Paleotempestology

The Science of Reconstructing Paleohurricane Activity

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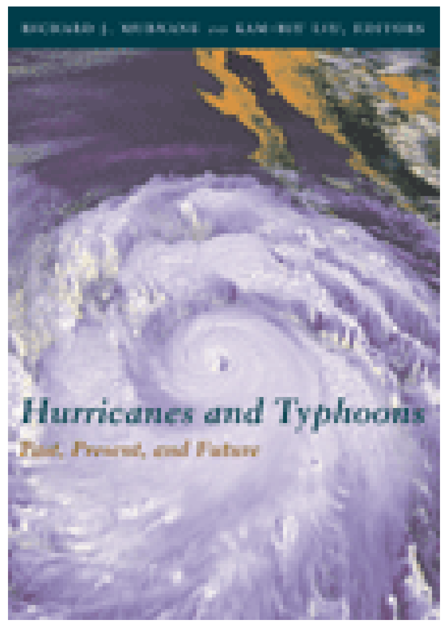


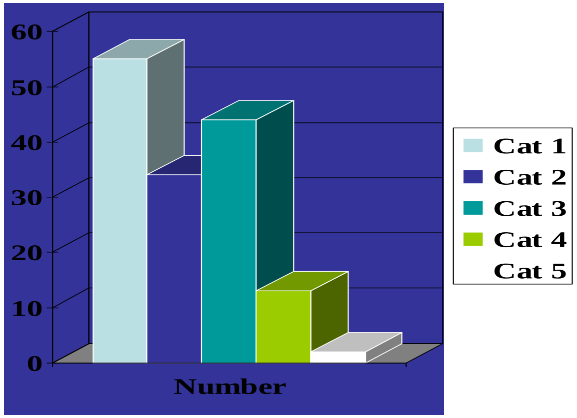
Acapulco, Mexico
March 12, 2009

What is paleotempestology ?

Paleotempestology is a young field of science that studies *past* hurricane activities by means of geological and archival techniques.

Why Study the Past?

- **A long-term perspective is vital for accurate risk assessment.**
- Observational record of hurricanes only span the last 150 years.
- Category 4 & 5 hurricanes are extremely rare.
- A long-term perspective is vital to forecasting the return period of the "Big Ones".
- e.g., Is Hurricane Katrina's direct hit at New Orleans a 50-yr, 100-yr, or 500-yr event ?



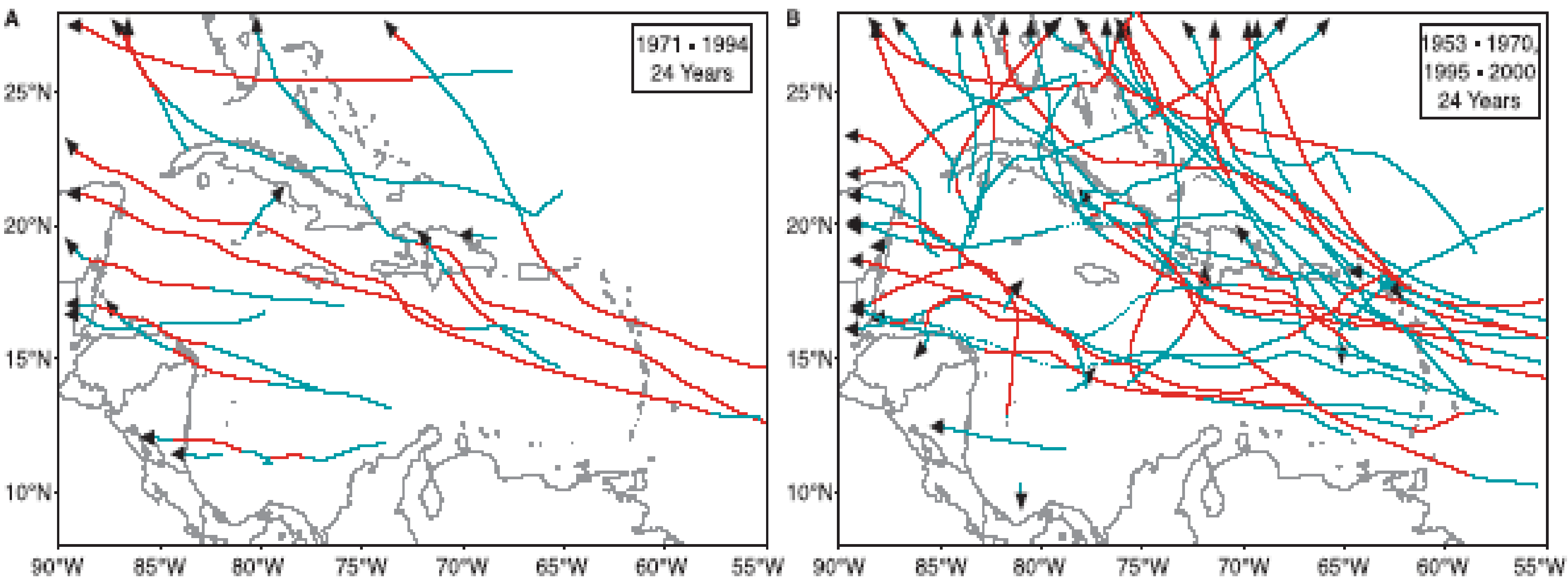
- **What is the probability for a Katrina-like hurricane to hit Acapulco?**

Multi-decadal variability
in Caribbean hurricane activity

- Linked to large-scale climate patterns such as the Atlantic Multidecadal Oscillation (AMO) and El Nino-Southern Oscillation (ENSO)

1971-1994 (24 years)
- cold AMO

1953-1970; 1995-2000 (24 years)
- warm AMO

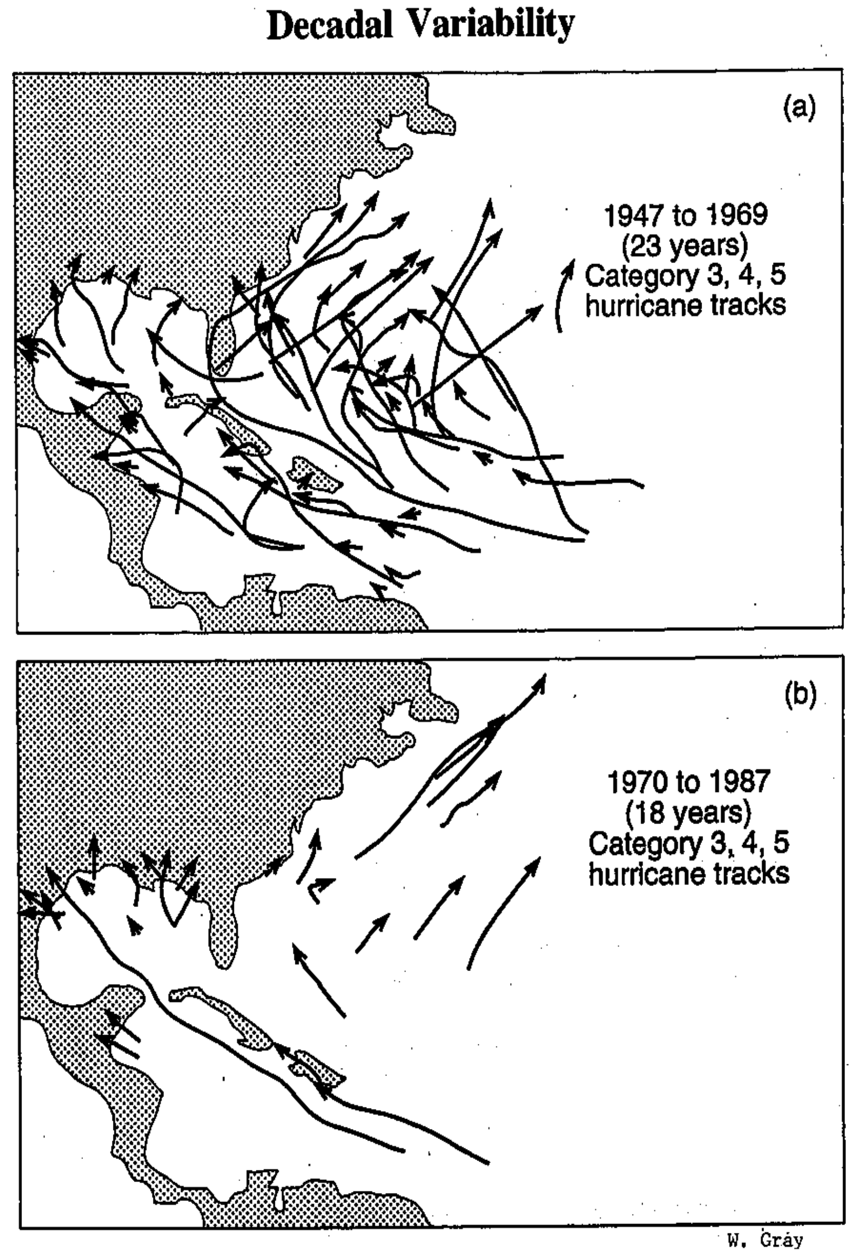


Goldenberg et al., 2001

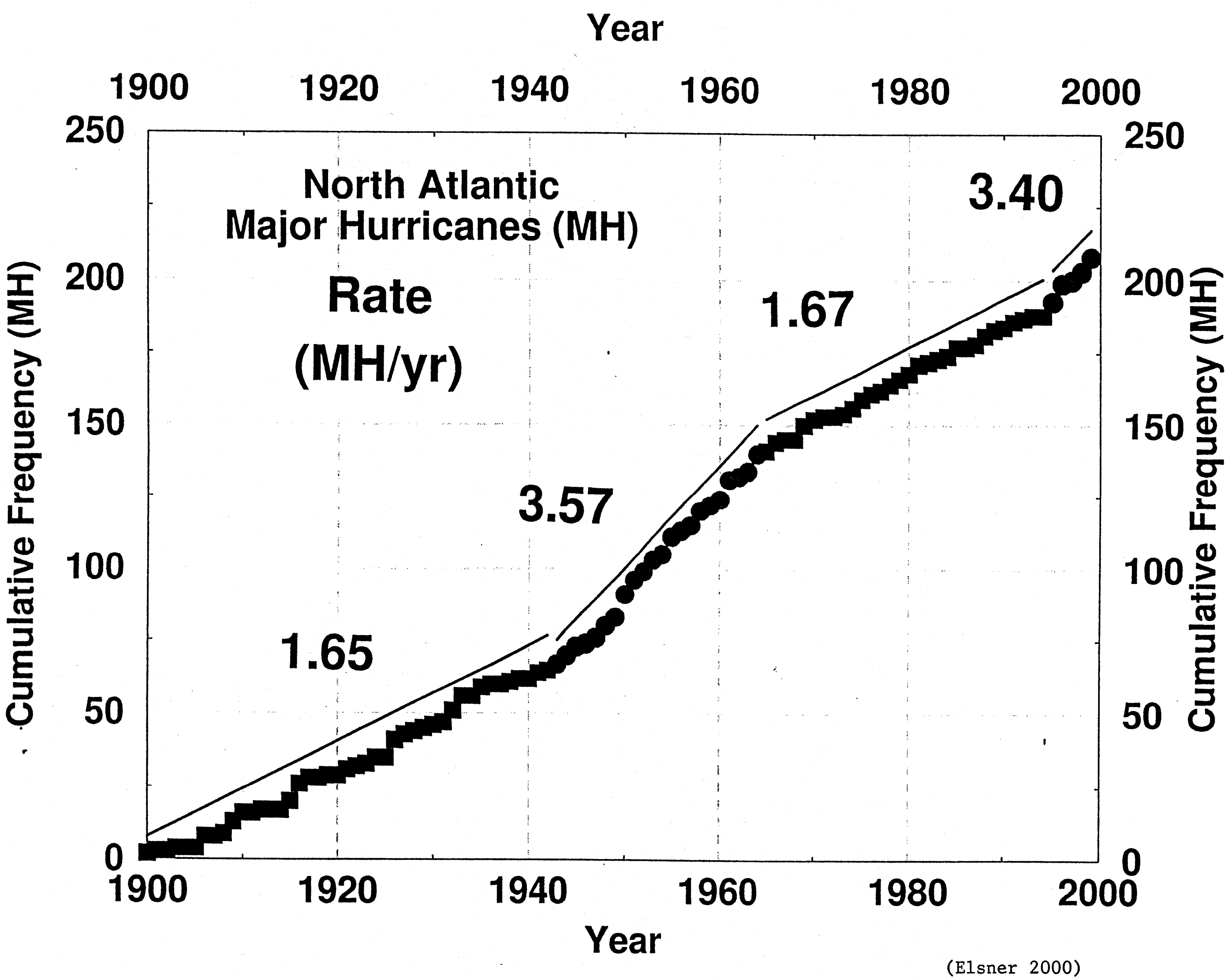
Multi-decadal variability

1947-1969 →

1970-1987 →



Gray, 1997



Elsner et al., 2000

The "Hockey Stick" Debate

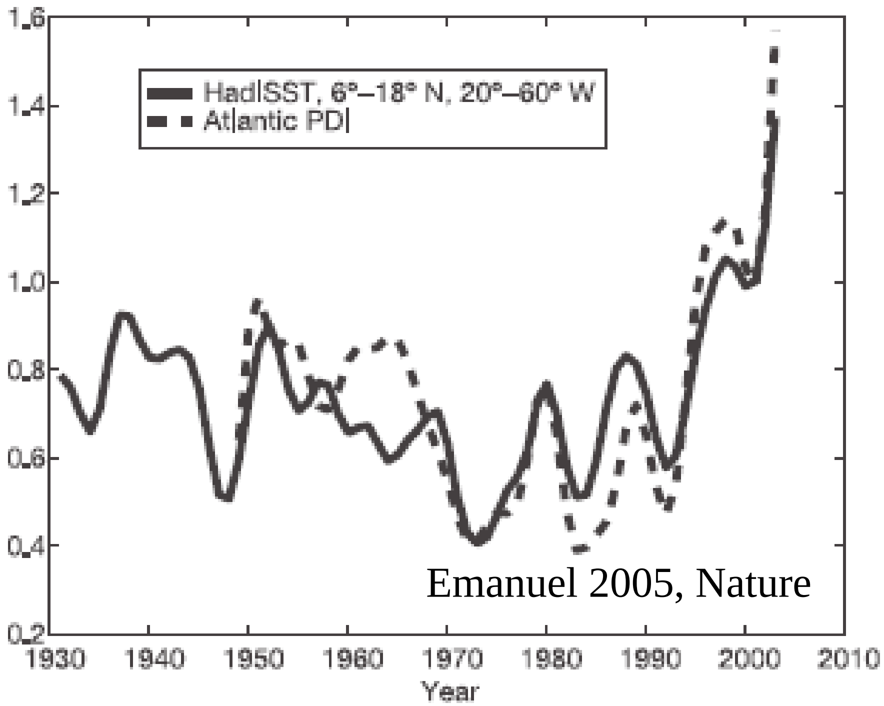


Figure 1 | A measure of the total power dissipated annually by tropical cyclones in the North Atlantic (the power dissipation index, PDI) compared to September sea surface temperature (SST). The PDI has been multiplied by 2.1×10^{-12} and the SST, obtained from the Hadley Centre Sea Ice and SST data set (HadISST)[22], is averaged over a box bounded in latitude by 6° N and 18° N, and in longitude by 20° W and 60° W. Both quantities have been smoothed twice using equation (3), and a constant offset has been added to the temperature data for ease of comparison. Note that total Atlantic hurricane power dissipation has more than doubled in the past 30 yr.

A long-term perspective is necessary:

- to decipher between signal and noise in climate changes,
- to distinguish between natural variability and anthropogenic impacts,
- to understand the large-scale climate mechanisms (e.g., SST, ENSO, NAO) controlling hurricane activity,
- to estimate the recurrence interval of extreme events,
- to help us prepare for worst-case scenarios

Research Questions

to be addressed by paleotempestology

- What is the probability for a given coastal location (Atlantic/Gulf/Pacific) to be directly hit by a catastrophic hurricane of category 4 or 5 intensity?
- How does this landfall probability vary temporally, and at what timescales?
  - Do hurricane activities vary from one century (millennium) to the next?
  - Are the 1940s to 1960s worst case scenario? If not, how bad can it be?
- How are these long-term changes in spatial and temporal patterns related to global climate changes?

How do we study the past ?

1. Geological proxy record

Principle: Detection of storm signal in geological proxy record

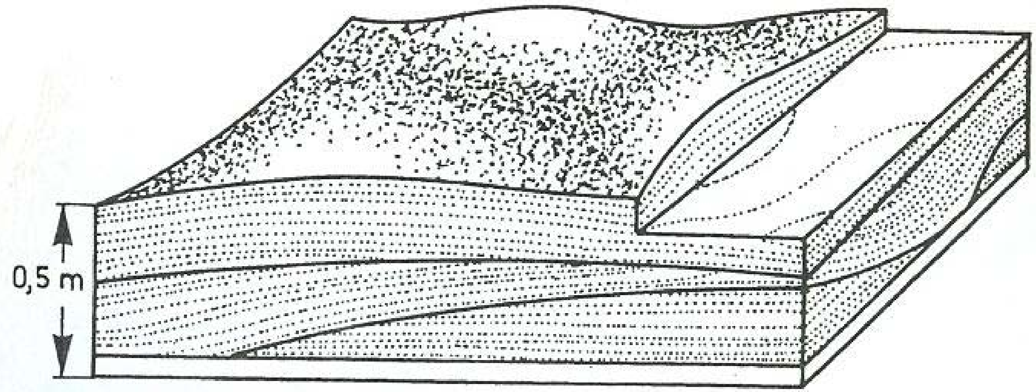
- Tempestites from marine sediments
- Beach ridges
- **Coastal lake/marsh sediments**
- Corals, speleothems, tree rings

2. Historical documentary record

- Local (county) gazettes – China
- Spanish colonial records – in archives in Madrid, etc.
- Local newspapers
- Diaries, plantation records
- Ship logs

Tempestites

- **In shallow-water marine sediments**



Hummocky cross stratification

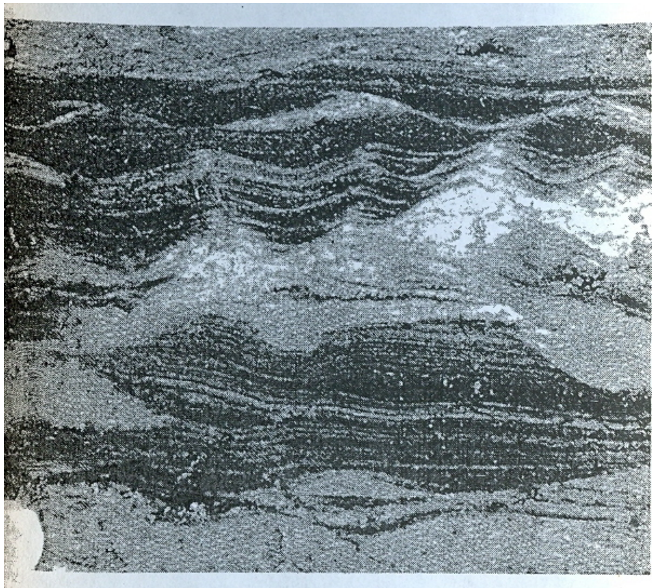


Fig. 584. Lagoonal sediments showing wave ripples, Almere Deposits, Netherlands

Fig. 557. Hummocky cross stratification (Harms 1975) or "truncated wave-ripple laminae" (Campbell 1966). Shoreface of barrier Island Norderney, North Sea. Water depth 3.8 m. (After Chowdhuri and Reineck 1978)

Reineck & Singh, 1980

Australian beach ridges (Nott and Hayne, 2001)

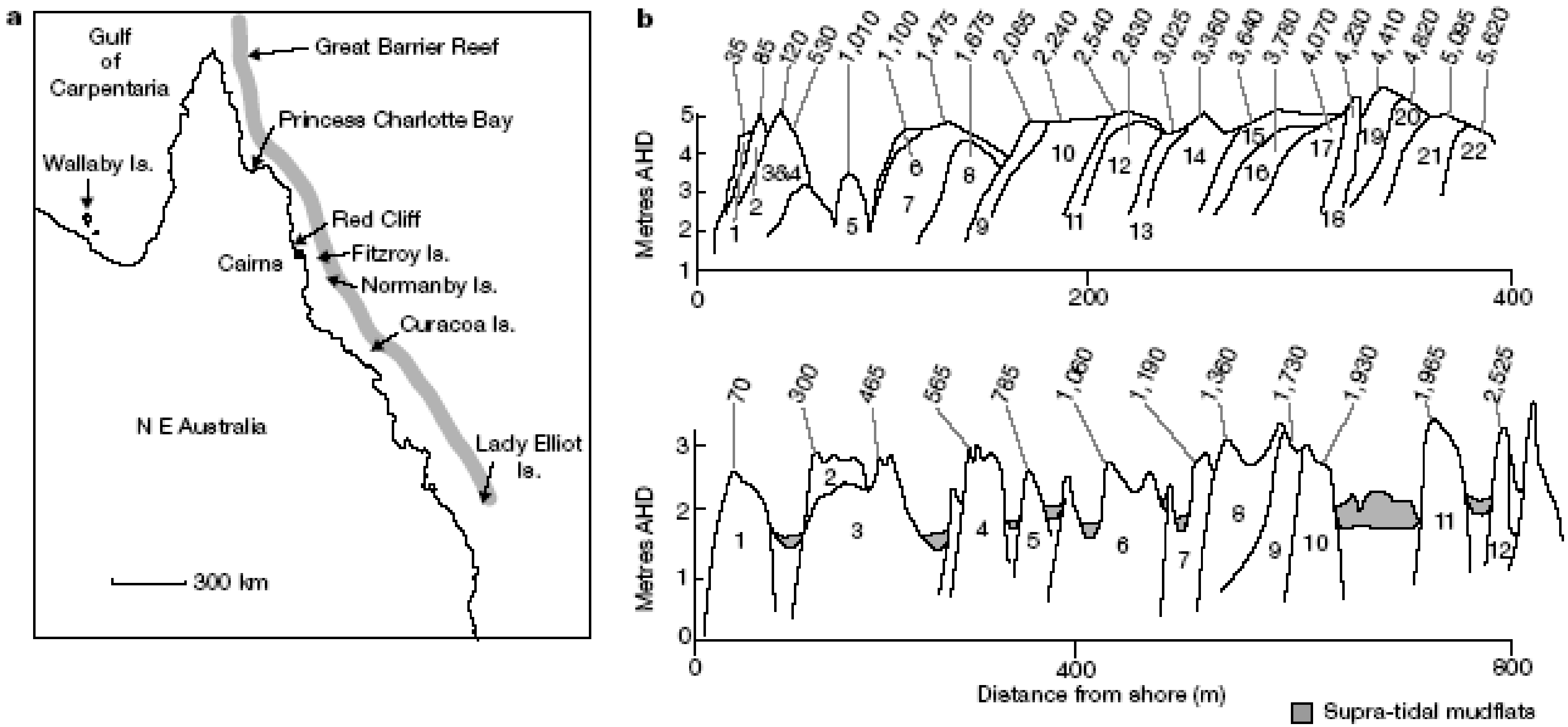
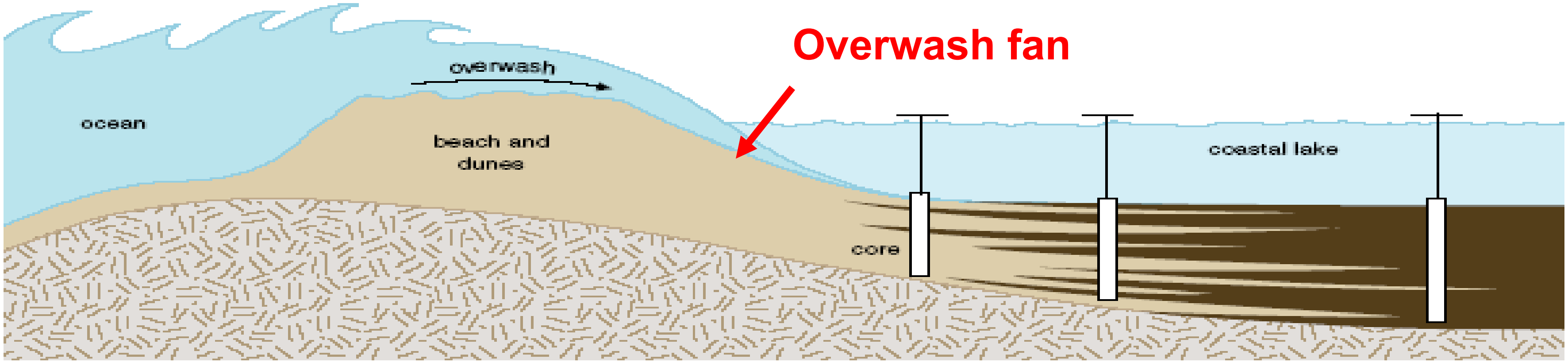


Figure 1 Study sites and storm deposit data. **a**, Location map of study sites. **b**, Stratigraphic relationship of storm deposit/ridges on Curacoa island (top) and Princess Charlotte Bay (bottom). Successive storm deposits are numbered accordingly. Mean reservoir-corrected radiocarbon age (in yr BP) for each ridge is shown above traces. Note progressive increase in age with distance inland. Age details in Table 1. Cross-sections modified from refs 10 and 11. AHD is Australian Height Datum.

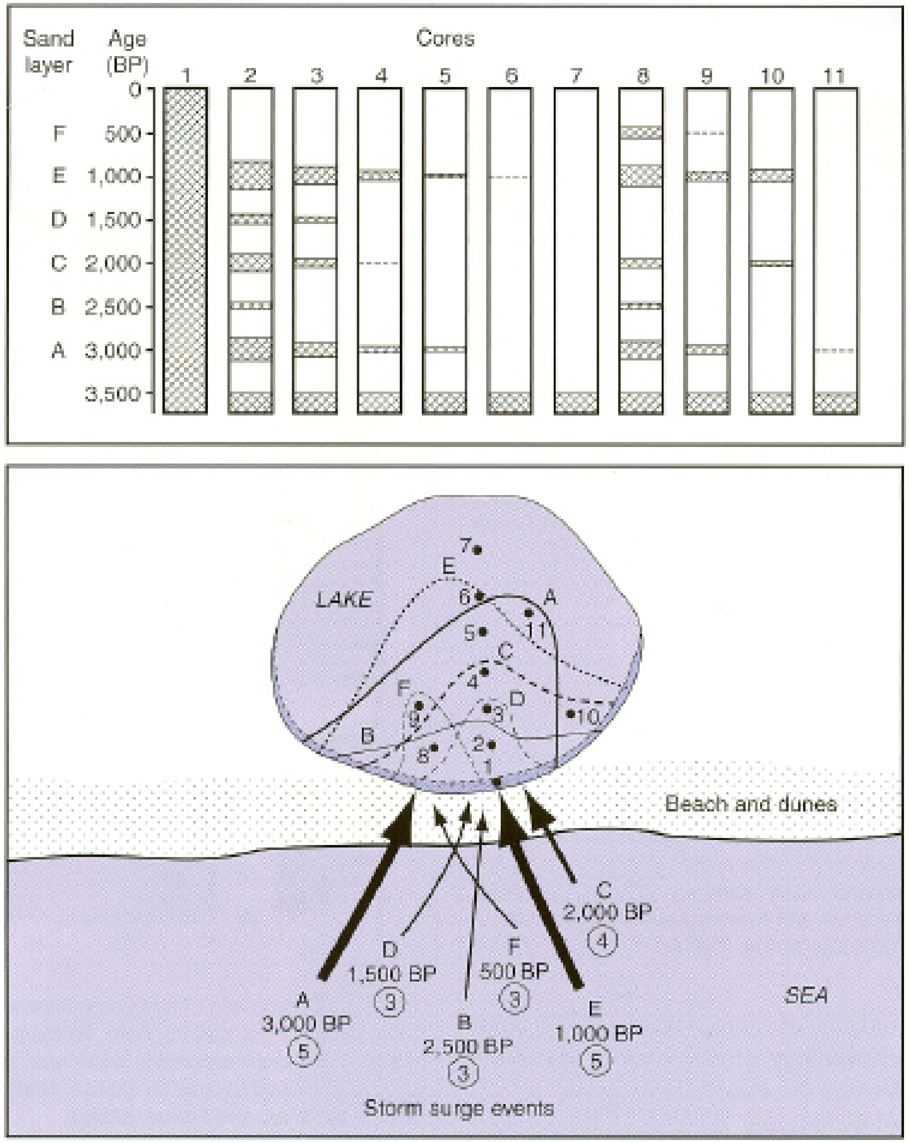
Overwash sand layers in coastal lake- and marsh-sediments



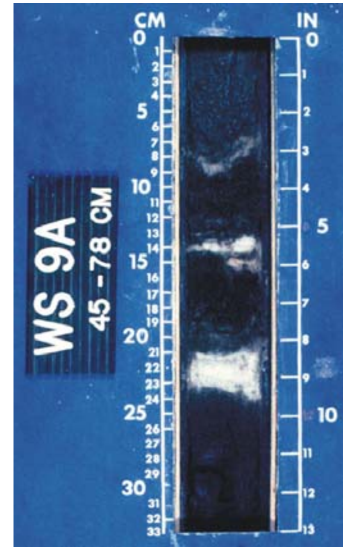
Detection of overwash events caused by intense hurricanes

Rodanthe, North Carolina after Hurricane Isabelle, Sept. 2003

Liu, 2007

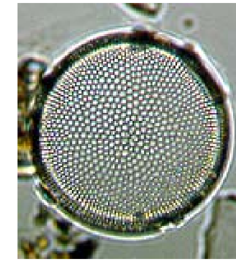


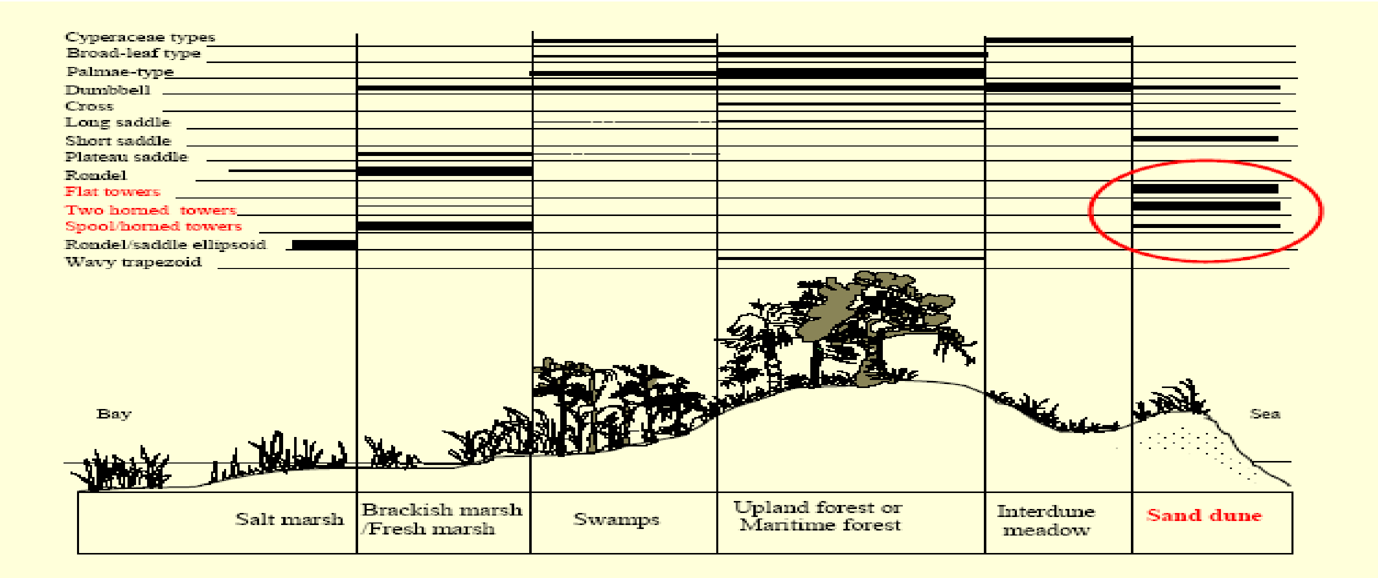
Model of overwash sand deposition in a lake and its stratigraphic implications (Liu and Fearn, 2000)



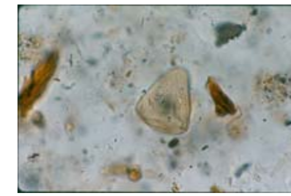
- **Stronger hurricanes will cause higher storm surge, hence bigger overwash fans;**
- **Overwash sand layers will be thicker near the lake shore, and thin out towards the lake center;**
- **Only the strongest hurricanes will be recorded in sediments at the center of the lake.**

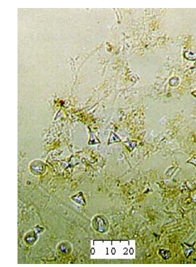
Microfossil data (diatoms, foraminifera, pollen, phytoliths) suggest seawater intrusion and transportation of materials from the sand dunes.



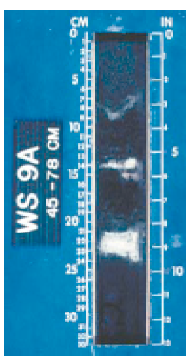


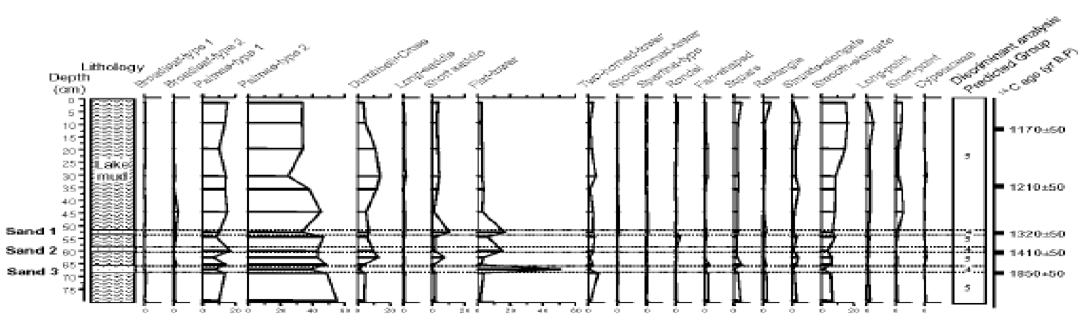
Phytolith assemblages of coastal vegetation zones in S.E. USA (Lu & Liu, 2003)





Western Lake, Florida



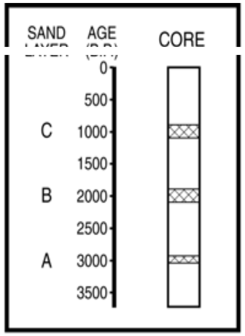


Phytolith assemblages from the sand layers are similar to those derived from sand dunes, thus supporting the notion that the sand was deposited by overwash processes.

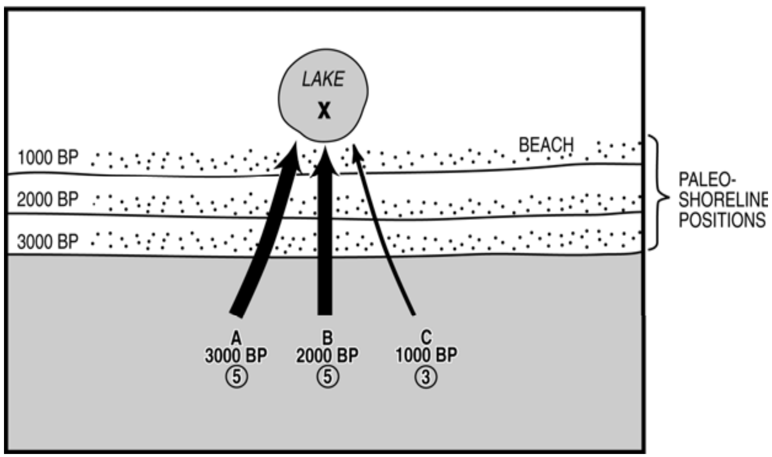
Fig.6

Lu & Liu, 2005

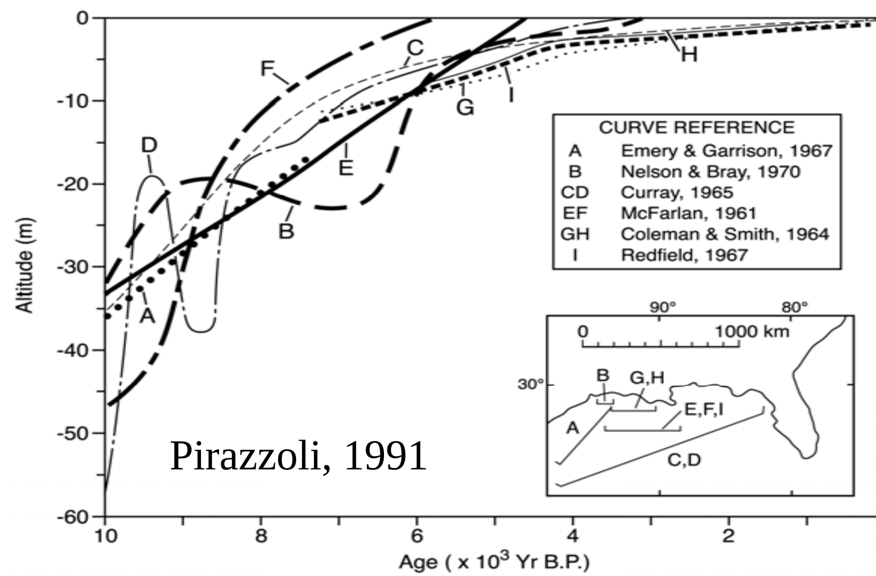
Effects of Holocene sea level rise



- Sea level since 5 ka has been within 5 m below present;
- Lake-sediment record shows stable lake environment since 5 ka;
- Only stronger storms are recorded in the past, when sea level was lower.



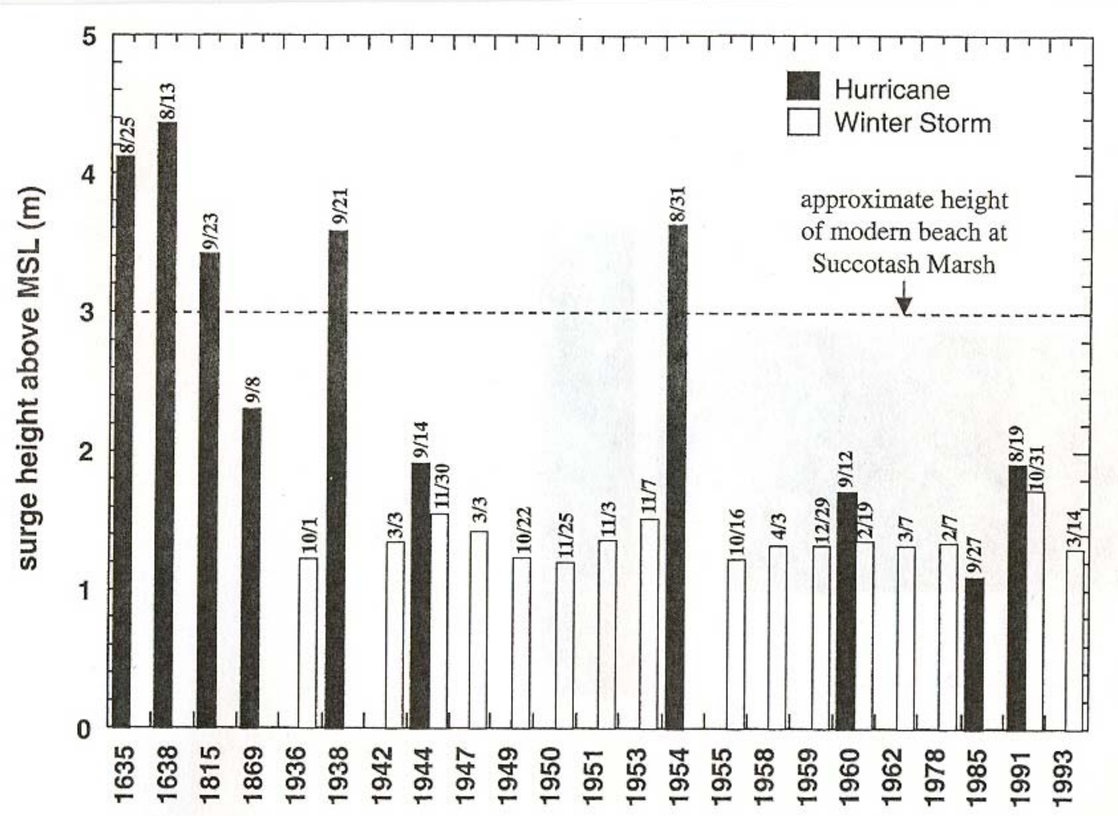
Effect of late-Holocene sea level rise on the paleotempestological sensitivity of a coastal lake (Liu, 2004)



Some Methodological & Theoretical Issues

Q: How do you know that the overwash sand layers are caused by hurricanes and not winter storms?

A: Storm surge heights caused by winter storms are typically much lower than those of hurricanes.



Donnelly et al., 2001

Ideal study sites:

Coastal backbarrier lakes

- subject to storm surge and overwash by intense hurricanes
- source of sand supply
- good preservation potential (closed basin, not tidally connected)
- no significant fluvial input

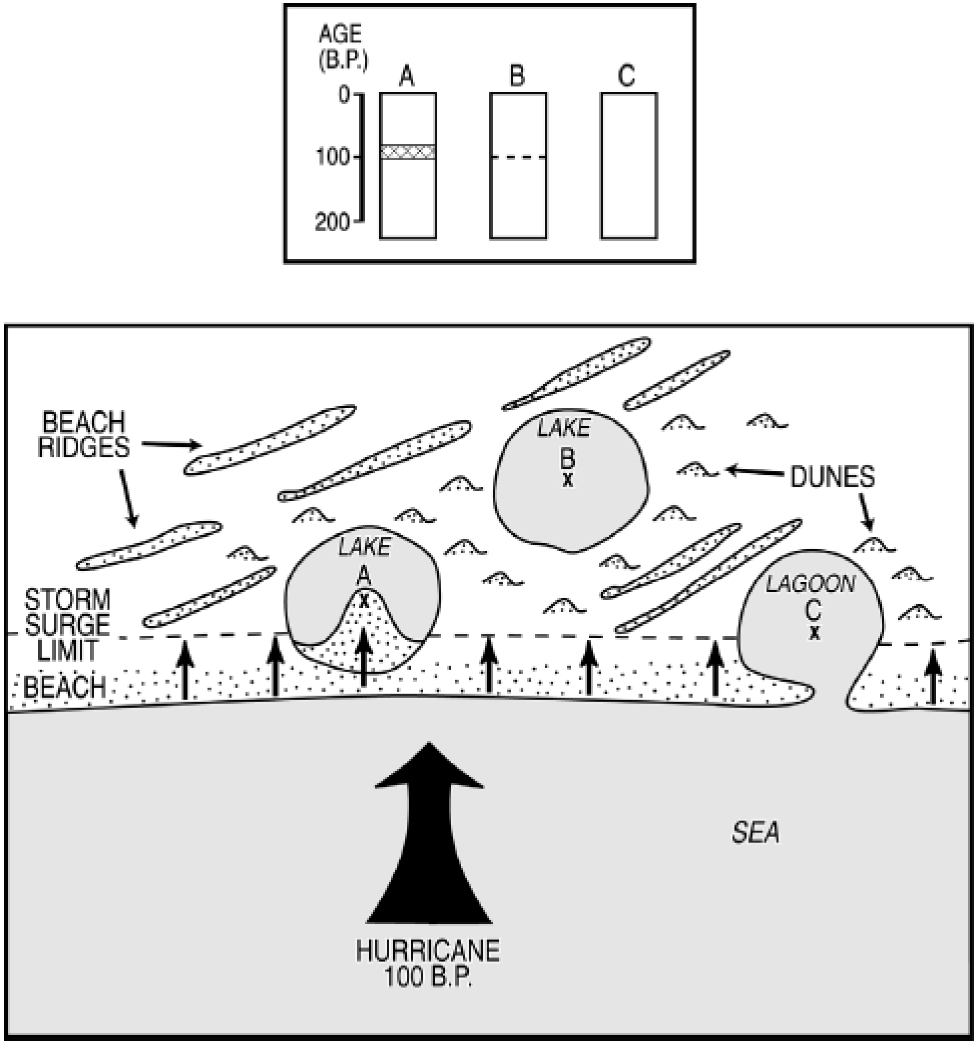


FIGURE 2.5 (*Top*) Hypothetical sedimentary records in three coastal lakes (A, B, C) of different geomorphic settings that were impacted by a hurricane strike and the associated overwash 100 years ago. Thick and thin sand layers are represented by cross-shaded bands and dotted lines, respectively. (*Bottom*) Geomorphic settings of the three lakes in relation to coastal sand barriers (beach, dunes, beach ridges) and the spatial limit of the storm surge generated by the landfalling hurricane. Small arrows indicate waves overtopping the beach barrier, causing an overwash. An overwash fan is formed in Lake A.

Liu, 2004

Coring

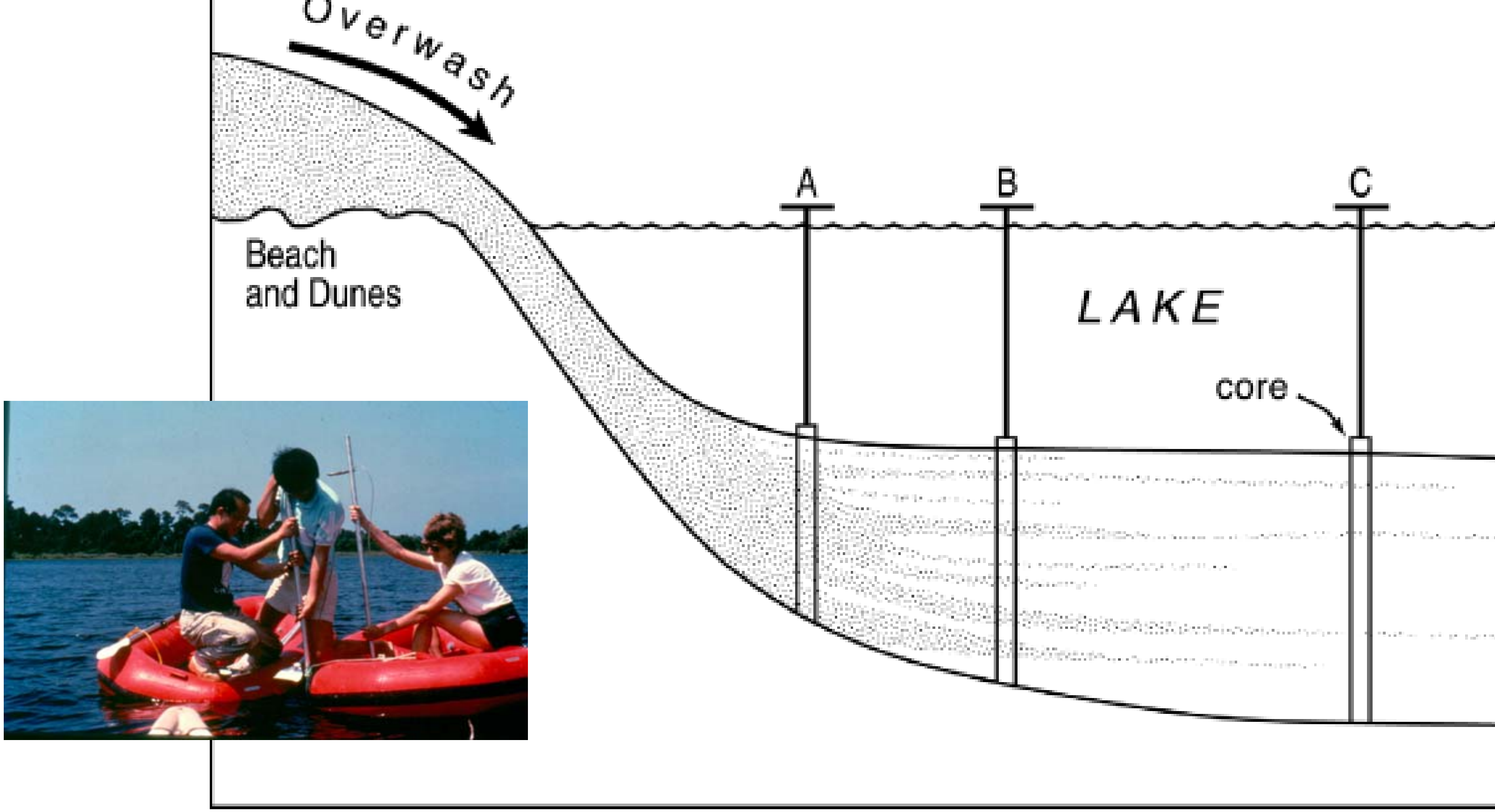
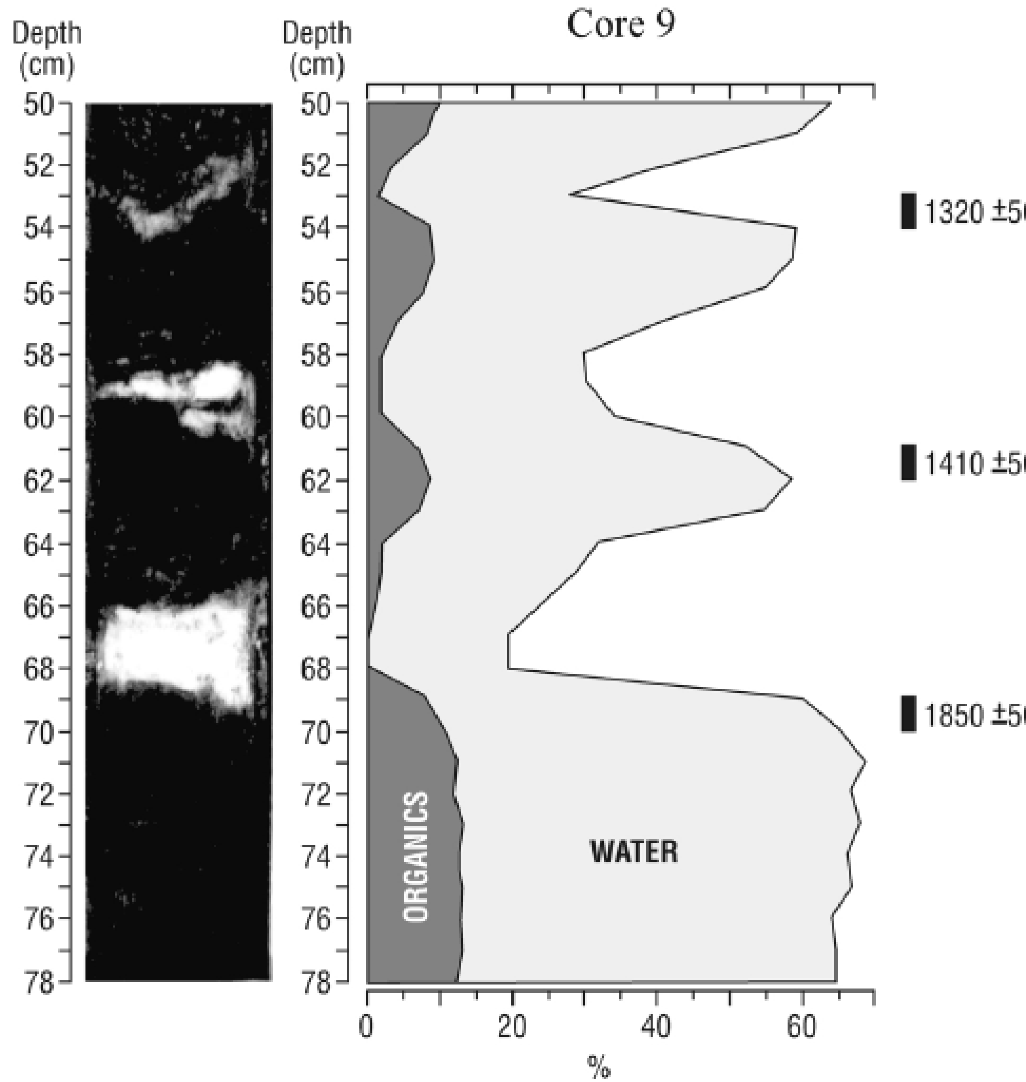


FIGURE 2.3 Hypothetical pattern of sand-layer deposition in a coastal lake subjected to repeated storm overwash events in the past. The overwash sand layers are thicker near the sand barrier and become thinner toward the lake center. A core taken from site B will contain more and thicker sand layers than one taken from site C. A core taken from site A, however, may consist of all sand without discrete layers.

Liu, 2004

Loss-on-ignition Analysis



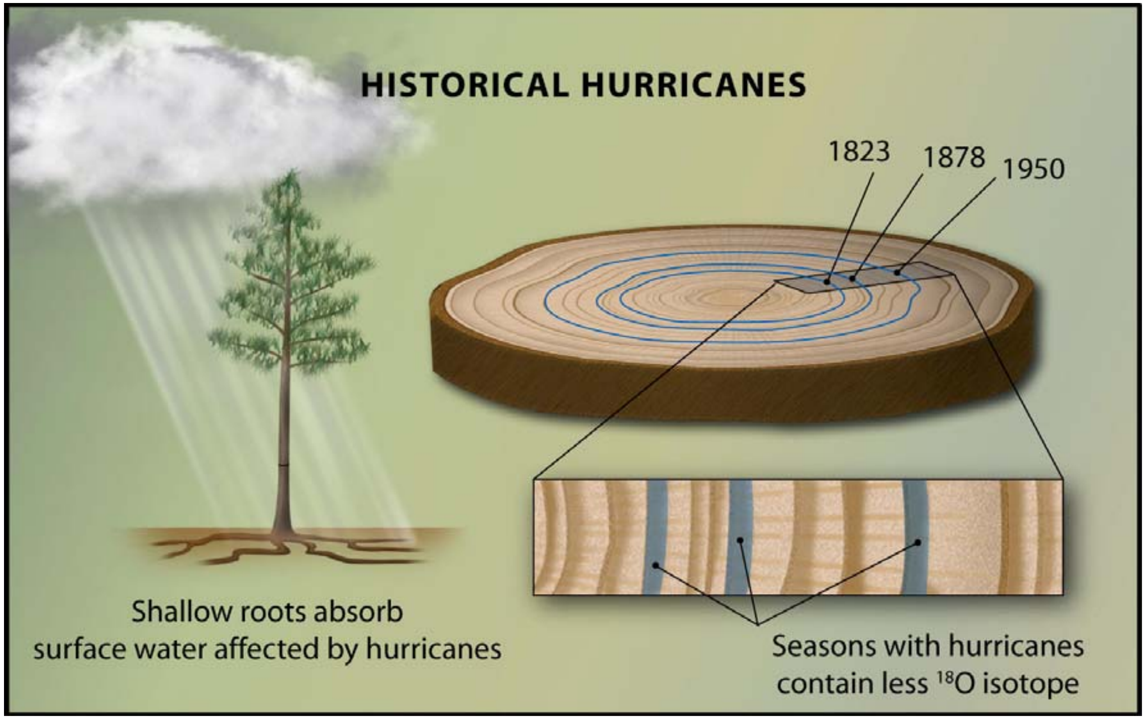
Liu and Fearn, 2000

Hurricane rains are strongly depleted in $\delta^{18}O$

Stable isotopic proxies from:

- **tree rings**
- **speleothems**
- **corals**

High-resolution proxy records from latewood in tree-rings



Miller et al., 2006

A 220-year (1770-1990) oxygen isotopic record from longleaf pine tree rings from S. Georgia (Miller et al., 2006)

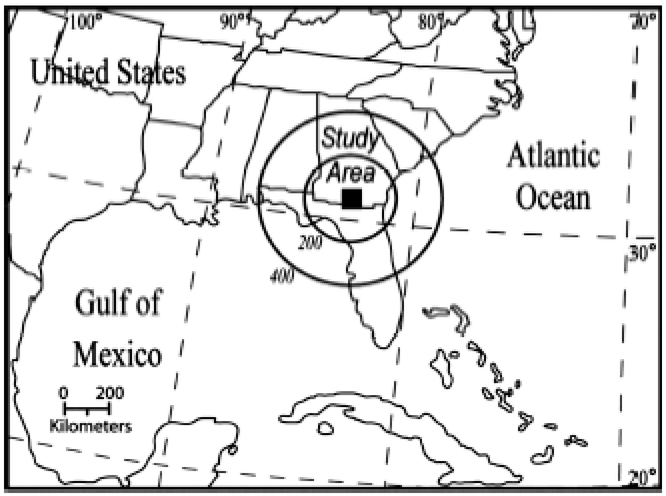


Fig. 1. Location of the study area near Valdosta, GA (shaded box). Most tropical cyclones producing precipitation captured in tree rings tracked within 200 km of the study area (inner circle), but several passing within 400 km (outer circle), or even more, were also detected.

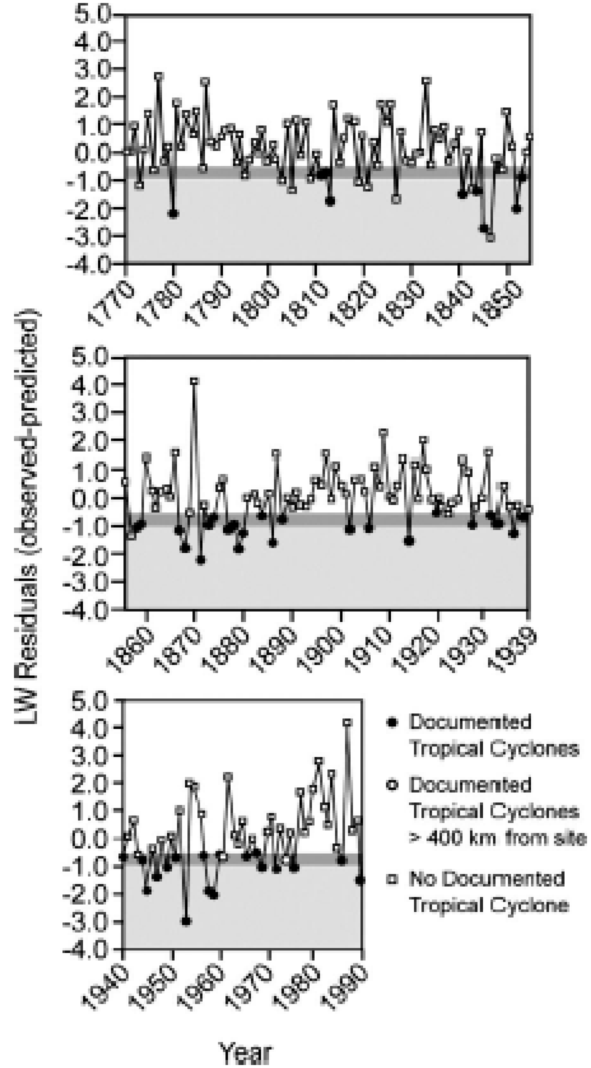
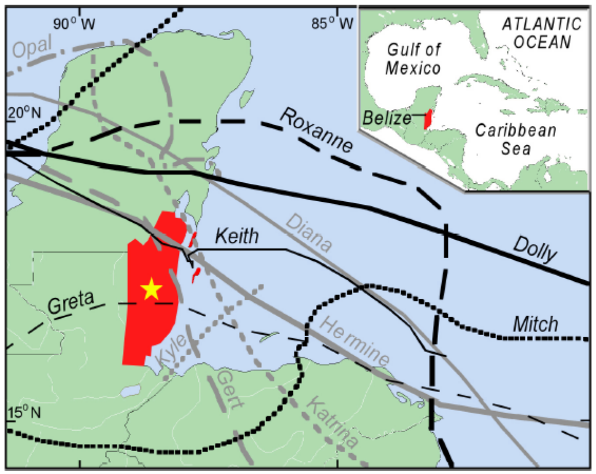
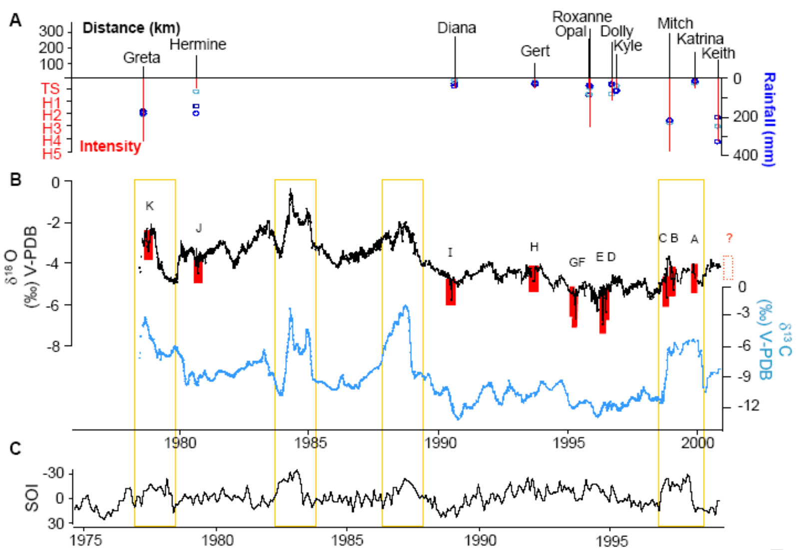


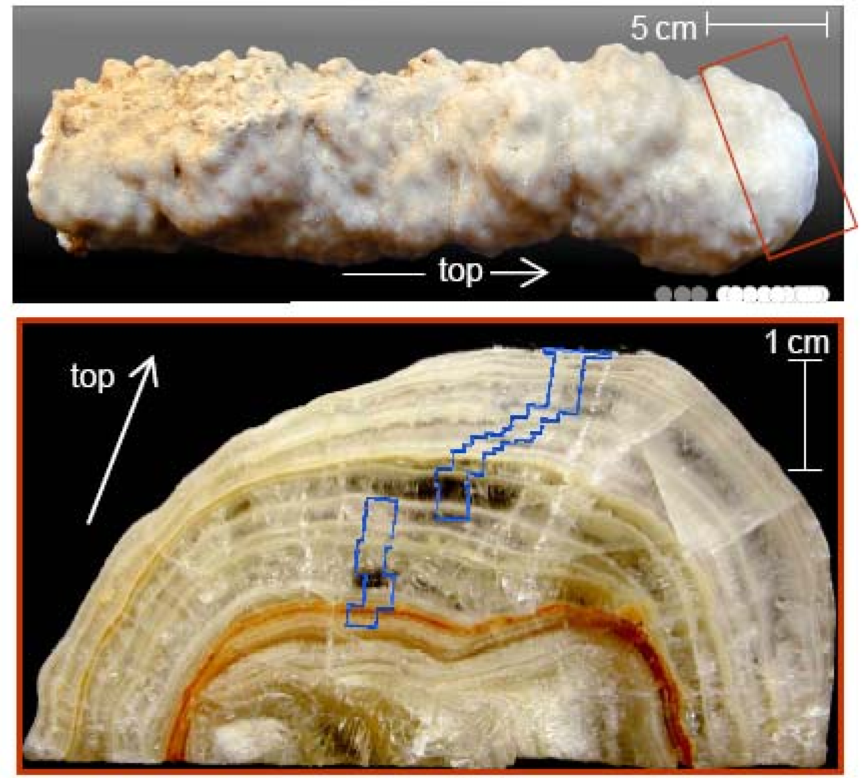
Fig. 3. AR (1) modeling of the LW (summer–fall) time series data. The great majority of tropical cyclones (TC) occur during late summer–fall, and TC stand out as the negative LW residuals (residual = observed − predicted value). The 1940–1990 record is compared with instrumental records of TC occurrence (see text).

Miller et al., 2006

Speleothems (stalagmites)



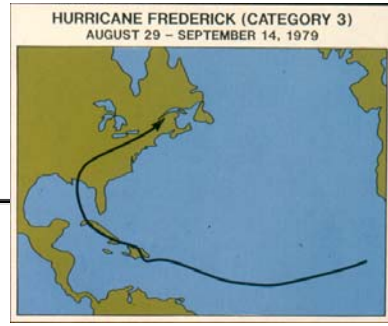


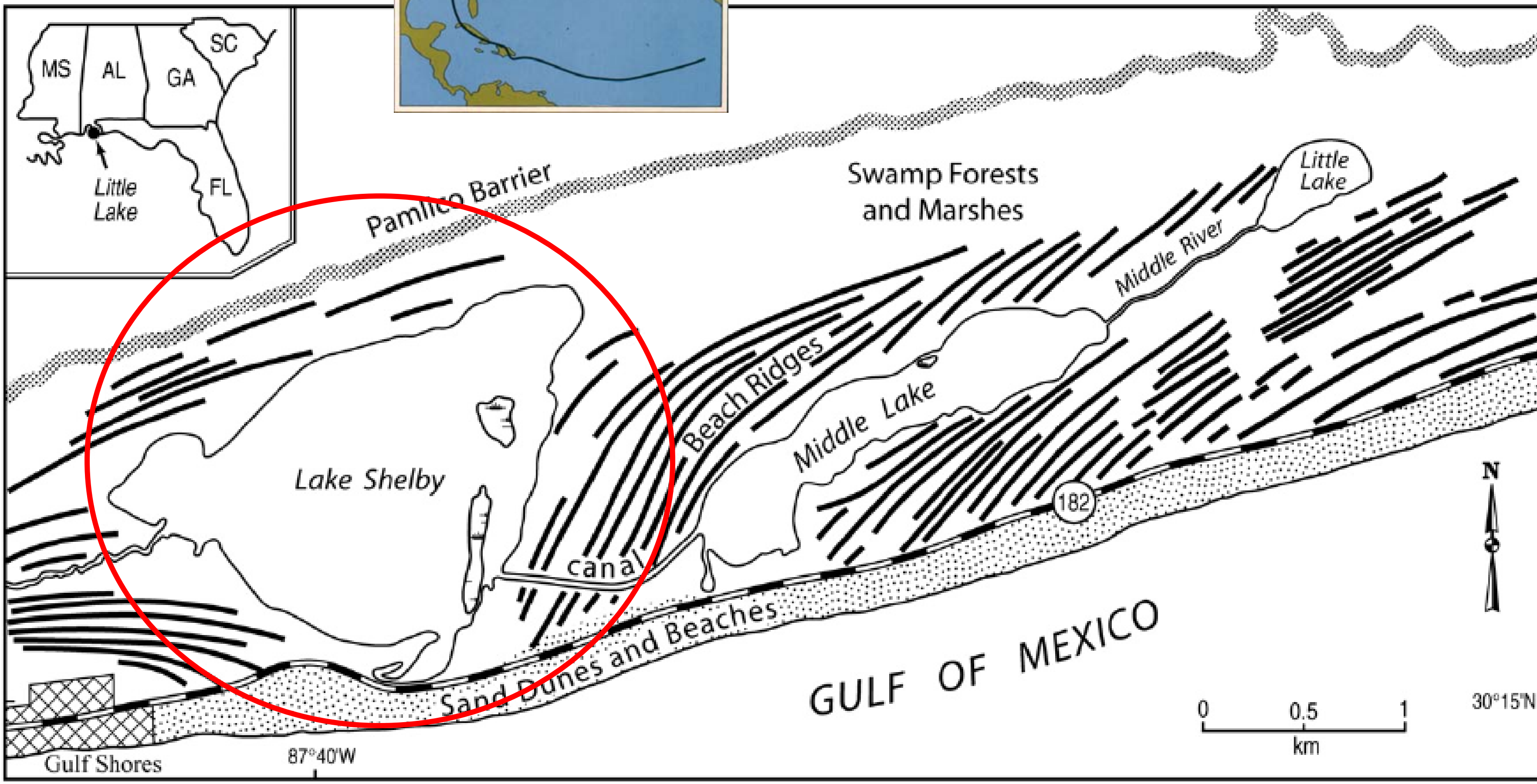


Photograph of stalagmite ATM7 showing depth of radiometric dating samples, and micromilling track across ~annually laminated couplets. White (gray) circles denote the stratigraphic position of γ-activity samples with positive (undetectable) ^{137}Cs activity. The onset of ^{137}Cs γ-activity indicates local deposition of global fallout from atmospheric thermonuclear bomb testing after 1953. The polished cross-section inset shows the continuous micromilling track (blue outline), which was positioned to maintain perpendicularity to the growth axis throughout sampling.

Frappier et al., *2007*

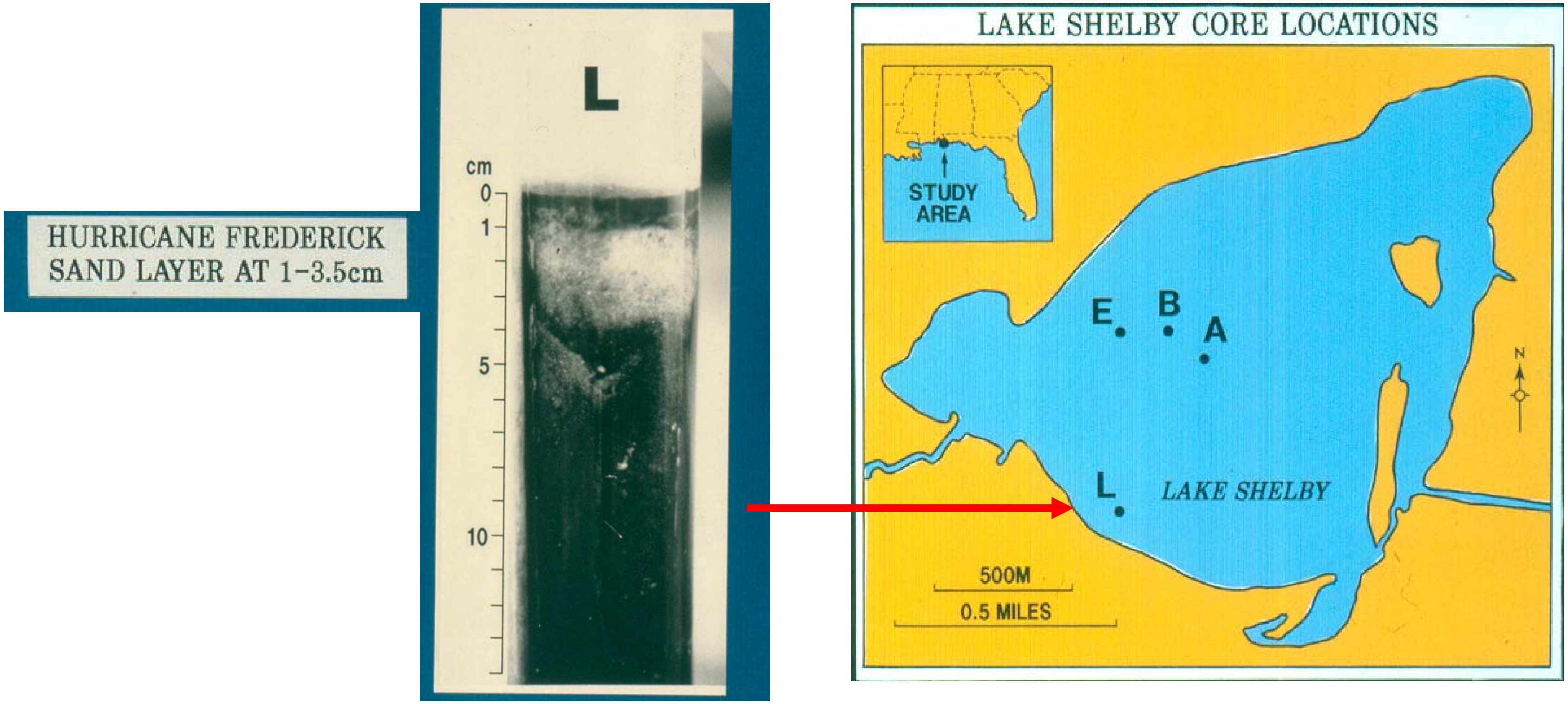
Lake Shelby, Alabama





Coastal Alabama (Gulf Shores-Orange Beach) was devastated by Hurricane Frederic in 1979, and again by Hurricane Ivan in 2004

Lake Shelby, Alabama



- **The Hurricane Frederic (cat 3) sand layer is confined to near-shore sediments (core L).**
- **Therefore older sand layer found in cores A,B,E are likely to be caused by stronger hurricanes (cat 4-5).**

Liu & Fearn, 1993

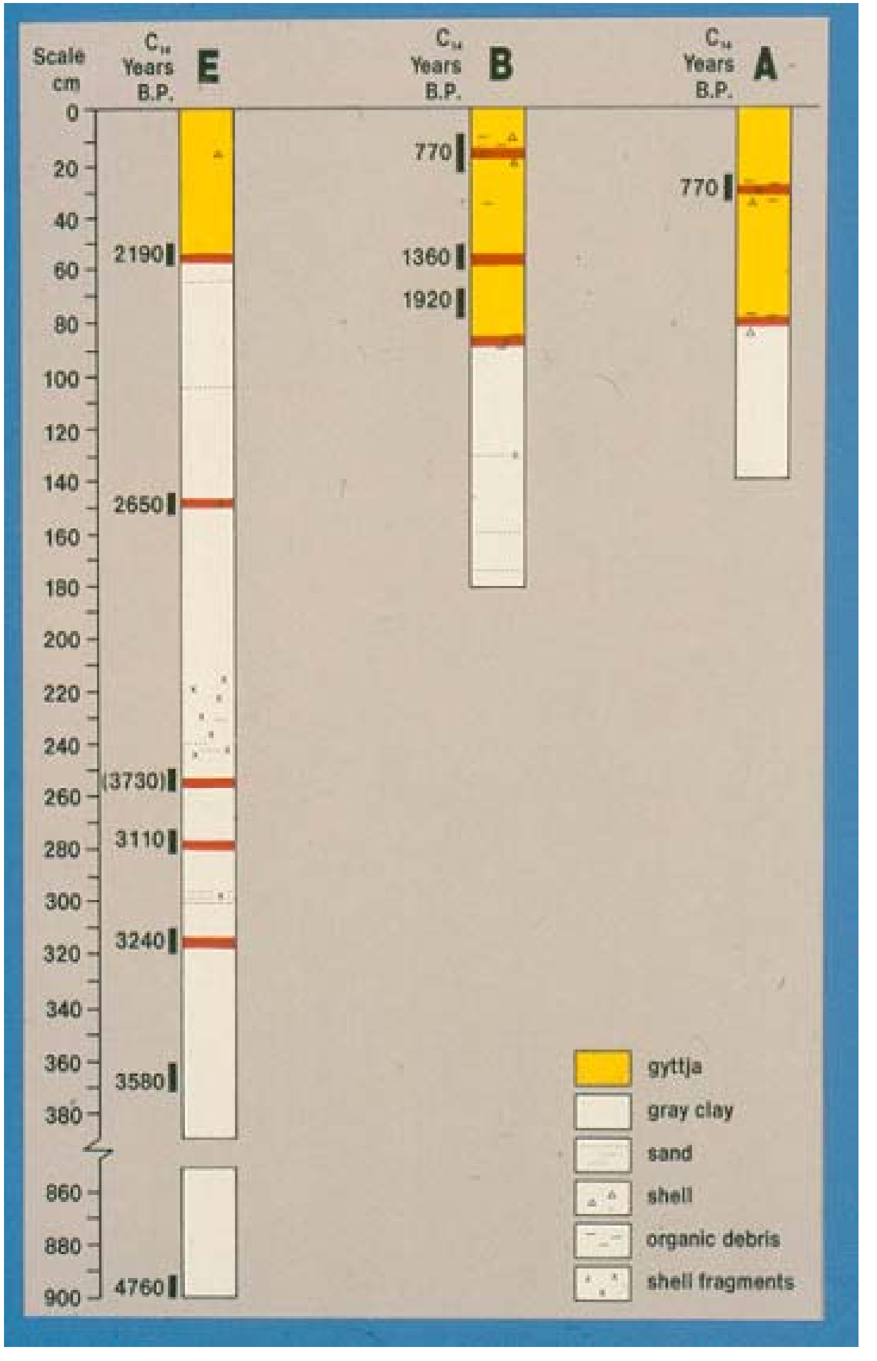
Lake Shelby, Alabama

- Cores A,B,E contain 11 sand layers, indicating 11 “direct hits” by catastrophic hurricanes over the last 3200 years.

- Return period = 300 years

- Landfall probability = 0.3% per year (for cat 4-5 storms)

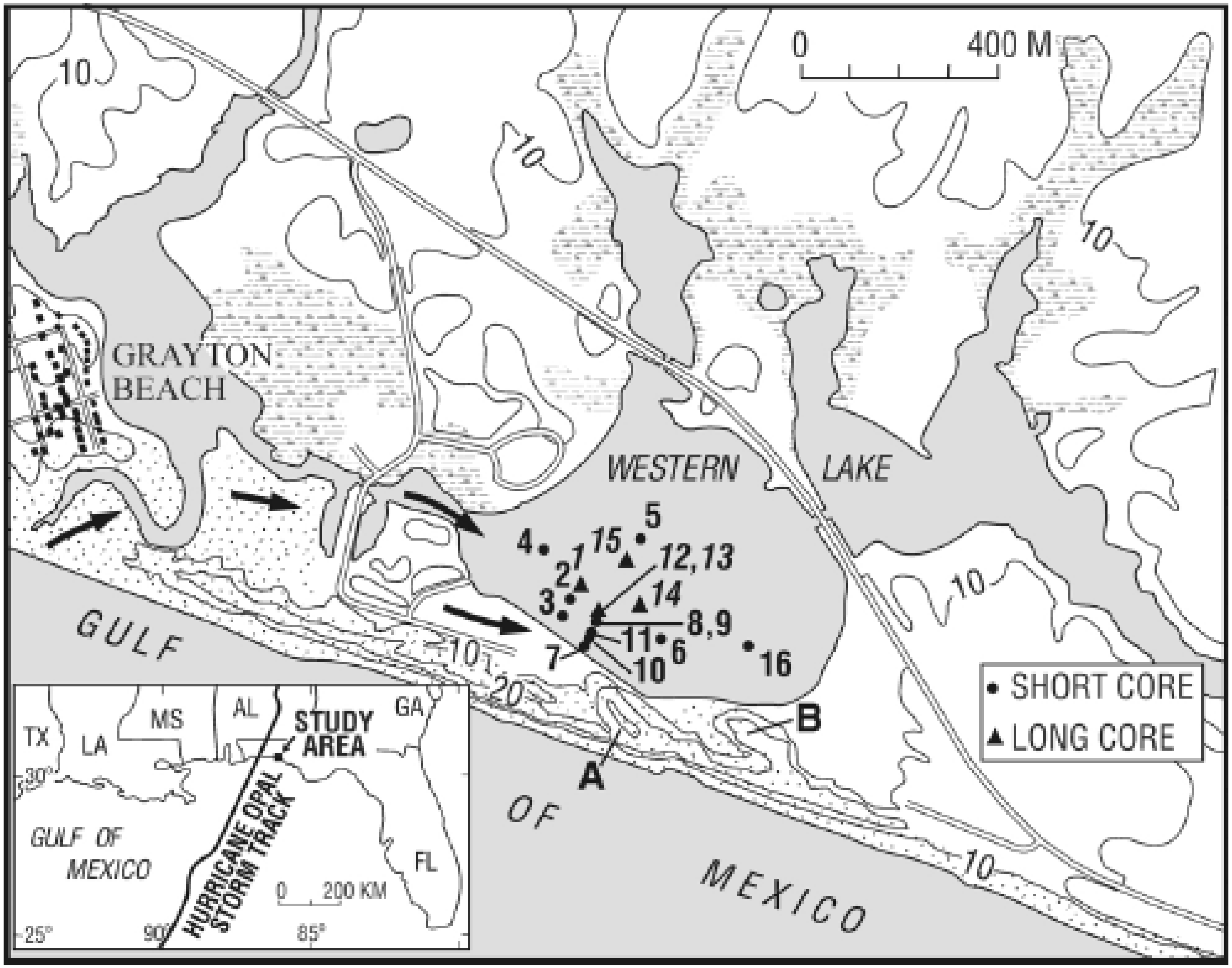
Liu & Fearn, 1993



Western Lake, Florida

Liu, 2007

Western Lake (NW Florida)



Liu and Fearn, 2000

Western Lake, FL

• Contains 12 sand layers deposited over the last 3400 years (Return period= 280 yr)

•Few events during 5000-3400 yr BP and during the recent millennium (past 1000 yr)

•Multiple strikes by catastrophic storms during “hyperactive period” of 3400-1000 yr BP.

Liu & Fearn, 2000

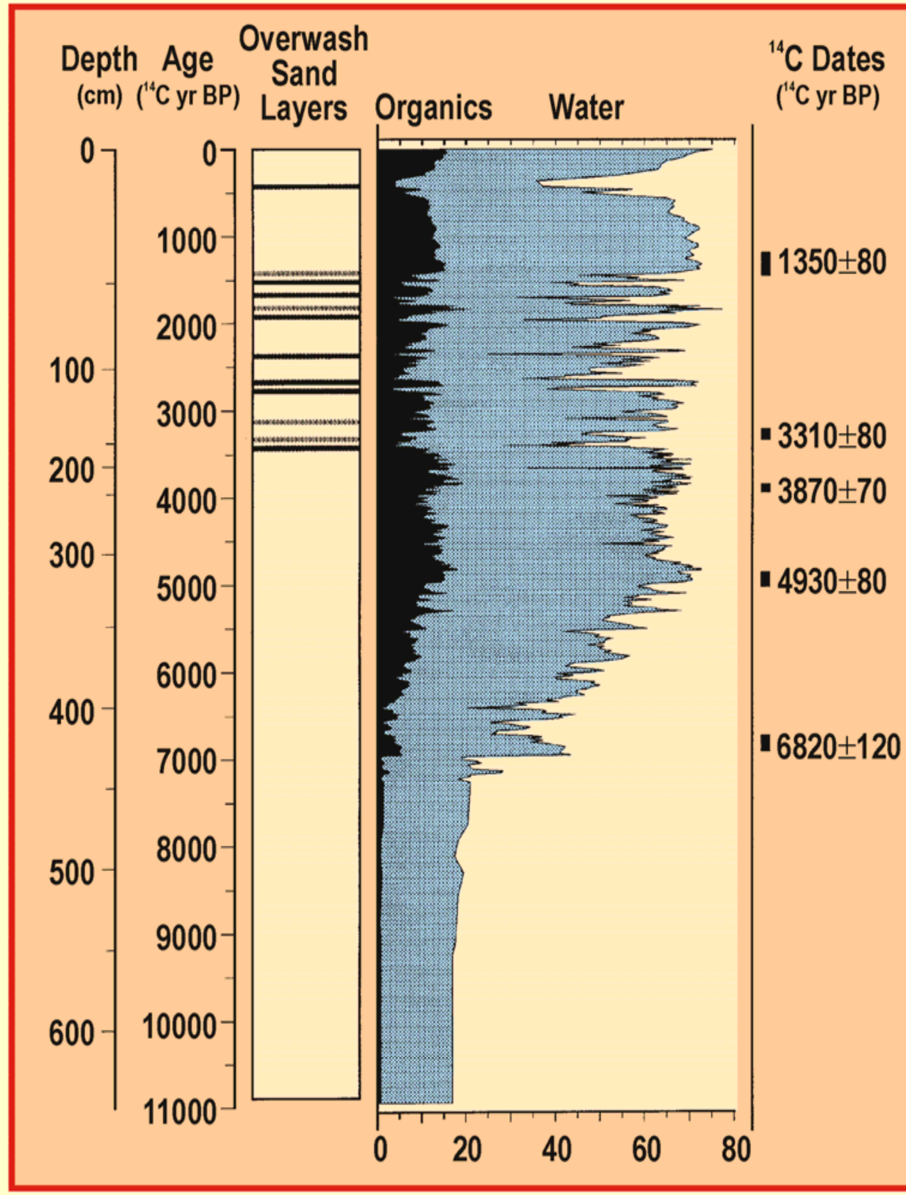


Fig. 11. Sediment stratigraphy of Western Lake determined by loss-on-ignition analysis.

Sedimentary proxy record from coastal marshes

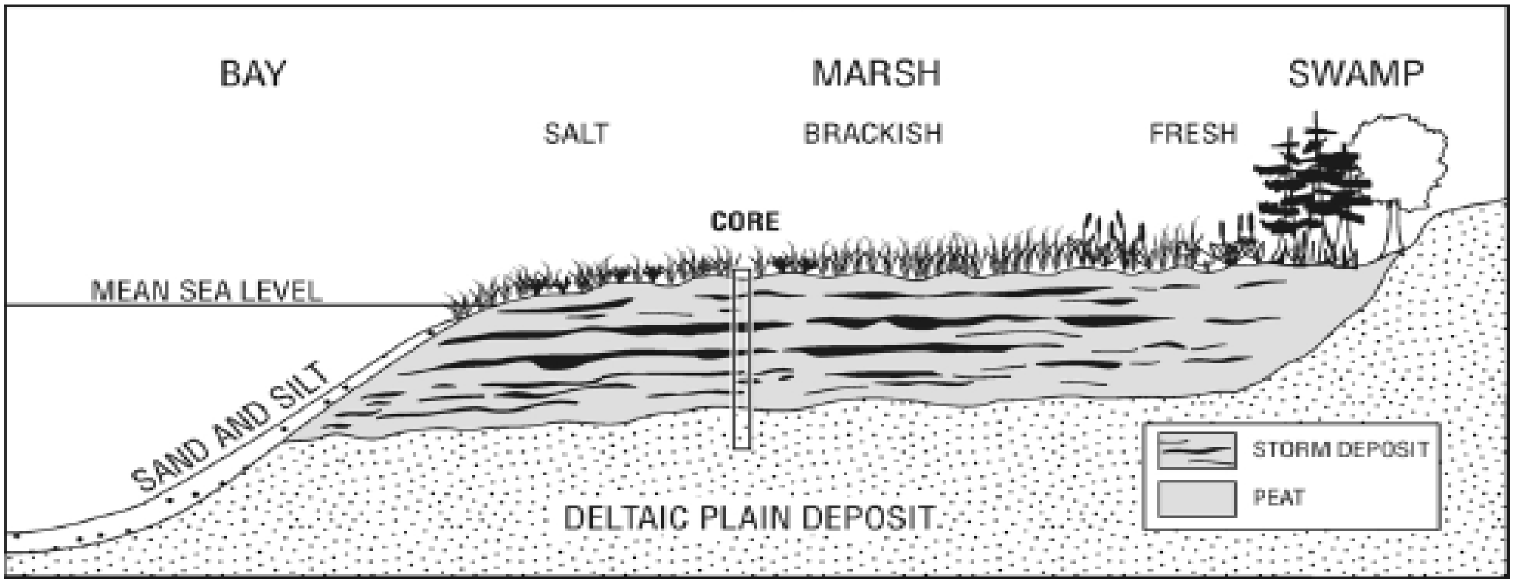
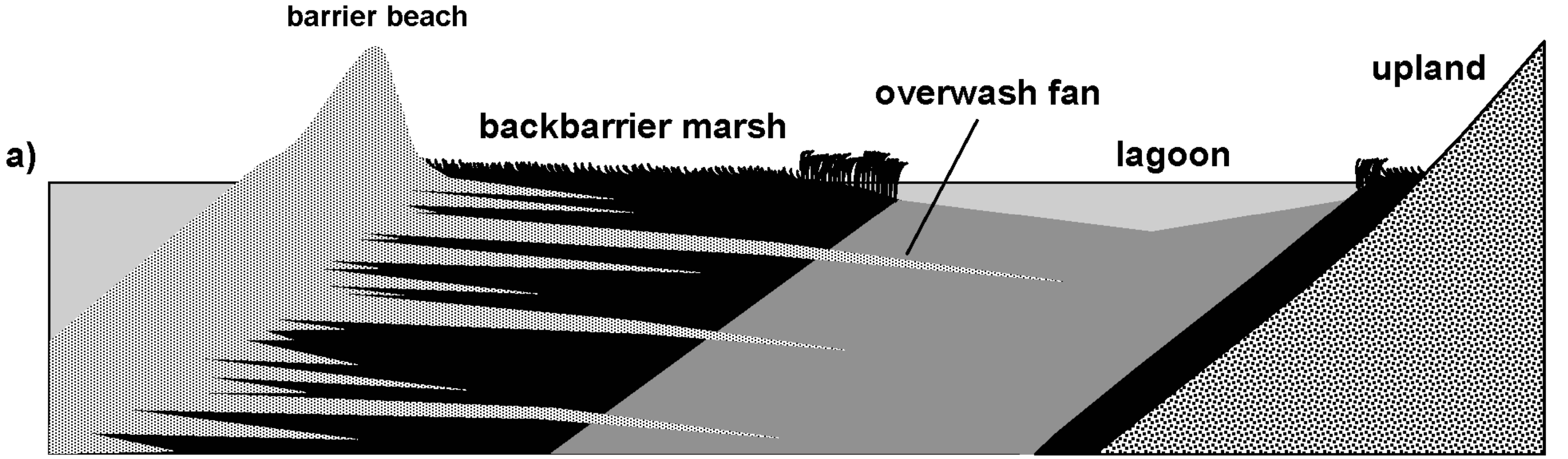


FIGURE 2.18 Hypothetical patterns of storm deposits in an estuarine marsh subjected to repeated hurricane strikes and storm surges in the past. A core taken from the marsh should contain multiple layers of storm deposits, which provide a proxy record of past hurricane strikes (after Liu and Fearn 2000a).

Liu, 2004

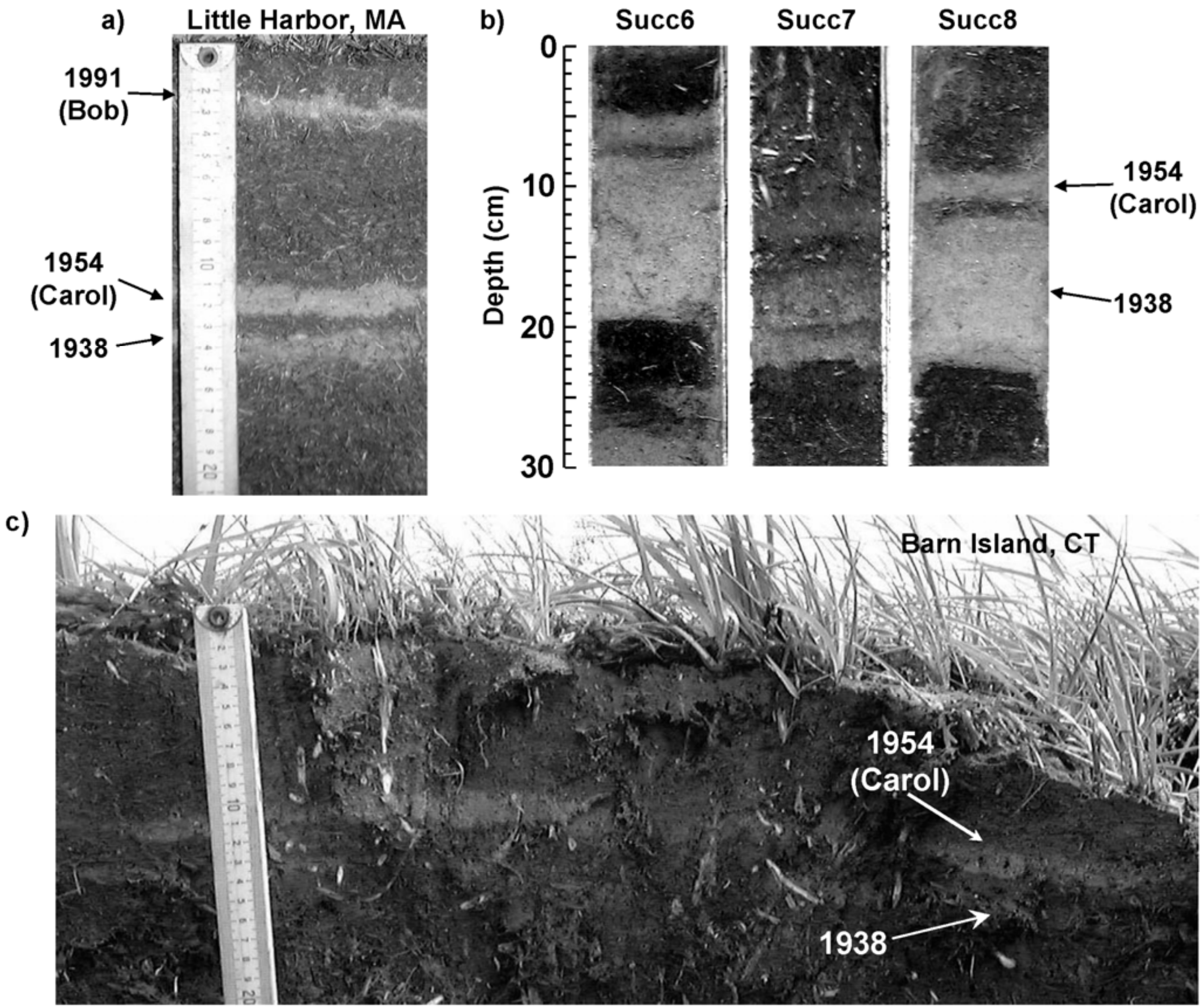
Backbarrier marshes



Conceptual model of overwash deposition and the landward translocation of the barrier-marsh system in a regime of rising sea level. Overtopping of the barrier beach by storm surge results in overwash fan deposition across back-barrier marshes. Overwash fans are preserved as sea level increases and they are covered with marsh deposits.

Donnelly and Webb, 2004

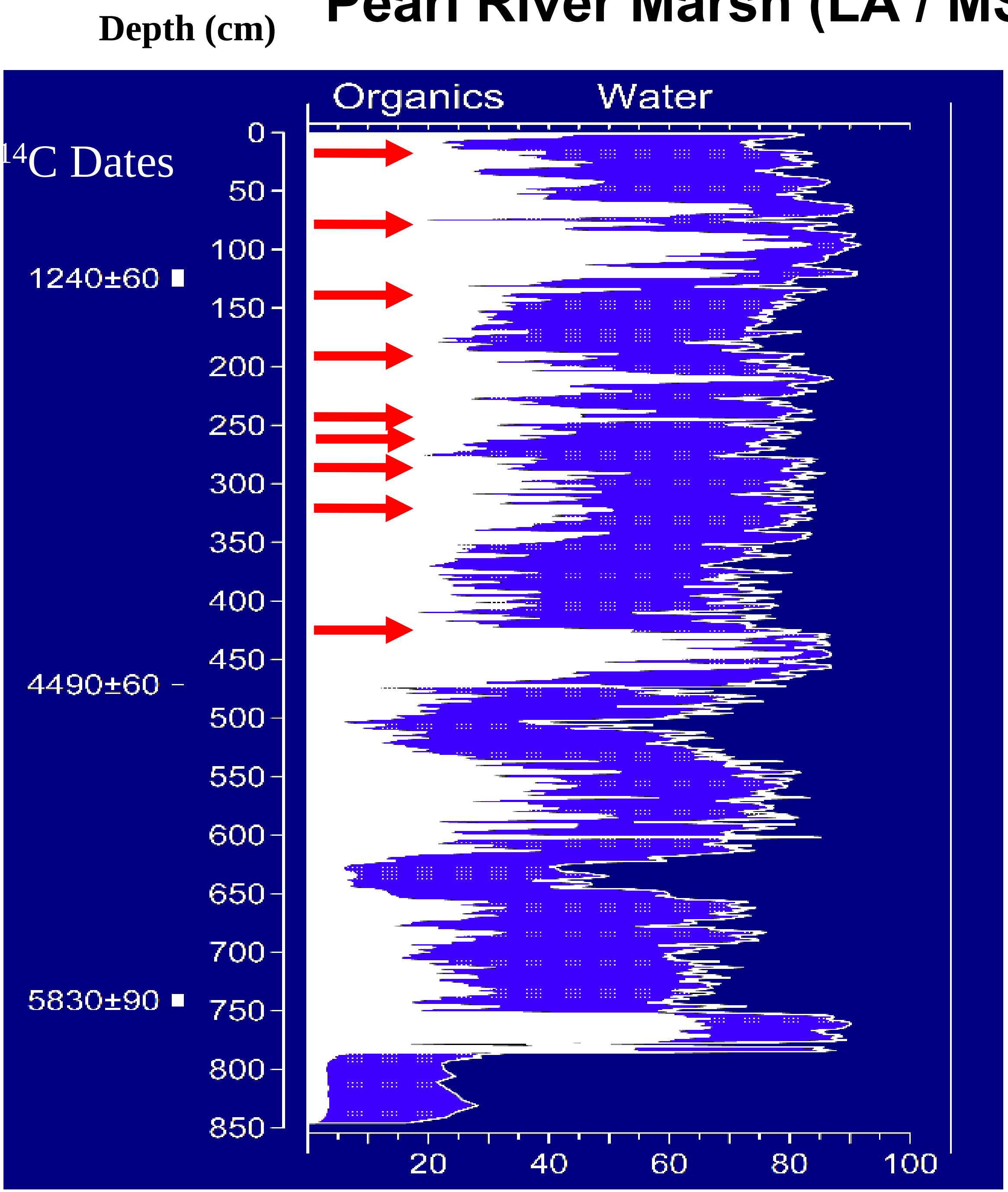
Overwash fan deposits in New England marshes



Donnelly – Figure 8

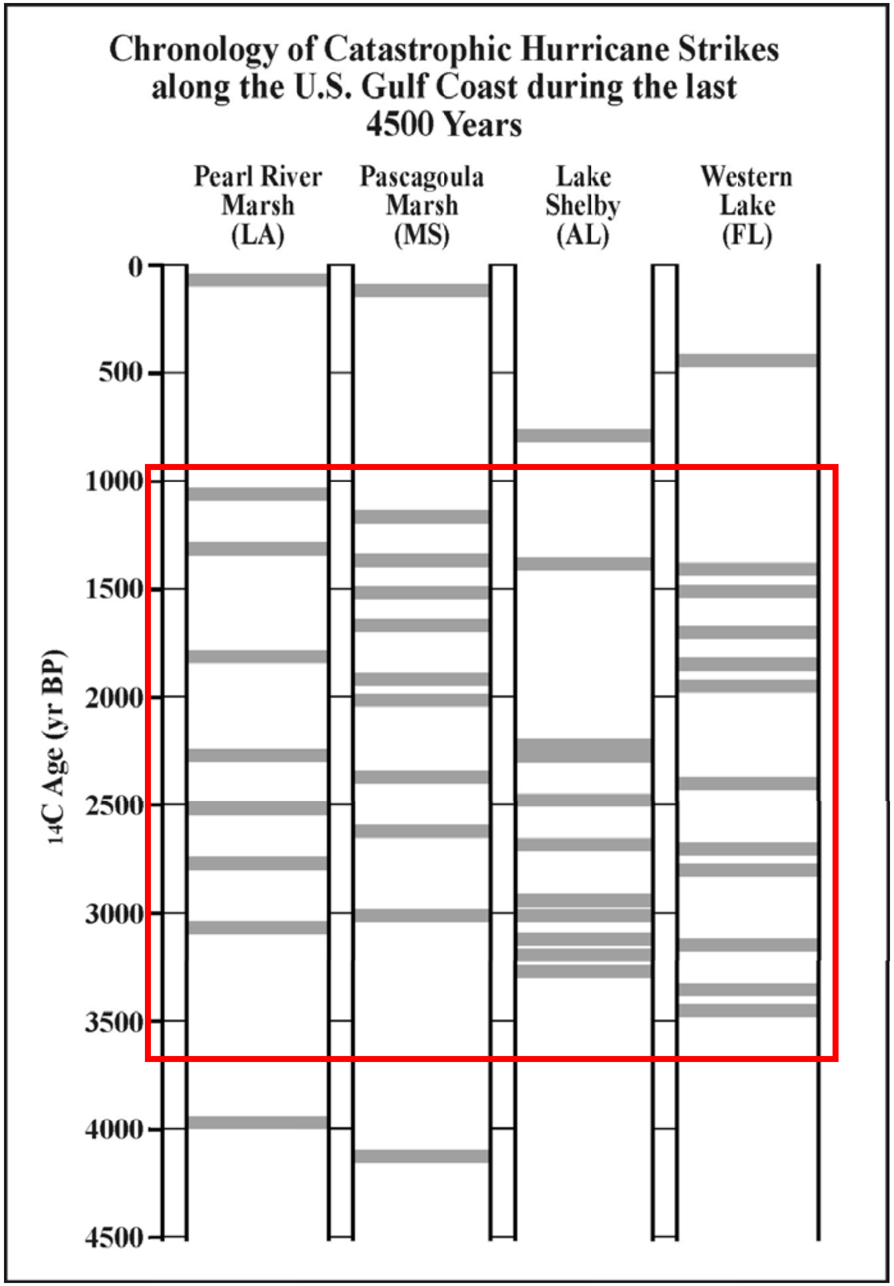
Donnelly and Webb, 2004

Pearl River Marsh (LA / MS)



- 9 sand layers over the last 4,000 years

Liu & Fearn, 2000



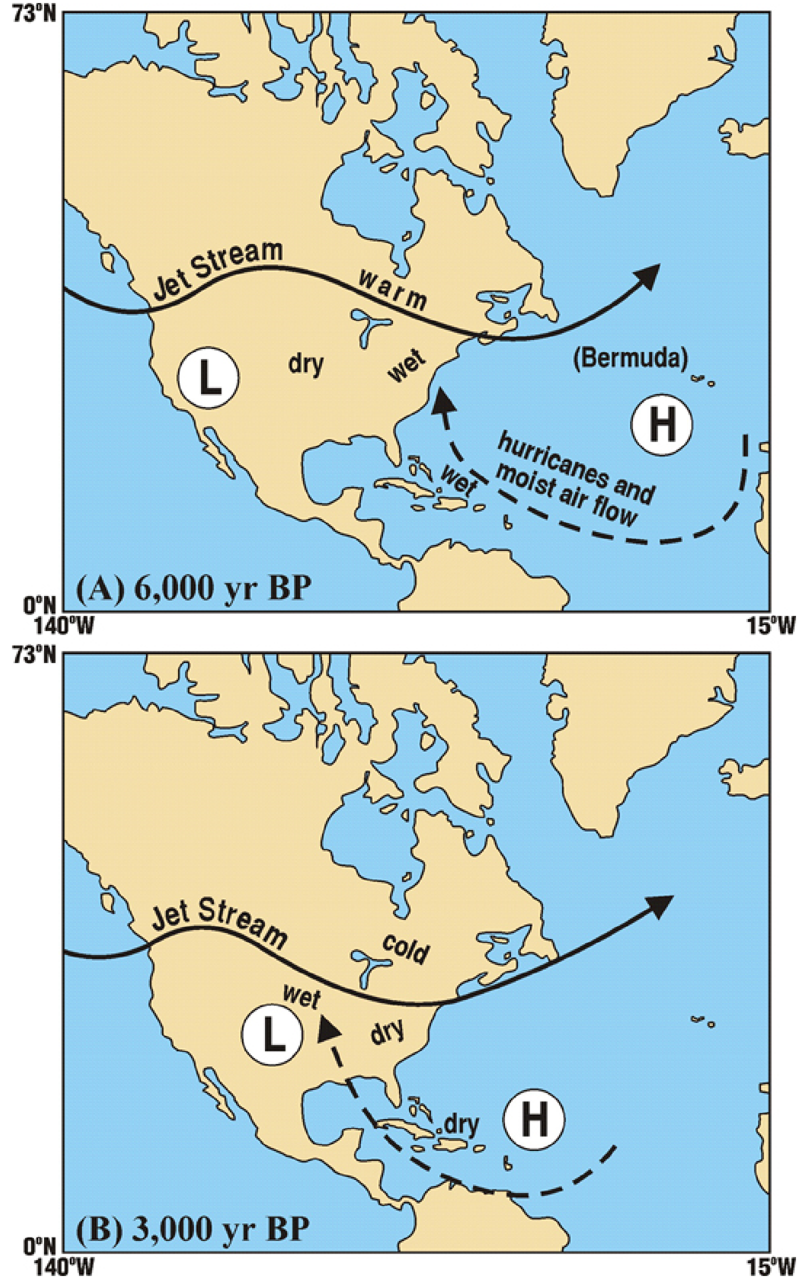
- **Major Findings from Gulf Coast Proxy Records:**

- Return period for catastrophic hurricanes = 300 yr
- Millennial-scale variability
- Hyperactive period 3800-1000 yr ago

The Bermuda High Hypothesis

- Bermuda High provides the steering mechanism that determines hurricane tracks
- A southwestward shift of the Bermuda High at 3800 BP steered more hurricanes towards Gulf coast
- Implication: Hurricane activities along the Gulf coast and Atlantic coast should be negatively correlated (anti-phase pattern)

Liu & Fearn, 2000



The Bermuda High – NAO Hypothesis

(Elsner et al., 2000; Liu & Fearn, 2000)

- **Strong NAO: More East Coast landfalls**
- **Weak NAO: More Gulf Coast landfalls**

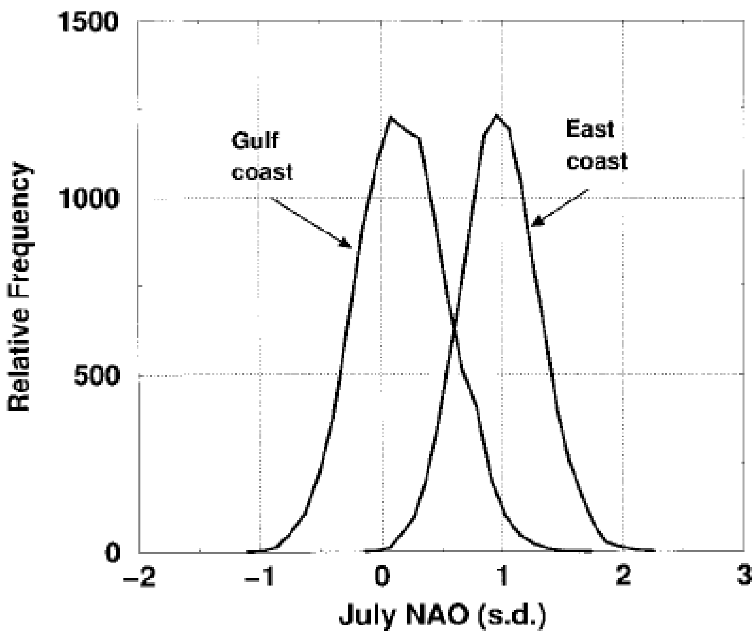
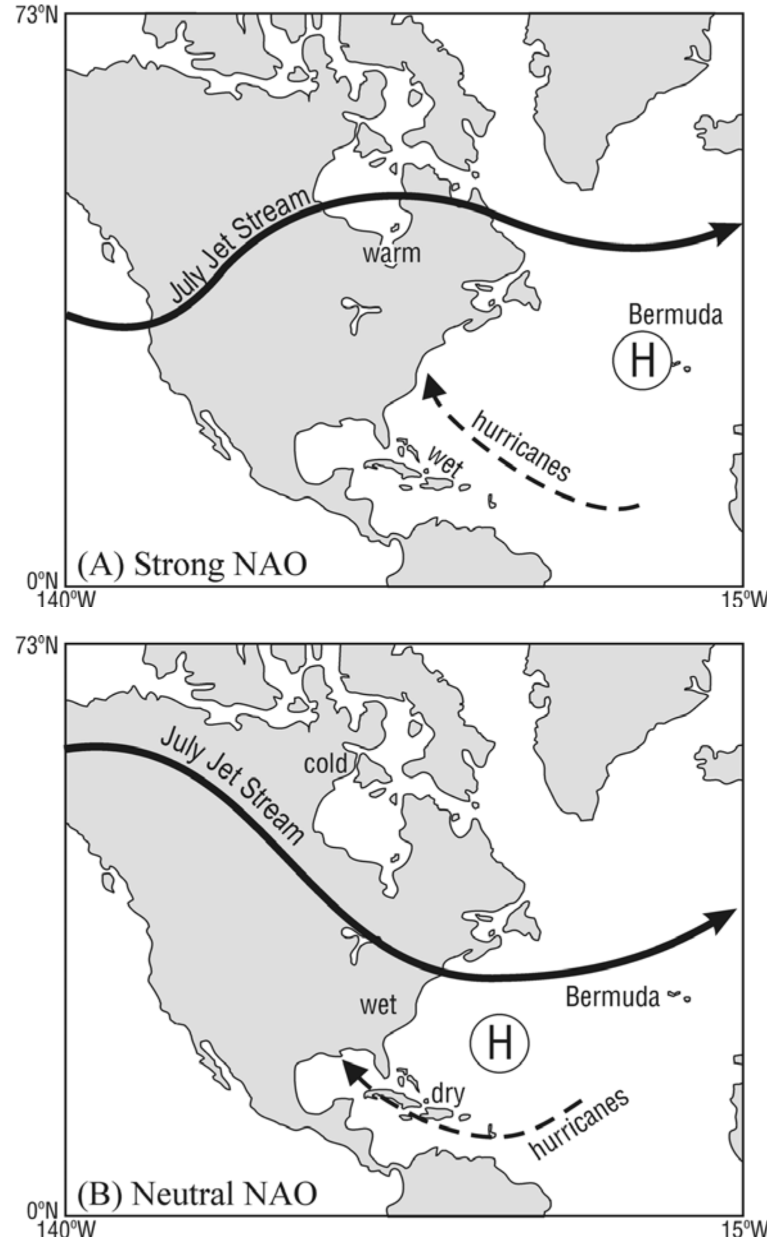
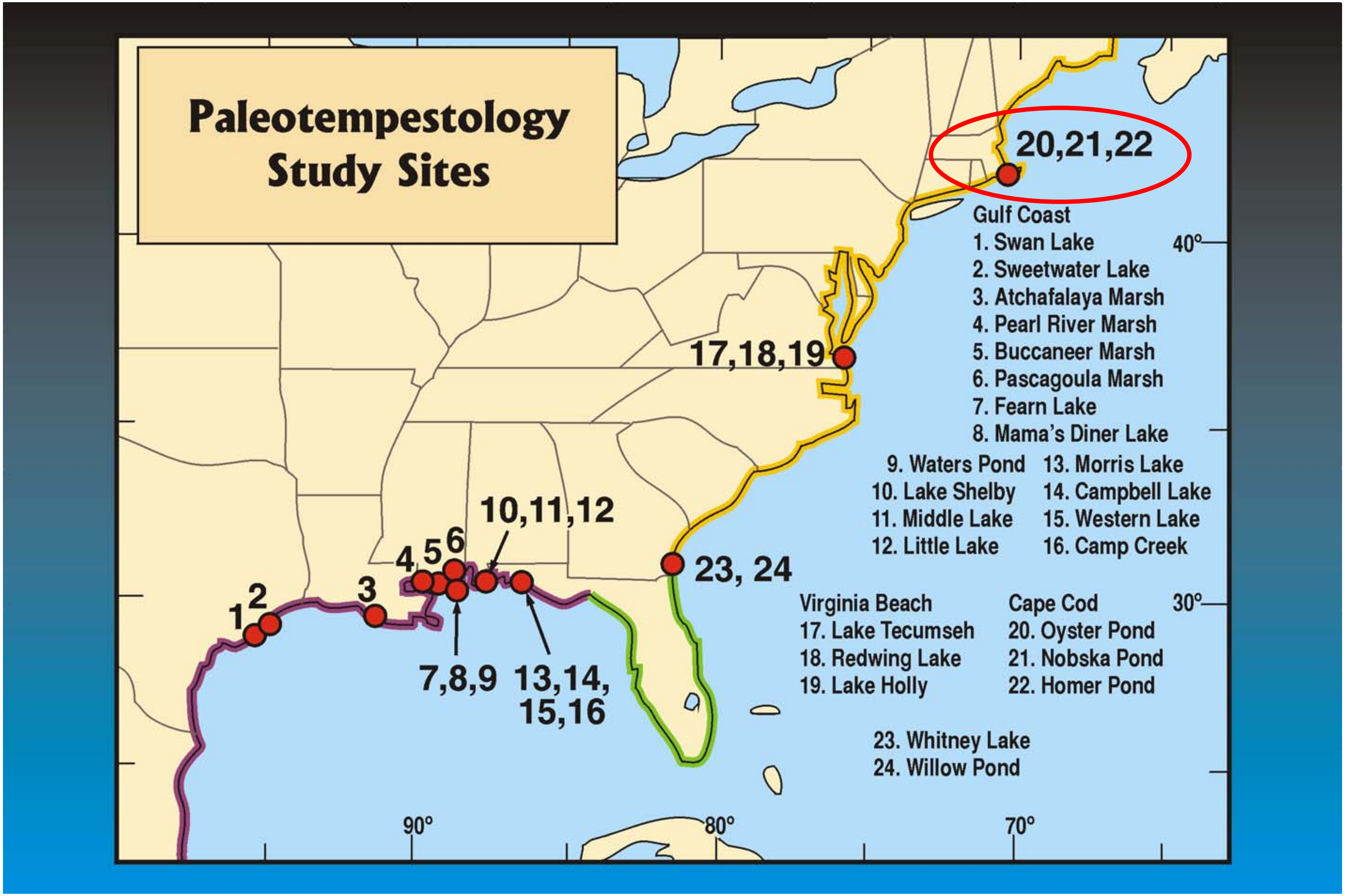


FIG. 11. Bootstrap distributions of the Jul NAO values for years with at least one major hurricane along the Gulf (TX–AL) and for years with at least one major hurricane along the East Coast (NC–ME). The ordinate values are relative frequency from 10^4 samples.



(Elsner, Liu, & Kocher, 2000)

Testing the Bermuda High hypothesis – New data from Cape Cod



Spatial and Temporal Variability:

Gulf Coast vs Atlantic Coast

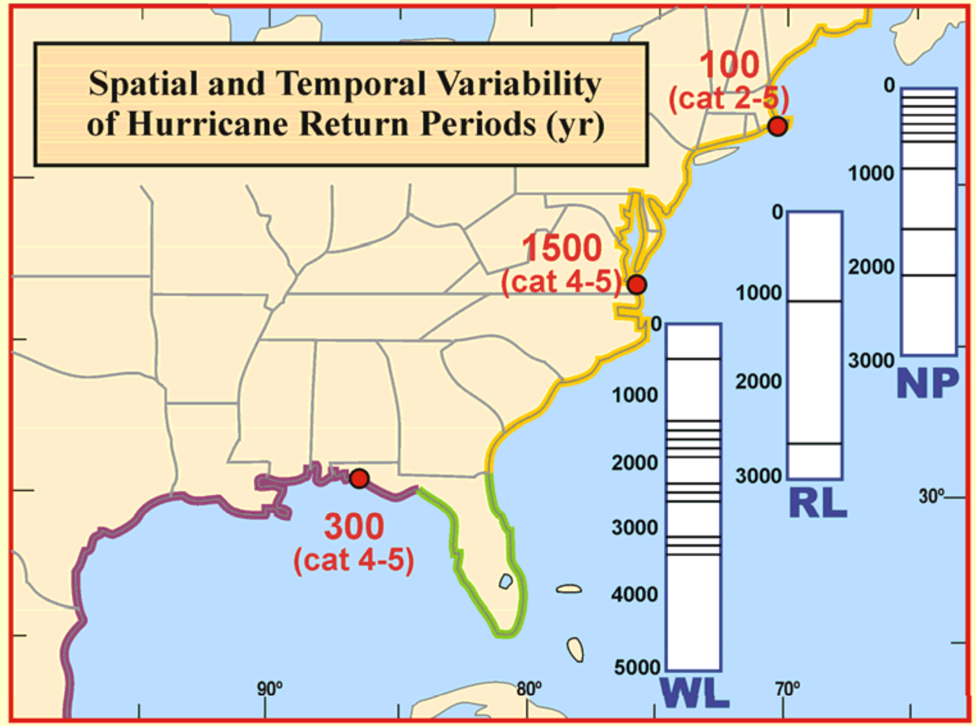
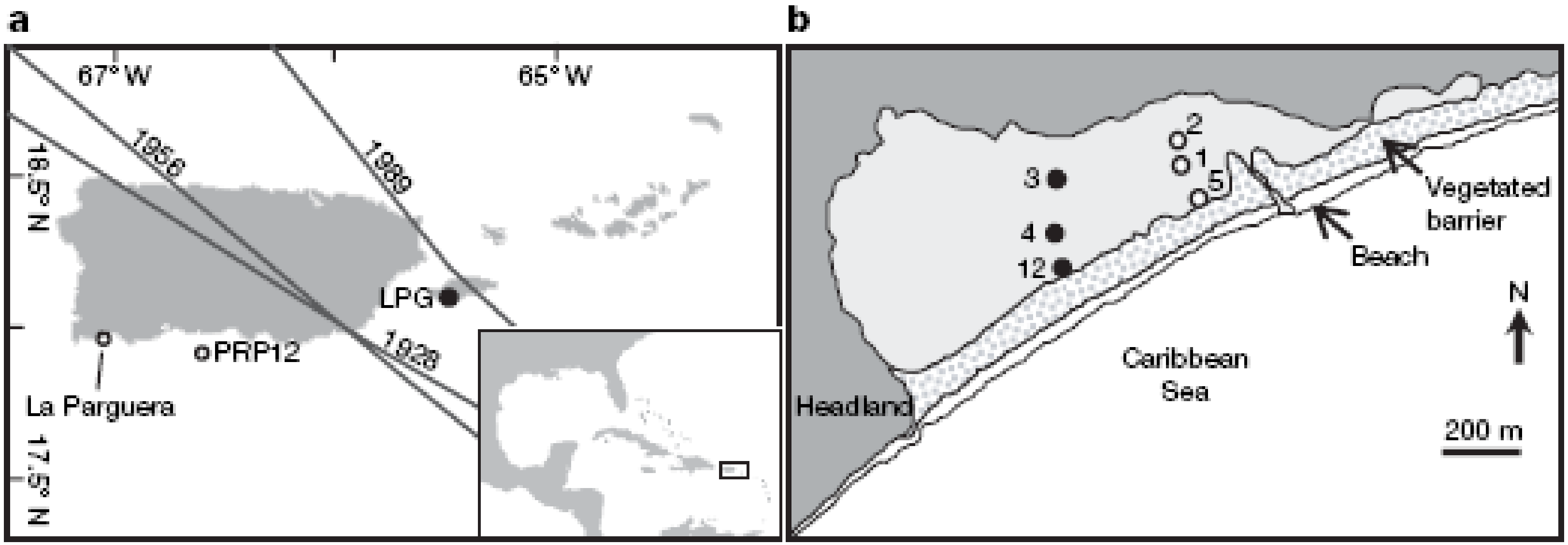


Fig. 18. Summary of proxy records and return periods from Nobska Pond (NP), Redwing Lake (RL), and Western Lake (WL) showing possible anti-phase pattern between the Atlantic coast and Gulf coast.

- Data support the hypothesis that hurricane activities along the Gulf Coast and Atlantic Coast are in a see-saw (anti-phase) pattern controlled by the Bermuda High.
- U.S. East Coast is in the active phase in the long-term hurricane activity cycle.

Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon

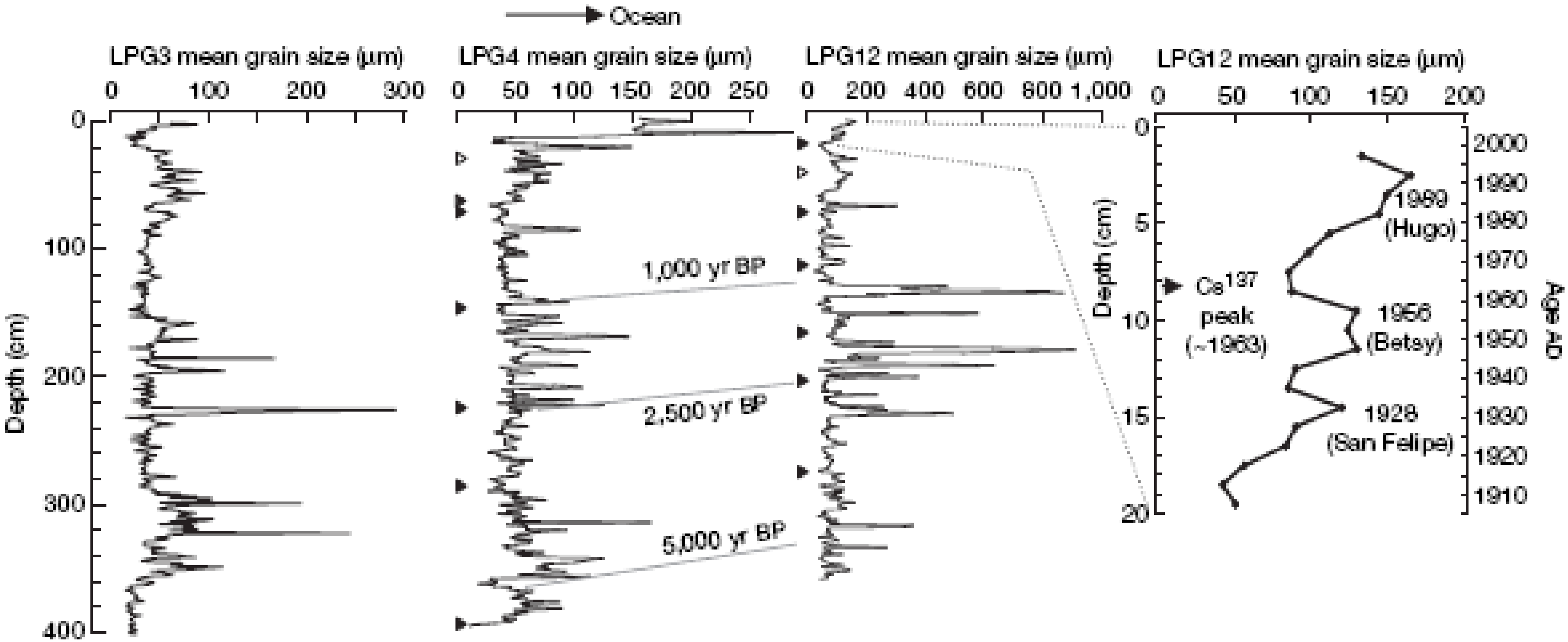
Jeffrey P. Donnelly[1] & Jonathan D. Woodruff[1]



High-resolution proxy record from Puerto Rico

Donnelly & Woodruff, 2007

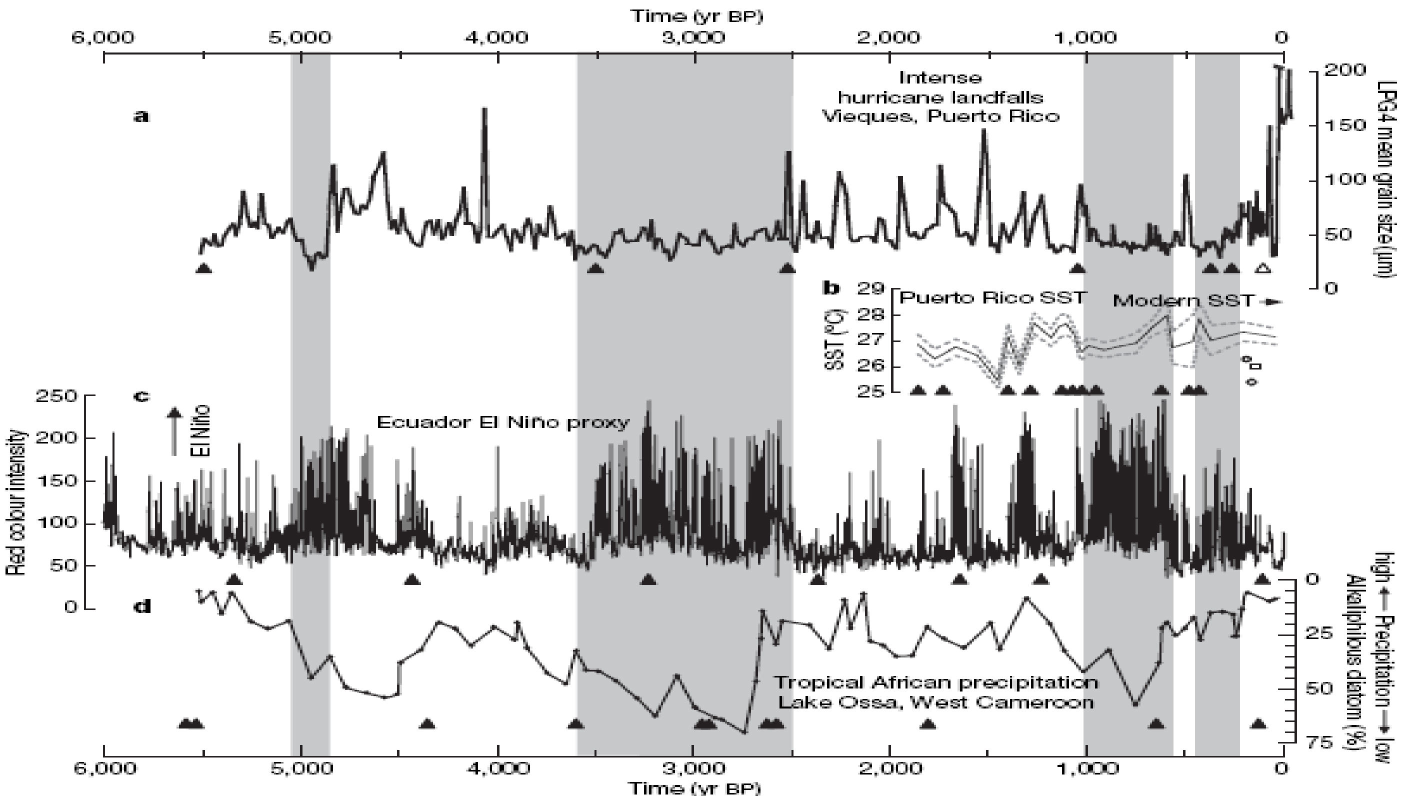
Laguna Playa Grande, Vieques, Puerto Rico



5400 – 3600 yr BP **Active**
3600 – 2500 yr BP **Quiet**
2500 – 1000 yr BP **Active**
1000 – 250 yr BP **Quiet**
250 yr BP – present **Active**

Donnelly & Woodruff, 2007

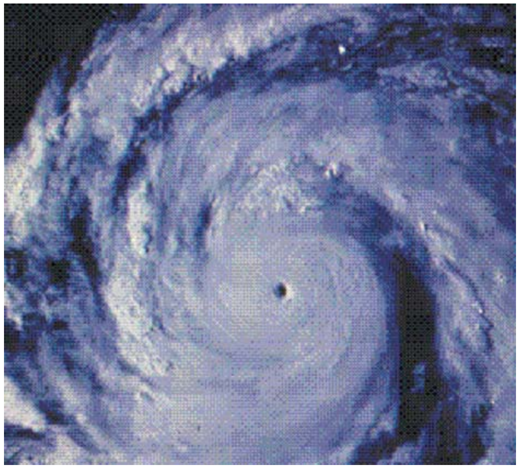
Proxy record from Puerto Rico suggests that hurricane activity was positively linked to the strength of the West African monsoon (and strength of the African easterly jet) and negatively with the frequency of strong El Nino events. However, the Puerto Rico record is out of phase with the Gulf coast record.



Donnelly & Woodruff, 2007

Ecological Applications……

Is there a link between hurricane and fire ?

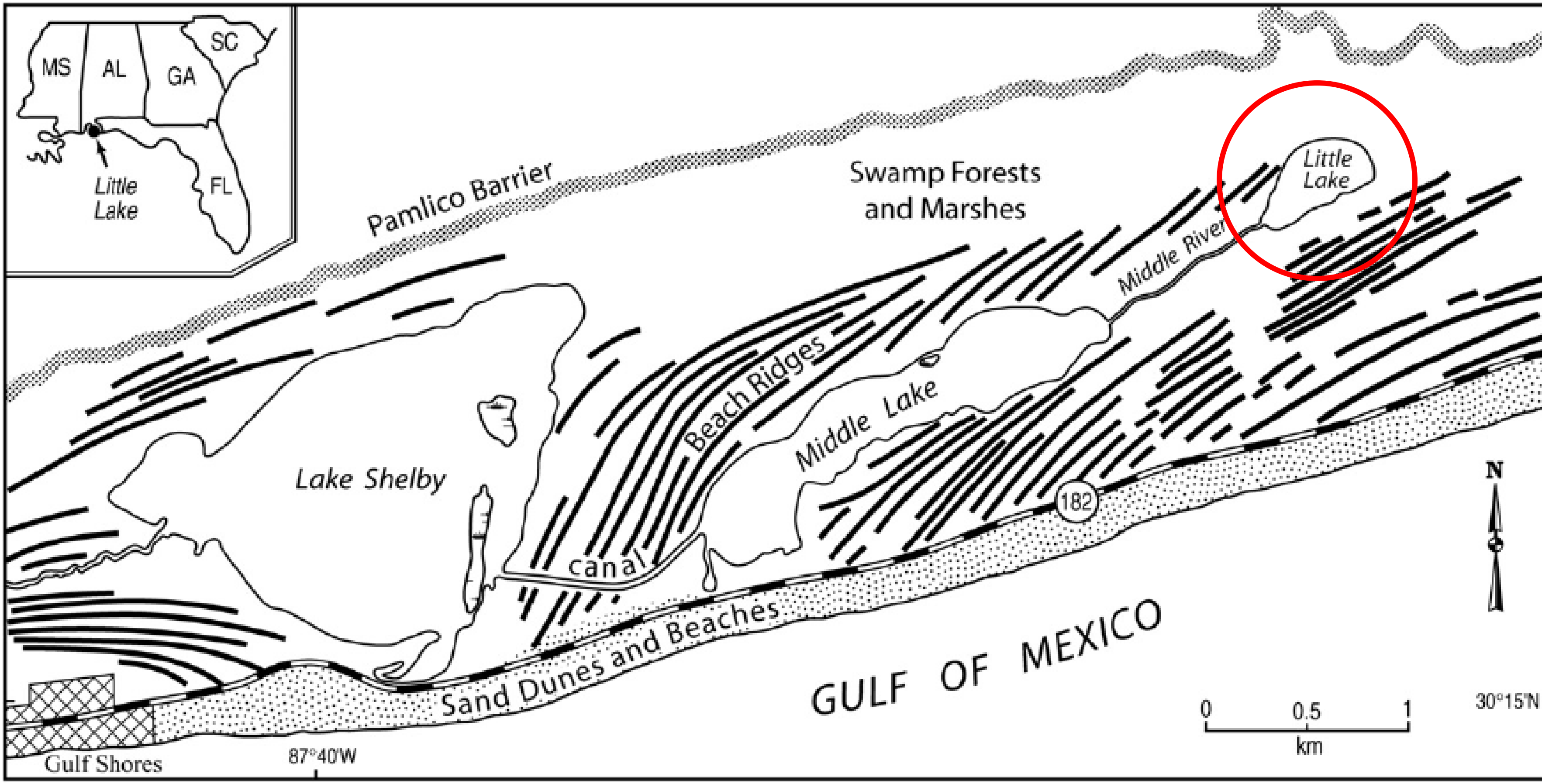


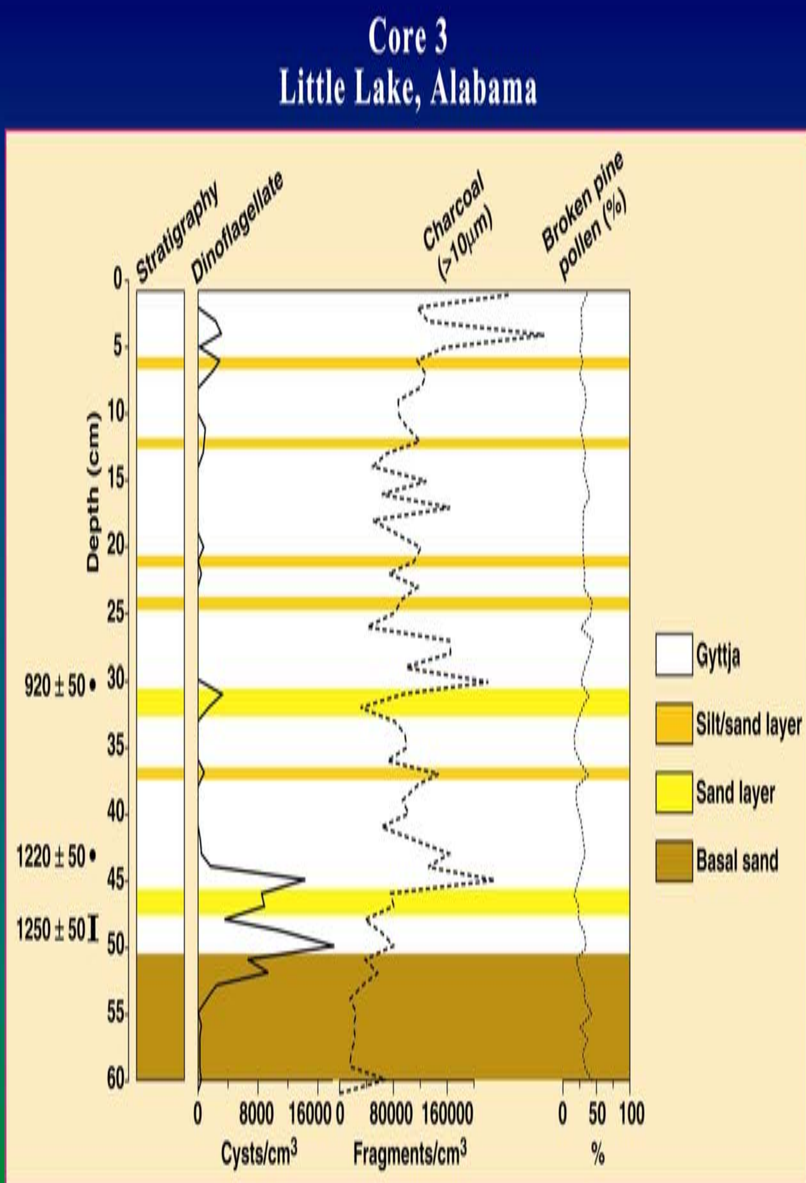
?

<u>Hypothesis of hurricane-fire interactions</u>: Fire hazard increases significantly after a major hurricane strike due to fuel accumulation (dead biomass) and drier microclimate.

Liu et al., 2008

Little Lake, Alabama



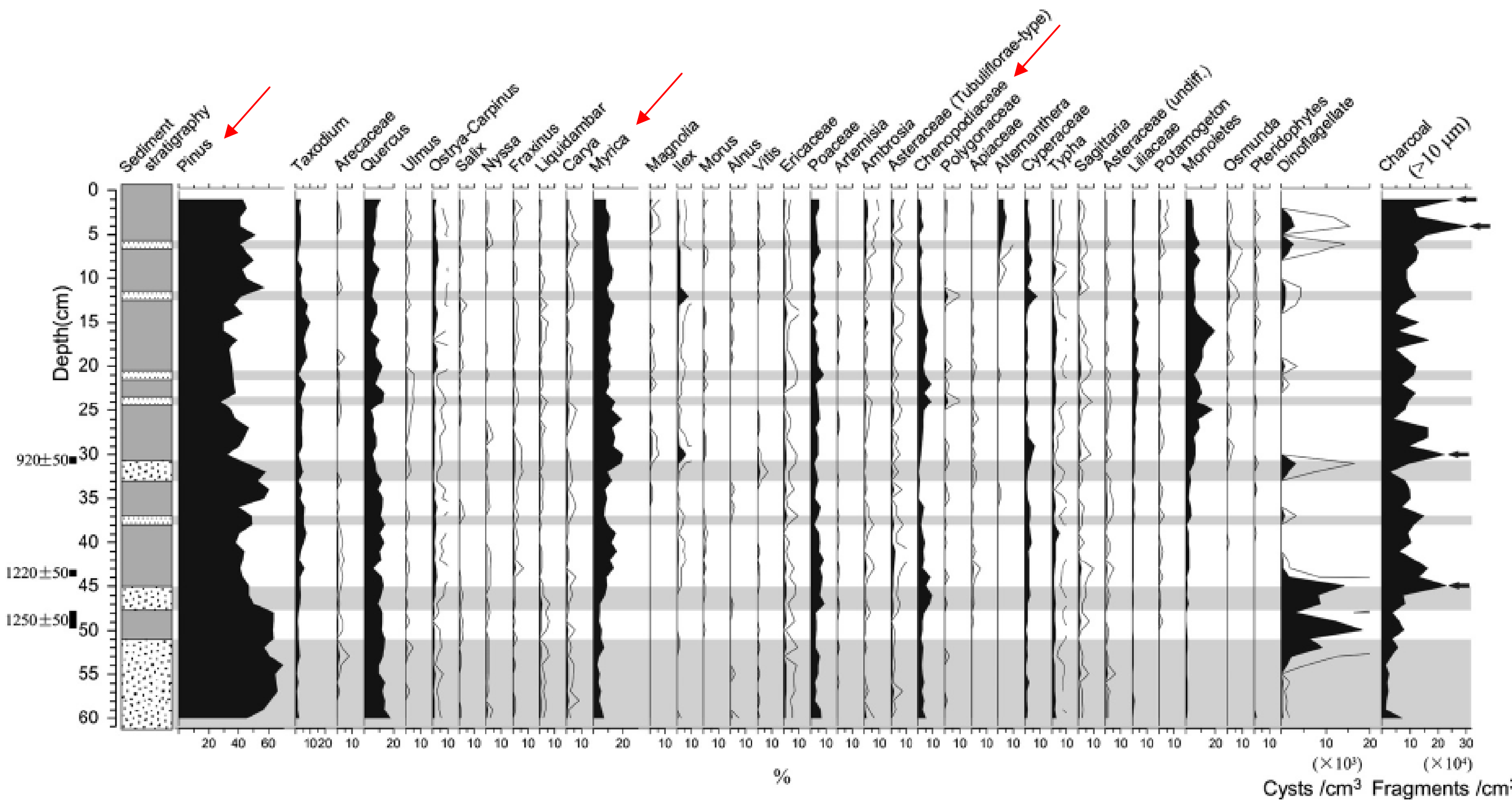


Liu et al., 2003, 2008

Hurricane-Fire Interaction:

- Dinoflagellate data confirm overwash origin of 7 sand layers.
- At least 11 charcoal peaks during past 1,300 years.
- 3 of 4 prominent charcoal peaks occur immediately above sand layers.
- Data support the hypothesis that fire hazard increases significantly after major hurricane strike.

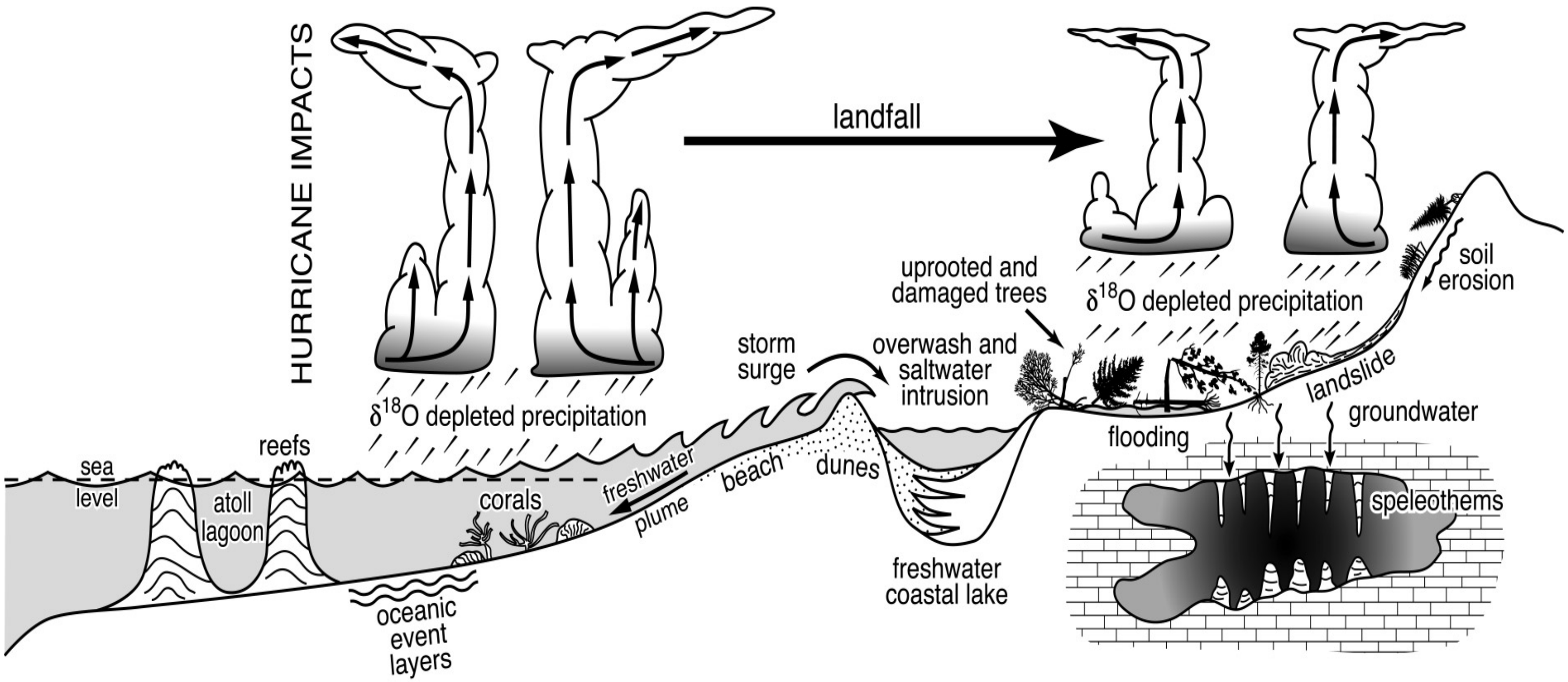
Pollen data from Little Lake reveal vegetation response to interacting disturbances between hurricanes and fires



Liu et al., 2008

The Expanding Frontiers of Paleotempestology…….

Multi-proxy Reconstruction of Prehistoric Hurricane Activities

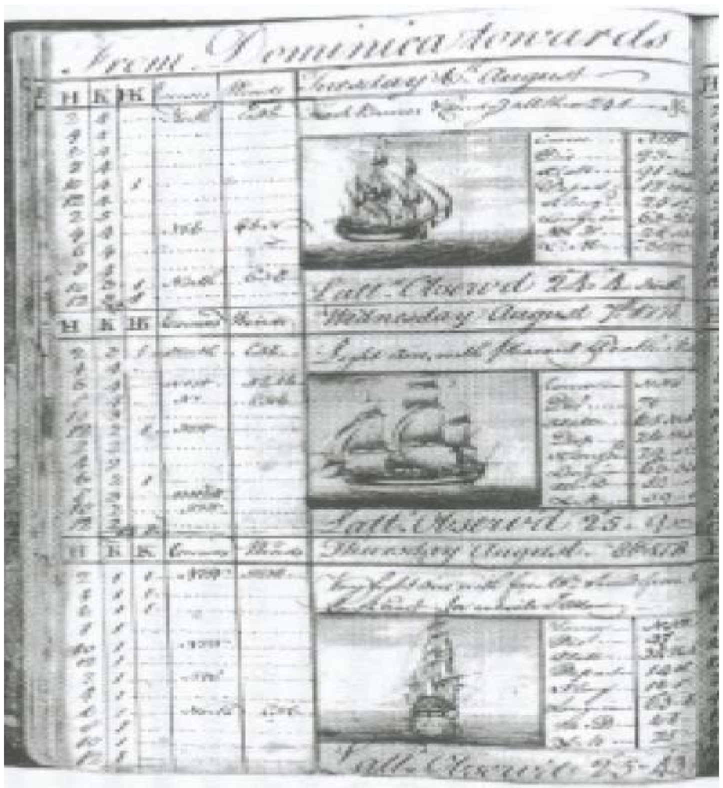


Liu, 2007

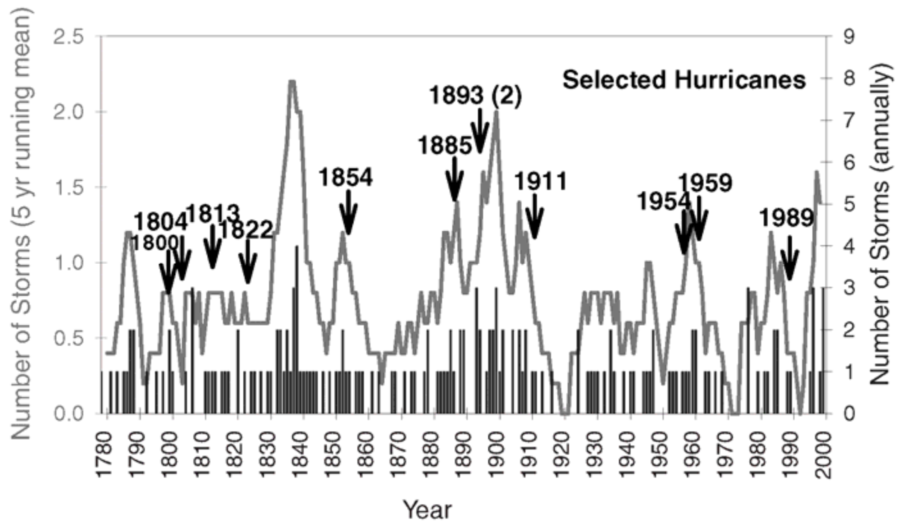
Approaches in Studying the Past

- Geological Proxy Records
- Historical Documentary Records

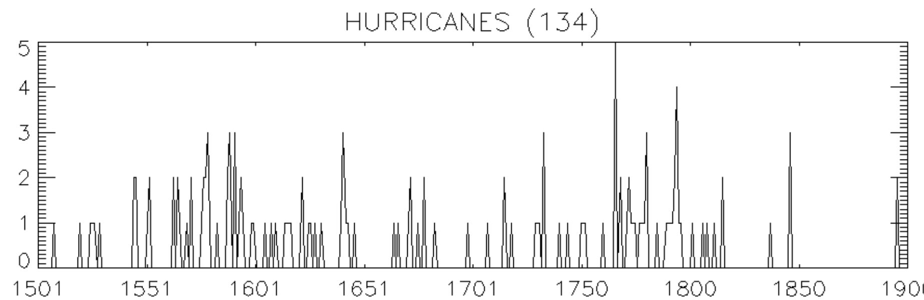
Spanish and English historical records

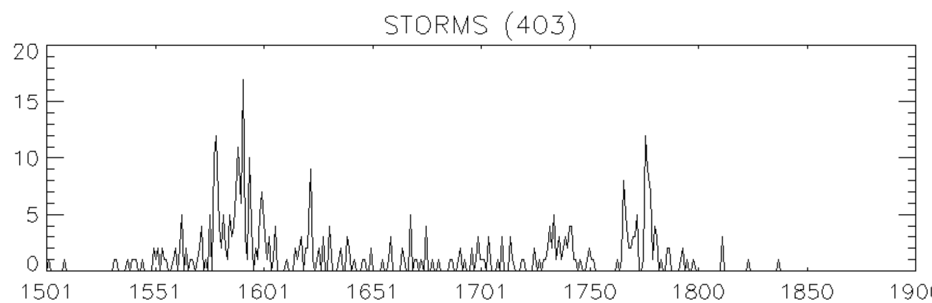


Garcia et al., 2004, 2005

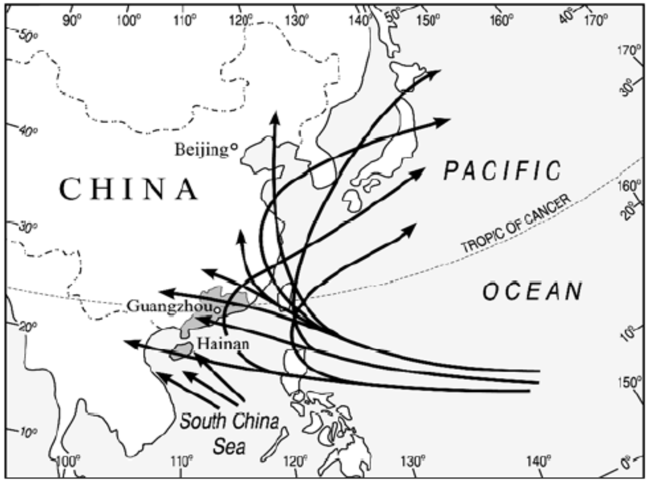


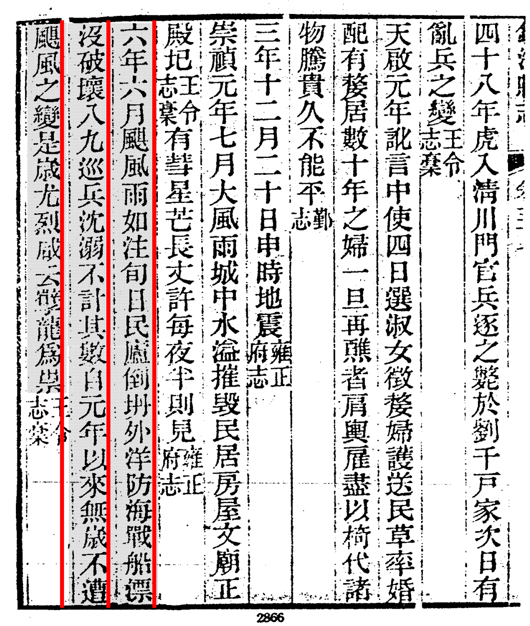
Mock, 2004





Historical Records of Typhoon Landfalls in China





四十八年虎入清川門官兵逐之斃於劉千戶家次日有
亂兵之變王令志稾
天啟元年訛言中使四日選淑女徵嫠婦護送民草率婚
配有嫠居數十年之婦一旦再醮者肩輿雇盡以椅代諸
物騰貴久不能平志勤
三年十二月二十日申時地震雍正府志
崇禎元年七月大風雨城中水溢摧毀民居房屋文廟正
殿圮王令志稾有彗星芒長丈許每夜半則見雍正府志
六年六月颶風雨如注旬日民廬倒坍外洋防海戰船漂
沒破壞八九巡兵沈溺不計其數自元年以來無歲不遭
颶風之變是歲尤烈咸云孽龍爲祟王令志稾

2866

Jufeng

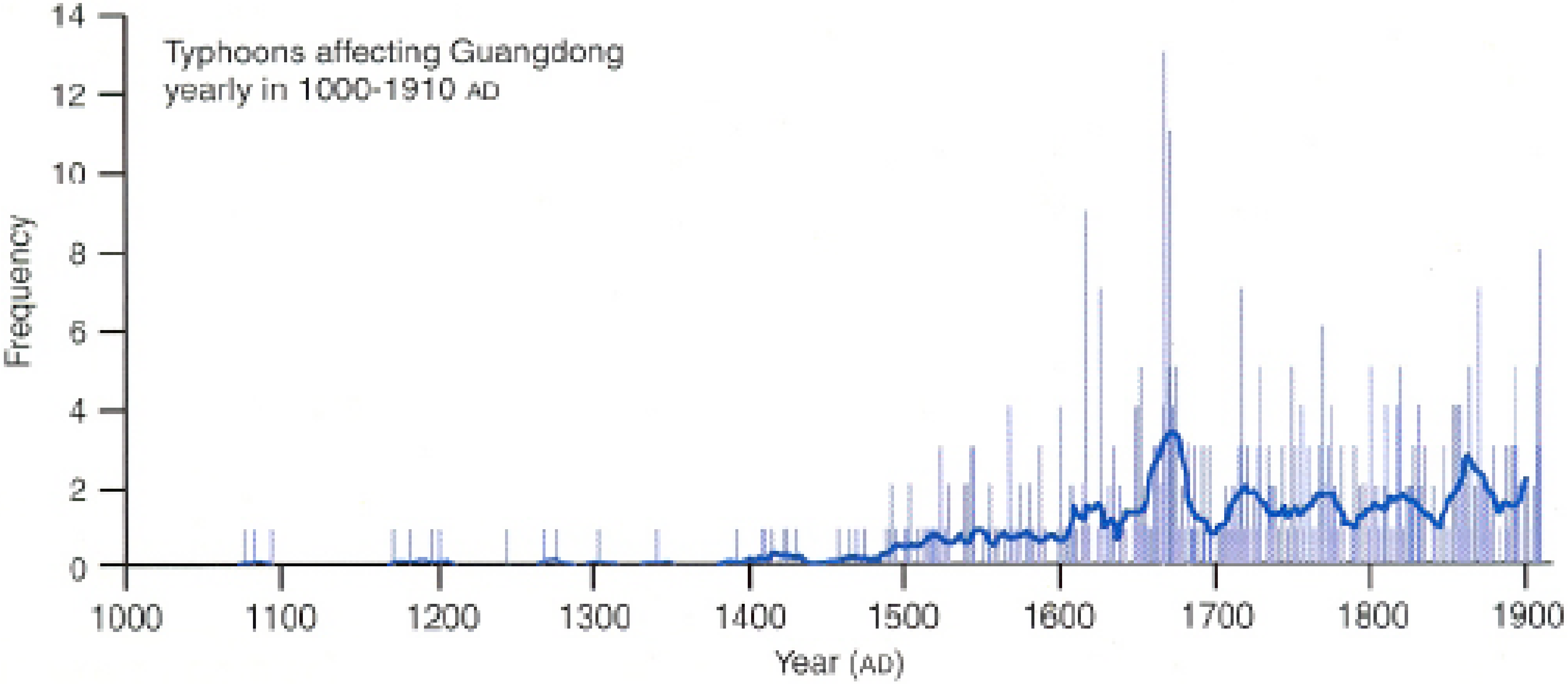
County gazette

"In the 6th lunar month of the 6th year of Emperor Chongzhen (1633 AD), typhoon struck. Torrential rain fell for ten days. Houses collapsed. Naval battleships were drifting in the sea; eight or nine out of ten were destroyed, drowning numerous soldiers. Since the first year of Chongzhen, there was no year without typhoon strikes. The damage was especially serious this year. It was widely believed that the culprit was a mischievous dragon."

-- *Zhenhai County Gazette, Zhejiang*

Louie & Liu, 2004; Liu et al., 2001

Typhoons Affecting Guangdong in 1001-1900



Note:

- Most active decades: AD 1660-1680, 1850-1880
- Approximately 50-year periodicity

Liu et al., 2001

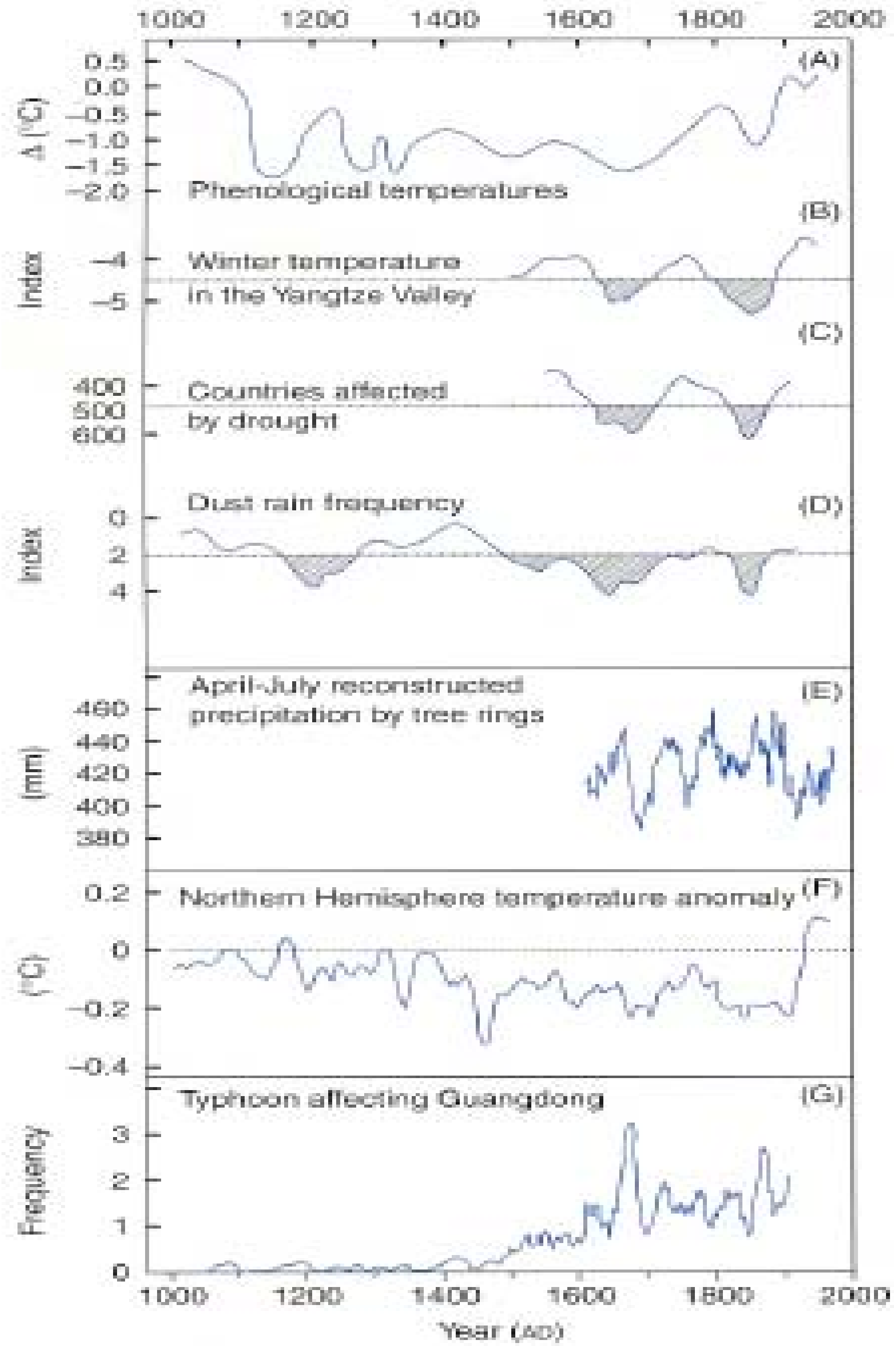
Comparison between Guangdong typhoon record with other paleoclimatic proxy records from China

• Little Ice Age cold period has two temperature minima

• Two active periods in Guangdong coincide with two of coldest & driest periods in north & central China

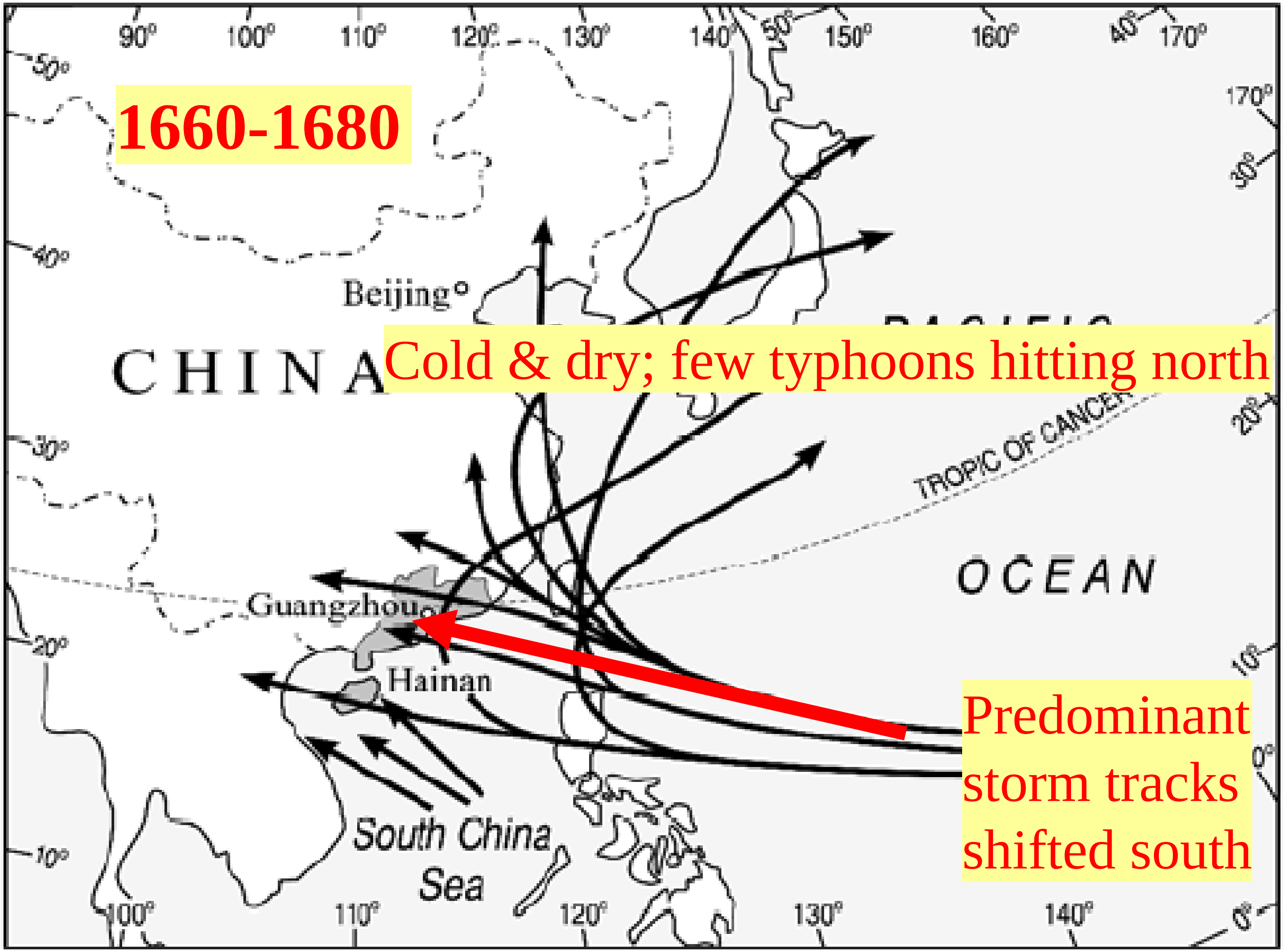
•Multi-decadal variability

Liu et al., 2001



<u>Hypothesis</u>:

Southward shift of typhoon tracks during AD 1660-1680



Liu et al., 2001

Lessons Learned from Paleotempestology

- Paleotempestology helps us understand the climate mechanisms controlling hurricane activities (e.g., Bermuda High & storm tracks; 50-yr typhoon cycles)
- For Gulf coast locations, catastrophic hurricanes (cat 4-5) have a return period of ca. 300 years (p = 0.3%/yr)
- For the Gulf coast, the past millennium is in the low-activity phase of the mega-cycle of hurricane activity. (*we haven’t seen anything yet!*)
- If the climate regime characteristic of the “hyperactive period” returns in the future, hurricane landfall probability for the Gulf coast may increase by 3-5 times.

Paleotempestology

Principles:

Methods:

Applications:

Users: