A 50,000-Year Record of Climate Oscillations from Florida and Its Temporal Correlation with the Heinrich Events

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Oscillations of *Pinus* (pine) pollen in a 50,000-year sequence from Lake Tulane, Florida, indicate that there were major vegetation shifts during the last glacial cycle. Episodes of abundant *Pinus* populations indicate a climate that was more wet than intervening phases dominated by *Quercus* (oak) and *Ambrosia*-type (ragweed and marsh-elder). The *Pinus* episodes seem to be temporally correlated with the North Atlantic Heinrich events, which were massive, periodic advances of ice streams from the eastern margin of the Laurentide Ice Sheet. Possible links between the Tulane *Pinus* and Heinrich events include hemispheric cooling, the influences of Mississippi meltwater on sea-surface temperatures in the Gulf of Mexico, and the effects of North Atlantic thermohaline circulation on currents in the Gulf.

Few continental records of climate change are available from North America for the last glacial period. Particularly rare are long, continuous stratigraphic records that might reveal oscillations in climate. In contrast, ice cores from Greenland and sediments from the North Atlantic Ocean record major oscillations during the last glacial period. Particularly notable are the Dansgaard-Oeschger events in the ice cores (*1*) and the recently recognized Heinrich events in the North Atlantic (*2–5*). A number of Pleistocene pollen sequences exist from Florida lake sediments, but none of these are continuous because of lowered water tables and lake desiccation at various times in the past (*6, 7*). Initial research from Lake Tulane (*8, 9*) suggested that it recorded significant vegetation changes during the Pleistocene. The lake is of sufficient depth that continuous sedimentation has occurred during the past 50,000 years, and the pollen record from the lake is the longest continuous sequence yet known from eastern North America. In this report we present and discuss additional pollen and radiocarbon data that indicate the occurrence of major oscillations in vegetation and climate during the last glacial period.

We obtained an 18.52-m core from Lake Tulane in 22.67 m of water. A series of radiocarbon dates from the core (Table 1) had an oldest finite date of 39,600 ± 500 years before present (B.P.); we rejected one finite date because of infinite dates stratigraphically above it. To interpolate ages between the dates and to extrapolate ages beyond the finite dates, we constructed an age model by fitting a second-order polynomial to the 16 finite dates (excepting the one rejected), the sediment-surface date (−34 B.P.), and the value of 46,000 for the >46,000 B.P. date (Fig. 1). The dates and sediment lithology indicate that sedimentation was continuous and regular. For the dates <30,000 B.P., the largest residuals from the fitted curve are during the late glacial and may result from atmospheric ^{14}C anomalies (*10*) rather than variable sedimentation rates. The dated material was bulk sediment (sections of core 10 or 20 cm deep). Although such dates are sometimes too old because of ancient carbon sources, the errors at Lake Tulane from this source are probably minimal. The lake was formed by the collapse of underlying limestone at depth, but the basin itself lies in a thick layer of overlying siliceous acid sands; the sediment contains virtually no carbonate minerals.

The most striking feature of the Lake Tulane pollen record (Fig. 2) is a series of oscillations between *Pinus* (pine) on one hand and *Quercus* (oak) and *Ambrosia*-type (ragweed and marsh-elder) on the other. The *Pinus* fluctuations from ~10 to ~60% represent major vegetation shifts from pine forest to an open oak–savanna or grassland vegetation-type. The abrupt transitions between the *Pinus* and *Quercus* and *Ambrosia* phases suggest that the vegetation changed rapidly between two modes (*11*). The oscillations are quite regular during the Pleistocene section, representing oxygen isotope stages 2 and 3. The pollen record indicates shifts in moisture balance: a high abundance of *Pinus* indicates wet intervals, whereas high abundances of *Quercus* and *Ambrosia*-type indicate dry intervals. The *Quercus* and *Ambrosia* phases have high percentages of herb pollen, including *Ambrosia*-type, Poaceae (grass family), Asteraceae (sunflower family), and Chenopodiaceae/Amaranthaceae (goosefoot and amaranth families), which indicate an open, grassland type of vegetation. The abundance of *Ambrosia*-type pollen, which includes weedy *Ambrosia* and some *Iva* species, suggests that soil disturbance was

Table 1. Radiocarbon dates from Lake Tulane. Depths are from the sediment surface, which was 2267 cm below the water surface.

Depth (cm)	Age (^{14}C years B.P.)	Lab number
108 to 118	1,670 ± 60*	Beta-37851
226 to 236	3,440 ± 80*	WIS-1646
325 to 335	4,650 ± 70*	WIS-1752
425 to 435	7,330 ± 90*	WIS-1647
531 to 541	9,810 ± 90*	WIS-1753
625 to 635	10,940 ± 120*	WIS-1648
785 to 795	13,730 ± 130*	WIS-1649
885 to 895	17,170 ± 210*	WIS-1754
985 to 995	20,380 ± 230*	WIS-1650
1085 to 1095	24,240 ± 400*	WIS-1755
1185 to 1195	26,120 ± 440*	WIS-1651
1245 to 1265	32,300 ± 450*	QL-4630
1325 to 1345	35,700 ± 650*	QL-4631
1385 to 1395	>33,000	WIS-1652
1395 to 1405	35,600 ± 400*	QL-4057
1609 to 1619	39,600 ± 500*	QL-4058
1720 to 1730	>46,000*	QL-4632
1793 to 1813	>40,500	QL-4633
1818 to 1828	32,200 ± 220†	QL-4059
1828 to 1838	>33,000	WIS-1618

*Date used in age model. †Date rejected as anomalously young.

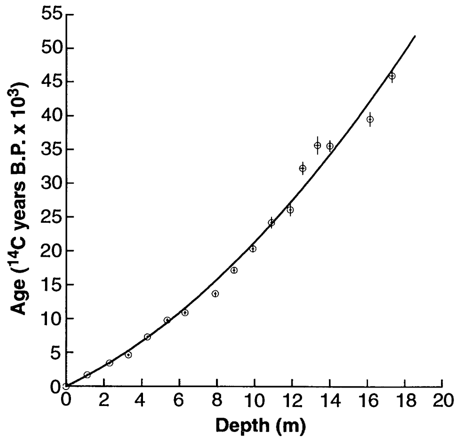

Fig. 1. Age-depth graph for the Lake Tulane core showing the points used to establish the age model and the curve fitted to the data. For each point the vertical bar represents ±2 SD except for the basal date (46,000), which is shown ±1,000 years. The fitted curve is a second-order polynomial with the sediment-surface date held constant (*32*): $Y = -34.0 + 13.5858X + 0.00781643X^2$.

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widespread, possibly associated with sand-dune activity. The maximum *Quercus* percentages of generally <40% are more typical of open woodland or savanna than of forest (*12*). The early Holocene is characterized by *Quercus* and Poaceae pollen, indicative of an open oak woodland, but differs from the Pleistocene *Quercus* intervals by having a lower abundance of *Ambrosia*-type and other forb pollen. The modern pine forest developed about 5000 years ago. In the late Holocene, the progression of perihelion to winter and the resultant increase in winter temperatures may have caused the development of the modern southeastern pine forest (*13*). However, this mechanism could not have caused the Pleistocene *Pinus* oscillations, which are more frequent than the 19,000-year and 23,000-year components of the precession periodicity.

We performed spectral analysis on the percent *Pinus* time series (Fig. 3) using the multi-taper method (*14–16*). The spectrum reveals significant peaks at periods of 5709, 3231, 2144, 1425, and 1224 years and the dominant periodicity at 5700 years is clear in the pollen diagram. Immediate causes of these oscillations are not apparent. The oscillations are of higher frequencies than the Milankovitch astronomical variations [100, 41, 23, and 19 ka (thousand years ago)], which influence the seasonal distribution of solar radiation that reaches the atmosphere. Although the Milankovitch frequencies are recognized in the marine oxygen-isotope record (*17*), higher frequencies reported in high-resolution marine records remain unexplained (*15*). Although periodic variations in solar radiation exist at even higher frequencies of <1,000 years (*18*), the causes of frequencies at 1,000 to 10,000 years remain unknown. The 1,224-year frequency in the Lake Tulane record is similar to that detected by Overpeck (*19*) in Holocene pollen time series from the Midwest. These time series suggest a quasi-periodic component to climate at the scale of 1,000 to 10,000 years, particularly at ~5,700 years.

Although the causes of the Lake Tulane *Pinus* variations are enigmatic, the peaks seem to correlate with the North Atlantic Heinrich events (Fig. 4). The Heinrich layers are a series of strata in sediments from the North Atlantic that are rich in ice-rafted lithic fragments and poor in foraminifera (*2–5*). Six of these layers were formed during marine oxygen-isotope stages 2 to 4, from ~12,000 to ~70,000 years ago. The layers contain carbonate rocks with source areas in eastern Canada and developed as a result of massive flows of icebergs from the eastern margin of the Laurentide Ice Sheet. Within the errors of the age models, a *Pinus* event matches Heinrich events H1 to H5. An extra *Pinus* event occurs between H3 and H4, but the double-peaked form of this event is matched by two smaller peaks in the Heinrich curve. Other minor variations in the two records seem to match as well. The fitted age-depth curve places the age of the *Pinus* peak that corresponds to H1 at ~15 ka (Fig. 2), whereas the direct radiocarbon date of this event is 13,730 ± 130 years B.P. (Table 1). The residual of this date from the fitted curve is the largest of any of the dates <30,000 years B.P. Thus, our age

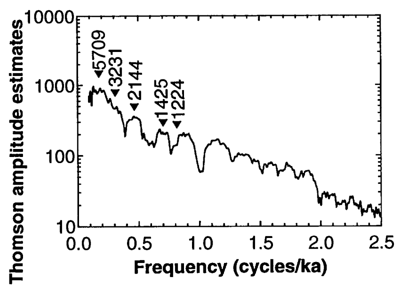

Fig. 3. Amplitude estimates for the multi-taper spectral analysis of the *Pinus* time series from Lake Tulane. Triangles indicate harmonic lines with *F*-test confidence levels >90% and are labeled with their period (years per cycle).

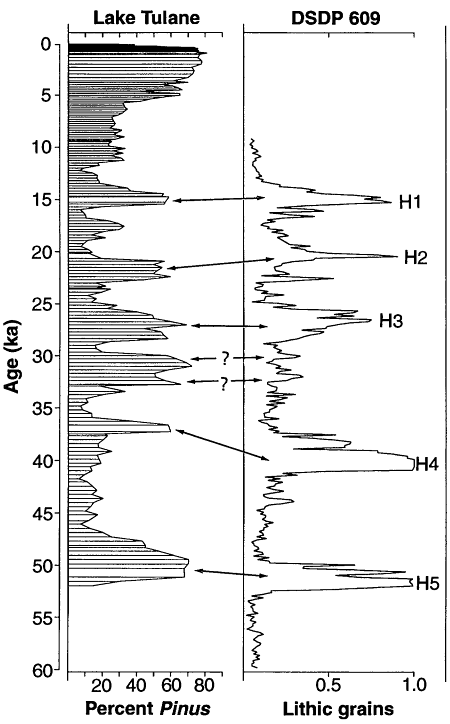

Fig. 4. Comparison of the Lake Tulane *Pinus* sequence and the lithic data from Deep Sea Drilling Project (DSDP) site 609 (*7*). The independent age model is used for each site, and the age model for DSDP 609 is from (*8*). The oldest radiocarbon date for DSDP 609 is 30,720 ± 730, and the older ages are determined by linear extrapolation. Heinrich events H1 to H5 are labeled. Heinrich layers occur in other deep-sea cores, but the most detailed analyses and best accelerator mass spectrometry radiocarbon dating are from DSDP 609 (*8*). For the lithic grain data, the total entities are >150 μm.

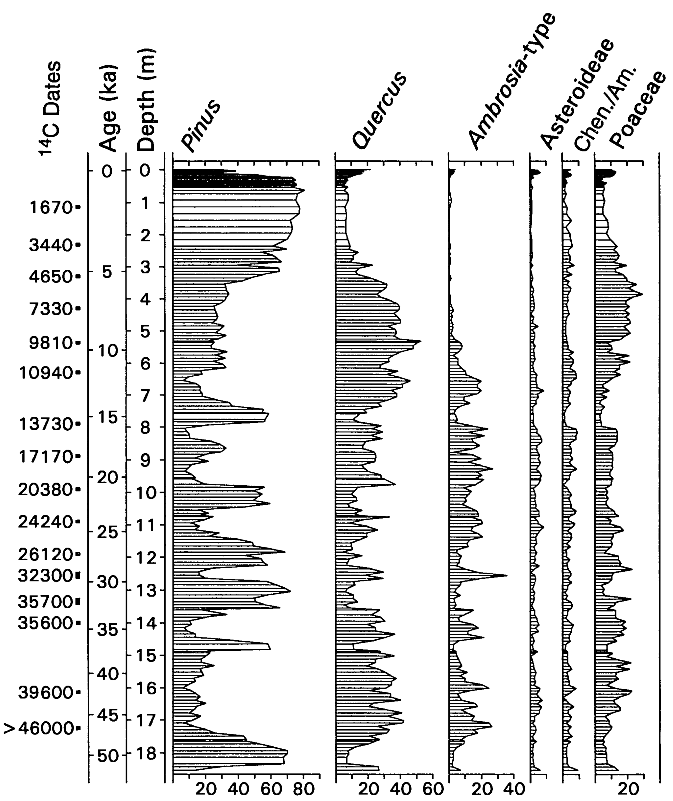

Fig. 2. Summary pollen diagram for Lake Tulane. Radiocarbon dates on left are those used for the age model. The age column indicates the fitted age model. Data for Asteroideae are for the undifferentiated types in the subfamily; Chen., Chenopodiaceae; and Am., Amaranthaceae.

model may place this peak ~1,000 years too old, although more dates for this event are necessary in both sediment records to establish its age definitively.

If events in the North Atlantic and the Florida peninsula are linked, their combined records may indicate hemispheric cooling, which caused ice streams from the Laurentide Ice Sheet to advance and altered the water balance in Florida in favor of *Pinus*. In this case, the primary effect on moisture balance may have been reduced temperature rather than increased precipitation. The foraminifera assemblages in the Heinrich layers provide some support for this hypothesis: They register cool sea-surface temperatures (SSTs) before the carbonate rock fragments from eastern Canada appear, suggesting that cooling preceded ice advance (*3, 4*). Heinrich events H1 and H2 and the corresponding *Pinus* events correspond well with the twofold late Wisconsin glacial maximum (*20*), with peaks at ~14 to 15 ka and ~20 to 23 ka.

Another possible mechanism is variation in cold meltwater emanating from the Mississippi River drainage (*21, 22*). Periodic influxes of cold meltwater could produce a cool freshwater cap on the Gulf surface, and model results indicate that cooler Gulf SSTs would shift the Bermuda high westward, producing a drier climate in the Gulf region. Although assumption of a cold meltwater cap is reasonable, it has little direct evidence. On the basis of a qualitative analysis of foraminifera assemblages in Gulf cores, Flower and Kennett (*23*) inferred that SSTs were cooler during the Younger Dryas, a time of low meltwater, and warmer during the preceding meltwater pulse at 12 ka. However, the results of a quantitative study of foraminifera assemblages from one of the same cores (EN32-PC4) show little change in SST during the Younger Dryas and no evidence for cooler SSTs during the meltwater pulse (*24*). The foraminifera assemblages may indicate unusual salinity conditions that resulted from major freshwater input. Moreover, cold freshwater may have formed a relatively thin cap on the Gulf surface, which supported few foraminifera or odd assemblages, with most of the foraminifera living in the more saline water below.

For isotope stage 2, the evidence is consistent with the climate-model experiments. Geological evidence (*25, 26*) and stable isotope records from the Gulf (*23, 27*) indicate a major meltwater pulse at ~12 ka with approximately five times the normal flow down the Mississippi (*26*). The meltwater pulse is coincident with low *Pinus* values at Lake Tulane, low lake levels throughout Florida (*7*), and dry conditions in Texas (*28*). Heinrich and *Pinus* events at ~20 to 23 ka and ~14 to 15 ka are coeval with the twofold glacial maxima in both the eastern and midcontinent sectors (*20*). For isotope stage 3 the Heinrich layers provide evidence for glacial advances in the eastern sector, but the midcontinent glacial history is poorly known for this period (*29*). However, the Roxana Silt (loess) deposited during this time indicates that glaciation spread into the northern Mississippi drainage. The loess deposition was discontinuous, but paleosols within the loess are poorly dated and correlation with other stage 3 events is uncertain. Fossil-pollen sequences from Farmdalian (~28 to 22 ka) sediments in Illinois and Iowa indicate a relatively warmer climate. From ~28 to 25 ka *Pinus* was abundant, whereas *Picea* (spruce) increased after ~25 ka, which indicates a cooler climate (*30*). The apparently warmer *Pinus* phase in the midcontinent coincides with Heinrich event H3 and ice advance in the eastern sector. Therefore, the Farmdalian record would seem to refute the advance of glaciers in the midcontinent, unless stage 3 is fundamentally different from stage 2. Perhaps stage 3 glacier advances were ice-stream surges and consequently not associated with colder climates some distance to the south.

North Atlantic thermohaline circulation opposes the influence of Mississippi River drainage. Today the Gulf of Mexico receives warm water by the loop current, which circulates warm water into the Gulf from the Caribbean (*21, 31*). This current, a branch of the Gulf Stream, would have operated normally between Heinrich events but may have diminished during these events (*4*). This decrease in current would have reduced the delivery of warm water to the Gulf. The pumping of warm water by the loop current into the Gulf between Heinrich events would have countered Mississippi meltwater effects. However, temperatures at the sea surface, where evaporation occurs, rather than overall water-column temperatures may be most strongly related to the presence or absence of a meltwater cap.

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