the seas.

Pangaea, which had barely begun to rift apart during the Triassic, broke into Laurasia in the north and Gondwanaland in the south during the early Jurassic. As the Period wore on, Laurasia itself began to rift apart into what would become present day North America and Eurasia as a narrow seaway that was to become the North Atlantic opened up between them. The breakup of Pangaea brought more land closer to ocean waters than during the Triassic, so the land became more humid, and the great Pangaean desert disappeared. Large forests like those of the Carboniferous again appeared, though primarily of conifers, cycads, and gingkoes this time, and several modern types were included in the mix. The undergrowth was primarily ferns and some *Equisetum*, which is a plant that's still surviving as a "living fossil," better known as horsetail. There would be no grass for another hundred million years.

As North America separated from Eurasia, much of Europe became a collection of large islands or small island continents. As the lands separated, this new paleogeography influenced evolution as species diverged into new ones when their members became geographically separated from one another. That's a well known, natural process called divergent speciation. An example is the Darwin finches of the Galapagos Islands. The different islands are home to finches that are obviously related, but the birds on each separate island have beaks that have become different from those on the other islands, specialized for eating the food available on their own particular island.

Dinosaurs became increasingly dominant, abundant, and diverse during the Jurassic, but they all shared Triassic ancestors such as *Herrerasaurus ischigualastensis* and *Eoraptor lunensis*. Most early dinosaurs that lived during the late Triassic were bipedal. Even herbivores such as *Plateosaurus* (length about 10 meters, or 33 feet), which lived in what is now Europe during the last 15 million years of the Triassic, walked on two legs. Possibly using two legs made early dinosaurs more agile and better able to avoid being food for other predators such as the crocodile-like *Saurosuchus* and *Postosuchus*, both members of late Triassic top-predator groups. But two legged herbivores had a problem. Because plants are always difficult to digest, the late Triassic herbivores developed increasingly large guts to give them more time for digestion, and there is some evidence that, like modern birds, some herbivores might have swallowed stones to help break down the tough plant fibers. Even two-legged *Plateosaurus* developed a bulky frame. *Plateosaurus* is called a prosauropod because its bone structure was a logical precursor to the great Jurassic sauropods, so its bone structure, large gut, small skull, and long neck were a foretaste of what was to come during the Jurassic. But the herbivore's increasingly large gut became too

Two Types of Dinosaurs

Most dinosaurs were herbivores like the Sauropod *Apatosaurus* (left), but some were carnivores like the Theropod *Tyrannosaurus Rex* (right). The late Jurassic was the peak of sauropod importance in the ecosystem. Classically, dinosaurs are classed according to their hip structure into those that had hips structured like those of lizards (Saurischia) and those that had hips structured like those of birds (Ornithischia). However, there is a modern thrust to reorder Dinosauria because some of the old classifications, such as Therapodia, don't fit into the traditional classes. Fossilized footprints indicate that at least some sauropods and ornithopods probably lived in herds.

much for two legs alone to support, so each new species gradually began to walk more and more on all fours. Their only defense had to shift from agility to an increasingly large size because predators retained their two legged gait and relatively small size to remain agile.

Thus it was that the Jurassic was the time when the biggest Dinosaurs that ever lived were commonplace, monster quadrupedal herbivores such as *Apatosaurus* (commonly called *Brontosaurus*) and *Diplodocus*, which could be as much as 27 meters (90 feet) long from its snout to the tip of its tail. *Apatosaurus* and *Diplodocus* both had the sauropod type of bone structure as did all the monster Jurassic herbivores. All Jurassic sauropods also had the small skull and long neck of their Triassic ancestors such as *Plateosaurus*. Paleontologists disagree somewhat about whether the huge sauropods used their long necks to reach up into trees to browse or out long distances horizontally; the question revolves around whether a sauropod's heart could pump blood up to its brain when its head was that far in the air. The large size of Jurassic sauropods was a double-edged sword because, on one hand, it reduced their threat of becoming prey, but on the other, made sustaining themselves difficult in bad times. In the end, sustenance proved the bigger problem because there are other strategies, such as armor, to avoid becoming prey. Few dinosaurs the size of *Apatosaurus* and *Diplodocus* were seen after their time came to an end at the close of the Jurassic.

There were a few Jurassic herbivores that had a type of bone structure different from the sauropods; these are called ornithopods. An example is the 1.2 meter (4 feet) long, bipedal *Heterodontosaurus tucki* that lived in South Africa at the beginning of the Period. The ornithopods never got as large as the lumbering sauropods like *Diplodocus*. Unlike the sauropods, they were generally small, light, bipedal creatures such as *Yandusaurus hongheensis*, which was 1.5 meters (5 feet) long, 7 kilograms (15.5 pounds), of middle Jurassic China, and they relied on speed to evade predation. Some ornithopods, such as *Dryosaurus*, which was 4.5 meters (15 feet) long and 90 kilograms (200 pounds), were heavy enough that they grew longer, stouter "arms" than other bipedal dionsaurs and cold walk on all fours at times, although they probably relied on speed to escape predators. There is some evidence that *Dryosaurus* was a herd animal, so it's not unreasonable to draw a parallel between *Dryosaurus* and its predators with modern African wildebeests and their predators. Although ornithopods were not a major part of the Jurassic landscape, they came to dominate the Cretaceous.

When the Jurassic was a little more than half over, around 167 million years ago, the first known armored dinosaur, *Huayangosaurus taibaii*, a stegosaur from China, appeared in the fossil record. Stegosaurs were lumbering, four-legged sauropods with a bone structure similar to that of *Apatosaurus* and *Diplodocus* but were smaller than their monster-sized cousins, reaching a length of no more than 10 meters (33 feet) as contrasted with 27 meters (90 feet) for *Diplodocus*. Stegosaurs were characterized by individual vertical plates that extended up from their back and continued down much of their tail. By the time the Jurassic period drew to a close, stegosaurs were all over the globe: *Dacentrurus armatus* from Europe, *Kentrosaurus* from Africa, and of course, *Stegosaurus* from the United States. This type of armored dinosaur became extinct by the mid Cretaceous.

But the late Jurassic saw another type armored herbivorous dinosaur appear in the fossil record, Ankylosaurs such as *Gargoyleosaurus parkpinorum* and *Mymoorapelta maysi*. They had thick armor plating of fused bone that were often interspersed with spikes. Some species even had armored eyelids. Many ankylosaurs also had a large bone on the end of their tails that formed a sort of "club." Ankylosaurs were not a prominent part of the Jurassic biosphere, but they became a significant part of the Cretaceous.

Of course, all these herbivores needed predators to weed out the sick and unfit, and nature provided an array of them, from small ones like *Compsognathus* to big ones like *Allosaurus*. Whenever there's something to be eaten, you can be sure that nature will always provide something to eat it. Nearly all Jurassic predators were agile, two legged dinosaurs, called theropods, with "arms" much smaller than their legs in the mold of their Triassic ancestors such as *Herrerasaurus*, *Eoraptor*, and *Coelophysis*. One specimen of the chicken- or turkey-sized *Compsognathus* had the intact remains of a small lizard in its thoracic cavity, suggesting that *Compsognathus* was an agile hunter and that it swallowed the meal whole.

On the other end of the spectrum was the terrible *Allosaurus*, 10 meters (33 feet) long and 2000 kilograms (4400 pounds) and looked very much like *T. rex*. And there were theropod predators of intermediate size such as *Megalosaurus*, which was the first dinosaur to be found, although it wasn't recognized as such at the time. A piece of what was probably *Megalosaurus* bone was found at Cornwall, England, in 1676 and was sent to Professor

Plot at Oxford University, who correctly identified it as part of the femur of a large animal, though he had no clue what kind, and published a description of it in his *Natural History of Oxfordshire*. Although the bone has been lost, Professor Plot's drawing is detailed enough to identify it as a *Megalosaurus* bone. No theropod predator, even *Allosaurus*, was able to single-handedly bring down a healthy, full-grown sauropod like *Diplodocus*, so they probably either scavenged the dead; hunted in packs; preyed on the old, the sick, the weak, and the young as predators often do today; or a combination.

Theropod dinosaurs pushed aside the Triassic crocodile-type predators like *Saurosuchus* as top predator on the land, so the crocodilians left the land to spend their entire life at sea eating fish like the modern gharial does. We don't know if these marine crocodilians with names like *Dakosaurus* and *Metriorhynchus* returned to the land to lay their eggs like modern marine turtles do. Each species probably had a relatively small geographic range because the crocodilian form is not well suited to long sea voyages. For example, *Dakosaurus maximus* was found in Europe, but *Dakosaurus andiniensis* was found in Argentina, and other of the 15 or so genuses of marine crocodilians have species similarly distributed.

But marine crocodilians were not the top marine predators of the Jurassic seas. That title was contested between the long necked plesiosaurs and the sleek, dolphin-like ichthyosaurs. The Jurassic saw fewer ichthyosaur species than the Triassic, but fossil bones suggest that the Jurassic bunch were considerably faster than their Triassic ancestors. Nevertheless, the Jurassic was the heyday of ichthyosaurs because plesiosaurs would replace them in the Cretaceous seas.

The first bird, *Archaeopteryx*, took to the air late in the Period, joining the pterosaurs that had been there for scores of millions of years. It was something of a strange bird, with a little bit of dinosaur (teeth) mixed in with modern bird feathers. Pterosaurs were featherless reptiles (with a reptile's bone structure) whereas *Archaeopteryx* was a feathered dinosaur (with a dinosaur bone structure). Only since the turn of the third millennium have paleontologists come to understand that some Jurassic dinosaurs had feathers because fossils of feathered dinosaurs that were obviously not birds have been found just since the 1990s. For example, *Epidendrosaurus ninchengensis*, a sparrow-sized specimen that has a foot structure enabling it to live in trees, was recovered in 2002 from the Daohugou fossil beds of northeastern China, which formed between 164 and 158 million years ago as measured using uranium decay to lead in Zircons. So now we all realize that the robin hopping around your front yard looking for worms is a descendant of the dinosaurs, and most paleontologists say actually is a living dinosaur.

One specimen of the feathered dinosaur *Sinosauropteryx* from China was found with three mammal jaws in its stomach region.

Mammals became a small part of the biosphere during the Jurassic. At the end of the Triassic, animals such as *Morganucodon*, which lived 205 million years ago, appeared that were stages in the evolution of mammal-like reptiles into mammals. For example, *Morganucodon* had a lower jaw made of fewer bones than reptiles, but not of a single bone like mammals have. *Morganucodon* species were spread throughout Pangaea, *M. watsoni* being found in Wales and *M. oehleri* in China. Then *Hadrocodium wui* appeared sometime after *Morganucodon* and had a single lower jaw bone like we have. Most of these Jurassic mammals such as *Megazostrodon* were small, furry, shrew-like animals around 10 to 12 centimeters (4 to 5 inches) long that probably ate insects and small lizards. Although *Megazostrodon* possibly suckled their young, most paleontologists believe that they still laid leathery eggs like their reptilian cousins did and modern monotremes such as the platypus still do. Around the turn of the third millennium, the largest currently known Jurassic mammal, called *Castorocauda lutrasimilis*, was unearthed in China. *Castorocauda* was a semi-aquatic critter that was very similar to the modern beaver both in appearance and lifestyle. The fossil was so exquisitely preserved that even evidence of its hair was identifiable.

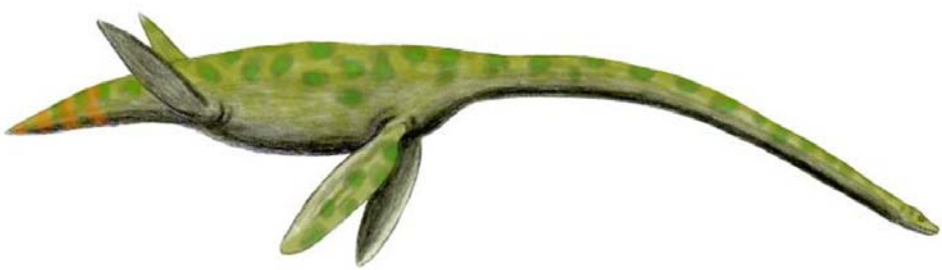
Mammals remained only a minor food source for dinosaurs during the Cretaceous although they would occasionally return the favor by gobbling small dinosaurs. At least at this level, Thomas Hobbes was right when he described life as "nasty, brutish, and short."

Cretaceous (145.5 to 65.5 million years ago)

Unlike the boundary between most other geologic periods, the transition from the Jurassic to the Cretaceous is not marked by any great mass extinction. It's more or less arbitrarily defined as the first appearance of the fossil ammonite *Berriasella jacobi* in the fossil record and has been radiometrically dated as occurring 145.5 million years ago, give or take 4 million years.

The Cretaceous was the first period in Phanerozoic times during which animal life didn't have a major, new development. During the Cambrian, sexual reproduction, which had evolved during Precambrian times, enabled a sudden diversification of multi-cell life forms. Animal life developed a backbone during the Ordovician Period. Life began to move into land during the Silurian. During the Devonian, seeds and amphibians appeared, and terrestrial animals developed the fundamental characteristics of four legs and five fingers and toes. The Carboniferous saw the first reptiles and forests and witnessed terrestrial animals' clear split into herbivores and carnivores. During the Permian, the basic architecture of mammals evolved from mammal-like reptiles. During the Triassic Period, the bone structure of dinosaurs and birds evolved. The Jurassic saw the first birds. So during the Cretaceous, all the characteristics that animals had accumulated during 400 million years of evolution since the Neoproterozoic were present and constantly molded into one form or another by an ever-changing environment.

Although animal life had no major evolutionary development during the Cretaceous, plants had a big one. A flowering plant (flowering plants are called angiosperms) called *Archaefructus* first appeared in China around 125 million years ago, and fossilized angiosperm pollen has been found that dates to around 130 million years ago. Finding pollen fossils older than plant



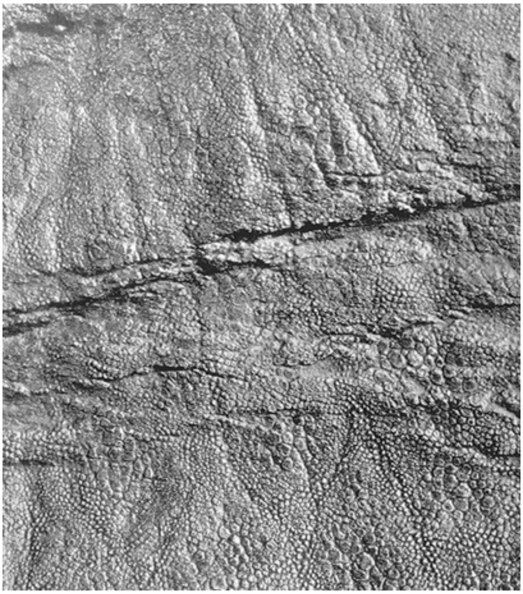
The Plesiosaur *Styxosaurus snowii*

Styxosaurus snowii lived sometime during the period that extended between 65 and 71 million years ago. It was around 11 to 12 meters (36 to 40 feet) long. Its chest cavity contained about 250 gastroliths, or "stomach stones." Most predators do not use gastroliths for grinding food, but almost all reasonably complete plesiosaur specimens similar to *Styxosaurus* include gastroliths. Although crocodiles and a few other modern animals sometimes use gastroliths for ballast, it appears that some plesiosaurs were using them as a gastric mill like modern birds do.

fossils is to be expected because it's really unusual for something to become a fossil. (Otherwise we'd be up to our eyeballs in fossils.) Conditions have to be just right for a dead plant or animal to resist decay and become fossilized, and the chemistry of pollen makes it much more resistant to decay than plants are. Prasad, Strömberg, Alimohammadian, and Sahni reported in *Science*, a publication of the American Association for the Advancement of Science, that they found evidence of grass in fossilized sauropod dung from the late Cretaceous, although grass doesn't appear in the fossil record until around 55 million years ago. Grasses and other angiosperms have become the dominate land plants and herbivore food in the past 130 million years.

Cretaceous herbivores had a bountiful supply of plants to dine on because carbon dioxide levels were several times higher then than during modern times (probably because of the volcanic activity that rifted Pangaea apart), giving the Cretaceous a very warm, greenhouse climate. Plants grew much closer to the poles, which were generally ice free, than during modern times. At about the same time, many modern groups of insects were beginning to diversify, and the oldest known butterflies appear along with aphids, grasshoppers, and gall wasps. Termites and ants appeared in the later part of the period. Around 100 million years ago, bees first appeared to help pollinate the flowering plants.

In the sea, the last sleek, dolphin-like ichthyosaur, whose kind had first appeared in the early Triassic, finally ceased roaming the oceans around 90 million years ago. Their place as top ocean predator was taken over by the long-necked plesiosaurs, which had first appeared in rudimentary form during the late Triassic or early Jurassic. Like ichthyosaurs, plesiosaurs came from a long line of reptiles that had left the land and returned to the sea around the late Carboniferous or early Permian. The "arms" and "legs" of the



Skin Impression from *Edmontosaurus annectens*

This skin impression is from very well-preserved fossil of the duckbill hadrosaur *Edmontosaurus annectens*. The noted paleontologist Henry F. Osborn's speculation on how it was preserved suggested that after a natural death, the body probably lay exposed to the sun for a long time and completely dried to a mummy-like state. It was unusual for a body to lie without being scavenged. At some later date, the mummy may have been caught in a sudden flood and rapidly buried in fine sand and clay. Osborn continued, "A cast, or impression, of the skin formed in the sand before the skin and other soft parts decayed. There is no remnant of the actual skin preserved only, its imprint."

plesiosaur's ancestral reptiles developed into paddles that plesiosaurs used for swimming.

Pangaea's breakup into the present day continents was completed during the Cretaceous, and the geographical isolation of the continents from one another meant regional differences in plants and animals increased, each in their own place. Duck-billed hadrosaurids such as *Edmontosaurus* appeared in Canada at the same time *Secernosaurus* appeared in Argentina and *Saurolophus* in China. Tank-like ankylosauria such as *Ankylosaurus* roamed the United States while *Tarchia* munched plant life in China. The tyrannosaurid *Tarbosaurus* terrorized China while *Tyrannosaurus rex* chewed its way through North American animal life. In general, life developed along similar lines on the separated continents because the environments on them were generally similar, offering similar ecological niches.

The Cretaceous was the long, lazy summer of the dinosaur's existence marked by several small extinctions. (We have the luxury of calling them small because we weren't involved.) Species and genera became extinct only to be replaced by others in the same ecological niche. In North America, the duck-billed hadrosaurid *Corythosaurus* gave way to *Lambeosaurus*, the ceratopsin *Centrosaurus* yielded to *Styracosaurus* which gave way to *Triceratops*, and the tyrannosaur *Daspletosaurus* was displaced by *Tyrannosaurus rex*.

The reasons for such extinctions vary but often involve the relationship a group has with its environment and the group's failure to adapt to environmental change. Sometimes an animal group becomes extinct when it becomes too specialized, and a small change in the environment makes their specialization a liability. The koala (which dines exclusively on *Eucalyptus* and related plant species) and the panda (which has a diet of 99%

Euoplocephalus tutus

Euoplocephalus, one of the largest ankylosaurian dinosaurs, was about the size of a small elephant. It was 6 meters (20 feet) long, 2.4 meters (8 feet) wide, and weighed about 2 metric tonnes (2.2 tons). The entire head and body were covered with bands of armor composed of a thick oval plate embedded in the thick surrounding skin, which was studded with short, horny spikes like those of crocodiles. It had large horns growing from the back of its head and a bony club at the end of its tail. The tail club could be swung from side to side for defense.

bamboo although they may eat minuscule amounts of other foods such as honey, eggs, fish, yams, shrub leaves, oranges, and bananas) are two modern examples of high specialization, and the sudden appearance of a microorganism that attacks *Eucalyptus* or bamboo could drive either of them to extinction.

The enormous sauropods of the Jurassic like *Diplodocus* faded from dominance during the Cretaceous, and by the time the great meteor struck ending life for all dinosaurs, only the herbiverous titanosaurs remained of their kind. Something in the neighborhood of 50 titanosaur species have been found although some of these finds might be of the same species because a complete skeleton of a large sauropod is seldom found, making definitive identification difficult. Yet enough extraordinarily large bones have been found to know that some titanosaur species, such as *Argentinosaurus*, were the largest animals to ever walk the Earth. A large titanosaur nesting ground was discovered in Patagonia that had eggs about 11 to 12 centimeters (4 to 5 inches) in diameter containing fossilized embryos complete with skin impressions. The large size of the nesting ground is evidence of herd behavior.

The giant saurischian titanosaurs were far outnumbered by a host of smaller ornithischian plant eaters such as *Iguanodons* (which were one of the most successful dinosaurs, living for 20 to 30 million years during the early Cretaceous and being found around the globe), many genera of armored ankylosaurids, numerous members of the Hadrosauridae (flat-headed, duck-billed) family, and several ceratopsian families (which included the famous *Triceratops*). It’s estimated that herds comprising thousands of hadrosaurs such as *Maiasaura* roamed North America like bison did in the nineteenth century before the buffalo hunters drove them to near extinction.

This great population of herbivores was controlled by an array of predators from large, terrifying tyrannosaurs like *Albertosaurus* and *T. Rex* to small Deinonychosauria. The name Deinonychosauria means "fearsome claw lizards" because of the sickle-shaped claw on their second toe, which the beast used to slash or stab prey. Some deinonychosaura, like the famous *Velociraptor*, are commonly called raptors.

Fossils of perhaps three genera of raptors (*Sinornithosaurus*, *Microraptor*, and *Cryptovolans pauli*, which might actually be the same as *Microraptor*) have been found with unmistakable evidence of feathers. The first feathered dinosaur, *Sinosauropteryx prima*, was found in China in 1996, and more than a dozen more have been found since. Dinosaurs fossils with feathers are strong evidence favoring the idea that birds are descended from dinosaurs.

British biologist Thomas Henry Huxley first proposed that dinosaurs are ancestors of birds shortly after Charles Darwin published *The Origin of Species*, but prominent paleontologists of that time strongly disagreed. So the idea was abandoned until the 1960s when paleontologists began to notice similarities between bird skeletons and those of theropod dinosaurs. For example, both birds and theropods like *T. rex* have fused clavicles (wishbones). Dinosaurs are divided into ornithischians (bird-hipped) and saurischians (lizard-hipped). Ornithischians are all herbivores and include stegosaurs (like *Stegosaurus*), ankylosaurs (like *Tarchia*), hadrosaurs (like *Maiasaura*), and ceratopsians (like *Triceratops*). Except for the hadrosaurs, these are all heavily built, plodding, four-legged creatures, which seems odd for a bird-hipped group. Saurischians include the gigantic, heavily built, plant eating sauropods (like the Jurassic *Diplodocus*) and the two-legged carnivorous theropods (like *T. Rex* and *Velociraptor*). The irony is that birds evolved from lizard-hipped theropods, not the bird-hipped ornithischians. It takes more than hips to make a bird.

Mark Norell, Curator-in-Charge of fossil reptiles, amphibians and birds at the American Museum of Natural History, has said, "The more that we learn about these animals the more we find that there is basically no difference between birds and their closely related dinosaur ancestors like *Velociraptor*. Both have wishbones, brooded their nests, possess hollow bones, and were covered in feathers. If animals like *Velociraptor* were alive today our first impression would be that they were just very unusual looking birds," but birds with teeth.

A fossil of the feathered dinosaur *Sinosauropteryx prima* was found with three mammalian jaws in its stomach region. Two of these jaws were identified as *Zhangheotherium quinquecuspidens* and the other belonged to *Sinobaatar lingyuanensis*. *Zhangheotherium* is known to have had a poisonous spur on its foot, like the modern platypus.

The Mongolian mammal *Repenomamus robustus* returned the favor by devouring a juvenile ceratopsian *Psittacosaurus*. A cousin of previously mentioned *R. robustus*, *Repenomamus giganticus*, which was about the size of

Yanoconodon allini

Yanoconodon allini lived 125 million years ago in what is now China. It's considered to be a transitional fossil because its middle ear was an intermediate evolutionary stage between modern mammals and less refined earlier mammal forms. Typical of most Cretaceous mammals, it was small, barely 13 centimeters (5 inches) long, lightly-built and fed on insects, worms, and other invertebrates. The small size and insect diet of most Cretaceous mammals was probably vital to their surviving the K-T extinction.

a small dog, has the honor of being the largest Cretaceous mammal found as of 2008, but most Cretaceous mammals, such as *Cimexomys minor* and *Neoplagiaulax nelsoni*, were the size of an average mouse and dined on insects. A few, like *Didelphodon*, were about the size of an opossum. Most Cretaceous mammals are only known from teeth, but some left more extensive fossil remains. *Didelphodon* fossils have been found in Alberta, Montana, and Wyoming.

Cretaceous mammal fossils cover the full spectrum of mammalian types. *Didelphodon* was a marsupial; *Steropodon galmani* was a monotreme, or egg-laying mammal like the Platypus; and *Maelestes gobiensis* was a placental mammal. In all, nearly a hundred mammal species lived under the feet of Cretaceous dinosaurs.

And it was the mammals that were among the survivors of the great end Cretaceous mass extinction, called the K-T (Cretaceous-Tertiary, Cretaceous is usually abbreviated as "K" from the German for Creaceous, "Kreide") extinction event. Mammals and birds that survived the extinction fed on insects, worms, and snails, which fed on dead plant and animal matter. Animals that lived on the sea floor or in freshwater streams both feed on detritus that washed from land or settled to the ocean bottom. Crocodilians survived because they were semi-aquatic, could live as scavengers, and could survive for months without food. Thus, it was omnivores, insectivores, and carrion-eaters that survived the extinction event.

The most likely cause of the K-T extinction event was impact of one or more asteroids. The impact would cause a fire storm and would eject countless tons of particles into the atmosphere. This scenario was proposed by a team led by Luis Alvarez after they noticed that sedimentary layers found at the K-T boundary all over the world contain an iridium concentration 30 to 130 times normal. Iridium is extremely rare in the earth's crust because it readily attaches to iron, so most of it sank into the earth's core with the iron around 4 billion years ago. Currently, the favored location for the devastating impact is the Chicxulub Crater, which is buried partly underneath Mexico's Yucatán Peninsula and partly under the Gulf of Mexico. The crater is more than 180 kilometers (110 miles) in diameter, and is the product of an impacting asteroid at least 10 kilometers (6 miles) in diameter.

Another theory is that the K-T extinction was caused by multiple impacts similar to the string of impacts that the Shoemaker-Levy 9 comet had with Jupiter. The proposed string includes the Silverpit crater under the North Sea, the Boltysh crater in the Ukraine, and the Shiva crater in the Indian Ocean west of Mumbai, India. All these craters date to about 65 million years ago. The Boltysh Crater is 24 kilometers (15 miles) in diameter, and the Shiva crater is a gigantic, teardrop-shaped 600 by 400 kilometers (373 by 249 miles) feature. The multiple-impact theory is not the currently favored explanation of the K-T extinction. There is some debate about whether the Shiva crater is an impact feature, and an article in the journal *Nature* suggested that Silverpit is actually a sinkhole depression.

A third theory is that the K-T extinction was caused by an extensive lava flow like that favored to have been the cause of the Permian-Triassic extinction event. Sixty-five million years ago, India was located over the Réunion hotspot of the Indian Ocean. A lava plume similar to the one under Hawaii flooded India with as much as 500,000 square kilometers (192,000 square miles) of lava, creating a plateau called the Deccan Traps. This eruption lasted for around 30,000 years. This eruption is small compared with the Siberian traps eruption.

We'd need a time machine to go back 65 million year to categorically determine the cause of the K-T extinction. But whether it was from one or more impacts, a great lava flow, or a combination of these event, one thing we know for certain: the dinosaurs all died, leaving the Earth for mammals to take over.