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A 1200-year proxy record of hurricanes and fires from the Gulf of Mexico coast: Testing the hypothesis of hurricane–fire interactions

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Abstract

We present here the first high-resolution pollen record of vegetation response to interactions of hurricane and fire disturbances over the past 1200 yr from a small lake in Alabama on the Gulf of Mexico coast. The paleotempestological record inferred from the overwash sand layers suggests that the Alabama coast was directly struck by Saffir–Simpson category 4 or 5 hurricanes twice during the last 1200 yr, around 1170 and 860 cal yr BP, suggesting an annual landfall probability of 0.17% for these intense hurricanes. The charcoal data suggest that intense fires occurred after each of these hurricanes. The pollen data suggest that populations of halophytic plants (Chenopodiaceae) and heliophytic shrubs (*Myrica*) expanded after the hurricane strikes, probably due to saltwater intrusion into the marshes and soil salinization caused by overwash processes. Populations of pines (*Pinus* sp.) decreased significantly after each intense hurricane and the ensuing intense fire, suggesting that repeated hurricane–fire interactions resulted in high tree mortality and probably impeded recruitment and recovery. Our data support the hypothesis that the likelihood and intensity of fire increased significantly after a major hurricane, producing responses by vegetation that are more complex and unpredictable than if the disturbance agents were acting singly and independently.

Keywords: Paleotempestology; Hurricanes; Fires; Pollen; Charcoal; Overwash; Coastal lakes; Gulf of Mexico

Introduction

Hurricanes and fires are two of the most frequent large-scale disturbances affecting ecosystems along the U.S. Gulf of Mexico coast. During the past century, the Gulf coast has been repeatedly struck by intense hurricanes (here defined as Saffir–Simpson category 3, 4, or 5) (Elsner and Kara, 1999), including Hurricanes Charley and Ivan of 2004 and Hurricanes Dennis, Katrina, Rita, and Wilma of 2005. The ecological impacts of hurricanes on the coastal forests of the southeastern U.S.A. and the pan-Caribbean region have been well documented in the literature (Craighead and Gilbert, 1962; Lugo et al., 1983; Weaver, 1989; Boucher, 1990; Boucher et al., 1990; Frangi and Lugo, 1991; Gardner et al., 1991; Gresham et al., 1991; Hook et al., 1991; Putz and Sharitz, 1991; Tanner et al., 1991; Walker, 1991; Whigham et al., 1991; Yih et al., 1991; Loope et al., 1994; Zimmermann et al., 1994; Armentano et al., 1995; Bellingham et al., 1995; Conner, 1995; Everham and Brokaw, 1996; Platt et al., 2000; Batista and Platt, 2003).

In addition to hurricanes, fires also play a major role in coastal and upland forests in the southeastern U.S.A. In the summer of 1998, for example, wildfires destroyed 500,000 acres (202,343 hectares) of forests in Florida alone (Graumann et al., 1998). Many ecosystems in this region, particularly the southeastern pine savanna and pine-dominated forests, are fire-prone and fire-adapted (Komarek, 1974; Glitzenstein et al., 1995; Platt, 1999; Beckage and Stout, 2000; Beckage et al., 2003). Wildfires are a common occurrence in the Gulf coast region due to a combination of reasons. This coastal zone has the highest frequency of thunderstorm days in the nation (USGS, 1970), coupled with a high frequency of lightning (Curran et al., 1997; Marshall Space Flight Center, 1998). The occurrence of pronounced wet and dry seasonal precipitation fluctuations,

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which are accentuated by global climate processes such as the El Nino Southern Oscillation (ENSO), further enhances the fire hazard (Beckage et al., 2003).

Large-scale disturbances like hurricanes and fires can interact to produce ecological effects that are more complex than would have been caused by these disturbance agents acting individually (Platt et al., 2002). One important aspect of such interactions, as hypothesized by Myers and van Lear (1998), is that the probability of a major wildfire increases significantly after an intense hurricane. According to this hypothesis, the post-hurricane increase in fire hazard results from an increase in fuel accumulation caused by abundant dry litter on the forest floor, as well as the creation of a drier microclimate as a result of increased insolation and higher wind speed under a more open canopy (Myers and van Lear, 1998). Although the notion of post-hurricane fire hazard has been postulated in several ecological studies of hurricane impacts (Webb, 1958; Craighead and Gilbert, 1962; Putz and Sharitz, 1991; Wade et al., 1993; Loope et al., 1994), there are no empirical data to support the hypothesis. The lack of modern case studies of major fire outbreaks after a recent hurricane strike could be a result of fire suppression and post-hurricane mitigation efforts conducted by modern societies, which alter the fire regime of natural ecosystems. Thus, data on hurricane and fire occurrences during the historic or prehistoric period should provide the most appropriate tests of the hurricane–fire interaction hypothesis.

In this paper we present a 1200-yr history of hurricanes and wildfires at one locality on the Gulf of Mexico coast. We reconstructed this history using the principles and methods of paleotempestology (Liu, 2004, 2007). The proxy record is mainly based on the study of sediment stratigraphy, pollen, and microscopic charcoal in a core taken from Little Lake in coastal Alabama. These data were used to test the hypothesis that major fires tend to follow intense hurricanes. The coupling of pollen and charcoal data having high-temporal resolution with the paleotempestological record also permits reconstruction of the ecological effects of past hurricanes and sheds light on the vegetation response to compounded perturbations due to both hurricanes and fires.

The study site

Little Lake (30°16.38′N, 87°36.92′W) is a freshwater coastal lake situated in Gulf State Park between Gulf Shores and Orange Beach, Alabama (Fig. 1). This oval-shaped lake is about 600 m long, 1.2 m (4 ft) deep, and has a flat bottom. It is the smallest and the innermost of three coastal lakes (Little Lake, Middle Lake, Lake Shelby) enclosed by a complex system of beach ridges that may have formed at different times after the mid-Holocene (Liu and Fearn, 1993). The beach ridge plain separating Little Lake from the Gulf of Mexico is about 1.1 km wide, and is fringed on the seaward side by a sandy beach with 1–2 m high dunes. The narrow land strip behind the beach has largely been converted to paved roads (state highway 182) and buildings. Little Lake is surrounded by flat topography and has a very limited drainage basin. It receives no inflowing stream and does not flow directly into the sea. It drains into Middle Lake downstream through a small channel, Middle River. Middle Lake is in turn connected with the much larger Lake Shelby by an artificial canal dug in the 1960s (Liu and Fearn, 1993). Lake Shelby ultimately drains into Little Lagoon, a sheltered arm of the Gulf behind a barrier beach, through a small river flowing to the west. None of the three lakes has an active tidal connection to the open waters of the Gulf of Mexico. Salinity measured in Little Lake in the summer of 1997 was 0.1 ppt.

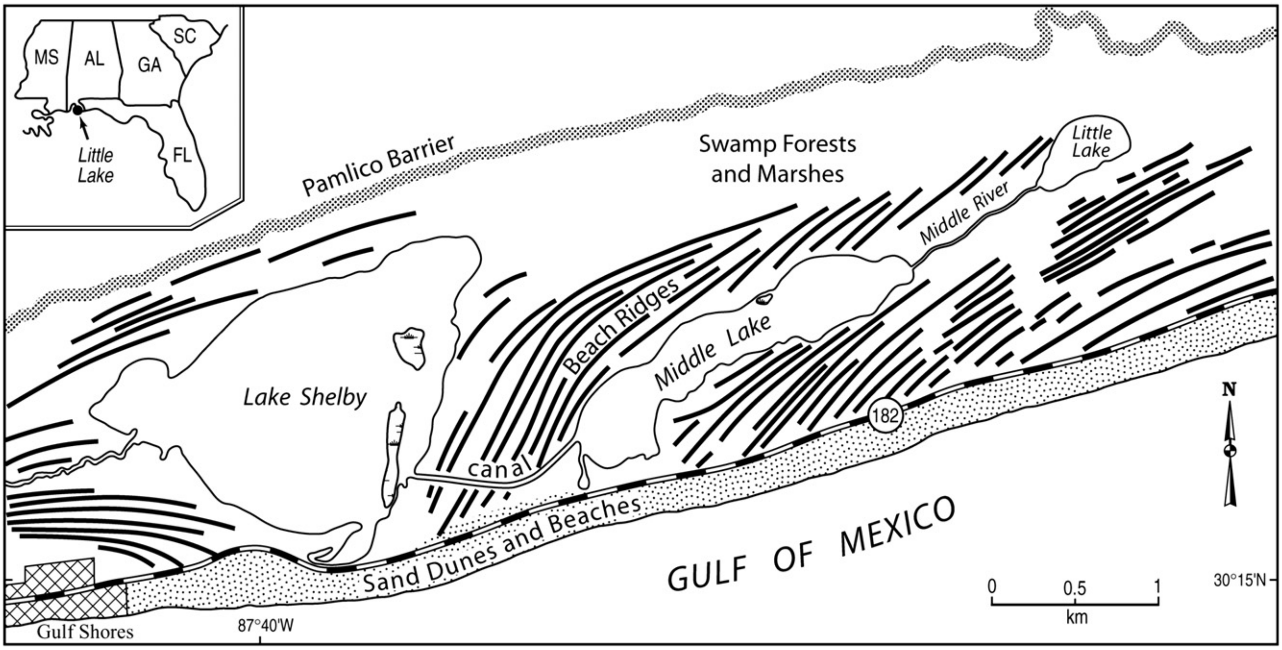

Figure 1. Map showing the location and geomorphic setting of Little Lake, Middle Lake, and Lake Shelby in coastal Alabama. Thick black lines are beach ridges. Black and white line is Alabama State Highway 182.

Vegetation around Little Lake is a subtropical maritime forest characterized by a diverse association of pines (*Pinus* spp.), oaks (*Quercus* spp.), hickories (*Carya* spp.), hollies (*Ilex* spp.), waxmyrtle (*Myrica cerifera*), magnolias (*Magnolia* spp.), and sweetgum (*Liquidambar styraciflua*). Pines and sclerophyllous oaks are especially abundant on the sandy beach ridge plain and in drier sites, often with saw palmetto in the understory. Like many pine-dominated communities in the southeastern U.S., the vegetation around Little Lake is a fire-adapted ecosystem. Extensive areas of marshes, swamps, and pitcher-plant bogs occur to the north and west of Little Lake, especially between the beach ridge plain and the Pamlico Barrier (a paleo-shoreline of probable Sangamonian interglacial age) behind the lakes. Swamps and marshes also occur along the small river that links Little Lake with Middle Lake.

Since 1900, 6 major hurricanes have made landfall on or near the Alabama coast—in 1906, 1916, 1926, 1979, 2004, and 2005 (Neumann et al., 1999). The two most destructive hurricanes that directly struck the Alabama coast were Frederic of 1979 and Ivan of 2004; both were category 3 hurricanes with a sustained wind speed of about 130 mph at landfall. The 3- to 4-m-high storm surges breached the barrier beaches and dune fields at the southern ends of Lake Shelby and Middle Lake, causing sand deposition and saltwater intrusion into these otherwise oligohaline lakes downstream from Little Lake. Little Lake was also affected by overwash processes and storm surge inundation, although the beach ridge plain south of the lake was not breached.

Materials and methods

A short core (core 3), about 60 cm long, was collected by means of a piston corer from a site slightly west of the center of Little Lake (Fig. 1). In the laboratory, the core was sampled at 1-cm interval continuously for loss-on-ignition analysis (Dean, 1974). The sediment samples were heated at 105°C, 550°C, and 1000°C to determine the water content, organic matter content, and carbonate content, respectively. Loss-on-ignition analysis has been proven to be an effective way to reveal lithological changes in lake-sediment cores and to detect the presence of overwash sand layers (Liu and Fearn, 2000; Shuman, 2003).

Sixty consecutive samples of 0.9 ml were taken at 1-cm intervals for pollen and charcoal analyses. Chemical processing for pollen and charcoal analyses followed standard laboratory procedure, which involved treating the samples with 10% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), 49% hydroflouric acid (HF), acetolysis solution, glacial acetic acid, and tertiary butanol alcohol (TBA) (Faegri and Iversen, 1975). During chemical treatment, the samples were stirred gently with a wooden applicator to ensure thorough contact between sediment and the chemical, but caution was taken not to cause excessive breakup of fragile pollen and charcoal particles. One *Lycopodium* tablet containing 12,542±200 spores was added to each sample before chemical processing to permit estimation of pollen and charcoal concentration in the sample (Stockmarr, 1971). The residues were suspended in silicone oil and mounted on microscopic slides for pollen and charcoal counting.

At least 300 pollen grains were counted in each sample. For *Pinus* (pine) pollen, the intact and broken grains were tallied separately. The number of broken pine pollen (usually fragments of the saccus or corpus) was summed and divided by 3, and that quotient was added to the number of intact pine pollen for the calculation of total *Pinus* percentage in each sample. The abundance of broken pine pollen was also calculated as a percentage of total pine pollen, and this percentage was used as a measure of the degree of mechanical breakage during deposition or during laboratory processing (see below). Dinoflagellates, a marine microorganism, were counted on the same slide as pollen; their presence was used as an indicator of saltwater influx into this freshwater lake. Microscopic charcoal was also counted on the same slide. Only those charcoal fragments >10 μm in size were counted. Charcoal counts ranged from 57 to 515, but for most samples the counts were between 100 and 400.

Diatom analysis was performed on 12 samples from selected levels to provide broad indications of salinity. Because few diatom valves are preserved in the thick sand layers, we used heavy liquid for the floatation of diatoms. The basic steps were: (1) remove organic matter by using hydrogen peroxide (H_2O_2); (2) remove carbonates by using 10–15% hydrochloric acid (HCl); (3) flotation by using a zinc bromide ($ZnBr_2$, density 2.35 g/cm^3) heavy liquid. The final residue contained diatom and other siliceous microfossils such as sponge spicules and phytoliths. The biogenic silica residues were permanently mounted on glass microscopic slides with Canada Balsam. More than 350 diatom valves were counted in each sample.

Results

Sediment stratigraphy and radiocarbon dates

Core 3 consists of 50 cm of gyttja overlying 10 cm of coarse sand at the base (Fig. 2). The gyttja has very high contents of water (>80% wet weight) and organic matter (50–60% dry weight). The lower part of the gyttja section contains two distinct layers of coarse sand, at 31–32 cm and 46–47 cm, which are registered in the loss-on-ignition curves by abrupt drops in water content (to 60–70%) and organic content (to 20–25%). The loss-on-ignition data also reveal the presence of five less distinct clastic layers at 6, 12, 21, 24, and 37 cm. These thin layers are reflected by significant drops in the organic matter content (to 40–55%) but only slight decreases in water content, suggesting that they are composed mostly of fine sand or silt mixed with lake mud.

Two AMS radiocarbon dates of 1250±50 ^{14}C yr BP (Beta 114473) and 1220±50 ^{14}C yr BP (Beta 175604) were obtained from the organic sediment below and above the second sand layer in core 3, at 47–49 cm and 44 cm, respectively. A date of 920±50 ^{14}C yr BP (Beta 175603) was obtained at a level of 30 cm, immediately above the first distinct sand layer. These ^{14}C dates are calibrated to about 1170, 1160, and 860 cal yr BP, respectively (Table 1).

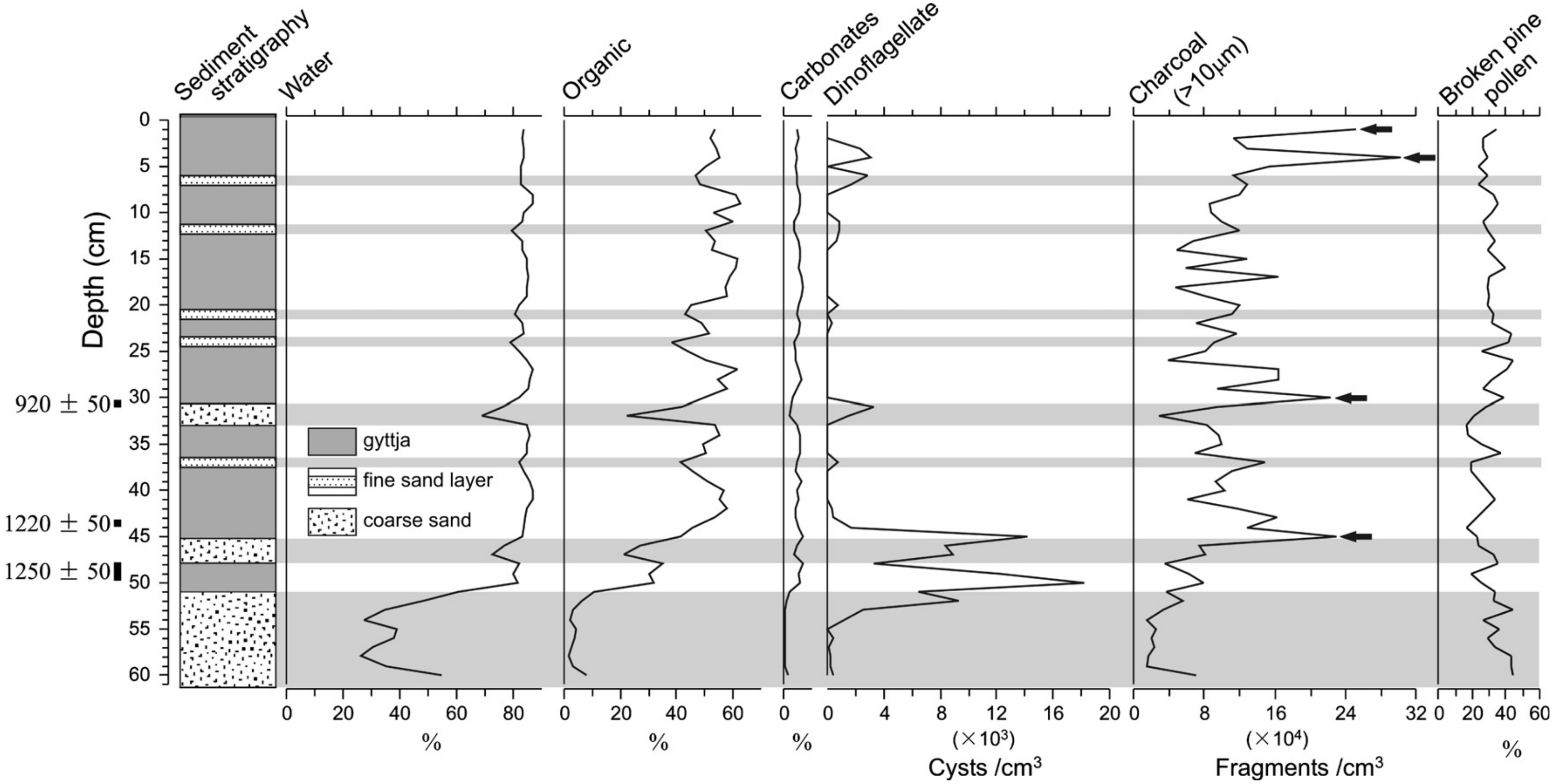

Figure 2. Radiocarbon-dated sediment stratigraphy, loss-on-ignition curves (showing percentages of water, organic matter, and carbonate contents), and abundance curves for dinoflagellates, microscopic charcoal, and broken pine pollen (as a percentage of total pine pollen) for core 3 from Little Lake. The four most prominent charcoal peaks are denoted by arrows.

Table 1
Radiocarbon dating results from Little Lake, core 3

Lab no.	Core depth (cm)	Conventional ^{14}C age (yr BP)	Intercept calibrated age (cal yr BP)	2-sigma calibrated range (cal yr BP)
Beta-175603	31	920±50	890 (AD 1060) 860 (AD 1080) 800 (AD 1150)	940 to 720
Beta-175604	43	1220±50	1160 (AD 790)	1270 to 1040 1030 to 1000
Beta-114473	47–49	1250±50	1170 (AD 780)	1280 to 1060

Pollen and charcoal stratigraphies

Thirty-five pollen and spore taxa were identified from 60 samples in core 3 (Figs. 3 and 4). The major taxa (defined as those occurring at >5% in at least one level) are *Pinus, Quercus, Myrica, Ilex, Taxodium,* Poaceae, Cyperaceae, Chenopodiaceae, and Polypodiaceae (monolete spores). *Pinus* is undoubtedly the dominant pollen type, accounting for 25–70% of the pollen sum. About 20–45% of the *Pinus* pollen are broken, but the percentages of broken pine pollen show no stratigraphic relationship with the occurrence of the clastic layers (Fig. 2). Overall, the percentage pollen diagram does not show any clear stratigraphic trends, except that *Pinus* is somewhat more frequent in the lowest part of the core (48–60 cm) and *Myrica*, Poaceae, and Chenopodiaceae seem to increase distinctly above that. Total pollen concentration values range from 85,500± 53,700 grains/cc in the basal sand (50–60 cm) to 175,700± 94,500 grains/cc in the uppermost levels (1–49 cm) of the core. A rise in *Ambrosia* pollen occurs at the 7-cm level in the pollen concentration diagram (Fig. 4), which is also evident though less distinct in the pollen percentage diagram (Fig. 3). The pollen diagrams are not divided into pollen assemblage zones due to their lack of clear, long-term trends.

Charcoal abundance is low (20,000–60,000 fragments per cc) in the sand at the bottom of the core, but becomes much higher (40,000–286,000 fragments per cc) in the gyttja section. The curve for microscopic charcoal fragments has multiple peaks and troughs, but four prominent peaks stand out at 1 cm, 4 cm, 30 cm, and 45 cm (Fig. 2). The latter two of these four peaks occur immediately above the two distinct sand layers, and another peak occurs above the first clastic layer near the top of the core. The uppermost charcoal peak occurs at the top of the core and is not associated with any clastic layer.

The charcoal peaks represent wildfires and not simply an artifact of increased breakup of charcoal into smaller fragments during laboratory processing. Charcoal abundance is lower in the sand layers and the bottom sand than in the organic sediments, suggesting that increased attrition or breakage in a sandy matrix is not affecting the charcoal counts. Moreover, there is no evidence of increased percentages of broken *Pinus* pollen in the same samples containing the charcoal peaks (Fig. 2). This further suggests that charcoal abundance in the core cannot be explained by the mechanical breakup or increased fragmentation of charcoal during the depositional process or as a function of the laboratory procedure.

Dinoflagellate and diatom stratigraphies

Diatoms occur abundantly in the core (Fig. 5). Fresh and oligohaline species dominate the gyttja section above 50 cm, particularly *Melosira granulata, Nitzschia scalaris, Eunotia pectinalis,* and *E. maior*. The thick sand layer at the bottom of the core is still dominated by freshwater to oligohaline species (*Diploneis ovalis* and *Rhopalodia giberula*), albeit of a different assemblage, but it also contains an array of marine species like *Diploneis bombus, Nitzschia granulata, Campylodiscus echeneis, Actinocyclus* sp., and *Coscinodiscus* sp.

Dinoflagellate cysts occur abundantly in the lower part of the core from 54 to 44 cm, especially at the top of the bottom sand and in and above the distinct sand layer at 46–47 cm (Fig. 2). They are absent at the core top and in most samples in the gyttja section above 44 cm, but virtually all the sporadic peaks are associated with the sand or silt layers.

Discussion

Reconstructing a millennial history of paleohurricane strikes

The seven clastic layers (two thick sand layers and five thin sand/silt bands) are probably storm deposits formed by intense hurricane strikes. Little Lake is a small, quiet-water lake unaffected by any fluvial input or slope wash. Under normal circumstances, only highly organic sediments (organic matter content 50–60%) accumulate on the lake bottom. Thus it takes high-energy events, most likely storm surge or overwash processes associated with intense hurricane landfalls, to mobilize the sand or silt and deposit them in the center of the lake. This interpretation is supported by the dinoflagellates, which show clearly that deposition of the clastic layers is accompanied by intrusion of seawater into this otherwise freshwater lake.

Hurricane overwash, or storm surge associated with an intense hurricane strike, is the only mechanism that can generate these high-energy events with seawater influx. There is no evidence of earthquakes or tsunamis affecting the Alabama coast in the historical record. The data cannot be explained by any other fluvial or lacustrine processes, (Otvos, 1999; Liu and Fearn, 2002; Liu, 2004). Support for the overwash origin of sand layers like these comes from phytolith evidence recovered from Western Lake, Florida—another paleotempestological study site on the Gulf coast. In that study Lu and Liu (2005) have demonstrated that the sand in the sand layers was derived

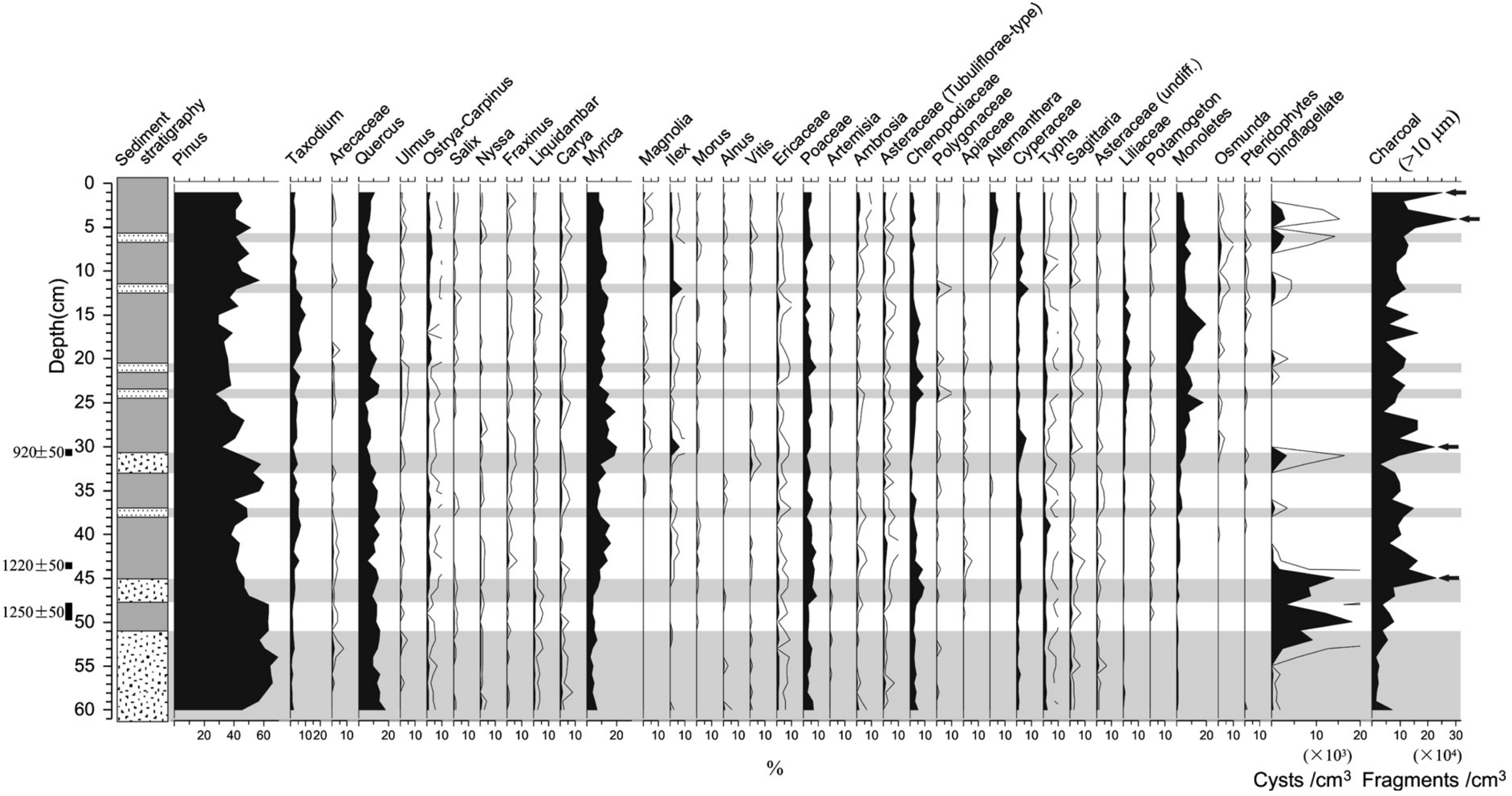

Figure 3. Pollen percentage diagram from core 3 of Little Lake. The dinoflagellate and charcoal curves are added on the right to facilitate comparison. Ages in left-had column are ^{14}C yr BP.

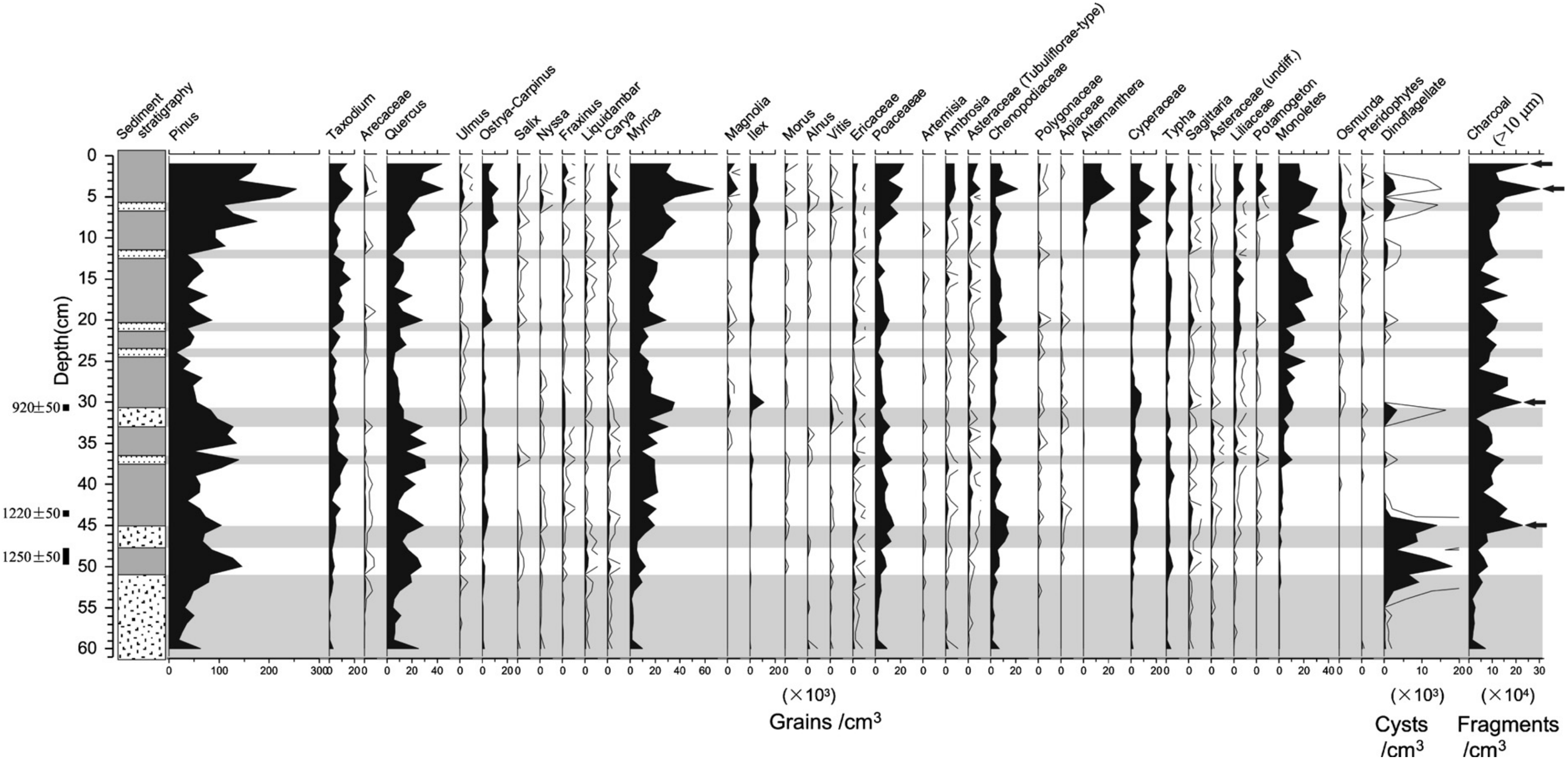

Figure 4. Pollen concentration diagram from core 3 of Little Lake. The dinoflagellate and charcoal curves are added on the right to facilitate comparison. Ages in left-had column are ^{14}C yr BP.

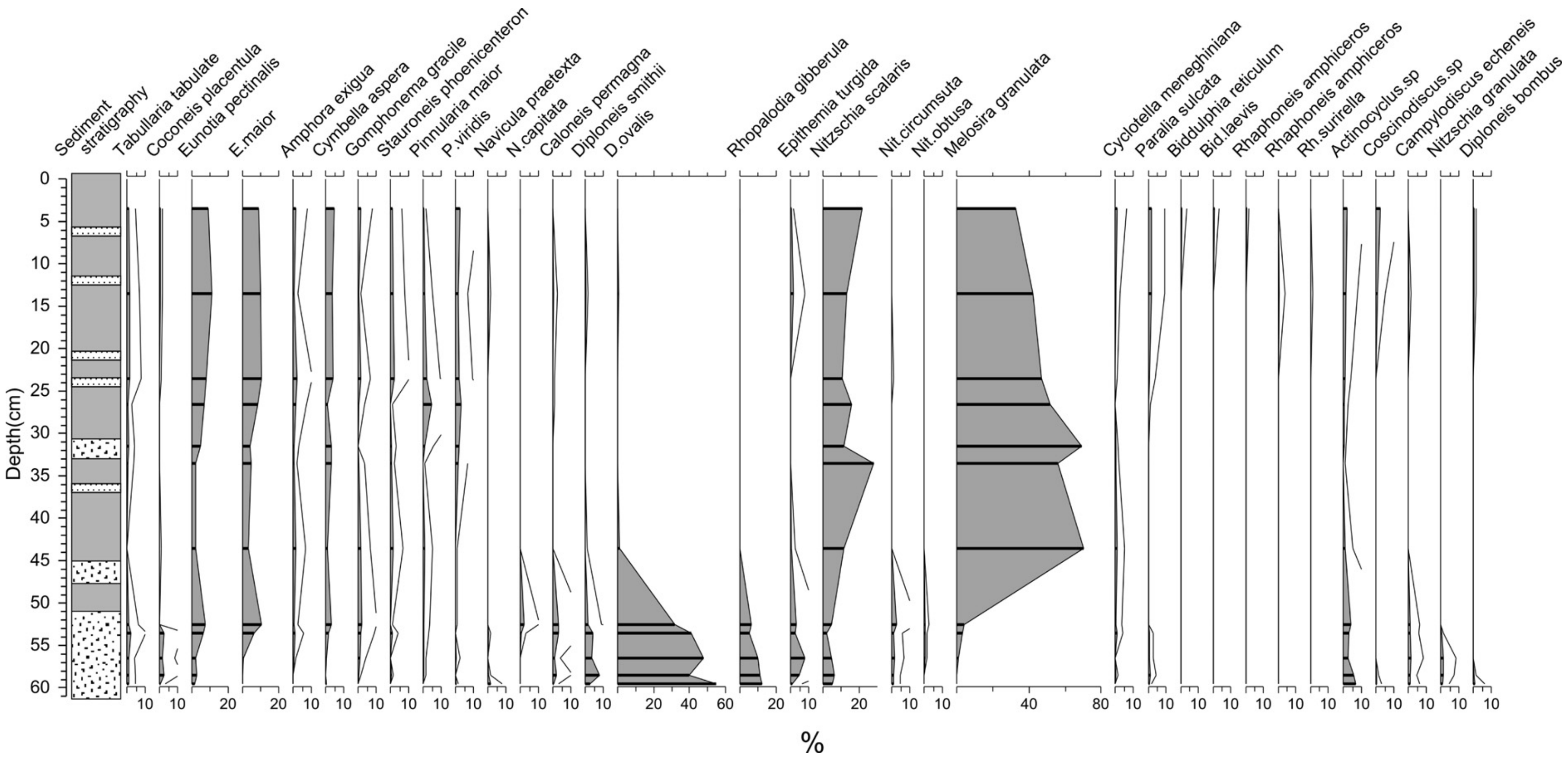

Figure 5. Diatom stratigraphy from core 3 of Little Lake.

from the sand dunes, thus showing that the sand layers must have been formed by overwash processes that washed the sand from the dunes into the lake bottom. Direct evidence suggesting that these sand layers were probably caused by direct strikes by intense hurricanes comes from Hurricane Ivan, a strong category 3 hurricane that made landfall near Gulf Shores in September 2004. Ivan's approximately 3-m storm surge washed sand from the beach ridge plain into the southeastern edge of Little Lake (Bianchette, 2007). The modern analog provided by Hurricane Ivan implies that it would have taken direct strikes by intense hurricanes as strong as Ivan to deposit the sand layers in Little Lake.

The five thin sand/silt layers, which have interpolated ages of approximately 166, 332, 583, 666, and 1010 cal yr BP, are thus probably attributable to strong category 3 hurricanes. However, the two distinct sand layers in the lower part of the core were probably formed by overwash processes that occurred during direct strikes by catastrophic hurricanes of category 4 or 5 intensity. The sand was probably derived from the dunes and beach ridges on the coastal plain south of Little Lake. That such overwash processes had occurred in the past is witnessed by a break in the beach ridges to the southwest of the lake (Fig. 1), which indicates truncation by an overwash event of unknown age. During the past century no catastrophic hurricane of category 4 or 5 intensity has directly struck the Little Lake area, and except for Ivan none of the other hurricanes of category 1–3 intensity that made landfall on or near the Alabama coast was strong enough to wash over the 1.3-km-wide beach ridge plain and directly deposit sand into Little Lake. Therefore, it can be inferred that the two overwash sand layers were formed by catastrophic hurricanes of category 4 or 5 intensity.

Comparison with the proxy record from neighboring Lake Shelby further supports the notion that the two overwash sand layers were probably caused by category 4 or 5 hurricanes. The two thick sand layers in Little Lake have been ^{14}C dated to 1250 ± 50 and 1220 ± 50 ^{14}C yr BP, and 920 ± 50 ^{14}C yr BP, respectively, suggesting that the two overwash events occurred about 1170 and 860 cal yr ago (Table 1). These are similar to two major overwash sand layers in a series of sediment cores from neighboring Lake Shelby that have been directly dated to 1330 ± 60 and 1360 ± 80 ^{14}C yr BP, and 770 ± 70, 770 ± 60, and 980 ± 60 ^{14}C yr BP (Liu and Fearn, 1993), which have overlapping calibrated age ranges with those from Little Lake. Liu and Fearn (1993) have established that the sand layers from Lake Shelby reflect direct hits by hurricanes of category 4 or 5 intensity. This conclusion has been supported recently by a statistical study that infers the return level (intensity) of past hurricanes hitting Lake Shelby from the return period (frequency) of hurricanes documented from the historical and proxy records (Elsner et al., in press). The Little Lake record complements the Lake Shelby record, suggesting that the same hurricanes that caused overwash into Little Lake 1170 and 860 yr ago also caused overwash into Lake Shelby. This is the first time in paleotempestological studies that overwash sand layers caused by the same paleohurricanes occur in two neighboring lakes.

The thick sand deposit at the bottom of the core (60–50 cm) is probably another overwash sand layer that represents a major hurricane landfall occurring prior to 1170 cal yr BP. This deposit is not a basal sand or beach sand underlying the lake basin, because it contains abundant dinoflagellates and a diatom assemblage dominated by freshwater to oligohaline species (*Diploneis ovalis*) mixed with some marine taxa, suggesting the intrusion of seawater into a limnic or lagoonal environment. Moreover, new cores taken from Little Lake have penetrated this sand layer, revealing more gyttja or lagoonal clay below this stratigraphic level.

Reconstruction of fire history

The abundance of charcoal throughout the core suggests that wildfires have been a common occurrence in the pine-dominated, thunderstorm-frequented environment of coastal Alabama. Here we focus on the four highest charcoal peaks that represent the four most intense wildfires of the last 1200 yr. Of the four most prominent charcoal peaks, the two lower ones (at 45 cm and 30 cm) occur immediately above the distinct sand layers of 45–47 cm and 31–33 cm, respectively, suggesting that major fires occurred after the hurricane strikes. Although the time interval between the hurricane and fire events cannot be more precisely estimated, it can be inferred from the interpolated sedimentation rate (25 yr per cm) that the major fire occurred within 25 yr of the catastrophic hurricane strike. The third prominent charcoal peak (at 4 cm) also occurs only slightly above the uppermost clay layer (at 6 cm), suggesting that fire occurred within 50 yr of an intense hurricane strike. The charcoal peak occurring at the core top (1 cm) is the only prominent one that is not associated with a storm layer. This charcoal peak may be attributed to the fire of June 26–July 4, 1968, which burned for many days along the Alabama coast, the largest in recent history (Foley Onlooker, 1968). This fire was started by arson and was not associated with any intense hurricane strike on the Alabama coast.

Less pronounced charcoal peaks at 37 cm, 23 cm, 20 cm, and 12 cm are also associated with storm-generated clastic layers. These suggest that less intense, but still significant, fires occurred after strikes by all major hurricanes. However, the occurrence of some charcoal peaks in gyttja (e.g., at 15, 17, 27–28, and 43 cm) independent of the storm layers indicates that fire could occur with or without hurricanes.

Testing the Hypothesis of Hurricane–Fire Interactions

The fact that three of the largest wildfires in coastal Alabama during the last 1200 yr occurred shortly after an intense hurricane strike implies a linkage between hurricanes and fires. The notion of increased fire hazard after a hurricane strike has been postulated in a number of ecological studies of hurricane impacts (Webb, 1958; Craighead and Gilbert, 1962; Putz and Sharitz, 1991; Wade et al., 1993; Loope et al., 1994). Based on his observations of "cyclone scrubs" and other tropical lowland rainforest vegetation types in cyclone-prone northern

Queensland, Australia, Webb (1958, p. 225) speculated that "When periods of dry, hot weather follow cyclone damage, fire risk is great, even in mesic tropical rain-forests traditionally regarded as immune to fire. The abundance of fallen branches and suspended dead vine, and of fragmented shriveled leaves, provides ideal conditions for the entrance of fires from adjacent sugar cane farms". In the U.S., similar speculations were made after Hurricane Hugo, a category 4 storm, devastated the forests of South Carolina in 1989: "With the immense amounts of timber downed, there is concern about fire and insect outbreaks. Southern pine beetles and ips beetles are likely to be serious problems next year, and the fire hazard level is extreme" (Boucher, 1990, p. 164). Recently, Myers and van Lear (1998) hypothesized that the probability of an intense wildfire increases significantly after a severe hurricane strike. According to this hypothesis, the post-hurricane increase in fire hazard is attributed to an increase in fuel accumulation caused by a greater abundance of dry litter on the forest floor, as well as the creation of a drier microclimate due to increased insolation and higher wind speed under a more open canopy (Myers and van Lear, 1998).

Despite its well-founded premises, few empirical data or direct observations are available to test this hypothesis of hurricane–fire interactions. The only reference to an actual fire outbreak after an intense hurricane strike in the U.S. is found in Craighead and Gilbert (1962, p. 26), who reported briefly that "Very severe fires followed the 1935 hurricane". These post-hurricane fires, which occurred in the dry season and were probably of anthropogenic origin, devastated the mahogany populations in the hardwood hammocks in the Everglades of South Florida. Elsewhere, dry-season fires after Hurricane Gilbert of 1988 were found to have caused significant tree mortality in the tropical dry forests of the northeastern Yucatan in Mexico (Whigham et al., 1991). However, no major or intense fires have been documented in the years after recent strikes by intense hurricanes such as Camille, Frederic, Hugo, Andrew, or Ivan. The lack of a modern case example of a major fire outbreak after a recent hurricane strike in the U.S. can be attributed to the success of fire suppression and post-hurricane mitigation efforts, which alters the natural fire regime of forest ecosystems. Consequently, this hypothesis may not be easily testable based on hurricane and fire data from modern societies, where human intervention is an important factor disrupting the hurricane–fire interactions. Thus, proxy data on hurricane and fire occurrences during the historic or prehistoric period without human interventions are needed to test this hypothesis.

The availability of proxy data on both paleohurricanes and wildfires from the same core in Little Lake provides a unique opportunity to empirically test the hypothesis of hurricane–fire interactions. The sedimentary and charcoal records show that coastal Alabama was directly struck by catastrophic hurricanes twice during the last 1200 yr, and a major fire followed each hurricane strike. Another major fire also occurred within a few decades of an intense hurricane strike during the early 19th century. The data from Little Lake do lend support to the hypothesis of hurricane–fire interactions.

Vegetation response to multiple disturbances and hurricane–fire interactions

The cm-by-cm continuous sampling of the core permits the reconstruction of a long-term and high-resolution (approximately 25 yr per sample) pollen record of vegetation response to multiple and interacting disturbances from hurricanes and fires in coastal Alabama. Although the vegetation response to hurricane or fire disturbance has been documented in several studies in the U.S. Gulf coast region (e.g., Craighead and Gilbert, 1962; Touliatos and Roth, 1971; Armentano et al., 1995; Slater et al., 1995; Menges and Deyrup, 2001; Batista and Platt, 2003), few studies (e.g., Platt et al., 2002) examine how coastal ecosystems respond to "compounded perturbations" (Paine et al., 1998) such as interacting hurricane and fire disturbances. Platt et al. (2002) found that prior fire regime, especially anthropogenic dry-season fires, has a strong effect on the mortality of south Florida slash pines during and after hurricane strikes, but studies are lacking on how vegetation responds to post-hurricane fires. Moreover, all of these ecological studies are based on short-term observations of vegetation response or forest recovery only several years or at the most a few decades after a hurricane strike, and data on long-term successional patterns and processes are notably lacking. Our high-resolution pollen data from Little Lake, coupled with the storm deposits and charcoal stratigraphy from the same core, offers an excellent opportunity to examine the long-term vegetation response to hurricane–fire interactions.

The most notable post-hurricane change in the pollen stratigraphy is an increase in the pollen percentages of Chenopodiaceae above the two prominent overwash sand layers. The family Chenopodiaceae includes halophytic plants that commonly occur in salt marshes and other saline coastal environments. Their increase after the two catastrophic hurricane strikes and associated overwash events is probably attributable to the intrusion of seawater into otherwise freshwater environments, perhaps turning some of the fresh marshes around and behind the three coastal lakes into brackish marshes. After floodwaters from the storm surge recede, the more saline soils on and between the beach ridges could provide habitats for halophytic plants. Increased Poaceae percentages above 47 cm, after the first catastrophic hurricane strike, may be due to the expansion of halophytic grasses (such as cordgrass, *Spartina alterniflora*) in brackish or salt marshes, or it may reflect post-hurricane succession by xerophytic grasses (such as sea oats, *Uniola paniculata*) on sand dunes and beach ridges. The increase in Polypodiaceae spores at 31 cm, after the second catastrophic hurricane strike, may reflect the expansion of marsh habitats around Little Lake. Aquatic ferns, such as marsh fern *(Thelypteris palustris)*, are a common component of fresh marsh communities.

In upland or terrestrial habitats, *Myrica* (waxmyrtle) increased in abundance after the two catastrophic hurricane strikes. *Myrica* is a heliophytic shrub commonly found on the foot or slope of sand dunes, on forest margins, and edges of marshes and ponds. Its expansion after hurricane disturbance is a response to improved light conditions in disturbed habitats.

Among canopy trees, *Pinus* populations decreased sharply after the catastrophic hurricane strikes, and they declined further during and after the ensuing intense fires. Except after the hurricanes of 1170 and 583 cal yr BP (corresponding to sand layers at 45–47 cm and 21 cm, respectively), pine populations ultimately rebounded, but recovery seemed to occur not immediately after the initial hurricane strike, but only some time after the subsequent fire event.

This palynologically documented population response of *Pinus*—an initial crash followed by rapid recovery—is consistent with the observation that pines in Gulf coast forests exhibit the "Resilient" syndrome of response to both hurricane and fire disturbances, which is characterized by high tree mortality but massive post-disturbance recruitment (Platt, 1999; Batista and Platt, 2003). However, pine populations showed no distinct signs of recovery after the catastrophic hurricane and fire events of 1170 cal yr BP and those of ca. 583 cal yr BP. We suggest that *Pinus* seedlings or young trees regenerating from the hurricane-destroyed pine forest were again destroyed by the intense fire that occurred years or decades later, but before they reached reproductive age. This second wave of massive mortality due to fire, compounded upon the initial hurricane disturbance, would have decimated the pine populations and significantly delayed or halted the population recovery. Thus, under certain circumstance, "compounded perturbations" such as hurricane–fire interactions can produce circumstances that are quite different and more complex than if the disturbances were to act singly or individually.

The pollen percentages of *Ostrya/Carpinus* increase moderately after some of the hurricane strikes. The response of these two subcanopy trees is consistent with their "Usurper" status (*sensu* Batista and Platt, 2003), that is, suffering little hurricane damage but responding positively to canopy disruption, resulting in substantial recruitment and growth of individuals in expanded gaps. The pollen of *Quercus*, another usurper, seem to exhibit a similar response, although some of the *Quercus* pollen may also have come from the scrubby sclerophyllous oaks (or sand live oaks, *Q. virginiana* var. *germinata*) growing on the sandy beach ridge plain and dunes around the lake. Two peaks in *Ilex* pollen occurring above the sand layers at 32 and 12 cm suggest that holly (especially yaupon, *Ilex vomitoria*) saplings in the understorey may respond positively to canopy disruption under certain conditions, though it may exhibit the more typical "Resistant" syndrome under other situations of hurricane disturbance. It is not surprising that tree species, especially those with small, scattered populations, may respond differently to different hurricane strikes because each storm has different environmental impacts.

Conclusions

The 1200-yr record from Little Lake is the first multi-proxy record from the Gulf of Mexico coast that involves high-temporal-resolution data from lake sediments, including microscopic charcoal, pollen, diatoms, and dinoflagellates. These multi-proxy data allow us to reconstruct not only a history of intense hurricane strikes and storm surges, wildfires, and vegetation changes along the Gulf coast of Alabama, but also the complex interactions among these events and processes. The major conclusions are summarized as follows.

(1) At least seven intense hurricanes directly struck the Little Lake area of coastal Alabama during the past 1200 yr. Two of these were probably hurricanes of category 4 or 5 intensity, and the other five were probably of category 3 intensity. This implies a return period of approximately 600 yr for a catastrophic hurricane of category 4 or 5 intensity, or a landfall probability of 0.17% per year. This is consistent with estimates derived from other Gulf coast sites, which generally suggest an annual landfall probability of 0.1% for the recent millennium and 0.3–0.5% during the preceding "hyperactive period" of 3800–1000 cal yr ago (Liu and Fearn, 2000; Liu, 2004).

(2) Wildfires were common in the pine-dominated subtropical maritime forests in coastal Alabama during the past 1200 yr. Although wildfires could and did occur independently of hurricane disturbance, the stratigraphies of charcoal and sand layers show that major fires tended to occur within years or a few decades after a catastrophic hurricane strike. These findings are consistent with the predictions of the hypothesis of hurricane–fire interactions.

(3) The Little Lake pollen record suggests that saltwater intrusion resulting from past storm surges and overwash processes caused an expansion of flooded or marshy environments, especially saline or brackish habitats that supported halophytic plants. Heliophytic shrubs, such as *Myrica*, seemed to expand in disturbed habitats. In upland forests, subcanopy trees like *Ostrya/Carpinus* and *Ilex*, and canopy trees like *Quercus*, tended to increase in response to improved light conditions, although their response varied from one hurricane strike to another. Generally, *Pinus* populations declined immediately after a major hurricane strike. Their recovery may be impeded if the regenerating populations were destroyed by intense fires that typically occurred after the hurricane strike. Thus the palynological record from Little Lake supports the notion that large-scale disturbances like hurricanes and fires can interact to produce ecological impacts that are more complex and unpredictable than would have been caused by these disturbance agents acting individually.

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