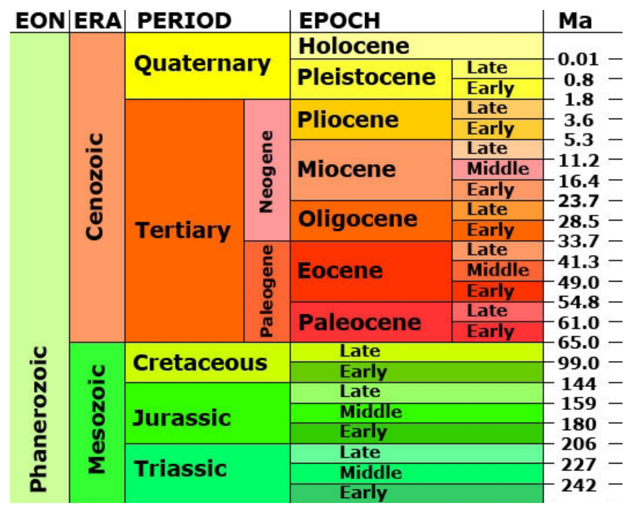
Paleoclimate: The Tertiary Period

THE CRETACEOUS/TERTIARY BOUNDARY

About 65 million years ago (considered the boundary between the Cretaceous and Tertiary periods, abbreviated KBT), a large asteroid slammed into what is today the Yucatan Peninsula. This caused an explosion so large that debris and sulfate aerosols were injected into the upper atmosphere and the terrestrial carbon around the impact crater was incinerated into atmospheric carbon. At first, global cooling occurred as the dust that "seeded" the upper atmosphere blocked out the sun, decreasing plant growth and causing many extinctions. As the dust settled, land plants started photosynthesizing again. Earth's terrestrial net primary production appears to have recovered within a decade, and terrestrial carbon storage recovered within a century. During the Cretaceous, Earth's average temperature was 68 degrees Fahrenheit, about nine degrees warmer than today, and atmospheric carbon dioxide (CO_2) levels were around 580 parts per million (compared to about 390 parts per million today). The high latitudes were significantly warmer and forests extended all the way to the poles, covering most of Antarctica.



Above: The Mesozoic and Cenozoic divisions of geologic time. Image courtesy of USGS: http://3dparks.wr.usgs.gov/coloradoplateau/timescale.htm

The high levels of atmospheric CO_2 (at least 2,300 parts per million) that were produced by the impact, however, caused Earth's temperature to rise an additional 13.5 degrees Fahrenheit over a period of centuries to millennia, further stressing ecosystems that were recovering from the sunlight block. The ocean stratification that the extreme high temperatures caused limited the amount of nutrient rich water coming up from the depths, devastating ocean ecosystems. These ecosystems took about three million years to recover, meaning that whole new species had to evolve to establish the biodiversity necessary to fill the ecological "niches" which promote ecosystem stability. This "delay" in recovery worked to perpetuate the extreme CO_2 levels; photosynthetic organisms at the ocean's surface take carbon out of the atmosphere, and eventually die and fall to the ocean bottom, which works to "capture" carbon. As the ocean ecosystems recovered and carbon levels fell, the temperature fell as well, although it did remain significantly hotter than today. The recent discovery of the fossilized remains of a 40 foot long snake indicate that average annual temperature in the tropics 60-58 million years ago was at least 91 degrees Fahrenheit, compared with 81 degrees today. Cool temperatures limit the maximum size that cold-blooded animals, such as snakes, can reach.

THE PALEOCENE/EOCENE THERMAL MAXIMUM

About 55.5 million years ago, after the Earth's ecosystems had recovered from the KBT asteroid collision, tectonic activity on continental margins caused the release of methane that had been stored in sediment for millions of years. As this methane was released (about 1.5 Gigatons worth, or 1.5 billion tons, over a period of 500-20,000 years; enough to raise atmospheric CO_2 levels to around 1000 parts per million), the high latitides warmed by about 10 degrees Fahrenheit and the tropics by about three degrees. Some of the climate nuances during this particularly warm time (known as the Paleocene-Eocene Thermal Maximum, or PETM, which lasted 100,000 years) include:

- Significantly "wetter" high latitudes, due at least in part to a poleward shift in the midlatitude storm tracks.
- Increased terrestrial methane cycling, due to the intensification in the global hydrologic cycle and an increase in the amount of methane-releasing wetlands, suggesting a positive feedback cycle between the original methane release and continuing methane production.

- A 40,000 year interruption in the ocean thermohaline circulation, or the system of currents driven by local differences in temperature and salinity, which, among other things, bring warm air masses to higher latitudes.
- A marked increase in the number and intensity of “extreme” rainfall events. Analysis of contemporary geologic strata indicate an increase in the number of “megafans,” river deltas with especially high sediment concentrations, suggesting increased land erosion. This phenomenon was pronounced in both coastal environments (modern day Spain, New Zealand, California and New Jersey) and continental interiors (modern day South Dakota). This increase in weathering increased the amount of carbon sequestered, which served as a negative feedback loop that sped the “recovery period,” when CO_2 declined.
- An increase in the photosynthetic activity in the Arctic Ocean, and a corresponding increase in the amount of carbon sequestered in the oceanic sediments that formed there.
- A covering of South America’s midlatitudes with tropical rainforests, which today only extend to about 15 degrees south in the perennial wet western Amazon (about the same latitude as La Paz, Bolivia).

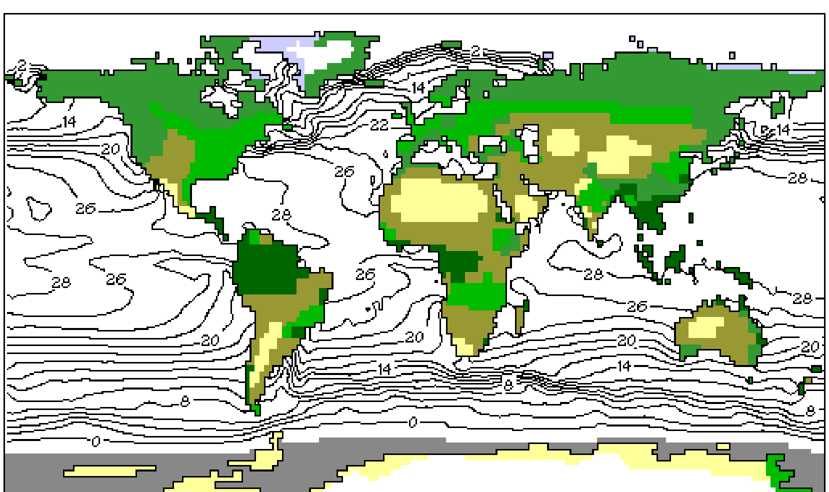
This process of increased carbon sequestration worked to gradually decrease the atmospheric carbon and Earth’s temperature until the Eocene-Oligocene boundary.

THE OLIGOCENE ONWARD

While the KBT and the PETM events have both been linked to disturbances that caused significant extinctions (the PETM to a much lesser extent), the transition from the “Greenhouse” or “Hot House” world of the Eocene to the cooler world of the Oligocene does not appear to have had this effect. The gradual cooling throughout the Eocene allowed the organisms that constituted Earth’s ecosystems to evolve along with the temperature trend. The two biggest stories of the Oligocene were the transition of the central parts of the continents from moist forests to more arid climates, particularly in North America, and the birth of the Antarctic ice sheets, which occurred during a 400,000 year glacial period that marked the beginning of the epoch. The growth of this ice sheet caused average Oligocene global sea level to be about 180 feet lower than mean Eocene values. Another glacial period marked the transition from the Oligocene to the Miocene, despite the fact that the Miocene was significantly warmer than the Oligocene. The warm period from the late Oligocene onward lasted until about 14 million years ago, after which temperatures steadily declined for the rest of the Tertiary.

Two Tertiary tectonic events proved to have major implications for Earth’s climate. First, around six million years ago, the Panama Seaway closed, separating the Pacific and Atlantic Oceans. This increased the salinity contrast between the two oceans, which worked to strengthen the thermohaline circulation that brings warm waters and moist air masses to the higher latitudes. Second, the uplifts of the Himalayan and Rocky Mountains caused greater “meandering” of the jet stream and the midlatitude storm tracks that bring moisture to the far north (i.e. before the mountains were born, storm tracks would not go too far north or too far south).

The increased moisture transport to the high latitudes as a result of the strengthening of the thermohaline circulation and more storm track meandering allowed for the continued “greening” of the higher latitudes, as well as the growth of the Greenland and Antarctic ice sheets. More high latitude vegetation, combined with the general stabilization of Earth’s ecosystems, led to a steady decline in CO_2. These lower atmospheric CO_2 levels worked to amplify Earth’s response to orbital cycles, and this amplification made possible the extensive glaciation events that characterized the next period, the Quaternary.



Pliocene vegetation distributions and August sea surface temperature isotherms (in Celsius). Note the extent of the boreal forests (dark green) all the way to the Arctic. Image courtesy of USGS: http://pubs.usgs.gov/of/1999/of99-535/

Sources:

Beerling, DJ et al. "An atmospheric pCO_2 reconstruction across the Cretaceous-Tertiary boundary from leaf megafossils." PNAS 99 (2002): 7836-7840.

Bornemann, A et al. "Isotopic Evidence for Glaciation During the Cretaceous Supergreenhouse." Science 319 (2008): 189-192.

Bowen, GJ et al. "A humid climate state during the Palaeocene/Eocene thermal maximum." Nature 432 (2004): 495-499.

Clenchenko, ER et al. "Terrestrial records of a regional weathering profile at the Paleocene-Eocene boundary in the Williston Basin of North Dakota." GSA Bulletin 119 (2007): 428-442.

Dowsett, H. "Bracketing Mid-Pliocene Sea Surface Temperature: Maximum and Minimum Possible Warming." USGS (2004): Data Series 14, Version 1.0 <http://pubs.usgs.gov/ds/2004/114/ds114.pdf>

Evanoff, E.. "Stratigraphy and Climatic Significance of the White River Group, Badlands National Park, South Dakota." Paper no. 77-3. 2006 Philadelphia Annual Meeting: Geological Society of America. <http://gsa.confex.com/gsa/2006AM/finalprogram/abstract_113761.htm>

Hinojosa, LF. "Tertiary Climate and Vegetation of Southern South America." Paper no. 16-8. 2003 Seattle Annual Meeting: Geological Society of America. <http://gsa.confex.com/gsa/2003AM/finalprogram/abstract_67707.htm>

Huber, M. "Snakes tell a torrid tale." Nature 457 (2009): 669-671.

John, CM et al. "North American continental margin records of the Paleocene-Eocene thermal maximum: Implications for global carbon and hydrological cycling." Paleoceanography 23 (2008): PA2217.

Kelly, DC et al. "Enhanced terrestrial weathering/runoff and surface ocean carbonate production during the recovery stages of the Paleocene-Eocene thermal maximum." Paleoceanography 20 (2005): PA4023.

Knies, J et al. "Surface water productivity and paleoceanographic implications in the Cenozoic Arctic Ocean." Paleoceanography 23 (2008): PA1S16.

Lomax, BH et al. "Terrestrial ecosystem responses to global environmental change across the Cretaceous-Tertiary boundary." Geophysical Research Letters 27 (2000): 2149-2152.

Lomax, B et al. "Rapid (10-yr) recovery of terrestrial productivity in a simulation study of the terminal Cretaceous impact event." 192 (2001): 137-144.

Lunt, DJ et al. "Late Pliocene Greenland glaciation controlled by a decline in atmospheric CO_2 levels." Nature 454 (2008): 1102-1106.

Miller, KG et al. "Eocene-Oligocene global climate and sea-level changes: St. Stephens Quarry, Alabama." GSA Bulletin 120 (2008): 34-53.

Nicolo, MJ et al. "Multiple early Eocene hyperthermals: Their sedimentary expression on the New Zealand continental margin and in the deep sea." Geology 35 (2007): 699-702.

Nunes, F and Norris RD. "Abrupt reversal in ocean overturning during the Palaeocene/Eocene warm period." Nature 439 (2006): 60-63.

Otto-Bliesner, BL and Upchurch Jr., GR. "Vegetation-induced warming of high-latitude regions during the Late Cretaceous period." Nature 385 (1997): 804-807.

Pagani, M et al. "Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum." Nature 442 (2006): 671-675.

Pancost, RD. "Increased terrestrial methane cycling at the Palaeocene-Eocene thermal maximum." Nature 449 (2007): 332-336.

Rea, D. "The Paleoclimatic Record Provided by Eolian Deposition in the Deep Sea: The Geologic History of Wind." Review of Geophysics 32 (1994): 159-195.

Schmidt, GA and Shindell, DT. "Atmospheric composition, radiative forcing, and climate change as a consequence of a massive methane release from gas hydrates." Paleoceanography 18 (2003): 1004.

Schmitz, B and Pujalte, V. "Abrupt increase in seasonal extreme precipitation at the Paleocene-Eocene boundary." Geology 35 (2007): 215-128.

Terry Jr., DO. "Paleoclimate Change Across the Terrestrial Eocene-Oligocene Boundary of the Northern Great Plains: The Paleosol Perspective." Paper no. 77-4. 2006 Philadelphia Annual Meeting: Geological Society of America. <http://gsa.confex.com/gsa/2006AM/finalprogram/abstract_116245.htm>

Wade, BS and Pälike, H. "Oligocene climate dynamics." Paleoceanography 19 (2004): PA4019.

Zachos, J et al. "Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present." Science 292 (2001): 686-693.

Zeigler, CL and Murray, RW. "Geochemical evolution of the central Pacific Ocean over the past 56 Myr." Paleooceanography 22 (2007): PA2203.