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Oligocene

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Introduction

The Oligocene Epoch was defined by Heinrich Ernst von Beyrich in 1854. This interval of geological time was based on marine strata in Belgium and Germany, thought to be younger than the Lyell's classic upper Eocene (*see* **Tertiary To Present:** Eocene) strata of the Paris Basin, but older than Lyell's (*see* **Famous Geologists:** Lyell) concept of Miocene rocks. Von Beyrich's original list of 'Oligocene' rocks contained a wide spectrum of units of varying ages, including those that are now clearly referable to the Eocene or Miocene. For example, one unit (the bone sand of Eppelsheim) produced a Late Miocene *Hipparion* fauna. In addition, the type strata of von Beyrich's Oligocene in Belgium and Germany do not overlie the type strata of the Paris Basin or Italian Eocene, so the Eocene–Oligocene boundary cannot be recognised in either area. As is true of the rest of the European Cenozoic, the type sections of the stages within the Oligocene are shallow-water deposits bounded by unconformities, and represent only a small portion of its duration.

For 130 years after von Beyrich's establishment of the Oligocene, there was considerable confusion over what was Eocene and what was Oligocene, not only in the western European type areas, but especially in other regions which could only be correlated indirectly to the stratotypes. For example, in North America, the Duchesnean land mammal age was thought to be late Eocene or Oligocene (it is now considered 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 regarded as Early Oligocene in age). Although these problems made the type Oligocene stages hard to correlate to other regions, the use of planktonic microfossils and magnetic stratigraphy has allowed geologists to correlate the classic shallow-marine European stratotypes and terrestrial sections to the global deep-marine standard (**Figure 1**). As a result, the Oligocene is now securely correlated around the world.

In 1989, the Eocene–Oligocene boundary was formally established at the last appearance of the spiny planktonic foraminiferal genus *Hantkenina* 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 still problems with this criterion. Most of the important climatic events that many scientists believe should mark the beginning of the Oligocene (e.g., the global oxygen isotope shift indicating the expansion of Antarctic glaciers, and related events such as the cooling on North America) are earliest Oligocene (magnetic Chron C13N, about 33 million years ago) using the hantkeninid criterion. Thus, there are grounds for revising

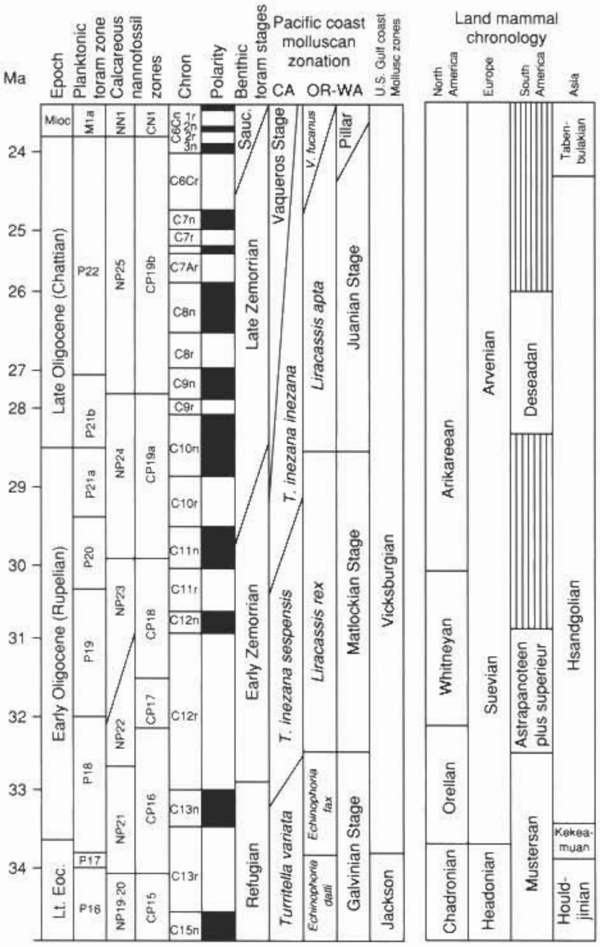

Figure 1 Correlation of various Oligocene biostratigraphic units to the global time-scale (left) and magnetic polarity time-scale (middle). Global time-scale and planktonic zonation (after Berggren *et al.* (1995)). Pacific Coast marine zonation after Prothero (2001). US Gulf Coast molluscan zonation (after Prothero *et al.* (2003)). North American land mammal chronology (after Prothero and Emry (1996)). Asian land mammal chronology (after Meng and McKenna (1998)). European land mammal chronology (after Barbera *et al.* (2001)).

the 1989 definition to a more 'natural' boundary. This would also place the beginning of the Oligocene after the end of the type Late Eocene (Priabonian Stage). However, no such revision has been formally proposed to date.

Only two stages are recognized in the 11-million-year (34–23 Ma) span of the Oligocene. The Early Oligocene Rupelian Stage includes the interval from 34–28.5 Ma. The Late Oligocene Chattian Stage is dated between 28.5–23.8 Ma. There is no formally recognized Middle Oligocene.

Oligocene Climate

The 11 million years of the Oligocene marked an important climatic transition in Earth history. The latest Paleocene and Early Eocene (55–50 million years ago) was the peak of global warming, a 'greenhouse' climate that exhibited the warmest global conditions since the Late Cretaceous. Climates were so warm and mild that crocodilians and temperate plants lived above the Arctic Circle in regions that experienced six months of darkness. Beginning in the Middle Eocene, though, this balmy climate began to transform, with the greenhouse climate gradually changing to a colder, more extreme climate. The end of the Middle Eocene (37 Ma) was marked by a major cooling event, which caused the extinction of many marine organisms adapted to warm, tropical waters.

During the three million years of the Late Eocene (37–33 Ma), there was a slight warming and recovery from the long-term cooling trend. At least three major comet or asteroid impacts struck the Earth in the Middle of the Late Eocene (35.5–36.0 Ma), but these caused no significant changes in climate, nor extinction of any importance. As noted above, the Eocene–Oligocene boundary is now formally recognized by the extinction of hantkeninid foraminifera, although no other major climatic or extinction events occurred at this time. (Note that this invalidates an old idea from the 1970s and 1980s that a 'Terminal Eocene Event' – comparable to the event that ended the Cretaceous – also marked the end of the Eocene).

The most significant climatic event of this interval occurred in the earliest Oligocene (as currently defined, using the hantkeninid criterion), at about 33 Ma. This is now known as the Oi1 event. In the marine record, both benthic and planktonic foraminiferal oxygen isotopic ratios show about a 1.3 per mil increase (**Figure 2**). It was calculated that about 0.3–0.4 per mil of the change was due to a major expansion of Antarctic ice-sheets that lowered global sea-level by at least 30 m. The remaining 0.9–1.0 per mil is explained by about 5–6°C global cooling, which lowered global mean temperature from as high as 13°C in the Early Eocene and 7°C in the latest Eocene to values just a few degrees above freezing (as a global average – the poles were well below freezing for the first time, while the tropics remains relatively unchanged).

Abundant data suggests that this global cooling event was due largely to the growth of the first major Antarctic ice-sheet since the Permian (over 250 Ma). Drilling on the margin of the Antarctic continent and in oceanic plateaus in the Southern Ocean (e.g., Maud Rise and the Kerguelen Plateau) have produced unmistakable evidence of ice-sheet growth. Not only do the isotopic records show its effect, but many of the sediments drilled from the

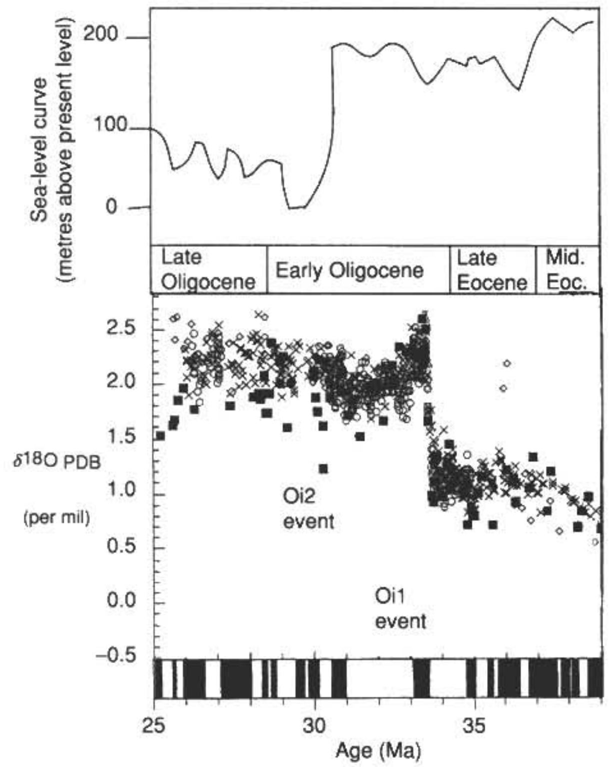

Figure 2 Details of oxygen isotope and sea-level record in the Oligocene (modified from Prothero and Dott, 2003, and Zachos *et al.*, 1999).

Antarctic margin are glacial in origin. In addition, there are even observations of sediments dropped by melting icebergs well out into the Southern Ocean.

What caused this global cooling and the extinctions in the Early Oligocene? A few geologists have suggested that the Late Eocene impact events, or major volcanic eruptions in the Ethiopian Plateau, might have been responsible, but these ideas are challenged by the stratigraphical sequence of events. As noted above, the impacts occurred in the Middle of the Late Eocene, about two million years before the Early Oligocene cooling and two million years after the End–Middle Eocene cooling. Likewise, the volcanic eruptions that formed the Ethiopian traps are now dated in the Late Oligocene, when no significant extinctions are recorded. For more than 30 years, the primary mechanism responsible for the Early Oligocene cooling has been identified as the development of the Circum-Antarctic current. Today, this current circulates in a clockwise direction around the Antarctic continent, forming a 'refrigerator door' that locks the cold temperatures formed on the poles. This current is one of the largest in the ocean, moving as fast as 25 cm sec. The volume of water that passes between Antarctica and Australia is about 233 million cubic metres per second, or more than 1000 times the flow of the largest river on Earth, the Amazon. The 'refrigerator door' also separates the polar currents from subpolar and temperate currents, so that each is isolated from the other. By contrast, in the Early Eocene tropical waters in the Atlantic and Pacific mixed all the way to the poles, decreasing the difference in temperature between the poles and the equator.

As these cold waters circulate around the poles, they sink, generating the Antarctic bottom waters. These cold, oxygenated waters then flow along the bottoms of the world's oceans, all the way to the northern hemisphere. The effect of this on global oceanic circulation and climate is enormous. Antarctic bottom waters contain up to 59% of the world's marine water, and transport this cold water all over the bottom of the ocean. This, in turn, increases the stratification of shallow- and mid-level currents in the ocean, further accentuating the climatic differences between pole and equator.

So what triggered the development of the Circum-Antarctic current? The most obvious factor is plate Tectonics (*see* **Plate Tectonics**). In the Late Cretaceous, Australia and South America were still attached to Antarctica as remnants of the ancient Gondwana supercontinent. As noted above, this caused the tropical currents to mix with polar currents along a much broader front since there were barriers between the Atlantic, Indian, and Pacific oceans, and no southern ocean. The climatic effect was expressed by moderate global temperatures. Geophysical evidence shows that these three southern continents began their separation in the latest Cretaceous, but they were not far apart enough to allow deep-ocean currents to pass through until the latest Eocene or Early Oligocene. By the Early Oligocene, deep-sea cores south of New Zealand reveal a blast of cold water was passing between Australia and East Antarctica. As the Oligocene progressed, the between-continent separation grew wider, resulting in the development of larger and more powerful cold-water currents. Originally, geologists thought that the separation between the tip of South America and the Antarctic Peninsula did not occur until the end of the Oligocene, but recent evidence has suggested that this passage also opened in the Early Oligocene. This implies that the entire Circum-Antarctic current developed in a relatively short period of geological time.

In addition to these important currents, it is also thought that another body of water, the North Atlantic Deep Water, which flows out of the Arctic Ocean past Greenland into the bottom of the North Atlantic, originated some time in the Oligocene. Thus, the global 'icehouse' conditions of the Oligocene can be largely attributed to the development of modern oceanic stratification and circulation patterns.

It has been suggested that a decline in greenhouse gases – especially CO_2 – might be a more important factor than the effects of oceanic circulation changes in steepening Oligocene climatic gradients. This interpretation is based on global circulation models of the atmosphere and oceans, coupled with simulation experiments in which the amount of atmospheric CO_2 was varied in the computer models. Certainly, there must have been a decline in CO_2 from the greenhouse world of the Cretaceous through Early Eocene to the icehouse of the Oligocene. But important questions have not yet been answered. Where is the global reservoir for all this carbon? There were no great bodies of unoxidized carbon locked up in coal deposits such as the one that terminated the Mid-Paleozoic greenhouse. Nor are there extensive Oligocene carbonates that might have locked up atmospheric CO_2. Those who favour this hypothesis suggest that the carbon was locked up in frozen methane hydrates on the sea-floor. Since the evidence of this frozen hydrate might not be preserved in the stratigraphical record, it is difficult to test this idea directly. Several other empirical studies also contradict this computer model. Chemical analyses of foraminifera suggests that Eocene CO_2 concentrations were not much higher than they are today. The number of stomata on the bottom of a leaf is strongly correlated with atmospheric CO_2 concentration, and it is observed that there is no evidence of higher CO_2 levels in Eocene leaf data. It has been argued that methane (CH_4), rather than CO_2, might have been the greenhouse gas responsible for Eocene warming. Given the clear evidence of oceanic circulation changes directly tied to sedimentological changes on Antarctica, and isotopic changes in the oceanic waters, there must have been a significant effect from the opening oceanic gateways and circulation changes.

The effects of these oceanic temperature changes are critical, not only to marine climates and organisms, but also to terrestrial climates as well. The most complete land-based record comes from North America, where palaeobotanical records show that mean annual terrestrial temperatures dropped 7–11°C in the earliest Oligocene. This is true of palaeofloral records all the way from Alaska and the Pacific North-west to the Gulf Coast. In addition to this rapid cooling, the record of ancient plants and soils also suggests that the continent underwent significant drying, with the establishment of much more seasonal, drought-prone climates. In the Big Badlands of South Dakota, Upper Eocene palaeosols (*see* **Soils:** Palaeosols) suggest over a metre of annual rainfall, supporting a dense forest. By contrast, in the Early Oligocene, mean annual rainfall was less than half a metre, and the vegetation was patchy scrubland with limited riparian forests. The land snails from the Badlands also change, from Late Eocene forms like those found today in tropical Central America, to Early Oligocene forms that are smaller and more drought-tolerant, and found today in Baja, California. In addition, the Late Eocene reptilian fauna that was dominated by crocodilians and pond turtles was replaced by dry land tortoises in the Early Oligocene.

Once the Early Oligocene climatic deterioration was completed, the Earth remained in this icehouse mode through the remainder of the Oligocene. The other significant Oligocene climatic event was several pulses of glaciation that occurred during the middle part of the Oligocene, about 30 Ma (the Oi2 event). Thick, extensive Mid-Oligocene glacial deposits are found throughout the Antarctic region, and benthic foraminiferal oxygen isotopes shifted by 1.6 per mil, suggesting another increase in ice volume and drop in global temperatures (**Figure 2**). As these ice-sheets grew, they pulled water out of the oceans, resulting in the largest drop in sea-level in the past 100 million years. Originally, it was suggested that sea-level dropped by almost 150 m, although more recent estimates suggest it was only half that amount (**Figure 2**). Whatever its magnitude, the Mid-Oligocene regression had a major effect on the shallow-marine realm, causing the continental shelves to become deeply incised once they were exposed to the subaerial erosion, and producing huge Mid-Oligocene unconformities in most marine rocks around the world.

The effect of the cooling and regression in the Middle Oligocene on land climates was less obvious. Sensitive tropical floral elements were already gone by the Mid-Oligocene, so the land plant record shows only minor cooling effects. The record of ancient soils from the Big Badlands of South Dakota shows that the climate became cooler and much drier, so that sand dune deposits became common in the Mid-west in the late Oligocene. These same soils suggest that vegetation was a mixture of scrublands and grasses, with few trees, by the Late Oligocene.

Oligocene Life

As the Eocene–Oligocene climatic deterioration began, the total diversity of land animals and both marine organisms decreased significantly from Eocene levels, reaching a Phanerozoic low in the Late Oligocene. The forests and jungles of the Early

Eocene were rapidly disappearing by the Late Eocene, so that by the Oligocene most of the temperate latitudes were covered by a mixture of forest and scrubland vegetation. This change in vegetation triggered by this cooling and drying was a major change in many of the land organisms. The Oligocene land-mammal fauna was dominated by primitive members of most living families. These included three-toed horses (which began to radiate into multiple lineages by the Late Oligocene), three different lineages of rhinoceroses, early camels, deer, and peccaries, as well as a handful of archaic land-mammal groups left over from the Eocene. Numerous modern carnivoran groups (especially early dogs, and the cat-like nimravids, as well as primitive members of the bear, weasel, and raccoon families) became the dominant predators as the last of the archaic carnivorous mammals (*see* **Fossil Vertebrates:** Placental Mammals), the creodonts, straggled on. On all the northern continents and Africa, rodents and rabbits both underwent a huge diversification as the niches for ground-dwelling seed-eaters 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 rhinoceroses and ruminants) to immigrate to Europe and drive many of the endemic natives to extinction. This Early Oligocene event is known as the Grande Coupure. However, there was only limited migration between Asia and North America via the Bering Strait. In Eurasia, the Oligocene saw a similar diversification of rhinoceroses (including one group, the giant indricotheres found in Mongolia and Pakistan, which reached 6 m at the shoulder and weighed 20 tonnes), plus some of the earliest members of the deer, giraffe, pig, and cattle families. Tree-dwelling mammals became much less common and vanished from many continents. For example, primates once flourished on all the northern continents during the Early and Middle Eocene. By the Oligocene, though, they became restricted to Africa and South America, where they evolved into Old World and New World monkeys, respectively. The remainder of the African fauna was also endemic to this island continent, which was not connected to Eurasia at the Arabian Peninsula until the Early Miocene. Instead, the African fauna was populated by archaic mastodonts, a wide diversity of hyraxes, and other peculiar endemic forms, such as the horned arsinoitheres. South America and Australia were also island continents, unconnected to the rest of the world, and each developed their own endemic faunas.

In the marine realm, the Early Oligocene extinctions triggered by global cooling were severe, causing major extinction in the planktonic and benthic foraminifera, and even in the planktonic algae (*see* **Fossil Plants:** Calcareous Algae) such as diatoms and coccolithophores. In the Gulf Coast of the US, 97% of the marine snail species and 89% of the clam species found in the Late Eocene did not survive into the late Early Oligocene, and over 50% of the sea urchins and sand dollars also became extinct. However, the overall taxonomic composition of the marine fauna remained essentially the same, with new species of clams, snails, and sea urchins replacing the extinct species (but at lower diversity), and making up the bulk of the fossilisable organisms in the Oligocene. By the end of the Early Oligocene, diversity was at an all-time low. Marine faunas were composed of groups tolerant of the cooler waters that began in the Oligocene. This is true especially in the molluscs (*see* **Fossil Invertebrates:** Molluscs Overview) of the Pacific Rim, which are mostly cold-water tolerant forms that migrated south to California from Alaska and Siberia during the Oligocene. Planktonic organisms were not only low in diversity, but occupied relatively few, simple biogeographic realms (since the area of the tropics had decreased), and evolved relatively slowly during the Oligocene.

Palaeogeography

With the Eocene separation of Australia from Antarctica and the collision of India with Asia, by the Oligocene most of the continents were approaching their present configuration. South America, however, would not finally separate from Antarctica until the beginning of the Oligocene, completing the breakup of Gondwana and opening the gateway for the full development of the Circum-Antarctic current. As discussed above, these continental movements brought about major changes in oceanic circulation, with the Circum-Antarctic current locking in cold conditions over Antarctica, initiating the first Antarctic ice-sheets, and also stimulating the flow of cold Antarctic bottom waters, which today control much of the world's 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 locked up in ice. The Late Oligocene regression turned the drowned coastal plains of the Atlantic and Gulf coast of North America into 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 biota.

On land, the Himalayas continued to develop, and the Alps began to rise rapidly as Africa began to collide with Europe and close the Mediterranean. The Andes began to erupt huge volumes of volcanic rocks, forming a mountain chain for the first time. In North America, the Rocky Mountains were no longer rising, but they continued to soar high above the western part of North America. The basins between the ranges began to fill up with sediments and volcanic debris erupted from the arc volcanoes to the west. Volcanic activity on the western edge of the continent, which had ceased when the Laramide Orogeny shut off the Sierran-Sevier arc, resumed in the Oligocene. The new arc was much further east than the previous arc, running in an irregular belt from central Mexico to New Mexico (the Mogollon-Datil volcanics) to south-west Colorado (the San Juan volcanics), Utah, and Nevada, and then up through Oregon and Washington (the ancestral Cascades), and British Columbia. These explosive volcanic centres erupted huge amounts of ash, much of which blew east and helped bury the Laramide uplifts of the Rocky Mountains. Much of this ash and sediment also spilled over onto the High Plains, forming the thick Oligocene deposits of the White River and Arikaree Groups (entombing their excellent record of fossils (*see* **Fossil Invertebrates:** Echinoderms (Other Than Echinoids)) and climates (*see* **Palaeoclimates**) in the Big Badlands of South Dakota and adjacent states. At about 30 Ma, the corner of the Pacific Plate was subducted under California, so the San Andreas transform fault began its activity. This, in turn, set off a wide variety of geologic events, including the beginning of the spreading of the Basin and Range Province in Arizona, Utah, and Nevada; the end of the eruptions in Nevada and California; the clockwise rotation of the Sierra-Cascade arc to the south-west by over 400 km; and the clockwise rotation of many tectonic blocks, including the Transverse Ranges of California. By the Miocene, all of these regional events (Basin and Range extension, Sierran rotation; cessation of southern volcanism; and Transverse Ranges rotation) were well developed and approaching their modern condition.

See Also

Famous Geologists: Lyell. **Fossil Invertebrates:** Echinoderms (Other Than Echinoids); Molluscs Overview. **Fossil Plants:** Calcareous Algae. **Fossil Vertebrates:** Jawless Fish-Like Vertebrates; Placental Mammals. **Palaeoclimates**. **Plate Tectonics**. **Soils:** Palaeosols. **Tertiary To Present:** Eocene.

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Miocene

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Introduction

The Miocene (23.8–5.3 Ma) is the interval during which the world began to assume much of the configuration and topography we know today. Major tectonic changes in North America uplifted the Coast Ranges, formed the Basin and Range, and saw the evolution of the San Andreas Fault Zone. In Eurasia, the ongoing collision of India and Asia elevated the Tibetan Plateau, drastically altering global atmospheric circulation patterns. In South America, global atmospheric and oceanic circulation were greatly affected by the uplift of the Andes and the closure of the Panamanian seaway, in ways that persist to this day. The Miocene separation of Australia and Antarctica altered oceanic circulation patterns, changing the prevailing currents off Europe. In Africa, the development of the Great Rift Valley formed the environments that were home to the early hominids (*see* **Fossil Vertebrates:** Hominids). Much of the flora and fauna of the Miocene belong to groups that are still living today, but several groups experienced large radiations during this time interval, such as the whales and the snakes. Two major ecosystems – grasslands and kelp forests – evolved during the Miocene. These changes form the foundation for modern conditions.

The Miocene Epoch is the fourth subdivision of the Tertiary Period. In 1828, Sir Charles Lyell (*see* **Famous Geologists:** Lyell) noticed that different layers of rock in Europe contained different proportions of living and extinct species of marine molluscs. Concluding that the variation in this proportion indicated that the rock layers were formed at differing times, and assuming that the higher the proportion of living to extinct species, the more recently the layer was laid down, he defined three epochs – the Eocene (Dawn Recent), Miocene (Middle Recent), and Pliocene (More Recent), where the transitions between epochs were specified as a given percentage of living to extinct species.

Because the species composition of a rock layer can vary depending on the type of depositional environment, geologists no longer use this definition, and rely on other methods. Two specific, internationally recognized localities (also known as stratotypes) are currently designated as being the boundaries of the Miocene for international correlation. The base, or start, of the Miocene is defined at the Lemme Carrosio section in the upper part of the Rigoroso Formation in northern Italy. The base of the Pliocene – which is also, by definition, the end of the Miocene – is defined at the base of the Trubi Formation in the Evaclea Minoa section, on the southern coast of Sicily (*see* **Tertiary To Present:** Pliocene).

Geochronology

The European Miocene is generally divided into six marine stages (oldest to youngest): the Aquitanian, Burdigalian, Langhian, Serravallian, Tortonian, and Messinian (**Figure 1**). Terrestrial fossils in Europe have generally been associated with these marine stages as European marine rocks interfinger with terrestrial deposits, thus allowing a clear correlation between terrestrial and marine units. However, a number of more isolated fissure-fill localities are more difficult to correlate. As a result, two other systems based exclusively on terrestrial mammals have been developed, the European Land Mammal Ages (ELMAs) and the Mammalian Neogene Reference Level system (MN Zones).

In North America, there are fewer localities with interfingered marine and non-marine beds, but many units are associated with strata that can be radioisotopically dated. The majority of these deposits are correlated using mammalian biostratigraphic units. The North American Land Mammal Ages in use for the Miocene include the Arikareean, Hemingfordian, Barstovian, Clarendonian, and the Hemphillian. Most of these are well associated with radioisotopic dates and/or paleomagnetic assessments.