CHAPTER 15

Paleoclimate of Florida

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We present our understanding of Florida's paleoclimate for the past ~50 million years (Myr). The paleoclimate of the Florida Platform is closely linked to global paleoclimate. Global climate change over the past 50 Myr is a record of declining atmospheric carbon dioxide, decreasing temperature, and progressive addition of ice sheets. The overall global climate narrative is one of transition from a greenhouse Earth (warm temperatures with higher sea levels) to an icehouse Earth (colder temperatures with lower sea levels). The early 21st century has been a period of extreme climate conditions in Florida, in that we have already seen very low lake levels, including complete drying of some water bodies for the first time in recorded history. Such complete drying was never reported previously and suggests that we have entered a new climate regime in this millennium.

Key Messages

- The peninsular morphology of Florida, created during the near-simultaneous tectonic opening of the Gulf of Mexico, Caribbean Sea, and western North Atlantic Ocean starting ~200 million years ago has always played a fundamental role in Florida's climate. When a large fraction of the peninsular land mass was exposed during sea level lowstands, huge thunderstorms formed thus defining a unique component of Florida's climate.
- The topographically low and flat morphology of the Florida Platform has also allowed climate-driven sea level changes to leave a robust stratigraphic record. From these rocks and sediments the paleoceanography and, to a lesser extent, the paleoclimate of the Florida Platform has been reconstructed.
- Over the past 50 Myr the climate of the Florida Platform followed the global climate change of declining atmospheric carbon dioxide (CO_2) and cooling, i.e., a transition from a greenhouse (warm) to an icehouse (cooler with cyclical glaciations and deglaciations) Earth. There were three major warming events that occurred during this prolonged cooling that impacted Florida's paleoclimate.
- Pleistocene data reveal a terrestrial climate comparable to the modern climate, with evidence of cool climate episodes that may have been influenced by regional upwelling of cold marine waters. As climate in Florida warmed after the Last Glacial Maximum and early Holocene (~18–~11.7 ka), there were profound consequences for Florida's terrestrial environment, as vast areas that had served as habitat for Pleistocene land plants and animals, some now extinct (e.g., mammoths, horses, giant sloths, tapirs), were inundated by rising seawater.
- Shortly after the onset of the Holocene Epoch (11.7 ka), rainfall increased contributing to rising groundwater tables and initial filling of Florida's more than 8,000 shallow lakes.

Keywords

Paleoclimate; Florida Platform; Sea level; Basement rocks; Carbonate rocks; Greenhouse Earth; Icehouse Earth; Milankovitch cycles; Quartz; Phosphate; Pollen; Geologic age; Biotic assemblages

Introduction

Inferring Paleoclimate from the Geologic Record

Climate can be broadly characterized by temperature and precipitation, and fluctuations in these two variables throughout Earth history are referred to as paleoclimate change. Although factors that influence climate are enormously complex, geoscientists know that Earth's climate has displayed extremes in temperature and precipitation over many time scales. Geology is the discipline that studies changes on Earth through time. Therefore, understanding paleoclimate variations relies on interpretation of the rocks and sediments left behind. That is what we have to work with to decipher the past.

One challenge for geologists is determining the age of sediments or rocks, which in turn enables us to calculate the timing and rate of key events in the past. The age and sequence of events helps elucidate Earth processes such as sea level change, mountain building, biological extinctions, continental breakup, etc. A fundamental tool in geological studies is the Geologic Time Scale. Specific time intervals (Eons, Eras, Periods, Epochs) are defined by terms such as Precambrian, Paleozoic, Jurassic, Eocene, and represent durations of billions, millions, or thousands of years. Discussion of the Earth's geologic past requires use of these terms even when "absolute" time, e.g. 50 million years ago, is presented. We provide The Geological Society of America Geologic Time Scale in Figure 15.1 for the readers' use.

Rather than referring to Eons, Eras, Periods, or Epochs, a variety of quantitative dating methods has been developed based on sound scientific principles to determine absolute geologic age (number of years in the past). They include use of the natural radioactivity in rocks as a clock (radiometric age dating), the magnetic properties of rocks (paleomagnetic properties such as polarity reversals), the isotopic composition of rocks (isotope geochemistry), and biological evolution of microfossils in rocks (biostratigraphy). As new techniques are developed and tested, the absolute age boundaries of the Eons, Eras, Periods and Epochs are refined, and events such as the massive meteor impact that created Yucatan's Chicxulub Crater in southeast Mexico can be dated more accurately and precisely. It is now determined to have struck Earth close to 66 Ma, perhaps within 100 kyr of that time. More accurate and precise age dating of Earth's past events are an essential, ongoing line of research.

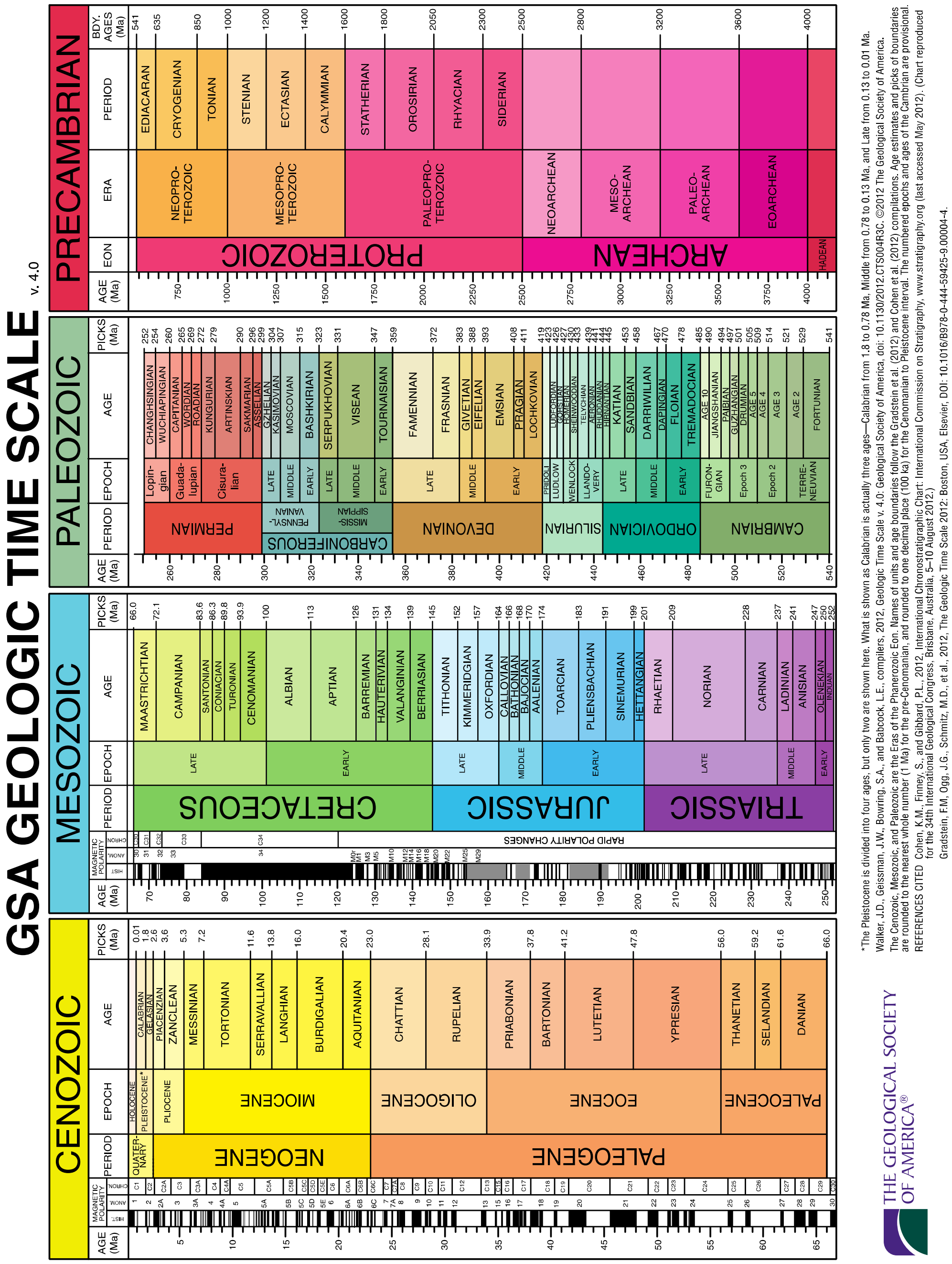

Figure 15.1. Geological Society of America Geologic Time Scale (2012, most recent version from GSA; Walker et al. 2013). Herein, **Ga** means a billion (1,000,000,000) years ago. **Ma** means a million (1,000,000) years ago (i.e., 100 **Ma** refers to something that happened 100,000,000 years ago; **ka** means a thousand (1,000) years ago; Additionally, **Gyr, Myr,** and **kyr**, express *geological duration*, i.e., an event lasted 10 **Myr** or the event's duration was 10 million years (10,000,000 years) long (Christie-Blick 2012).

A third challenge in reconstructing Florida's paleoclimate after age determination and gaps in the rock record is that Florida's sedimentary geological formations, which date back to 50 Ma, formed largely underwater. These rocks reflect ocean behavior and not rainfall or paleo-temperature of the atmosphere per se. Thus, most of the Florida Platform's rock and sediment formations only generally and indirectly preserve information about Florida's paleoclimate. The rock and sediment formations (called lithologic units) were emplaced as a result of global rise and fall of sea level. In particular, during warm climate intervals, which are associated with high sea level, carbonate sediments derived from corals, shell-bearing organisms such as mollusks, and mud from algae, were deposited in shallow seas that covered the Florida Platform. Because Florida's land elevation is so close to sea level, vertical fluctuations cause widespread land inundation (sea level highstands) or exposure of land to the atmosphere (sea level lowstands). Even though marine sedimentary rocks are not direct paleoclimate indicators, they can serve as important indirect indicators of paleoclimate. For instance, warm sea surface temperature is linked to warm air temperature and evidence for regional salinity decreases can be caused by increased freshwater runoff, potentially indicating higher rainfall.

During sea level lowstands, direct paleoclimate indicators such as tree pollen are buried in inland lake sediments and a stratigraphic study of pollen grains can be used to infer paleoclimate. But these non-marine sedimentary deposits in Florida are often thin and discontinuous. Also, oxidation and erosion of these sediment units during exposure to the atmosphere can remove and alter them, rendering paleoclimate reconstructions even more challenging.

Before we examine Florida's paleoclimate, we must answer a fundamental question—What is Florida? Florida is much more than the political boundaries and coastline that define the state of Florida. The entire Florida Platform extends well beyond the state of Florida's borders (Figs. 15.2 and 15.3) and is structurally bounded by faults created during the near-simultaneous tectonic opening of the Gulf of Mexico, Caribbean Sea, and western North Atlantic Ocean. The creation of these ocean basins resulted from the tectonic breakup of the mega-continent Pangea, which began ~200 Ma (Figs. 15.4, 15.5). So any study of Florida's geological history, including its paleoclimate, must consider the present-day, submerged portions (modern continental shelves and slopes), as well as the emerged areas, which we know of as the state of Florida.

The submerged portions of the Florida Platform are difficult to reach because of their large area and the depth of the overlying coastal ocean. Therefore, we are restricted to the rocks and sediments that are easily accessed, i.e., those rock and sediment formations exposed on land, which extend back ~50 Myr. These 50-Ma and younger sedimentary rocks and sediments can be studied more comprehensively than small rock samples retrieved from a few deep drill sites. This accessible rock record is revealed on the geologic map of Florida (See Florida Geological Survey). For these reasons we begin our narrative of Florida's paleoclimate at that point in time, 50 Ma.

We will follow a simple strategy of first presenting the global climate record and then discussing how the Florida Platform has responded to these global climate changes. As with practically all geologic studies that cover vast amounts of time, the more recent events (hundreds to tens of thousands of years ago) are better represented in the rock record and provide much more detail than events that occurred hundreds or even tens of millions of years ago.

First, however, we present a brief look at the Florida Platform's geologic history in deep time (hundreds of millions of years ago). We do this to set the stage for our examination of the last 50 Myr of the Florida Platform's paleoclimate.

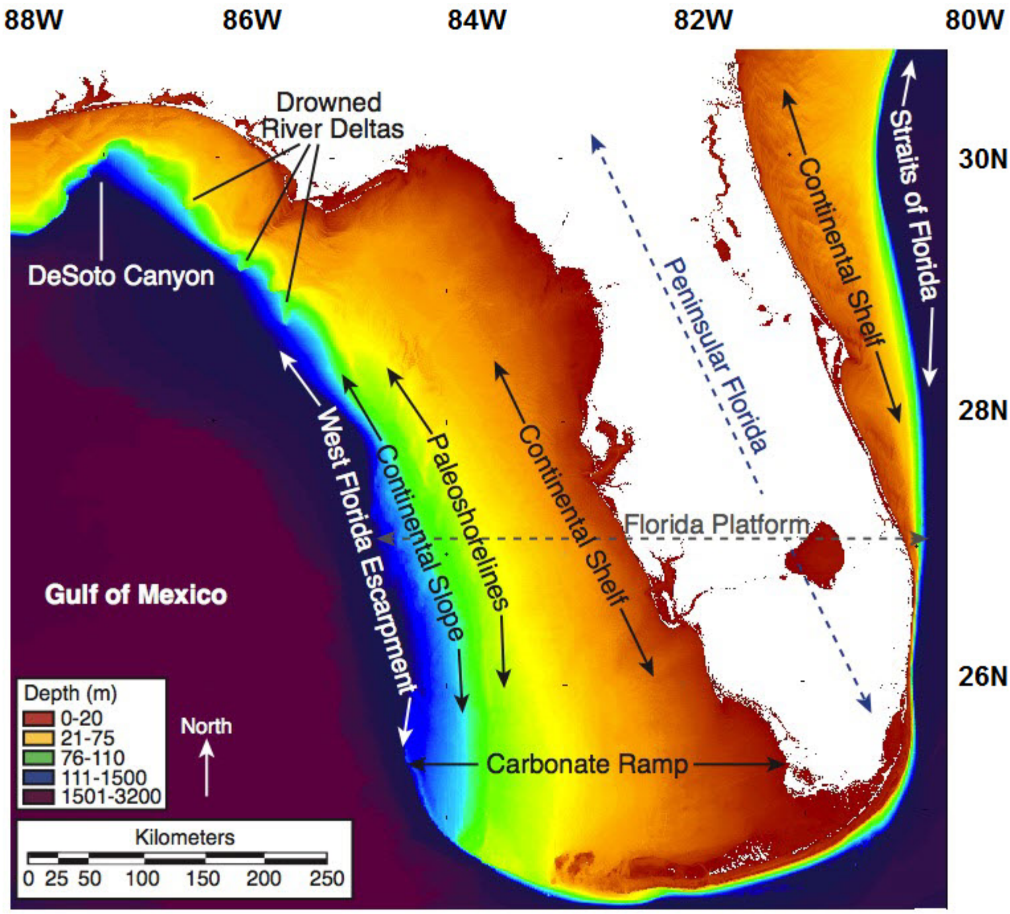

Figure 15.2. Exposed and submerged portions of the Florida Platform. Geologists consider the Florida Platform to be a single entity that includes the emerged state of Florida, as well as the vast area that today lies under water. The size of the exposed portion of the Platform changed dramatically over geologic time as sea level rose and fell (from Hine 2013; *Geologic History of Florida: Major Events That Formed the Sunshine State* by Albert C. Hine. Gainesville: University Press of Florida, 2013. Reprinted by permission; modified from USGS Open File Report 2007-1397; courtesy of Dr. L. Robbins).

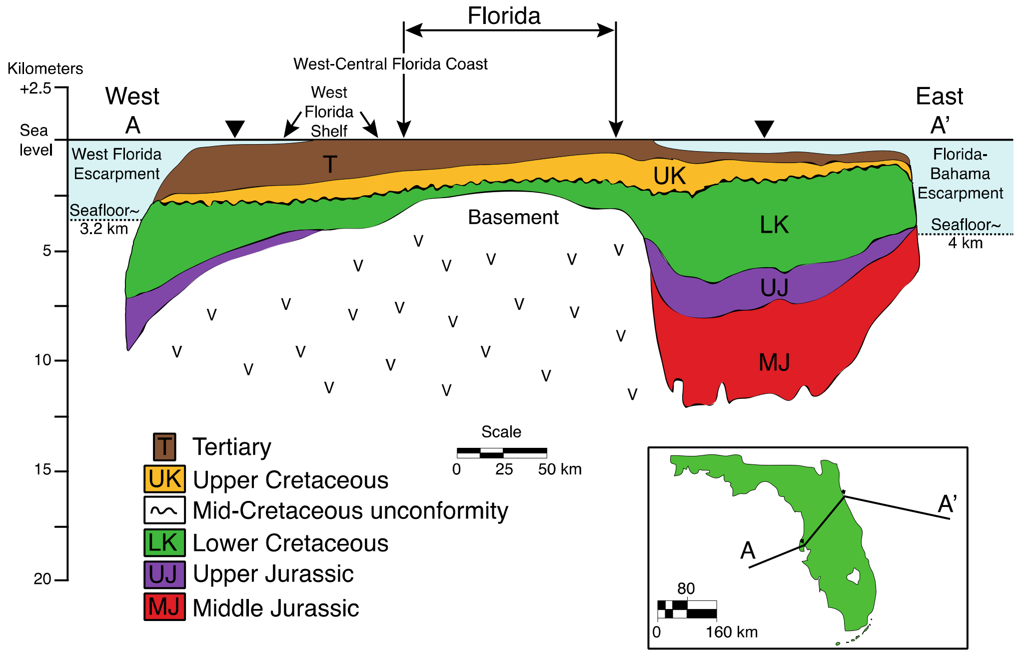

Figure 15.3. West-to-east depth section across the central Florida Platform—part of the even larger Florida-Bahamas Platform. This diagram shows two distinct rock types that underlie the Florida Platform: (1) >500-Ma-old basement rocks (white component marked with "v") overlain by (2) much younger, mostly limestone (marked with colors; MJ, UJ, LK, UK, T). There is a third geologic unit, mostly quartz-rich sand, which overlies the limestone. The sand covers most of the exposed Florida Platform and forms most of our beaches. But this youngest geologic unit is so thin that it cannot be represented in the above figure. It is thinner than the thickness of the black line that represents the top of the Florida Platform. This chapter focuses on the climate inferred from the rock record extending back 50 Ma, i.e., the brown unit labeled "T" (Tertiary and Quaternary; modified from Hine et.al 2003; Hine 2013; *Geologic History of Florida: Major Events That Formed the Sunshine State* by Albert C. Hine. Gainesville: University Press of Florida, 2013. Reprinted by permission.), which is exposed at the surface today.

Long-Term History of the Florida Platform

Seven hundred million years ago, the basement rocks that underlie the Florida Platform were located near the South Pole and were part of a larger continental landmass called Gondwana, which eventually collided over millions of years with another large land mass called Laurasia, forming the megacontinent Pangea in the Paleozoic, from ~350 Ma to ~250 Ma (Hine 2013). Thus, the > 500-Ma-old basement rocks that underlie the present Florida Platform (Fig. 15.3) once formed part of the African and South American continents. Basement rocks are generally crystalline igneous and metamorphic rocks. They form the basic crust of continents and possess very little paleoclimate information that geologists can exploit. The climate at the South Pole ~500 Ma was freezing and the basement rocks were probably covered by a thick ice sheet. Over the next ~500 Myr, these basement rocks migrated northward about 13,000 km (8,150 miles) via plate tectonic processes, traveled through the tropics, crossed the Equator and arrived at their present location ~200 Ma (Fig. 15.5).

The Paleozoic sedimentary rock on top of the Platform's basement rocks has been eroded or is deeply buried, and has been rarely sampled (Klitgord et al 1984; Sheridan et al. 1988; Pindell and Barrett 1990; DeBalko and Buffler 1992; Randazzo and Jones 1997; Redfern 2001). Before the Pangean megacontinent breakup, starting around 200 Ma, Florida's basement rocks were at a mid-continent location, probably thousands of kilometers (1,000 km = 621 miles) from the oceans that existed at that time (Fig. 15.4). Although there is no rock record from that time for study of past climate, we surmise that tropical rain forests probably dominated because the area was at low latitudes.

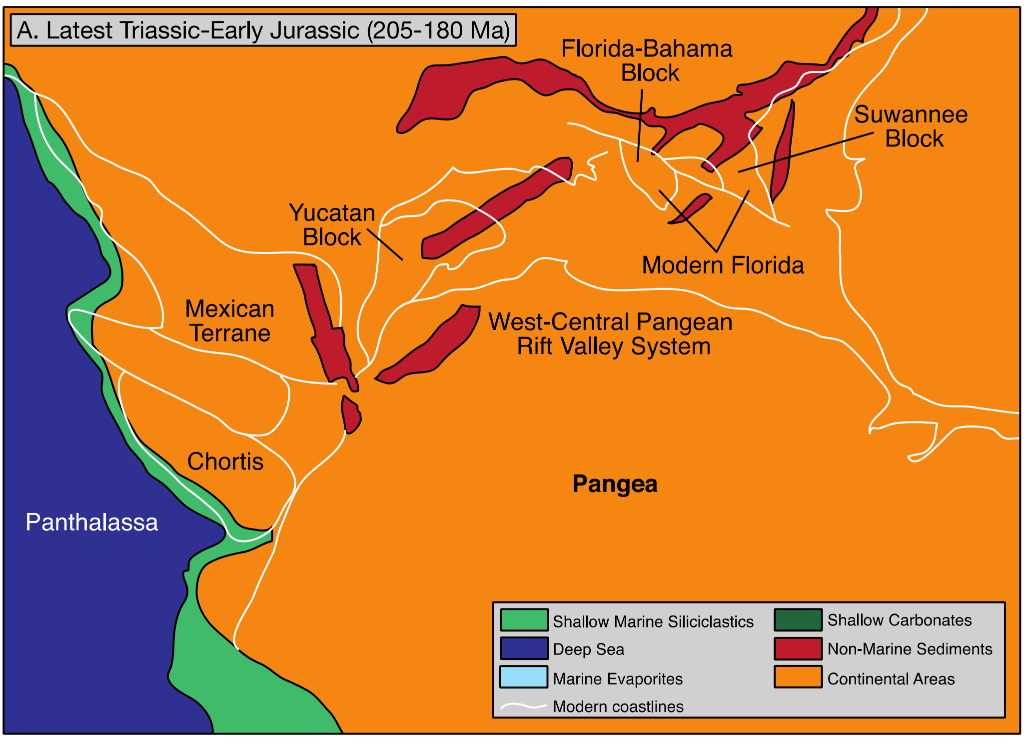

Figure 15.4. Paleogeographic reconstruction of mega-continent Pangea, from 205 to 180 Myr. The Equator runs across the center of the diagram. Note the components of Florida's basement rocks—Florida-Bahama Block and Suwannee Block, which together form the basement rock beneath the modern Florida Platform. The location was far inland, probably >1,000s of km from the global oceans at that time. The terrestrial environment must have been something like the equatorial rain forests we see today in South America and Africa (used by permission from Iturralde-Vinent 2003).

Florida's paleoclimate is unique because the platform became a peninsula during the early breakup of the Pangean megacontinent around 200 Ma and was almost completely surrounded by seawater by 160 Ma (Fig. 15.5). The peninsular morphology of the Florida Platform has fundamentally controlled Florida's climate at times when large areas of land mass were exposed to the atmosphere. Because of its relatively low heat capacity compared to ocean water, land heats up quickly on hot days, forcing air to rise, which brings in warm moist air from above the ocean to both Florida's east and west coasts. These local winds are known today as sea breezes. Rising air over the heated land produces, and has produced for millions of years, thunderstorms that reach great altitudes (>18,000 m ~>59,000 ft). Such storms, which extend high into the atmosphere, capture dust and aerosols that originated on other continents and deposit them on Florida. These seasonal thunderstorms are some of the largest and most intense in the world, thus earning Florida the nickname of the "thunderstorm and lightning capital of the United States." The Florida Platform has probably been influenced by substantial thunderstorm activity since the western North Atlantic Ocean to the east, the Gulf of Mexico to the west, and the Caribbean Sea to the south first formed.

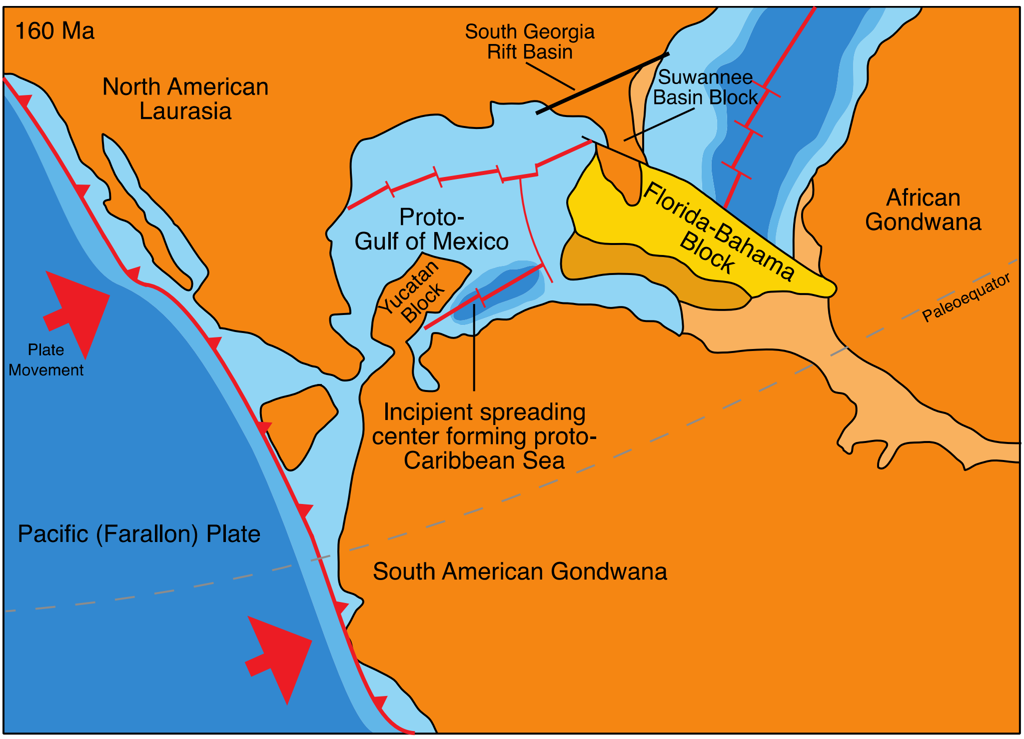

Figure 15.5. Paleogeographic map showing the late-stage breakup of the Pangean megacontinent. Note position of the Equator at this time relative to the land masses. Darker blue indicates deep ocean water, and light blue indicates shallower water. Darker brown indicates continental rocks. Light brown indicates non-marine sediments erode from continental rocks. Florida-Bahama Block is highlighted in yellow. The map illustrates the newly opened Gulf of Mexico and the newly opened western North Atlantic Ocean that formed by seafloor spreading. At that time (160 Ma), the Caribbean Sea was starting to open as well. Note that the Florida Platform was already north of the Equator, roughly at the same latitude as it is today. The basement rocks beneath the Florida Platform were surrounded by seawater and formed the beginning of the peninsular Florida Platform (modified from Redfern 2001; published in Hine 2013).

From about 200 to 150 Ma, the Florida Platform's basement rocks were exposed to the atmosphere, with non-marine sediments deposited only sporadically. A Late Jurassic (164-157 Ma), non-marine formation superimposed on the igneous and metamorphic basement rocks indicates that an arid climate must have dominated, given the presence of sand dunes (Norphlet Formation) of Upper Jurassic (UJ) age (the purple formation in Fig. 15.3). Inferring paleoclimate during the very early development of the Florida Platform is problematic and quite speculative.

Marine carbonate rocks (limestones, dolomites) and other sedimentary rocks (evaporites) covered the Florida Platform's basement rocks and early non-marine rocks, and extend back to the Late Jurassic/Early Cretaceous (~150 - 140 Ma). These formations are nearly six km thick. The climate signals contained within this deeply buried rock likely reflect the global warm temperate/tropical climate of the Earth at that time.

For the next 100 Myr (150-50 Ma), the Florida Platform was mostly under water, with occasional periods of exposure when sea level fell (Fig. 15.6, 7B). It was during that time that much of the sedimentary carbonate cover on the Florida Platform accumulated. Not until the late Oligocene (~ 25 Ma) did widespread carbonate sedimentation cease and become largely restricted to the extreme southern portion of peninsular Florida. This carbonate rock, which covers the deeper basement rocks, contains the Floridan aquifer and features the famous springs and sinkholes that dominate much of today's exposed Florida Platform.

Figure 15.6. A sea level highstand flooded all of Florida, much of the area surrounding the modern Gulf of Mexico, and the seaway that connects the Gulf of Mexico to the Arctic Ocean. This is the paleogeography of North America at ~100 Ma, when warm, shallow seas covered much of the region. During that time, the rocks labeled "LK, UK" and the lower part of "T" (Fig. 15.3) were deposited. Although this rendering is for 100 Ma, sea levels were similarly high at 50 Ma (from Ron Blakey, Colorado Plateau Geosystems with permission; Hine 2013, Hine et al. 2016).

Climate from the Eocene Greenhouse to the Pleistocene Icehouse

Global Climate

The history of global climate change over the past 50 Myr is a story of declining atmospheric carbon dioxide (CO_2), decreasing temperature, and progressive addition of ice sheets, first on Antarctica and later in the Northern Hemisphere. This period also includes an overall decline of global sea level (Fig. 15.7A, B, C). Global cooling did not occur gradually and continuously through time. Instead, the declining temperature trend was interrupted by intervals of rapid cooling and ice growth, and warmer intervals of ice retreat that are referred to as "climatic optima."

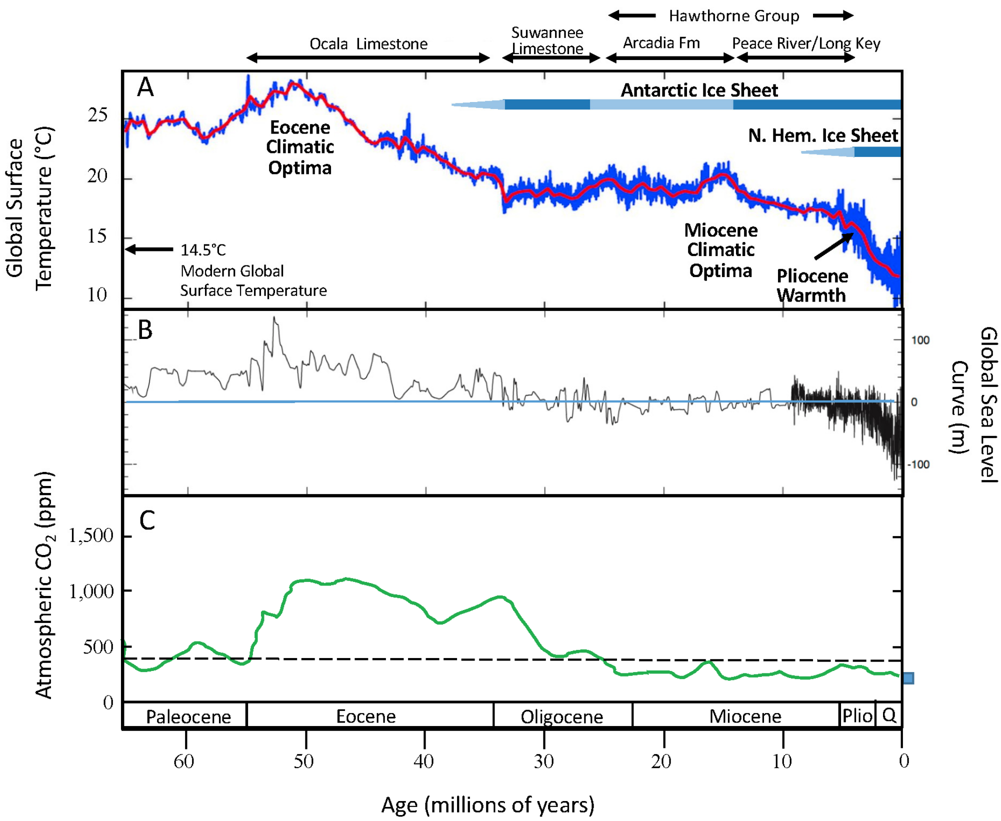

Figure 15.7 A, B, C. Cenozoic climate conditions. A. Global surface temperature derived from stable isotope measurements ($\delta^{18}O$) on carbonate shells of deep-sea benthic foraminifera (Zachos et al. 2001, 2009). Blue bars represent a qualitative estimate of ice volume in each hemisphere. Darker blue coincides with maximum extent of the ice sheets. B. Variations in global sea level relative to modern sea level (0 m) are from Miller et al. (2005). C. Earth's atmospheric CO_2 history is from Beerling and Royer (2011). Line connects data points from terrestrial and marine proxies for atmospheric CO_2. Error bars for individual data points are typically several hundred ppm (parts per million) CO_2. Horizontal dashed line indicates modern CO_2 value of ~400 ppm. Blue box at bottom right represents range of Pleistocene glacial to interglacial CO_2 values from ice cores.

There is no evidence for development of major ice sheets in either hemisphere during the early Eocene Climatic Optimum, at ~50 Ma. Estimates indicate that CO_2 was ~1,000 ppm, roughly three times pre-industrial atmospheric concentrations (Beerling and Royer 2011), and that the global mean temperature, averaged across land and sea at all latitudes, was ~28 °C (80 °F), i.e., about 14 °C (20 °F) warmer than today! Although the Antarctic continent sat over the South Pole at that time, it was covered by subtropical vegetation (ferns, cypress and beech trees), rather than ice, because of warm global temperatures. Determining sea level so far back in time is difficult, but estimates range from 20-100 m (66-328 ft) higher than today, with the most recent estimate ~75 m (246 ft) (Müller et al. 2008). Under such conditions, almost the entire Florida Peninsula would have been under water.

Over the next 16 Myr (ending ~34 Ma), global surface temperatures gradually cooled by about 4 °C (~8 °F). At that point, the Earth's climate system appears to have crossed a critical threshold, possibly caused by lower atmospheric CO_2 levels (DeConto and Pollard 2016), and ice grew rapidly on Antarctica. Within ~ 300 kyr, an ice sheet approximately the size of the modern Antarctic Ice Sheet that extended to the coastline covered this southernmost continent. As water was removed from the ocean to form the ice, global sea level dropped by ~70 m (230 ft).

For the next 18 Myr (ending ~16 Ma), the Antarctic Ice Sheet retreated (shrank) and advanced (grew), varying between about 33% and 100% of its current size. Yet no major ice sheets formed in the Northern Hemisphere. Atmospheric CO_2 concentrations declined from ~800 ppm, when the ice sheet first formed, to ~500 ppm, only about 100 ppm higher than today.

This waxing and waning of the Antarctic Ice Sheet was interrupted at ~16 Ma by dramatic warming and ice melt during the period referred to as the Miocene Climatic Optimum (Miocene Epoch; 23.0-5.3 Ma). This interval is puzzling because there is clear evidence of warming and ice sheet retreat, but the change in atmospheric CO_2 associated with this warming appears to have been small. This observation has led scientists to suggest that the climate system is more sensitive to changes in atmospheric carbon dioxide concentrations when CO_2 values are relatively low. The Miocene Climatic Optimum ended at ~14 Ma with renewed cooling and ice growth on Antarctica, which continued until another climate threshold was crossed—the transition to global icehouse conditions.

A period of renewed warmth at ~3 Ma in the Pliocene is particularly interesting because this is the last time period for which estimates of atmospheric CO_2 concentrations were as high as they are today (~400 ppm). It is somewhat surprising then that the global mean temperature was believed to be 2-3 °C warmer than pre-industrial times, or 1-2 °C warmer than today. This magnitude of warming is similar to Intergovernmental Panel on Climate Change (IPCC 2013) estimates for global temperatures for the 21st century and represents the warmest temperature experienced by Earth in the past 3 million years. Estimates of sea level during warm intervals of the Pliocene range from 6 to 25 m higher than today, with likely contributions from ice melt on both Greenland and Antarctica. There is also evidence that the Arctic Ocean was seasonally icefree. One possible explanation for warmer conditions in the Pliocene, despite atmospheric CO_2 concentrations similar to those today, is that the modern climate system has not yet reached equilibrium with respect to CO_2 concentrations driven largely by human activity, which rose very rapidly compared to past rates of increase, driven solely by natural additions to atmospheric CO_2. Another idea is that there may have been additional feedbacks within the climate system, such as changes in ocean circulation, which enhanced heat transport by the ocean and contributed additional warming.

Major growth of ice in the Northern Hemisphere began ~2.6 Ma, when the Earth's climate system began to alternate between colder glacial and warmer interglacial intervals. During glacial periods, large ice sheets covered Greenland, much of North America, and Scandinavia (Fig. 15.8).

Figure 15.8. Map of North America during the Last Glacial Maximum (~20 ka). Light blue areas were exposed by a drop in sea level of ~130 m (427 ft) associated with ice growth at high latitudes. The Florida Platform was much wider at that time (from Ron Blakey, Colorado Plateau Geosystems with permission; Hine 2013, Hine et al. 2016).

During interglacial intervals, conditions were similar to today, with continental ice sheets persisting at high latitudes; for example, Antarctica, Greenland, and smaller glaciers present atop high mountains at lower latitudes (e.g., in the Andes). Fluctuations between these glacial and interglacial states are believed to have been a consequence of subtle changes in the Earth's orbit around the Sun, i.e., Milankovitch Orbital Cycles (Fig. 15.9). The Earth's tilt on its axis and the shape of its orbit around the Sun are affected by interactions with other planets and result in predictable changes in the way the Sun's incoming energy is distributed across the Earth surface. These variations were small, but under the generally cool conditions that developed over the past 50 Myr, such small changes were enhanced (amplified) by fluctuations in atmospheric CO_2 and ocean circulation, which led the Earth in and out of glacial intervals.

During the last major glacial advance around 20 ka, known as the Last Glacial Maximum or end of the last Ice Age, global temperatures were ~5 °C (9 °F) cooler than today, atmospheric CO_2 concentrations decreased from ~280 ppm to ~200 ppm, and global sea level was an astonishing 130 m (427 ft) lower than today (Fig. 15.10). See Ruddiman (2008) for a detailed explanation of the Earth's global climate history.

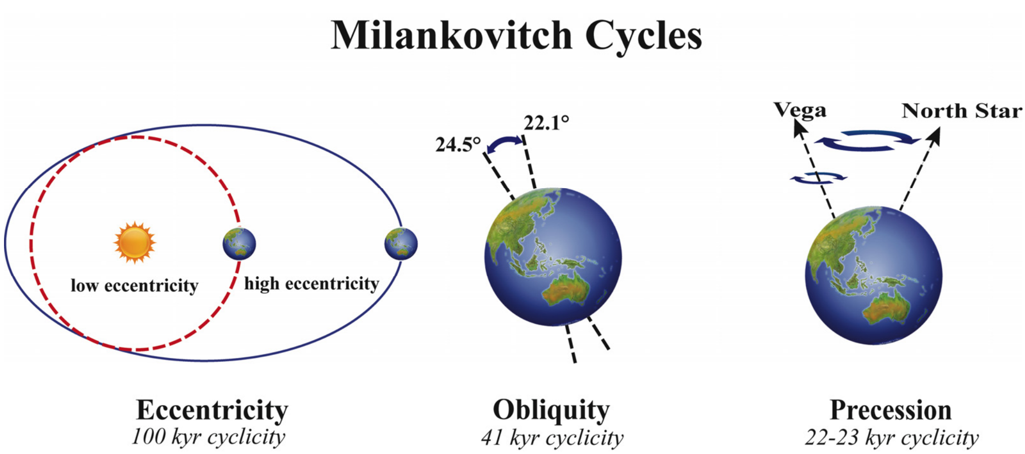

Figure 15.9. Milankovitch cycles of 100 kyr, 41 kyr, and 22-23 kyr, caused by changes in the Earth's orbit around the Sun (eccentricity), the tilt of the Earth's axis of rotation (obliquity), and the wobble (precession) (modified from Hine et al. 2016; *Sea Level Rise in Florida; Science, Impacts, and Options* by Albert C. Hine, Don P. Chambers, Tonya D. Clayton, Mark R. Hafen, and Gary T. Mitchum, Gainesville: University Press of Florida, 2016. Reprinted by permission).

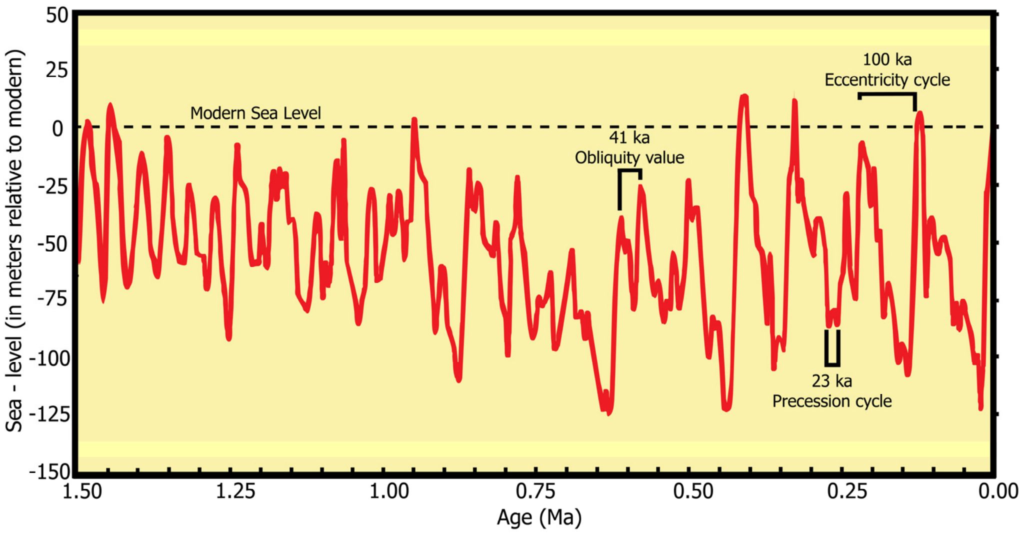

Figure 15.10. Global sea level fluctuations over the past 1.5 Mya related to Milankovitch orbital cycles. These cycles have periodicities of 22-23 ka (precession), 41 ka (obliquity), and 100 ka (eccentricity). Note that the last sea level lowstand at approximately 20 ka (0.02 Ma) was about 130 m (427 ft) below present-day sea level. These cycles are driven by variations in Earth's orbital and rotational characteristics (modified from Hine 2013; *Geologic History of Florida: Major Events That Formed the Sunshine State* by Albert C. Hine. Gainesville: University Press of Florida, 2013. Reprinted by permission.).

Florida's Climate History

We follow the same time line over the past 50 Myr to examine the effect of the global climate variations (Eocene Climatic Optimum, Miocene Climatic Optimum, Pliocene Warm Period) on the Florida Platform glacial/interglacial events). The response of the Florida Platform to glacial/interglacial events is presented separately in a later section (Florida's Climate in the Global Glacial/Interglacial World—The Icehouse).

The Marine Narrative (Eocene Climatic Optimum, Miocene Climatic Optimum, Pliocene Warm Period)

During the Eocene Climatic Optimum, the Florida Platform was mostly covered by warm tropical/subtropical seas during an extended sea level highstand (Fig 15.7B). Carbonate sedimentation dominated in these shallow seas. The accumulating fossiliferous sediments formed the upper limestone portion of Florida's carbonate platform and generated the rocks seen today in mines, pits, sinkholes, and sometimes at the land surface. These sediments and rocks formed the Ocala Limestone (Fig. 15.7A).

The Miocene Climatic Optimum was also a period of relatively high sea level, during which Florida's abundant phosphate deposits accumulated. These sediments constitute part of the Hawthorn Group of formations (Fig. 15.7A), which yield ~30% of the world's phosphate, mined primarily to produce agricultural fertilizer. The mining industry contributes to the economy of

Central Florida where phosphate-rich minerals, originally formed on the shallow seafloor during periods of elevated sea level, are extracted. From ~23 to ~10 Ma (i.e., during much of the Miocene Epoch), strong ocean currents crossed the central Florida Peninsula, providing the ideal environment for accumulation of the economically important phosphate deposits. Even though these minerals formed on the seafloor, it can be argued that the global climate change that flooded the central Florida Platform was ultimately responsible for their deposition (Popenoe 1990; Riggs 1979; Riggs 1984; Riggs et al. 2000; Hine 2013).

During the late Pliocene Warm Period, river deltas, starting in the Caloosahatchee River/Lake Okeechobee area, migrated at least 200 km (125 miles) southward, forming the Peace River Formation and the Long Key Formation. These quartz-rich sediments underlie younger limestone that are exposed in the Florida Everglades and form the Florida Keys (Pleistocene-age Miami Limestone and Key Largo Formations). These deltaic sediments are characterized by quartz-rich sands and gravels, and prograding deltaic slopes that display up to 100 m (328 ft) relief, indicating that these river delta deposits accumulated in water at least that deep (Warseski et al. 1996; Cunningham et al. 1998; Missimer 1976; Missimer 1999; Guertin et al. 1999; Cunningham et al. 2003). No modern rivers in Florida carry that much sediment. Water and sediment discharged in these large Pliocene rivers and streams were much greater than anything we see today and was probably caused by much heavier rainfall (Hine et al. 2009; Hine 2013).

The Terrestrial Narrative (Eocene Climatic Optimum, Miocene Climatic Optimum, Pliocene Warm Period)

Florida's terrestrial paleoclimate record has been inferred using preserved plant macrofossils and microfossils (e.g., leaves and pollen). One challenge associated with using fossil pollen and plant records in Florida for paleoclimate inference is that floral diversity is low in the southeastern US for the past 50 Myr (Rich 1995). This means that there were relatively few plants to serve as unique bio-indicators of specific climate regimes. Since Florida's mean elevation was close to sea level, the potential for terrestrial or marginal-marine sediments to preserve plant fossils likely varied with relative sea level. Also, the oldest terrestrial or marginal-marine sediments that did accumulate would have had a greater probability of erosion. Consequently, sediments that are available for study provide the most complete record of Florida's climate mainly for the past ~3 Ma, and we have only spotty coverage of terrestrial plants extending back to the Eocene (56.0-33.9 Ma).

Florida's terrestrial climate from the Eocene to the early Pliocene (56-5 Ma) changed as the Earth transitioned from globally warm to cooler temperatures (Fig. 15.7A). The oldest known terrestrial plant remains in Florida are from the Eocene and indicate a climate similar to modern-day South Florida and the circum-Caribbean. These fossils are geographically scattered and fragmentary, and mostly represented by seagrass macrofossils (Ivany et al. 1990). Fossil fern spores and pollen grains in Eocene deposits from central and southern Florida locales indicate a terrestrial landscape that ranged from a tropical to subtropical coastal climate, as observed on modern beaches in Central America and islands of the Caribbean. Inland south-central Florida likely had a somewhat more temperate climate in exposed, inland, forested areas, as indicated by pollen derived from pine, oak, hickory, mallow, and perhaps sycamore (Jarzen and Dilcher 2006; Jarzen and Klug 2010; Gradstein et al. 2012).

By the time of the Miocene (~23.0-5.3 Ma), pollen and other plant fossils indicate that north-central Florida had transitioned to a climate similar to that of the present. Leaves of hickory, elm, and buckthorn, as well as a large number of temperate taxa represented by pollen, fruits, and seeds, suggest a warm-temperate climate in North Florida (Corbett, 2004). The plant community type was similar to that in the modern, northern Gulf Coast of Florida, where elm-hickory-cabbage palm forests occur near oak- and pine-dominated landscapes.

The culmination in the late Pliocene (~3.6-2.6 Ma) of the transition to colder global temperatures is represented in Florida by a climate similar to that of today, but with cooler conditions and evidence for fluctuations between dry and wet. There were abundant cypress, arrowhead, black gum, sweetgum, and elm in Central Florida, all suggestive of a freshwater swamp landscape (Emslie et al. 1996), but one that became drier at times, as indicated by abundant pine and occasional oak pollen. Occasionally, there were also colder conditions in South Florida, similar to modern coastal mid-Atlantic states, which may have been related to coastal upwelling of cooler, deeper water along the coastal Gulf of Mexico (Willard et al. 1993).

Florida's Climate in the Global Glacial/Interglacial World—The Icehouse

The Pleistocene (2.6 Ma to 11.7 ka) climate of Florida under global icehouse conditions can be reconstructed using fossils from the same central and northern Florida locations that were used for Pliocene reconstructions. During glacial maxima, extensive, thick ice sheets covered North America and Western Europe, and there was significant enlargement of mountain, alpine-type glaciers worldwide.

During Pleistocene, sea level lowstands, strong, easterly trade winds transported iron-rich dust from the Sahara to the Caribbean, to the southeast US including Florida, and even northward up to Bermuda. Such dust events still occur today, causing limited visibility and pulmonary stress for some people. But during cooler periods, when the Northern Hemisphere supported huge glaciers, Saharan dust events were more common. The result in Florida was the formation of extensive reddish soils (caliche/duricrust) that accumulated on exposed limestone—particularly in the Florida Keys. During these sea level lowstands, prolonged exposure of the Pleistocene limestone to slightly acidic rainwater etched and dissolved these rocks, forming the karst topography we see today (Multer et al. 2002). In addition, the exposed portion of the Florida Platform was cooler, windier, and drier than today.

Similar to the Pliocene, Pleistocene terrestrial climate was comparable to the modern climate, with evidence of episodic climate transitions that may have been influenced by regional upwelling of cold marine waters. Baseline Pleistocene climate was also generally similar to the modern climate, with a range of mesic (moist) to xeric (dry) woodlands, scattered marshes and wetlands, inferred from geologic studies in North Florida's Trail Ridge, Central Florida's Leisey Shell Pits (Hillsborough County) and Peace Creek sinkhole (Polk County), and southwest Florida (Sarasota County) (Rich 1985; Rich and Newsom 1995; Hansen et al. 2001; Emslie et al. 1996; Willard et al. 1993).

In North Florida, climate at the Plio-Pleistocene transition (~3 Ma to 2.6 Ma) was similar to that of the Holocene (11.7 ka to present), with evidence for cypress forests that possessed shrubby undergrowth and standing water (Rich 1985). The transition then, from the Pliocene into the Pleistocene, was accompanied by generally drier conditions, dominated by shrubs and herbs, with periods of drought and fire, the latter indicated by abundant charcoal.

This drier episode was followed by an interval at ~2.2 Ma, when shrub-dominated swamps indicate wetter conditions. Alternations between wetter and drier conditions are also observed in Polk County, where three pine-oak pollen cycles are described for samples from ~2.8 Ma (Hansen et al. 2001). The longer pine phases are interpreted as reflecting drier climate conditions, whereas the shorter oak phases are thought to represent wetter conditions. These wet-dry variations may have been driven by the same orbital cycles (Milankovitch orbital cycles) that drove glacial-interglacial cycles. Hansen et al. (2001) noted an almost complete absence of pollen from tropical plant taxa that are now common in southern-most Florida. This suggests the presence of a long-term climate barrier that confined tropical species to areas south of Central Florida, and may point to occasional Pleistocene incursions into Florida of Arctic air and frost, as occur today.

In Southwest Florida, the climate of the early-middle Pleistocene was similar to that of today, but with notable episodes of cooler conditions in the earliest Pleistocene (Willard et al. 1993). In South Central Florida, pollen associations argue for a climate similar to that of the modern Florida Panhandle, with a transition in the earliest Pleistocene to conditions like those of modern coastal Florida. Invertebrate and vertebrate marine fossils from the later Pleistocene Epoch (2.6 Ma to 11.7 ka) showed this interval was less tropical, with slight cooling of coastal waters (15–25 °C; 59–77 °F), which may be explained by upwelling of cold water in the Gulf of Mexico resulting from changes in the circulation of the Gulf of Mexico due to tectonic movements in the lower Caribbean Sea, the absence of El Nino events, or the absence of red tides (Willard et al. 1993; Emslie et al. 1996).

Coming Out of the Last Ice Age—Up to the Arrival of Humans

The Last Glacial Maximum (26 to 18 ka) spans the period during the most recent ice age when ice sheets achieved their greatest spatial coverage. Because so much water was stored in ice at that time, and ocean temperatures were much colder than today, sea level was approximately 130 m (427 ft) lower than present. Extensive areas off the modern coast of Florida, especially in the shallow Gulf of Mexico, were exposed at that time, i.e. there was much more "real estate" on the peninsula than there is today (Fig. 15.11).

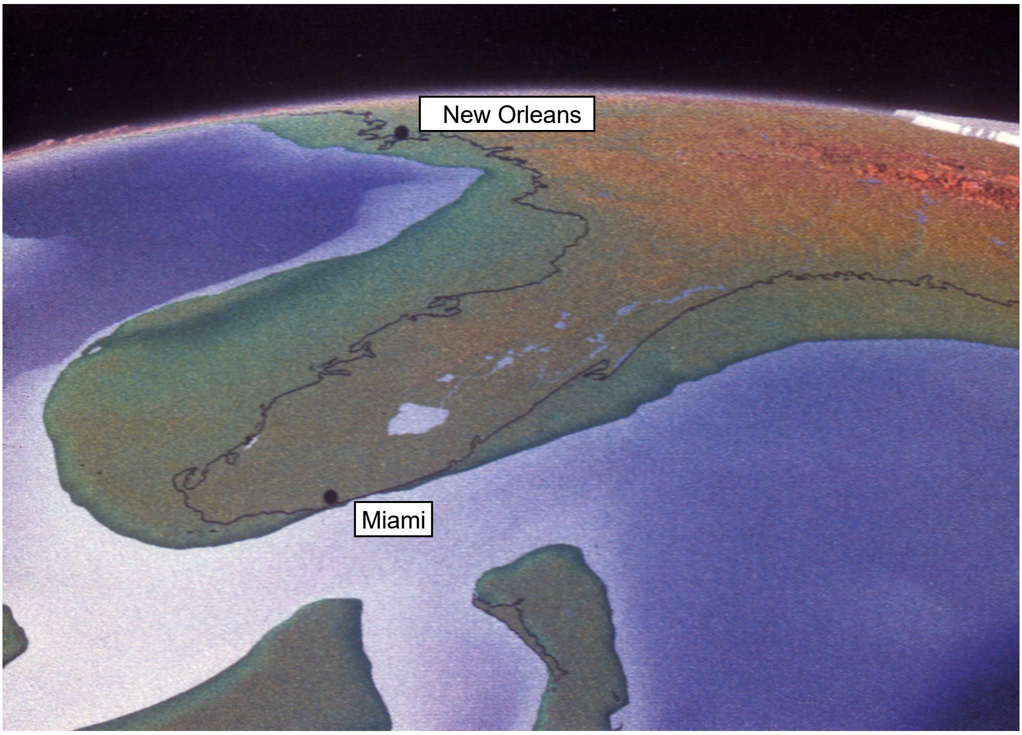

Figure 15.11. Most of the Florida Platform was exposed during the Last Glacial Maximum (~26 to 18 ka), when sea level was 130 m (427 ft) below present. This land area was approximately twice as large as the present state of Florida (modified by Hine, 2013; *Geologic History of Florida: Major Events That Formed the Sunshine State* by Albert C. Hine. Gainesville: University Press of Florida, 2013. Reprinted by permission; originally from Geotimes, now Earth Magazine; used by permission).

Periods of sea level lowstands were cooler, windier and drier, and parabolic dunes dating back some 20 ka, to the Last Glacial Maximum must have been very common, as they are so abundant along the modern west – central Florida coastline and coastal interior (Wright et al 2005). For example, Cedar Key and Seahorse Key in Levy County are the modern remains of these sand dunes. These dunes formed from a persistent wind (from the southwest) and limited sand supply, and were anchored by sparse vegetation. As sea level rose, the dunes became isolated sandy beaches along the shoreline, temporary offshore sandy islands, and eventually sand shoals when they were completely submerged or eroded by waves. Further inland, they retained their parabolic shape and became vegetated hills as humidity increased, allowing trees and shrubs to become more common. These elevated areas, surrounded by flat topography, were very useful to pre-Columbian, Native Americans (Sassaman et al., 2017 in press).

A period of global warming commenced about ~18 ka, signaling the end of the Last Glacial Maximum. Melting of the glaciers (deglaciation) at higher latitudes began, associated with a dramatic, rapid rise in sea level, especially during the period from ~18 to ~8 ka (Fig. 15.12). By about ~8 ka, sea level was within ~10–20 m (33–67 ft) of its current position. Thereafter, it continued to rise, albeit at a much slower rate.

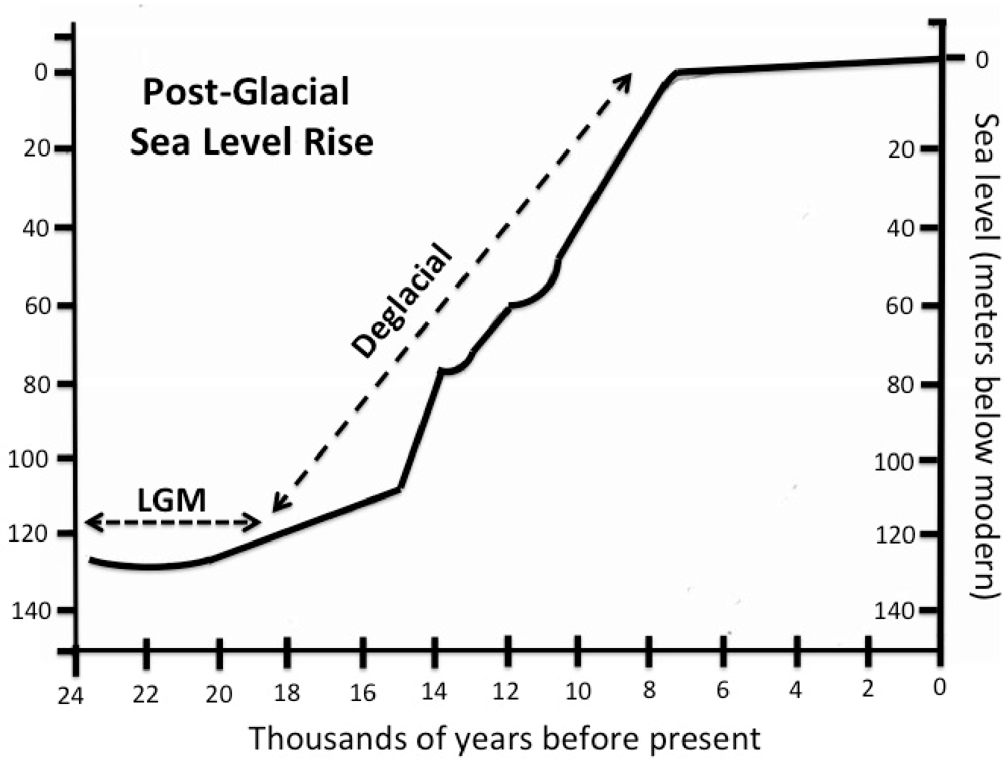

Figure 15.12. Sea level history for the past 24 kyr. Note the irregular character of the sea level curve since the Last Glacial Maximum (LGM) (modified from Lambeck et al. 2014).

Some of what we know about late glacial, deglacial, and recent climate conditions in Florida comes from study of sediment cores collected in Florida's lakes. These sediment profiles provide a window into past climate and environment on the peninsula. Lake sediments accumulate in an orderly fashion, with younger sediments continuously accruing atop older deposits. Lake sediments typically accumulate at rates ranging from <1 to several mm/yr (0.04 to ~0.1 inch), enabling fairly high-resolution reconstructions of past conditions if cores are sampled at close intervals. Sediment cores are relatively easy to obtain and age–depth relations for such profiles, extending back in time >40 ka or more, can be established by radiocarbon (^{14}C) dating. The paleoclimate and paleoenvironmental information preserved in these cores can be gleaned from stratigraphic study of pollen grains (which are informative about past vegetation), geochemical measurements on carbonate shells of snails or ostracodes (which reflect changing regional evaporation to precipitation ratios), diatom (siliceous algae) assemblages, and other physical, chemical and biological characteristics of the sediments.

Some lakes located along the upland, central "spine" of the state are relatively deep, with maximum water depths on the order of 20–30 m (67–98 ft). Studies of sediment cores from several such lakes show that some held water through even the driest episodes of the late glacial (Watts 1975, 1980; Watts and Stuiver 1980; Watts et al. 1992). At least one, Lake Tulane in Highlands County, held water continuously on the landscape for some 60 ka (Grimm et al. 1993, 2006). High amounts of *Ambrosia* (ragweed) pollen in the Pleistocene sediments of Lake Tulane indicate that Florida climate at the end of the Last Glacial Maximum was generally much cooler than present, but displayed fluctuations between times of somewhat warmer and wetter conditions as were revealed by high relative abundance of pine pollen and elevated lake levels, and times of relatively colder and drier conditions, dominated by oak pollen and lower lake levels.

As climate in Florida warmed during the "deglacial" and early Holocene (~11.7 ka), there were profound consequences for Florida's terrestrial environment. Vast areas that had served as habitat for Pleistocene land plants and animals, some now extinct (e.g., mammoths, horses, giant sloths, tapirs), were inundated by rising seawater. And as sea level rose, the freshwater aquifers that underlie the region were forced upwards, ultimately causing Florida's famous artesian springs to begin to flow.

Archaeological excavations at Salt Springs near Lake Kerr revealed wood beneath anthropogenic deposits, and a radiocarbon date on that wood suggests spring flow began about 9.45 to 9.25 ka (O'Donoughue et al. 2011). Similarly, at Silver Glen Run on the west side of Lake George a radiocarbon assay on organic deposits that sit atop mineral sediment, and therefore reflect rising water, yielded a date of 8.59 to 8.45 ka (O'Donoughue 2017).

Shortly after the onset of the Holocene Epoch (11.7 ka), rainfall in the region increased. The combination of greater precipitation and rising groundwater tables probably contributed to initial filling of Florida's more than 8,000 shallow lakes, many of which have maximum depths less than 5 m (~<16 ft) (Brenner et al. 1990). Similar to evidence from the springs, filling of the shallow lakes in the state commenced about 9.0 to 6.0 ka. The onset of filling has been established at a number of water bodies by collecting sediment cores and radiocarbon dating the organic material that lies directly atop the clay seal or sand that lines the basin bottoms.

Sediment cores from upland lakes along the Lake Wales Ridge and Trail Ridge (Fig. 15.13) show that early Holocene pollen assemblages were dominated by oaks; but by about 5.0 ka, there was a transition to pine dominance (Watts 1969; 1971; 1980; 1983; Watts and Hansen 1988).

The flora, as we know it today, was largely in place by about 5 ka ago. Since that time, however, there have been some notable shifts, such as the spread of bald cypress (*Taxodium*), beginning a little more than 2.0 ka. The spread of these trees, which typically occupy saturated soils, may reflect a rise of the shallow groundwater table or simply the colonization of new sites as the plants moved across the landscape and occupied appropriate habitats. Geochemical measurements on snail shells in a sediment core from Lake Panasoffkee, north–central Florida, suggest that the climate became substantially wetter in the earliest Holocene, in general agreement with pollen records, with a more gradual increase in moisture thereafter.

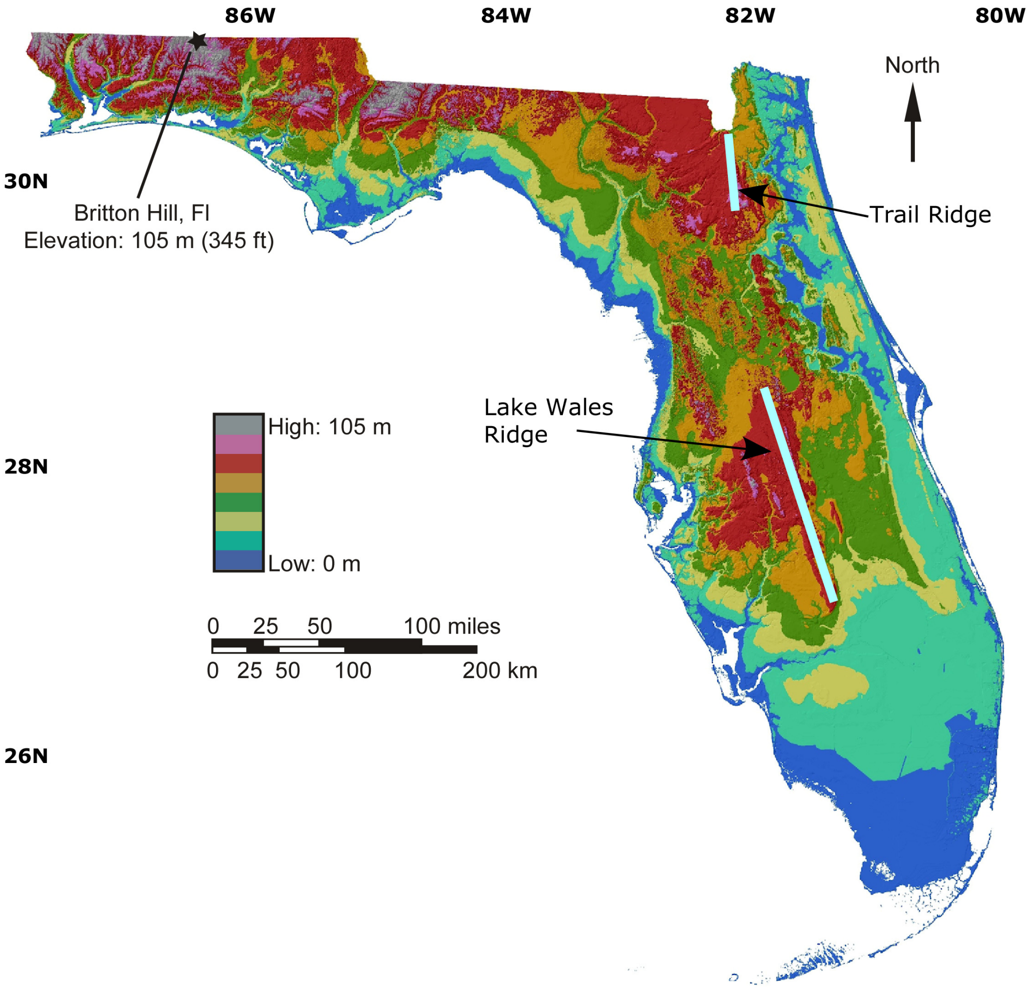

Figure 15.13. Location of Lake Wales Ridge and Trail Ridge (base map from the Florida Geological Survey, Tallahassee, FL; modified from Hine 2013; *Geologic History of Florida: Major Events That Formed the Sunshine State* by Albert C. Hine. Gainesville: University Press of Florida, 2013. Reprinted by permission.).

Most of the long paleoclimate records from Florida come from upland lakes in well-drained terrains. The Newnans and Lochloosa lakes near Gainesville, however, occupy poorly-drained areas. A recent study of sediment cores from these two water bodies found that pine dominated the pollen assemblages over the past >8.0 ka at both sites, and that charcoal concentrations and accumulation rates were high only in the early parts of the records, before about 7.0 ka (Larios 2015). In contrast to records from lakes in the well-drained uplands, the evidence for abundant fires around Newnans and Lochloosa might suggest overall drier conditions in the early

Holocene. Alternatively, the data from the Newnans and Lochloosa cores may indicate greater seasonality in the early Holocene, with wetter wet seasons and drier dry seasons at low latitudes in the Northern Hemisphere. Such a pattern would have enabled a build-up of "fuel" during the rainy season, drying of that organic material during the intense dry season, and ignition by lightning at the onset of each new wet season.

We are able to obtain a "brushstroke" picture of climate change in Florida since the Last Glacial Maximum using lake cores (Fig. 15.14). There were pronounced changes in both temperature and rainfall during the Pleistocene–Holocene transition (11.7 ka), marked by a shift from generally colder and drier to warmer and wetter conditions. Studies of recent shifts in instrumentally-measured rainfall, lake levels, and groundwater tables illustrate how dynamic the state's climate can be, even on short timescales (Deevey 1988). Regional lakes rise and fall synchronously, with little to no lag, in response to fluctuations in monthly rainfall. And longer-term "ups and downs" in lake levels are linked to the height of the deep, Eocene-age Florida aquifer, which exerts pressure on the lakes and surficial water table through thick, overlying, Miocene-to-Pliocene deposits. Droughts lasting just a few years (e.g. those of the middle 1950s, early 1980s, and early 2000s) are characterized by low lake stands and declines in the level of the Floridan aquifer.

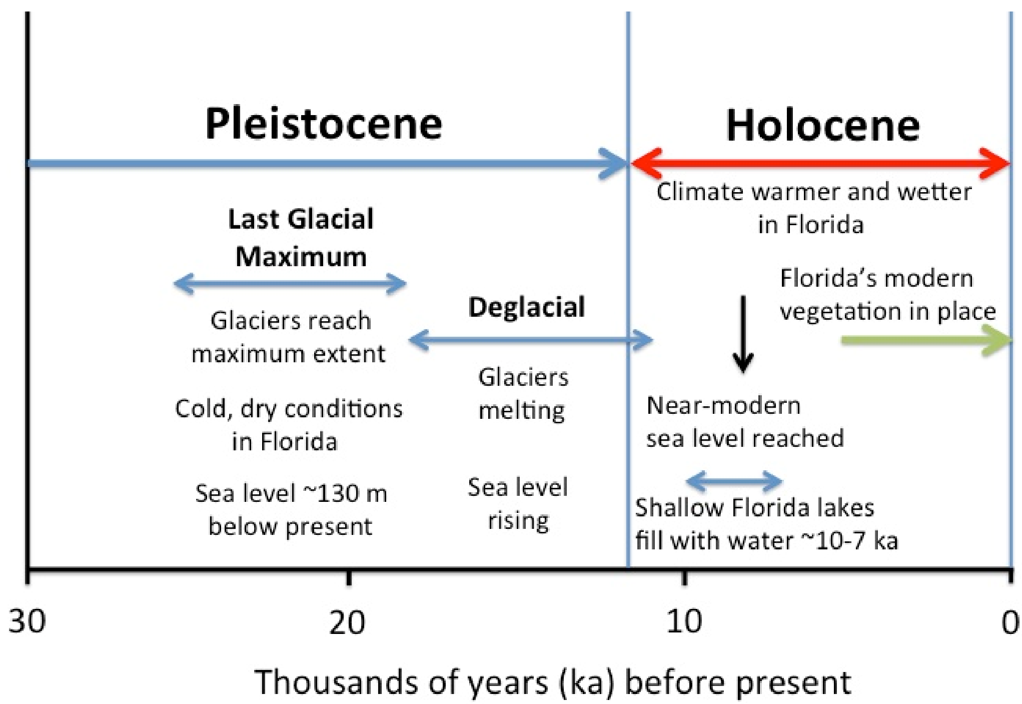

Figure 15.14. Summary of climate change in Florida derived from lake cores.

Modern Day

The early 21st century marked a period of what appears to be extreme climate conditions in Florida, in that we have already seen very low lake levels on two occasions and complete drying of some Florida lakes for the first time in recorded history. Rainfall deficits in the first years of the new millennium led to a pronounced decline in stage at Newnans Lake. More than 100 prehistoric canoes were discovered along the exposed shoreline in 2000, and radiocarbon dates on these vessels spanned a range from about 5000 to 500 years ago (Wheeler et al. 2003). The fact that the discovery was made so recently suggests low lake stands of such magnitude had probably not occurred at any other time in the past 500 years.

Dry conditions were evident into the second decade of the new millennium, and Little Lake Johnson, in Mike Roess Gold Head Branch State Park, north of Keystone Heights, dried completely in 2012 (Fig. 15.15 A, B), also revealing a prehistoric canoe.

Anthropogenic water withdrawals have been invoked by some to explain the lake desiccation, but there is ample evidence that persistent rain deficits were the true culprit. Again, the fact that complete drying was never reported prior to this time suggests that we have moved into a new climate regime.

A B

Figure 15.15 A, B. Little Lake Johnson is a recreational water body in Mike Roess Gold Head Branch State Park, north of Keystone Heights, Florida. In 2012 (A), the lake dried completely, an unprecedented event in historic times and one that may signal a pronounced change in our local climate. By 2014 (B), the lake again held water, but had not returned to previously measured higher levels.

Conclusion

We focused on the past ~50 Myr of geologic time because rocks of this age and younger are accessible near or at the surface on the Florida Platform, thus allowing geoscientists to obtain a more complete understanding of past climate. We tied global climate changes over the past 50

Myr to specific climate responses on the Florida Platform. In general, the climate of the Florida Platform tracked global climatic events.

A key response to past climate change was sea level fluctuation, which covered the continental margins with seawater or exposed them to the atmosphere. Sedimentary rocks, initially of non-marine origin, followed by marine limestone (carbonate), began to record past sea level fluctuations after the Florida Platform was formed during tectonic, mega-continent breakup at ~200 Ma. The Platform has been topographically flat and low, thereby promoting deposition of carbonate sediments derived from corals, shell-bearing organisms such as mollusks, and mud-producing algae in shallow, surrounding seas. During sea level lowstands, the flat, topographically low Florida Platform was exposed to the atmosphere, subjecting terrestrial plants and animals to temperature and humidity variations. For at least 160 Myr, the surrounding oceans created a unique climate on the peninsular Florida Platform. Powerful seasonal thunderstorms developed, particularly when a significant portion of the platform was exposed to the atmosphere.

The history of global climate change over the past 50 Myr is a story of declining atmospheric carbon dioxide (CO_2) and cooling, i.e., a transition from a greenhouse (warm) to an icehouse (cooler with cyclical glaciations and deglaciations) Earth. This global cooling did not occur gradually and continuously through time. Instead, the declining temperature trend was interrupted by intervals of rapid cooling and ice growth, and warmer intervals of ice retreat that are referred to as "climatic optima."

Three global climatic optima occurred during this 50-Myr timeframe, which resulted in distinct geologic responses in Florida. First was the early Eocene Climatic Optimum at ~50 Ma, during which CO_2 was estimated to be ~1,000 ppm, roughly three times pre-industrial concentrations. Warm, shallow seas covered the Florida Platform, depositing widespread carbonate sediments, which are called the Ocala Limestone.

Second, the waxing and waning of the Antarctic Ice Sheet was interrupted at about 16 Ma by dramatic warming and ice melt during a period referred to as the Miocene Climatic Optimum. In Florida, the resulting higher sea level led to the deposition of economically valuable phosphate deposits, emplaced on the west–central portion of the peninsula. These are some of the richest phosphate deposits in the world and form a key component of Florida's Hawthorn Group of rocks and sediments.

Third, the global Pliocene Warm Period around 3 Ma resulted in the migration of river deltas with 100 m (327 ft) relief at least 200 km (125 miles) southward, to positions beneath what are now the modern Florida Everglades and the Florida Keys. These sediments were quartz-rich sands and gravels and formed the Peace River and Long Key formations. These large water- and sediment-laden Pliocene rivers and streams must have been fed by very large amounts of rainfall.

The major growth of ice in the Northern Hemisphere, initiating the icehouse Earth, began ~2.6 Ma when the Earth's climate system started to alternate between colder glacial and warmer interglacial intervals, driven by Milankovitch cycles. Numerous glacial and interglacial periods occurred since that time, and Earth today is in an interglacial interval. Florida climate responded to both sea level lowstands, and highstands.

Florida's Pleistocene terrestrial paleoclimate record has been reconstructed using plant macrofossils and microfossils (e.g., leaves and pollen). Similar to data from the Pliocene, Pleistocene data reveal a terrestrial climate comparable to the modern, with evidence of cool climate episodes that may have been influenced by regional upwelling of cold marine waters. As climate in Florida warmed after the Last Glacial Maximum, which ended at ~18 ka, and in the early Holocene (~11.7 ka), there were profound consequences for Florida's terrestrial environment as much of the Florida Platform was exposed prior to that time. Vast areas that had served as habitat for Pleistocene land plants and animals, some now extinct (e.g., mammoths, horses, giant sloths, tapirs), were inundated by rising seawater.

Shortly after the onset of the Holocene Epoch (11.7 ka), rainfall in the region increased; it was probably the combination of greater precipitation and rising groundwater tables that contributed to initial filling of Florida's more than 8,000 shallow lakes.

The early 21st century has marked a period of what appears to be extreme climate conditions in Florida, in that we have already seen very low lake levels on two occasions and complete drying of some Florida lakes for the first time in recorded history. Such complete drying was never reported previously and suggests that we have entered a new climate regime in this millennium.

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References

Beerling, David J. and Royer, Dana L. "Convergent Cenozoic CO2 history." *Nature Geoscience* 4 (2011): 418-420.

Brenner, Mark, Michael W. Binford, and Edward S. Deevey. "Lakes." In *Ecosystems of Florida*, edited by Ron L. Myers and John J. Ewel, 364-391. Orlando: University of Central Florida Press, 1990.

Christie-Blick, N. "Geological Time Conventions and Symbols." *Geological Society of America Today* 22, no. 2 (2012): 28-29. doi: 10.1130/G132GW.1.

Corbett S.L. 2004. The middle Miocene Alum Bluff flora, Liberty County, Florida [M.S. thesis]. [Gainesville (FL)]: University of Florida.

Cunningham, K. J., D. F. McNeill, L. A. Guertin, P. F. Ciesielski, T. M. Scott, and L. de Verteuil. "New Tertiary Stratigraphy for the Florida Keys and Southern Peninsula of Florida." *Geological Society of America Bulletin* 110, no. 2 (1998): 231-58. doi: 10.1130/0016-7606(1998).

Cunningham, K. J., S. D. Locker, A. C. Hine, D. Bukry, J. A. Barron, and L. A. Guertin. "Interplay of Late Cenozoic Siliciclastic Supply and Carbonate Response on the Southeast Florida Platform." *Journal of Sedimentary Research* 73, no. 1 (2003): 31-46. doi: 10.1306/062402730031.

DeBalko, D. A., and R. T. Buffler. "Seismic Stratigraphy and Geologic History of Middle Jurassic through Lower Cretaceous Rocks, Deep Eastern Gulf of Mexico." *Gulf Coast Association of Geological Societies Transactions* 42 (1992): 89-105. doi: 10.1306/A1ADDD5A-0DFE-11D7-8641000102C1865D.

DeConto, Robert M., and Pollard, David. “Contributions of Antarctic to past and future sea-level rise. *Nature* 531 (2016): 591-597. doi: 10.1038/nature17145.

Deevey, Edward S. Jr. “Estimation of Downward Leakage from Florida Lakes.” *Limnology and Oceanography* 33, no. 6 part 1 (1988). 1308-1320.

Emslie, Steven D., W. D. Allmon, F. J. Rich, J. H. Wrenn, and S. D. DeFrance. 1996. Integrated taphonomy of an avian death assemblage in marine sediments from the late Pliocene of Florida. Palaeogeography, Palaeoclimatology, Palaeoecology 124:107–136.

Evans, M. W., and A. C. Hine. "Late Neogene Sequence Stratigraphy of a Carbonate-Siliciclastic Transition: Southwest Florida." *Geological Society of America Bulletin* 103, no. 5 (1991): 679-99. doi: 10.1130/0016-7606(1991)103<0679:lnssoa>2.3.co;2.

Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G., 2012. The Geologic Time Scale 2012. Elsevier, Amsterdam (1176 pp.).

Grimm, Eric C., G. L. Jacobson Jr., W. A. Watts, B. C. S. Hansen, and K. A. Maasch. “A 50,000-Year Record of Climate Oscillations from Florida and Its Temporal Correlation with the Heinrich Events.” *Science* 261, no. 5118 (1993). 198-200.

Grimm, Eric .C., W.A. Watts, G. L. Jacobson Jr., B.C.S. Hansen, H. R. Almquist, and Ann C. Dieffenbacher-Krall. “Evidence for Warm Wet Heinrich Events in Florida.” *Quaternary Science Reviews* 25, No. 17-18 (2006). 2197–2211.

Guertin, L.A., D.F. McNeill, B.H. Lidz, and K.J. Cunningham. Chronologic Model and Transgressive-Regressive Signatures in the Late Neogene Siliciclastic Foundation Long Key Formation) of the Florida Keys. Journal of Sedimentary Research 69, no. 3 (1999): 653-666.

Hansen, Barbara C.S., Eric C. Grimm, William A. Watts. 2001. Palynology of the Peace Creek Site, Polk County, Florida. Geological Society of America Bulletin 113: 682–692.

Hine, A. C., B. Suthard, S. D. Locker, C. K.J., D. D. Duncan, M. W. Evans, and R. A. Morton. "Karst Subbasins and Their Relation to the Transport of Tertiary Siliciclastic Sediments on the Florida Platform." *International Association of Sedimentologists Special Publication* 41, no. Perspectives in Sedimentary Geology: A Tribute to the Career of Robert N. Ginsburg (2009): 179-97.

Hine, A.C., 2013, Geologic History of Florida; Major Events that Formed the Sunshine State; Gainesville, FL: University Press of Florida, 229p.

Hine, A.C., D. P. Chambers, T.D. Clayton, M.R Hafen, and G. T. Mitchum, 2016, Sea Level Rise in Florida; Science, Impacts, and Options, Gainesville, FL: University Press of Florida, 179p.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi: 10.1017/CBO9781107415324.

Iturralde-Vinent, M.A., The conflicting paleontologic versus stratigraphic record of the formation of the Caribbean Seaway. In Circum-Gulf of Mexico and the Caribbean Hydrocarbon Habitats, Basin Formation and Plate Tectonics, ed. C. Bartolini, R. T. Buffler, and J.T. Bilickwede, 75-88. Tulsa, American Association of Petroleum Geologists, 2003.

Ivany, L. C., R. W. Portell, and D. S. Jones. 1990. Animal-plant relationships and paleobiogeography of an Eocene seagrass community from Florida. Palaios 5:244–258.

Jarzen, D.M. and D.L. Dilcher (2006): Mid-Eocene terrestrial palynmorphs from the Doline Minerals and Gulf Hammock Quarries, Florida; Palynology, 30: 89-110.

Jarzen, D.M., and C. Klug. 2010. A preliminary investigation of a lower to middle Eocene palynoflora from Pine Island, Florida, USA. Palynology Vol. 34 (2): 164-179.

Klitgord, K. D., P. Popenoe, and H. Schouten. "Florida: A Jurassic Transform Plate Boundary." *Journal of Geophysical Research* 89, no. B9 (1984): 7753-72. doi: 10.1029/JB089iB09p07753.

Lambeck, K., H. Rouby, A. Purcell, Y. Sun, M. Sambridge, 2014, Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, PNAS, v. 14, no. 43, p. 15296-15303; www.pnas.org/cgi/doi/10.1073/pnas.1411762111.

Larios, Kalindhi, “Florida Wildfires During the Holocene Climatic Optimum (9,000-5,000 cal yr BP)” MS Thesis, University of Florida, Gainesville, 2015.

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. Science, 310, 1293-1298. doi: 10.1126/science.116412.

Missimer, T. M., and R. A. Gardner. "High-Resolution Seismic Reflection Profiling for Mapping Shallow Water Aquifers in Lee County, Fl." In *Water-Resources Investigations Report* 30. Tallahassee: U.S. Geological Survey, 1976.

Missimer, T. M. "Sequence Stratigraphy of the Late Miocene—Early Pliocene Peace River Formation, Southwestern Florida." *Gulf Coast Association of Geological Societies Transactions* 49 (1999): 358-68. doi: 10.1306/2DC40C53-0E47-11D7-8643000102C1865D.

Müller, R.D., M. Sdrolias, C. Gaina, B. Steinberger, and C. Heine, Long-term sea-level fluctuations driven by ocean basin dynamics. *Science* 319 (2008): 1356-1362.

Multer, H.G., E. Gischler, J.Lundberg, K.R. Simmons, and E.A. Shinn. "Key Largo Limestone Revisited: Pleistocene Shelf Edge Facies, Florida Keys, USA". *Facies* 46, no. 1 (2002): 229-72 (doi: 10.1007/BF02668083).

O'Donoughue, J.M. 2017. Water from stone: archeology and conservation at Florida's springs. University of Florida Press, Gainesville. 245 p.

O'Donoughue, J.M., K.E. Sassaman, M.E. Blessing, J. B. Talcott, and J.C. Byrd. 2011. Archaeological investigations at Salt Springs (8MR2322), Marion County, Florida. Technical Report 11, Laboratory of Southeastern Archaeology, Department of Anthropology, University of Florida Gainesville. 151 p.

Pindell, J. L., and S. F. Barrett. Geological Evolution of the Caribbean Region; a Plate Tectonic Perspective. In *The Caribbean Region*, edited by G. Dengo and J. E. Case. The Geology of North Florida, 405-32. Boulder, CO: The Geological Society of America, 1990.

Popenoe, P. "Paleoceonography and Paleogeography of the Miocene of the Southeastern United States." In *Phosphate Deposits of the World*, edited by W. C. Burnett and S. R. Riggs. Cambridge Earth Science Series, 352-80. New York: Cambridge University Press, 1990.

Randazzo, A. F., and D. S. Jones, eds. *The Geology of Florida*. Gainesville, FL: University Press of Florida, 1997.

Redfern, R. *Origins: The Evolution of Continents, Oceans and Life.* Norman, OK: University of Oklahoma Press by special arrangement with Cassell and Co, UK, 2001.

Rich, F. J. 1985. Palynology and paleoecology of a lignitic peat from Trail Ridge, Florida. Florida Bureau of Geology Information Circular 100.

Rich, F. J., and L. A. Newsom. 1995. Preliminary palynological and macrobotanical report for the Leisey Shell Pits, Hillsborough County, Florida. Bulletin of the Florida Museum of Natural History 37 Pt. I(4):117-126.

Riggs, S.R.Phosphorite Sedimentation in Florida; a Model Phosphogenic System. *Economic Geology* 74, no. 2 (1979): 285-314. doi: 10.2113/gsecongeo.74.2.285.

Riggs, S. R. "Paleoceanographic Model of Neogene Phosphorite Deposition, U.S. Atlantic Continental Margin." *Science* 223, no. 4632 (1984): 123-31. doi: 10.1126/science.223.4632.123.

Riggs, S.R., S. Snyder, D. Ames, and P. Stille. Chronostratigraphy of the Upper Cenozoic Phosphorites on the North Carolina Continental Margin and the Oceanographic Implications for Phosphogenesis. Marine Authigenesis: From Global to Microbial 66, SEPM Special Publication (2000), 369-385. doi: 10.2110/pec.00.66.0369.

Ruddiman, W. F. *Earth's Climate: Past and Future.* 2nd ed. New York: W.H. Freeman and Company, 2008, 388p.

Sassaman, K.E., and 13 others, Keeping pace with rising sea: The first six years of the lower Suwannee archeological survey, Gulf coastal Florida: Journal of Island and Coastal Archeology.

Sheridan, R. E., H. T. Mullins, J. A. Austin, M. M. Ball Jr., and J. W. Ladd. "Geology and Geophysics of the Bahamas." In *The Atlantic Continental Margin: U.S.*, edited by R. E. Sheridan and J. A. Grow. Geology of North America, 329-64. Boulder, CO: The Geological Society of America, 1988.

Walker, J.D., J. W. Geissman, S. A. Browning, and L. E. Babcock, 2013, The Geological Society of America Time Scale: Geological Society of America Bulletin 125, (3/4) p. 259-274.

Warzeski, E. R., K. J. Cunningham, R. N. Ginsburg, J. B. Anderson, and Z.-D. Ding. "A Neogene Mixed Siliciclastic and Carbonate Foundation for the Quaternary Carbonate Shelf, Florida Keys." *Journal of Sedimentary Research* 66, no. 4 (1996): 788-800. doi: 10.1306/d426840a-2b26-11d7-8648000102c1865d.

Watts, W. A., A Pollen Diagram from Mud Lake, Marion County, North Central Florida. *Geological Society of America Bulletin* 80, no. 4 (1969). 631-642.

Watts, W. A., Postglacial and Interglacial Vegetation History of Southern Georgia and Central Florida. *Ecology* 52, no. 4 (1971). 676-690.

Watts, W. A., A Late Quaternary Record of Vegetation from Lake Annie, South-Central Florida. *Geology* 3, June (1975). 344-346.
Watts, W. A. The Late Quaternary Vegetation History of the Southeastern United States. *Annual Review of Ecology and Systematics* 11 (1980). 387-409.
Watts, W. A., Vegetational History of the Eastern United States 25,000 to 10,000 Years Ago. In *Late Quaternary Environments of the United States*. Volume 1, edited by Herbert E. Wright, 294-310. Minneapolis: University of Minnesota Press, 1983.
Watts, W.A. and M. Stuiver. 1980. Late Wisconsin climate of northern Florida and the origin of species-rich deciduous forest. Science 210: 325-327.
Watts, W. A., and B.C.S. Hansen, Environments of Florida in the Late Wisconsin and Holocene. In *Wetsite Archaeology*, edited by Barbara A. Purdy, 307-323. Caldwell: The Telford Press, 1988.
Watts, W.A., B. C.S. Hansen, and E. C. Grimm. Camel Lake: A 40,000-Yr Record of Vegetational and Forest History from Northwest Florida. *Ecology* 73, no. 3 (1992). 1056-1066.
Wheeler, Ryan J., James J. Miller, Ray M. McGee, Donna Ruhl, Brenda Swann, and Melissa Memory. Archaic Period Canoes from Newnans Lake, Florida. *American Antiquity* 68, no. 3 (2003).
Willard, D.A., Cronin, T.M. Ishman, S.E., and Litwin, R.J., 1993, Terrestrial and marine records of climatic and environmental changes during the Pliocene in subtropical Florida: Geology, 21: 679-682.
Wright, E.E., Hine, A.C., Goodbred, S.L., and Locker, S.D., 2005, The effect of sea-level and climate change on the development of a mixed siliciclastic –carbonate deltaic coastline; Suwannee River, FL; Journal of Sedimentary Research, v. 75. p. 621-635; DOI: 10.2110/jsr.2005.051
Zachos, James, Pagani, Mark, Sloan, Lisa, Thomas, Ellen, Billups, Katharina. “Trends, rhythms, and aberrations in global climate.” *Science* 292 (2001): 686-693.
Zachos, J. C., G. R. Dickens, and R. E. Zeebee, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451 (2009): 279-283. doi:10.1038/nature06588.