TERTIARY HISTORY

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Summary

The Tertiary Period lasted from 65 million years ago, when the dinosaurs died out, to about 2 million years ago, when the current ice ages began. Long known as "The Age of Mammals," it was the time when shrew-like mammals emerged from 130 million years of hiding from the dinosaurs to take over the planet, and by 50 million years ago, they had diversified into groups ranging from bats to whales. Birds, too, underwent a huge diversification into essentially all the modern groups, as did a number of groups of insects. On land, the flowering plants, which originated in the Cretaceous Period, covered the entire planet, with temperate vegetation above the Arctic Circle about 50 million years ago. The sea floor was populated by essentially modern groups of marine organisms (such as the clams, snails, modern corals, and sea urchins), although many early Tertiary marine groups are members of extinct lineages that did not survive into the late Tertiary.

The Tertiary Period is the earliest timescale term still used in geology. Coined by Giovanni Arduino in 1759, it referred to the horizontally stratified, loosely consolidated sediments and sedimentary rocks that were thought to be deposited during and after Noahs Flood, and lay across tilted "Secondary" sedimentary rocks (now considered late Paleozoic and Mesozoic,) and the "Primary" granitic, and metamorphic basement rocks. Together with the Quaternary Period (2 million years ago to present) the Tertiary makes up the earlier part of the Cenozoic Era (65 million years ago to present). The Tertiary is divided into 5 epochs: the Paleocene (6555 million years ago); the Eocene (5534 million years ago); the Oligocene (3423 million years ago); the Miocene (235 million years ago); and the Pliocene (52 million years ago). Some geologists prefer to divide the Cenozoic into two more equal parts: the Palaeogene (Paleocene, Eocene, Oligocene) and the Neogene (Miocene, Pliocene, Pleistocene, Recent). Recently, a number of geological organizations have recommended abandoning the archaic term "Tertiary" in favor of Palaeogene and Neogene.

In climatic terms, however, the most natural subdivision of the Cenozoic occurs between the middle and late Eocene (about 37 million years ago), when the Earth went from "greenhouse" climatic conditions left over from the Mesozoic to the "icehouse" conditions that prevail today. In the early Eocene (5550 million years ago), tropical jungles grew as far north as Montana, and temperate plants and crocodiles

lived above the Arctic Circle, surviving six months of warm conditions but total darkness. In the late Eocene and Oligocene, a series of plate movements caused changes in oceanic circulation, which in turn caused climatic deterioration of the "greenhouse" world.

By the early Oligocene (33 million years ago), there were glaciers on Antarctica, and by the middle Miocene (15 million years ago), those glaciers were permanent. In addition, the rise of the Himalayas (caused by the collision of the Indian Sub-continent with Asia in the early Eocene) may have contributed to the general cooling and drying of the planet by absorbing atmospheric carbon dioxide through increased weathering. Throughout the Miocene, this cooling and drying trend continued, so that by 7 million years ago, widespread grasslands and savannas were found in all temperate and tropical latitudes. About 3.5 million years ago, the Isthmus of Panama closed, uniting South and North America. This had a two-fold effect. Not only did it allow mammals from the North to migrate south and replace the endemic native mammals that had evolved when South America was an island continent, but it also cut off the flow of tropical water between the Caribbean and Pacific. This in turn changed oceanic circulation so that warm currents (the Gulf Stream) moved into the North Atlantic, providing moisture over the long cold but dry Arctic Ocean, and triggering the development of the Arctic ice cap. From this point onward, the Earth was locked into a bipolar glacial state, with alternating glacial and interglacial cycles every 100 000 years triggered by changes in the Earths orbit and distance from the sun. Those glacial-interglacial cycles reached their peak during the Pleistocene ice ages. We are still in the ice ages, but at the end of an interglacial episode (the Holocene or "Recent" Epoch,), which began 10 000 years ago (see, *Mesozoic History*, and *Quaternary History*).

1. General Characteristics of the Tertiary

The Tertiary Period (and the Cenozoic Era) is not as long as the Paleozoic or Mesozoic eras, but it was a very eventful time, when most of the characteristics of the modern world were established. In addition, we know so much more about the Tertiary and Cenozoic than we do over earlier times, and know it in much more detail, because such young deposits are more likely to be preserved and exposed, and less likely to be eroded or metamorphosed than the much older, more deformed rocks of the Mesozoic and especially Paleozoic. In some cases, we can get extremely high-resolution deep sea cores, which can distinguish events from millions of years ago on 1000-year time scales or lessmuch better than the dating or resolution available for the Paleozoic or Mesozoic.

1.2 Evolution of Life in the Tertiary

At the end of the Mesozoic, the non-avian dinosaurs, which had dominated the land, and the ammonites and giant marine reptiles, which dominated the oceans, had both become extinct. However, most other denizens of the Late Cretaceous world survived. On land, most plants were unaffected, as were the reptiles and amphibians (especially crocodilians, turtles, and salamanders), which show that the Cretaceous extinctions were not as dramatic or catastrophic as some scientists have claimed. The mammals, which had been shrew-, or rat-sized creatures for the first 130 million years of their history, suddenly inherited a planet empty of large land vertebrates (except for huge predatory flightless birds, the sole survivors of the dinosaurian lineage). During the Paleocene, mammals underwent a huge evolutionary radiation to fill these vacant ecological niches, and by the middle Eocene, some had reached elephantine size; others were occupying niches as diverse as the seas (whales) and the air (bats). Birds, too, underwent a huge evolutionary radiation in the early Tertiary, diversifying from a few archaic Mesozoic groups to almost all of their modern orders by the middle Eocene. The evolution of insects is not as well known. Although most of the modern orders were around in the Cretaceous, it appears that their diversification, and establishment of most modern families occurred in the Tertiary.

In the oceans, only the ammonites (relatives of the living chambered nautilus), the marine reptiles (mosasaurs and plesiosaurs,) and a few groups of plankton, and bizarre clams died out at or near the end of the Mesozoic. The vast majority of the dominant marine invertebrates groups (especially clams, snails, corals, sea urchins, and most planktonic organisms) survived with only moderate extinction. During the Tertiary, these groups recovered completely, and continued to diversify, with many new forms emerging (such as more advanced, burrowing snails and clams, and the burrowing sand dollars). Single-celled organisms (the amoeba-like shelled foraminifer and radiolarian, and the shelled algae known as coccolithophorids, and diatoms) also evolved rapidly in the oceans, where they serve as the timekeepers for marine rocks of Cenozoic age. Occasionally, there were spectacular developments in these groups. During the middle Eocene, the single-celled nummulitic foraminifer grew calcite skeletons the size and shape of coins. They were so numerous in the tropical seas of Eurasia and Africa that they make up huge volumes of limestone, from which the Pyramids of Egypt are built. By the middle Eocene, there were archaic whales over 20 m long. In the middle Miocene, a gigantic relative of the great white shark appeared which was over 18 m long, and probably hunted whales. Seals, sea lions, and walruses also appeared in the Miocene, along with most of the modern groups of bony fishes (in both the marine, and fresh waters).

1.3 Evolution of the Principal Ecosystems in the Tertiary

The terrestrial habitats vacated by the dinosaurs at the end of the Cretaceous were dominated by flowering plants, although mostly represented by archaic groups, such as the magnolias. Gymnosperms such as conifers, and archaic plants such as ferns, had already been forced into restricted habitats by the Cretaceous explosion of flowering plants. During the Tertiary, the spread of flowering plants continued, with many modern groups of plants appearing for the first time. By the early Eocene, tropical jungles prevailed even up to places as far north as Montana and Wyoming, as the "greenhouse" world of high atmospheric carbon dioxide reached its peak. Temperate conditions were found in the Arctic and Antarctic. Although these regions were dark for six months of the year, they were apparently warm enough to sustain the deciduous plants.

The inhabitants of this world were essentially modern groups: mammals, birds, and many types of insects, along with holdovers from the Mesozoic, like the living groups of reptiles (turtles, snakes, lizards, and crocodiles), amphibians, and most modern groups of bony fish. However, the ecological complexity of this more homogeneous, tropical world was not as great as it is today, when we have many more levels of animals in the food web, and we have much more varied climates and vegetation. For example, among the mammals most were either tree-dwelling seed- and fruit-eaters, or ground-dwelling leaf eaters. Since there were no grasslands, there were no grazers. The predatory mammals were rather primitive, with simple unspecialized teeth for eating meat and carrion. In the absence of dominant mammalian carnivores, 2 m tall flightless birds were actually the largest land predator in the middle Eocene.

By the late Eocene and Oligocene Periods, the global climate began to change dramatically, and one with cooler, drier climates, and greater seasonality replaced the warm, tropical "greenhouse" world of high atmospheric carbon dioxide. This climatic transformation was probably triggered by plate tectonic changes, which in turn affected oceanic circulation. Before the late Eocene, Australia and Antarctica were still connected and circulation in the South Pacific and South Atlantic mixed polar waters with equatorial waters, decreasing the temperature extremes from pole to equator. By the late Eocene, Australia had separated enough from Antarctica that cold, deep currents could flow between the two continents for the first time. This established the beginning of the circum-Antarctic current, which spirals around Antarctica and locks in the cold over the Antarctic. This current was completed in the early

Miocene, when the separation between Antarctica and South America was complete. Today, the circum-Antarctic current not only locks in the cold polar waters in a spiral around the Antarctic continent, but also generates the cold Antarctic Bottom Waters, which flow north along the ocean floor all the way to the Arctic. The timing of this change is manifested in the first Antarctic ice sheets in the early Oligocene, and the permanent Antarctic ice cap by the middle Miocene.

During the Oligocene and Miocene, this long-term cooling and drying trend had a significant effect on life. On land, the jungles of the Eocene were replaced by a more mixed woodland-scrubland habitat in the Oligocene, and by the late Miocene, by true grasslands and savannas across most temperate and tropical regions. Land animals responded to these changes as well. The mostly tree-dwelling seed and fruit eaters of the Eocene nearly vanished as the dense forests were decimated, as did the archaic hoofed mammals that fed primarily on leaves. In their place were mammals adapted for more open habitats, and by the late Miocene, there were many herbivores adapted for grazing, with ever-growing molars that can stand the abrasion this gritty diet, and long legs for rapid escape from predators across the open plains. The Oligocene and Miocene saw the origination or diversification of most of the modern groups of land herbivores (especially rhinos, camels, horses, peccaries, and pronghorns in North America, and rhinos, horses, mastodons, pigs, and ruminants such as deer, antelopes, giraffes, and cattle in Eurasia). It also witnessed the radiation of more specialized predators, the order Carnivora (including the first true cats, dogs, and bear and weasel relatives), which replaced the archaic carnivorous mammals and giant flightless predatory birds of the middle Eocene. Finally, the archaic small mammals of the Eocene jungles (such as the archaic lemur-like primates and the egg-laying multituberculates) were replaced by the rodents and rabbits, which underwent a huge diversification in the Tertiary to become the most numerous, and diverse mammals on Earth.

In the marine realm, the overall structure of the ecological communities was not much changed since the early Mesozoic, when the sea floor dominated by snails, clams, and sea urchins was first established. However, the effects of the long-term cooling trend were dramatic. The high diversity of tropical mollusks, and echinoderms of the Eocene gradually diminished by the Oligocene and Miocene, with many tropical groups replaced by a less diverse assemblage of temperate and cold-tolerant groups. As the "icehouse" world of the Oligocene and Miocene took effect, oceanic circulation also became more vigorous and complex, with stratification of warm surface currents, intermediate currents, and cold bottom waters. This is in contrast to the warm Eocene ocean, which was relatively unstratified and sluggish in circulation. Complex oceanic circulation triggered evolution and diversification in marine organisms (especially the plankton, which track specific water masses). By the Miocene, it also stimulated the revival of modern hermatypic coral reefs, which are adapted to surviving in low-nutrient conditions typical of modern oceans.

1.4 Paleogeographic Characteristics of the Tertiary

The breakup of the Pangaea super continent, which began in the Triassic and reached its peak during the Cretaceous, continued during the Tertiary. Although most of the Pangaean fragments were already separated by the beginning of the period, these trends were amplified by the last 65 million years of plate movement. The Atlantic widened from a narrow Cretaceous ocean to its present width. The separation between the Gondawana continents, such as Africa, South America, India and Antarctica, increased. India moved rapidly from its Gondwana starting point across the entire Indian Ocean to collide with Asia in the early Eocene, causing the rise of the Himalayas. Of the Gondwana continents, only the separation of Australia from Antarctica did not occur in the Cretaceous, but developed during the Eocene.

As the Pangaean fragments moved apart, many paleogeographic changes took place. The collision of

Africa with Europe, and India with Asia closed up the tropical Tethys Seaway that once ran from Gibraltar to Indonesia. In its place was a much-restricted Mediterranean Sea, with a completely different bio geographic effect than the global tropical seaway that once existed. This collision also caused the rise of not only the Himalayas in Asia, but also the Alpine chain (including the mountains of western Asia), and greatly changed Eurasian geography. By 20 million years ago, the Asia was attached to Africa, the eastern Mediterranean was closed, and many endemic mammals of Africa (such as mastodons and hyraxes) were able to spread to other continents.

In the Americas, South America was an island continent, with little connection to the rest of the world until the Isthmus of Panama rose about 3.5 million years ago. In both North and South America, the western half of these continents experienced extensive mountain building, as the subduction of the undergoing plate caused major volcanic arcs to arise (the Andes in South America, the Cascades in North America). The eastern halves of these continents, however, were generally low in relief, and frequently drowned during the high sea levels of the early Tertiary. By the Oligocene and Miocene, however, the volume of seawater trapped in the great polar glaciers caused sea level to drop considerably, and many of the long-submerged shallow shelf habitats and drowned continents became emergent as low coastal plains. Likewise, much of Europe was immersed in shallow seas during the Eocene, and a long north-south seaway, the Obik Sea, stretched across Siberia just east of the Ural Mountains, separating Asia from Europe and connecting the Arctic and Indian Oceans. All of these seas had dried up by the Miocene, allowing continuous land connection between all the Old World continents.

The final major paleogeographic changes occurred in the latest Tertiary. About 6.5 million years ago, mountains were rising across the Straits of Gibraltar, and a glacially triggered drop in sea level cut off the Mediterranean from its sole water source, the Atlantic Ocean. For over a million years, the Mediterranean basin was gigantic version of the Dead Sea; over 1000 m deep, hot, dry, and floored with salt and gypsum formed when occasional Atlantic spillover events flooded the bottom, and then dried up. About 5.5 million years ago (the Miocene-Pliocene boundary event), the Gibraltar dam broke, forming a giant waterfall thousands of times larger than any the Earth has ever seen, and the Mediterranean refilled catastrophically. This "Messinian event" had dramatic effects on global climate and on oceanic salinity (since so much salt was locked up, and then released). Finally, the rise of the Isthmus of Panama not only reconnected North and South America for the migration of mammals both ways, but it also severed the Caribbean-Pacific connection, and caused the marine organisms on both sides to evolve separately from one another.

1.5 Extinctions and Recoveries in the Tertiary

Principles of extinctions and recoveries and their history in Earth ecosystems are defined and described in *Past Global Crises*. This paragraph briefly summarizes the extinctions of the Tertiary.

After the extinctions at the end of the Cretaceous Period that began the Tertiary Period, the first 15 million years were dominated by a remarkable recovery of organisms. Some groups (such as turtles, crocodiles, and most marine organisms) suffered only minimally at the end of the Cretaceous, so their recovery was relatively rapid. Other groups (such as birds and mammals) underwent a huge evolutionary radiation to fill the niches of the formerly dominant land animals, the dinosaurs. By the early Eocene, nearly all-marine and terrestrial groups had reached a peak in diversity that would never again be equaled.

The climatic deterioration that began in the middle Eocene was punctuated by a few minor episodes of extinction. The largest occurred at the end of the middle Eocene (37 Ma), when many of the tropical groups died out on both land and sea. Other minor extinction events were scattered through the late Eocene and Oligocene. Contrary to popular misconception, there was no single large catastrophic "Terminal Eocene Event" comparable to the event that ended the Mesozoic. Instead, the EoceneOligocene extinctions are spaced out over about 10 million years, and appear to be largely caused by gradual climatic changes triggered by plate tectonic movements and oceanic circulation. Major impact events are well documented from the middle of the late Eocene (35.536.5 million years ago), with large craters identified from underneath Chesapeake Bay and from Siberia (Popigai). However, none of these impacts caused extinctions or climatic changes of any consequence, in dramatic contrast to the alleged effects of the impacts that concluded the Cretaceous (see, *Climate and Atmosphere*).

Lesser extinctions occurred in the later Tertiary as climate changed, and major bio geographic changes caused migration of exotic faunas. For example, in the early Oligocene, Asian mammals migrated wholesale into the formerly isolated European archipelago, causing extinction of many European natives in an event known as the Grande Coupure. In the middle Pliocene, the immigration of North American land mammals (especially mastodons, horses, elephants, camelids, tapirs, and cats and dogs) drove many of the endemic South American native mammals to extinction. This event was triggered by the rise of the Isthmus of Panama, and is known as the Great American Interchange. Other extinctions, such as the disappearance of rhinos, most horses, camels, and pronghorns, and several other native North American groups (such as protoceratids and dromomerycids) at the end of the Miocene were probably triggered by the global climatic changes due to the Messinian event.

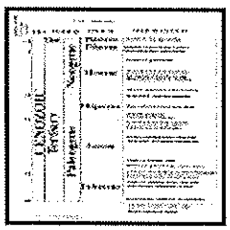

Figure 1. Tertiary stratigraphy

2. Tertiary Epochs

2.1 Palaeocene

2.1.1 Definition

Paleobotanist W. P. Schimper first defined the Paleocene Epoch in 1874. Originally, it was based on northern European strata containing land plants, which made it difficult to correlate with marine beds elsewhere, so it was not widely adopted until the 1930s. Before then, most geologists called Paleocene beds "Lower Eocene." Currently, the base of the Paleocene is defined at the CretaceousTertiary boundary stratotype at El Kef in Tunisia, which is marked by the iridium anomaly caused by the global effects of the impact of an asteroid. It is also defined by the first appearance of a number of distinctive earliest Paleocene planktonic foraminifer. Its duration of ten million years is currently divided into three standard global marine stages, the Danian (6561 million years ago), the Selandian (6158 million years ago), and the Thanetian (5855 million years ago).

2.1.2 Palaeocene Life

The Paleocene was marked by the recovery of life from the Cretaceous extinctions. In the marine realm, this was a relatively minor extinction and rapid recovery, with new groups of clams, snails, sea urchins and plankton rapidly replacing the extinct groups and restoring diversity to pre-extinction levels. In other groups, the recovery was slower. The loss of nearly all large terrestrial vertebrates (the dinosaurs) at the end of the Cretaceous meant that the mammals had to quickly diversify and radiate to fill these available niches. Most early Paleocene mammals were no larger than cats or rats, and consisted mostly of archaic groups, such as archaic hoofed mammals, squirrel-like multituberculates (an archaic Mesozoic group of mammals that probably laid eggs), lemur-like primates, and diverse insectivorous mammals. By the late Paleocene, the largest mammals (the pantodonts) were as large as sheep, but still most were members of archaic groups that are now extinct.

2.1.3 Paleogeography

The ten million years of the Paleocene were marked by only slight changes in paleogeography from that of the Late Cretaceous. India moved across the northern Indian Ocean, the Atlantic got slightly wider, and Africa began to shift northward and close up the Tethys Seaway. Australia and Antarctica, however, were still connected. South America was connected to Antarctica, but not to North America, so the early South American endemic mammalian fauna includes archaic groups left over from the Cretaceous (such as edentates and archaic hoofed mammals), as well as marsupials found all over Gondwanaland in the Cretaceous. Warm climates and high sea levels prevailed, so that most coastal regions were drowned, Europe was an archipelago, and the Obik Sea separated Europe from Asia. In North America, the Laramide Orogeny caused huge mountains and deep basins to arise in the present Rocky Mountain region. Indeed, our best terrestrial records of the Paleocene come from these Laramide basins.

2.2 Eocene

2.2.1 Definition

The Eocene was one of the three original Tertiary epochs defined by Charles Lyell in the third volume of his landmark book *Principles of Geology* (1833). Originally, he based his concept of the Eocene not on typical rocks, but on the relative percentage of living mollusk species. This definition proved inadequate for many reasons, so later geologists named stratotypes for Eocene stages in Europe than now serve as the standard for this epoch. Currently, the best candidate for the PaleoceneEocene boundary stratotype is base of the Ieper Clay (type Ypresian) in Belgium, and the first appearance of the nannofossil *Tribrachiatus digitalis* is considered the best index of the beginning of the Eocene. This horizon is dated at 54.37 million year ago. However, some scientists prefer to use the global carbon isotope signal associated with the late Paleocene warming and benthic foraminifer extinctions, and major turnover in land mammals, which occurs in the late Sparnacian (55.8 million years ago).

The beginning of the Eocene (the PaleoceneEocene) boundary is marked by a dramatic oceanic event that caused mass extinction in bottom-dwelling foraminifers. The causes of this event are controversial, but it is clear that there was extremely rapid, short-term global warming and stagnation of the ocean bottom, possibly created by a rapid introduction of carbon dioxide into the oceans, and atmospheres.

The long 21-million year duration (5534 million years ago) of the Eocene is currently divided into four standard global marine stages: the early Eocene Ypresian Stage (5549 million years ago), the middle Eocene Lutetian (4941 million years ago) and Bartonian (4137 million years ago) stages, and the late Eocene Priabonian Stage (3734 million years ago).

2.2.2 Eocene Life

Life in the Eocene Period reached a peak of diversity for the entire Cenozoic Era, as the Cretaceousearly Tertiary "greenhouse" climates peaked in the early Eocene. As described above, early Eocene land vegetation was a jungle from the tropics to the high latitudes, and temperate even above the Arctic and Antarctic circles, where it was dark (but apparently warm) six months of the year. Inhabiting this jungle were many archaic mammals left over from the Paleocene (such as lemur-like primates, multituberculates, archaic hoofed mammals, and insectivores) along with a number of new groups, such as the earliest odd-toed hoofed mammals (archaic horses, rhinos, and tapirs,) and even-toed deer-like hoofed mammals, and also the first rodents. Recent fossil discoveries suggest that all three of these groups originated in Asia in the late Paleocene, and in the early Eocene immigrated to North America via the Bering land bridge, and then across Iceland, and Greenland to Europe.

By the middle Eocene, the climatic deterioration had begun, and some of the archaic groups (most of the multituberculates, archaic hoofed mammals and lemur-like primates) had disappeared. However, there were still huge elephant-sized uintatheres, which had six paired knob-like horns on their foreheads, and huge canine teeth. By the late Eocene, there were huge brontotheres with paired blunt battering-ram horns on their noses. Other groups, such as the horses, rhinos, and even-toed hoofed mammals underwent a great diversification and evolved into many different lineages. By the late Eocene, the forested habitat was rapidly disappearing, and most of the tree-dwellers, and leaf-eating hoofed mammals were rapidly becoming extinct. At the end of the Eocene, the brontotheres, multituberculates, and a few other archaic groups disappeared for good.

In the marine realm, early Eocene taxonomic diversity was also at its highest levels of the entire Tertiary. Numerous warm-adapted taxa ranged from the tropics to the middle latitudes, and in the tropical Tethys Seaway, huge volumes of nummulitic limestone were laid down. In the early Eocene, huge bear-like carnivorous hoofed mammals called mesonychids became increasingly more aquatic, so that by the middle Eocene, they had evolved into whales more than 20 m in length. In the sea floor, the major new addition was the appearance of sand dollars, which evolved from less-flattened irregular sea urchins. Again, the climatic deterioration of the middle and late Eocene caused the stepwise extinction of many of these warmth-loving taxa, especially at the dramatic cooling event that marked the middlelate Eocene boundary (37 million years ago).

2.2.3 Paleogeography

The Eocene saw a continuation of most of the continental motions started by the breakup of Pangaea in the Mesozoic. The Atlantic widened (so that by the middle Eocene, the land bridge across Iceland and Greenland was no longer connected), Africa continued to move north and began to cause the collision that became the Alps, and the Americas continued to override the plates of the Pacific Ocean. The remaining Gondwana fragments, however, caused the major events. For example, the collision of India with Asia started the uplift of the Himalayas, and chopped the Tethys Seaway in half, which disrupted the tropical circulation that ran around the world at the time. In the latest Eocene, the separation of Antarctica from Australia started the development of the circum-Antarctic current, which had a major effect on global climate discussed above. In South America, the eruption of the Andean arc began in earnest. In North America, the Laramide Orogeny ceased by the middle Eocene, but in its place a chain of late Eocene and Oligocene volcanic arcs developed (see Gondwana, Pangea, and Thetys).

The earlymiddle Eocene greenhouse climates meant that sea levels were again at their highest levels, and most of the low-elevation coastal plains (such as that on the Atlantic and Gulf coasts of North America, or the margins of Africa facing the Tethys Seaway) were drowned. In addition, portions of many continents (such as Europe) were largely under water, forming an archipelago of low-relief islands. Consequently, Europe had many endemic mammals that were isolated from those of other continents. South America and Africa were isolated from every continent except Antarctica since the Cretaceous, so they too had their own endemic faunas. Australias Eocene fauna is poorly known, but it also appears to be endemic, since Australia was connected only to Antarctica at this point, and would lose even that connection by the end of the Eocene.

2.3 Oligocene

2.3.1 Definition

H.E. von Beyrich defined the Oligocene in 1854 for marine strata in Belgium and Germany thought to be younger than the classic upper Eocene of the Paris Basin, but older than the classic Miocene strata. For the next 130 years, there was considerable confusion of what was Eocene and what was Oligocene, not only in the type areas in western Europe, but especially in other regions which could only be indirectly correlated to the stratotypes. For example, in North America, the Duchesnean land mammal age was thought to be late Eocene or Oligocene (it is now middle Eocene), the Chadronian land mammal age was correlated with the early Oligocene (it is now known to be late Eocene in age), and the Orellan and Whitneyan land mammal ages were thought to be middle and late Oligocene (they are now both early Oligocene in age). These controversies have since been resolved by using the planktonic microfossil standard from the deep sea, and calibrating it with a combination of magnetic stratigraphy and argonargon dating.

Currently, the EoceneOligocene boundary has been established at the last appearance of the spiny planktonic foraminifers known as hantkeninids in a quarry section near Massignano, Italy. However, later work has since shown that part of the type upper Eocene Priabonian stage is early Oligocene by this definition, so there are problems with this criterion. Only two stages are recognized in the 11 million years (3423 million years ago) of the Oligocene. The early Oligocene (Rupelian) runs from 3428.5 million years ago. The late Oligocene (Chattian) is dated between 28.523.8 million years ago. There is no formally recognized middle Oligocene.

2.3.2 Oligocene Life

As the climatic deterioration of the Eocene and Oligocene began, the total diversity of land mammals or marine organisms decreased significantly from Eocene levels, reaching an all-time low in the late Oligocene. The forests and jungles of the early Eocene were rapidly disappearing by the late Eocene. So, in the Oligocene most of the temperate latitudes were covered in a mixture of forest, and scrubland vegetation. Along with the change in vegetation triggered by this cooling and drying was a major change in many of the land organisms. Land snails that were typical of the tropics were replaced by those tolerant of drier conditions. Crocodilians and aquatic turtles became much rarer, and in the early Oligocene in North America dry-land tortoises replaced them. In this realm lived a land mammal fauna dominated by primitive members of mostly living families. These included three-toed horses, three different lineages of rhinos, early camels and deer and peccaries, as well as a handful of archaic groups left over from the Eocene. Numerous modern carnivoran groups (especially early dogs, and the catlike nimravids) became the dominant predators as the last of the archaic carnivorous mammals straggled on. Tree-dwellers became much less common and vanished from many continents. For example, primates were restricted to Africa and South America, where they evolved into Old World and New World monkeys, respectively. Rodents and rabbits both underwent a huge diversification as the niches for ground-dwelling seedeaters increased, and the habitat for squirrel-like nut, and fruit eaters diminished.

In Eurasia, many of the same trends were apparent. In the early Oligocene, the Turgai Strait across the Obik Sea between Europe and Asia opened up, allowing Asian mammals (such as rhinos and ruminants) to immigrate to Europe and drive many of the endemic natives to extinction. This event is known as the Grande Coupure. However, there was only limited migration between Asia and North America via the Bering Strait. South America, Africa, and Australia continued to be unconnected to the rest of the world, and each developed their own endemic faunas.

In the marine realm, diversity was also at an all-time low, dominated by groups known to be tolerant of the cooler waters that began in the Oligocene. However, the overall taxonomic composition of the marine fauna remained essentially the same, with clams, snails, and sea urchins making up the bulk of the fossilizable organisms. Planktonic organisms were not only low in diversity, but occupied relatively few, simple bio geographic realms (since the area of the tropics had decreased), and evolved relatively slowly during the Oligocene.

2.3.3 Paleogeography

With the separation of Australia from Antarctica and the collision of India with Asia in the Eocene, most of the continents were approaching their present configuration by the Oligocene. South America, however, would not finally separate from Antarctica until the end of the Oligocene, completing the breakup of Gondwanaland and finishing the full circum-Antarctic current. As discussed above, these continental movements brought about major changes in oceanic circulation, with the circum-Antarctic current locking in the cold over Antarctic, initiating the first Antarctic ice sheets in the early Oligocene, and also stimulating the flow of cold Antarctic bottom waters, which today control most of the rest of the worlds oceanic circulation.

The growth of Antarctic glaciers meant that the high sea levels of the Eocene "greenhouse" world were gone, and much of the seawater was locked up in ice causing global regression. In fact, the late Oligocene regression is thought to be a 150 m drop in sea level by some geologists, which would be the largest lowering of sea level ever recorded. Much of the drowned coastal plains of the Atlantic and Gulf coast of North America became emergent floodplains, and the European archipelago largely dried up. This regression also dried up the Obik Sea and ended the separation of Europe and Asia. The Tethys Seaway was already partially disrupted by the collision of India with Asia, but global regression destroyed the remaining vestiges of this seaway, and its unique tropical fauna.

On land, the Himalayas continued to develop, and the Alps began to rise in earnest as Africa began to collide with Europe and close up the Mediterranean. The Andes began to erupt huge volumes of volcanics, forming a mountain chain for the first time. The Rocky Mountains were no longer rising, but they continued to soar high above the western part of North America, but the basins between them began to fill up with sediments, and volcanic debris erupted from the arc volcanoes to the west.

2.4 Miocene

2.4.1 Definition

The Miocene Period was another of the three original Tertiary epochs defined by Charles Lyell in the third volume of *Principles of Geology* (1833). As in the case of the Eocene, it was originally defined on the percentage of modern mollusk species known from the fossil record, and this definition proved to be unworkable. Instead, a series of local marine stages were established in Europe, and these have been calibrated using planktonic microfossils in the past two decades. Currently, the 18 million years of the

Miocene (23.85 million years ago) is divided into six global marine stages: the early Miocene Aquitanian (23.820.5 million years ago) and Burdigalian (20.516.5 million years ago) stages; the middle Miocene Langhian (16.515 million years ago) and Serravillian (1511 million years ago) stages; and the late Miocene Tortonian (117 million years ago,) and Messinian (75 million years ago) stages. The stratotype for the OligoceneMiocene boundary was designated at the level 35 m from the top of the LemmeCarrosio section in the southern Piedmont of northwestern Italy. It is associated with a number of microfossil data, including the first appearance of the planktonic foraminifer *Globorotalia kugleri*. Its age is estimated at 23.8 million years ago.

2.4.2 Miocene Life

In the Miocene, the cooling and drying trend of land vegetation begun in the Eocene continued, with mixed scrublands and forests of the early Miocene replaced by widespread grasslands and savannas by the late Miocene in middle latitudes. These scrublands and grasslands were inhabited by a mammalian fauna, which resembles that found in the modern savanna of East Africa, except that the taxonomic groups varied from continent to continent. In Eurasia and Africa, it included early antelopes, giraffes, and cattle, deer, three-toed horses, as well as mastodons, and early pigs. However, in North America, entirely different, native groups occupied the same niches. Camels occupied the niches of giraffes and antelopes. The latter niche was also occupied by pronghorns (which are not true antelopes, but an endemic native North American family,) and horse. In fact, there was a huge diversity (12 species in one locality) of three-toed, and one-toed horses. Hippo-like rhinos occupied the hippo niche, while other rhinos were more like the living terrestrial rhinos. Dogs performed the roles of hyenas, and dromomerycids, and protoceratids the roles of deer, and moose, respectively. Peccaries (which are pig-like, but an endemic North American group) performed the role of pigs. When mastodons immigrated to North America in the middle Miocene, they performed the role that elephants occupy in Africa.

Other continents saw similar niche substitution. In South America, native endemic hoofed mammals evolved into forms that closely resembled rhinos, horses, camels, giraffes, hippos, and elephants, even though none of these animals are actually related to their ecological counterparts. Before Africa ended its isolation in the early Miocene, there were rhino-like hyraxes, as well as the rhino-like arsinoitheres, both of which are more closely related to elephants than they are to rhinos. But by the middle Miocene, the connection with Eurasia had been established across the Middle East. Mastodons and hyraxes escaped Africa and flourished in Eurasia, while Eurasian groups such as rhinos, three-toed horses, ruminants, and many groups of carnivorans became established in Africa.

In the marine realm, the sea bottom fauna was an increasingly modern-looking mixture of clams, snails and sea urchins, which was more cold-adapted than any seen in the Eocene or Oligocene. Extensive coral reefs began to develop in the tropics for the first time since the Mesozoic, possibly because the changes in oceanic circulation favored hermatypic corals, which are better adapted than coralline algae and other colonial organisms to low-nutrient conditions. However, there were some additions to the Miocene seas that were never seen before. The earliest seals, sea lions, and walruses evolved by the early Miocene, and the baleen and toothed whales began to diversify after their origination in the Oligocene. In the middle Miocene, there was a gigantic (18 m long) relative of the Great White Shark that was so large it probably preyed on whales.

2.4.3 Paleogeography

By the Miocene, most of the continents were near their present positions or just about to arrive there. Australia had moved rapidly away from Antarctica, widening the Southern Ocean, and the connection between South America and Antarctica was severed by the Drake Passage, completing the circum-Antarctic current. By the middle Miocene, the modern Antarctic ice sheet was in place, and it has been there ever since.

The early Miocene, closing the eastern Mediterranean, and forever destroying the remnants of the Tethys Seaway, established the connection across the Arabian Peninsula from Africa, and Eurasia. By the late Miocene, the Mediterranean was so enclosed that only the Gibraltar Strait remained to replenish it with Atlantic seawater (since it evaporates more rapidly than its few rivers supply it in that dry climate). As described above, during the Messinian event (6.55.5 million years ago), the rise of the Atlas Mountains across Gibraltar, and a glacially induced drop in sea level caused the Mediterranean to dry up, and become a gigantic, 1000 m deep Dead Sea.

Around the world, great mountain ranges were rising. The Himalayas had nearly reached their present elevation, and some geologists think that the deep weathering that this caused was critical to withdrawing carbon dioxide from the atmosphere and driving the world from greenhouse to icehouse conditions. The Alps were also rising rapidly, as were the connecting mountain ranges in Turkey, Iran, the Caucasus, and Afghanistan. The Andean eruptions accelerated developing the high mountain chain we see today, and further accentuating the tropical rain forests of the Amazon basin. In North America, the Rockies, and their intervening basins, were nearly buried in their own debris and disappeared, but in the late Miocene renewed uplift raised them up again and stripped the basins of most of their fill. Meanwhile, the complex tectonics of the San Andreas transform zone and the spreading of Nevada and Utah to form the Basin and Range province were taking place. The Cascades continued to erupt in California, Oregon, and Washington, and many of the great volcanic arcs of the Pacific Rim (such as Japan, the Philippines, and Indonesia) began to erupt in the Miocene as well. The tectonics of the Miocene is an extremely complex subject, so the reader is referred to Dott and Prothero (1994) in the references for further details.

2.5 Pliocene

2.5.1 Definition

Like the Eocene and Miocene, the Pliocene was the third of the three original Tertiary epochs defined by Charles Lyell in the third volume of *Principles of Geology* (1833). Originally based on the relatively small percentage of extinct mollusks in the fauna, it has since acquired the meaning as the time interval between the Messinian event that ended the Miocene, and the onset of Pleistocene glaciations. However, recent research shows that the orbital ice age cycles that were once thought to be restricted to the Pleistocene are also known from the Pliocene, so that original meaning has been lost. The stratotype of the MiocenePliocene boundary has yet being determined, but currently the prime candidate is the base of the stratotype of the Zanclean Stage in the Eraclea Minoa section, near Capo Rosello, Sicily. The Pliocene-Pleistocene (and therefore Tertiary-Quaternary) boundary has been placed at the base of a section near Vrica, in Calabria, Italy. This boundary occurs with the Olduvai Magnetozone, and is dated at 1.80 million years ago. Some geologists have favored moving the Pliocene-Pleistocene (Tertiary-Quaternary) boundary to the beginning of the ice age cycles, around 2 million years ago, although this suggestion has not been accepted by the official international committees, or by the majority of geologists.

The 3.4 million years of the Pliocene (5.21.8 million years ago) has been subdivided into three formally recognized global marine stages: The early Pliocene Zanclean Stage (5.23.5 million years ago,) and the late Pliocene Piacenzian (3.52.5 million years ago,) and Gelasian (2.51.8 million years ago) stages.

2.5.2 Pliocene Life

After the Messinian event that terminated the Miocene, terrestrial climate became even cooler and drier in middle latitudes. Much of North America, Africa and Eurasia were covered by more open, steppe-like grasslands, which supported a much lower diversity of mammals than did the savannas of the late Miocene. In North America, this fauna consisted of a lower diversity of horses (some three-toed but predominately one-toed), pronghorns, camels, and peccaries, as well as immigrants such as the earliest North American deer and both mastodons and mammoths. True dogs and cats, as well as hyena-like borophagine dogs, dominated the carnivoran fauna; the archaic carnivorous mammals were gone forever. A high diversity of rodents (mostly members of modern families, and some members of modern genera as well) as well as rabbits made up the small mammal fauna.

In Eurasia and Africa, the mammalian fauna consisted mostly of primitive members of the living fauna, including ruminants (deer, giraffes, antelopes, and cattle), pigs and hippos, horses and rhinos, plus mastodons and mammoths. However, Australia still had its endemic native marsupial fauna, and the South American fauna at the beginning of the Pliocene was largely endemic as well. In the mid-Pliocene, however, this changed as the Panamanian Isthmus opened, and the Great American Interchange took place. Most of South Americas native endemic mammals died out when competing with the invading North American mammoths, mastodons, horses, camels (ancestors of the modern llama, alpaca, guanaco, and vicua), tapirs (which today are virtually restricted to South America), plus an array of modern carnivorans, including saber-toothed cats, and the ancestors of South Americas endemic dog radiation. Meanwhile, only a small portion of South Americas native fauna managed to migrate to North America, since there is a big difference between the tropics of Central America and the Amazon Basin, and the much drier habitats of Mexico, and the United States. Only ground sloths, armadillos (and their giant relatives, the glyptodonts) became a significant part of the North American mammalian fauna in the Pliocene and Pleistocene.

In the marine realm, the community of clams, snails, and sea urchins were significantly affected by the rapid changes in water temperature and circulation caused by the ice age cycles. In addition, the closure of the Panamanian Isthmus meant that Caribbean and Pacific marine faunas were forever cut off from one another. The diversion of these warm tropical waters into the Gulf Stream meant that marine faunas of the Atlantic Coast of North America, and even of the North Atlantic, were adapted to much warmer waters than would be predicted for their latitude. The same Gulf Stream provided the moisture that allowed the Arctic ice cap to develop in the late Pliocene, and providing the warmth and moisture that keeps such regions as the British Isles much milder in climate than their latitude would predict.

2.5.3 Paleogeography

In the brief interval of the Pliocene, few significant tectonic or paleogeographic changes had occurred since the late Miocene. The most important event, of course, was the closure of the Isthmus of Panama, which had profound bio geographic, and oceanographic effects discussed above. The most important of these effects was the growth of the Arctic ice cap, which in turn was responsible for the climatic decline of the planet into full glacial/interglacial cycles every 100 000 years. These cycles had been shown to be caused by the Milankovitch cycles in the Earths orbital motions. The 100 000 year cycle is caused by changes in eccentricity in the Earths orbit, and is the most important cycle in determining the length of glacial/interglacial cycle. The lesser cycles of 43 000 years (caused when the Earths axis changes tilt between 21 and 25) and the precession cycle of 21 000 years (caused when the Earths axis changes its orientation with regard to the stars) have a lesser effect on the global climatic cycles. These cycles are present at all times in Earth history, of course, but only when the Earths climate is particularly sensitive to the small variations in solar radiation do their effects become obvious (see insulation, Milankovitch cycles).

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Related Chapters

Related Links will be activated soon!

Glossary

Antarctic Bottom Waters: Cold, oxygenated currents created by the chilling of water near Antarctica. These cold, dense waters then sink to the ocean bottom and flow north as the bottom-most layer in a stratified ocean, eventually reaching the North Atlantic and North Pacific, where they meet cold bottom waters from the Arctic. These currents essentially drive oceanic circulation and modern climate.
Brontotheres: Extinct group of rhino-like odd-toed hoofed mammals which, by the late Eocene, evolved into elephant-sized animals with a pair of blunt, slingshot-like battering ram horns on their noses. They died out at the end of the Eocene, presumably because their leafy diet became scarce.
Carnivore (and Carnivoran): Carnivores are flesh-eating animals, including many different orders of mammals and birds. Carnivorans are members of the mammalian order Carnivora (the cats, dogs, bears, weasels, raccoons, civets, hyenas, seals, and their kin), flesh-eating mammals with a specialized shearing dentition, which happen to be the only mammalian carnivores today.
Circum-Antarctic current: Modern current which flows clockwise around the Antarctic. It locks in the cold over the South Pole, and creates the climatic extremes between pole and equator, as well as the Antarctic Bottom Waters, that dominate modern climate. Its birth and growth during the Eocene and Oligocene was largely responsible for the global cooling seen at that time.
Foraminifer: Single-celled amoeba-like marine protistans that secrete a calcareous internal shell. Although they are both planktonic (free-floating,) and benthic (bottom-dwelling), the planktonic foraminifer are so abundant and evolve so rapidly in the Tertiary that they are the primary marine index fossil of that time.
Grazing: Eating grasses.
Greenhouse: Climatic conditions that include high concentrations of atmospheric gases (such as carbon dioxide or methane,) which traps solar energy before it radiates back into space, warming the planet (similar to what happens with the glass on a gardeners greenhouse). During greenhouse conditions, the Earth is much warmer, the polar ice caps are melted, and sea level is much higher.
Icehouse: Climatic conditions that include low concentration of atmospheric greenhouse gases, so that the planet is cooler, ice caps can form, and sea level is generally lower.
Insectivore: Insect-eating mammals. Living members of the order Insectivora include moles, shrews, and hedgehogs.
Marsupials: Pouched mammals (such as the kangaroo, opossum, wombat, and koala, etc,) that give birth to a premature live young, but then nurse it inside a pouch until it is old enough to live outside the mother.
Milankovitch Cycles: Cycles of variation of the Earths orbit, which affect how close the Earth is to the sun, and therefore how much radiation (and how warm) the Earth becomes. Although always operating, they are most effective when the Earth has large amounts of ice, at which time they can trigger glacialinterglacial cycles.
Multituberculates: Archaic group of extinct mammals, distantly related to the egg-laying platypus,

which originated 200 million years ago, but died out in the Eocene. Most were very squirrel-like, with teeth adapted for slicing and grinding seeds, nuts, and fruits; the rodents may have replaced them.
Nannofossil: Tiny planktonic algae known as coccolithophorids secrete even tinier (a few microns across) button-shaped calcareous plates known as nannofossils. They are important time indicators in marine Tertiary rocks.
Plankton(ic): Microscopic organisms that are so tiny they float in the open ocean, particularly at the surface. They include: amoeba-like protistans (foraminifer and radiolarian,) and plants (coccolithophorids, and diatoms).
Ruminants: Mammals, which digest their plant food with a four-chambered stomach by "chewing the cud." Today, they include camels, giraffes, deer, pronghorns, and the cattle family (cattle, goats, sheep, and antelopes).

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Donald R. Prothero is Associate Professor of Geology at Occidental College, Los Angeles, California, U.S.A. Born in

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