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Indirect Response of the Peace River, Florida, to Episodic Sea-Level Change

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ABSTRACT

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Rivers must respond to base-level change but the timing, nature, and location of the response varies with the river. This response includes incision and aggradation as recorded in the flood-plain sediment and soil and calibrated by radiocarbon dates.

Stream response to sea-level variations in a karst terrain is identified along the Peace River in central Florida. Incision and aggradation of this small river, more than 35 km upvalley from its mouth, primarily respond to changes in water-table elevation. This elevation in turn responds to both sea-level and climate changes. As a consequence, river response to sea-level change is indirect and nonsynchronous with sea-level variations and with that of other non-karst streams that respond more directly to sea-level fluctuation.

Incision of the Peace River occurred prior to 22 ka, during the initial decline of sea level and dry climate associated with the late Wisconsin glacial stage. These conditions caused the depression of the water table and hence the potential incision for the Peace River. As the river incised, upstream fluvial and eolian erosion of dry upland surfaces increased sediment load and subsequently caused aggradation of the Peace River, despite a declining sea level.

The present incision of the river occurred within the last few millennia when sea level was at or near its present high stand and the climate was humid, thus resulting in a shallow water table. The wet vegetated ground surface restricted erosion therefore reducing sediment load of the Peace River, which then began to incise during a sea-level maximum.

ADDITIONAL INDEX WORDS: *Base level, flood plain, radiocarbon dates, climate change, water table.*

INTRODUCTION

Sea level, defined as base level (SCHUMM, 1993), has changed dramatically in the past 35,000 years and impacted streams worldwide. Two critical questions for coastal regions are how far inland does the fall and rise of sea level impact a stream and what, if any, is the lag time of the system's response? Flume simulation models have confirmed that sediment from the "hinterland" is supplied to continental shelf and slope deposits and that incision of the channel does reach the coastal plain (WOOD, 1992) though it only occurs a relatively short distance upstream (SCHUMM, 1993). However, the analogue nature of these physical experiments inhibits the scientist's ability to quantify the distance inland that a river responds to base-level changes, and studies of actual streams are necessary.

The second critical question for coastal regions, the timing of stream response to changes in base level, has also been examined using physical models (SCHUMM *et al.,* 1987; WOOD, 1992; SCHUMM, 1993). These experiments indicate that there is a lag between the lowering of base level onto the continental shelf and stream incision on the adjacent coastal plain. The time lag is dependent on the rate of base-level lowering. WOOD (1992) reports that the greatest lag corresponds to a relatively rapid fall in base level. If incision does not keep pace with the fall of sea level, then it does not occur on the coastal plain until the later part of sea-level lowstand. At this time, knickpoints, inflections in the longitudinal profile, retreat from the continental slope where the greatest gradient changes occur, across the continental shelf, and up to the coastal plain. There is also a lag between sea-level rise and aggradation within the incised channels (WOOD, 1992). The lag is a function of the depth/volume of the incised valleys, slope of the coastal plain, the amount of lowstand fill contained within the incised valley (WOOD, 1992), and sediment supply of the stream. This model for a lag time in stream response to base-level changes

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Table 1. *Size and sediment load of selected rivers, Gulf of Mexico.*

River	Length (km)	Drainage Basin (km^2)	Mean Discharge (m^3 sec^{-1})	Load
Mississippi	6,019^{1}	3,230,419^{3}	12,820^{3}	mixed
Colorado	970^{2}	107,874^{4}	104^{6}	mixed
Peace	186	6,195^{5}	40^{5}	bed

^{1}Times Staff, 1991
^{2}Rand McNally Staff, 1980
^{3}Iseri and Langbein, 1974
^{4}Water Resources Staff, 1959
^{5}Coffin and Fletcher, 1991
^{6}Prior to dam construction, Kanes, 1970

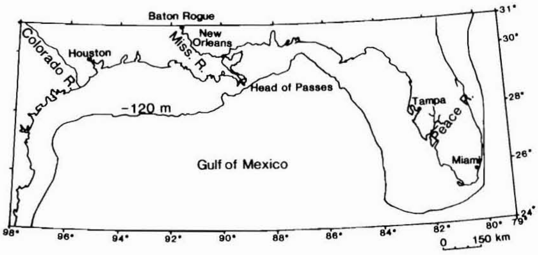

Figure 1. Map of the northern Gulf of Mexico, with the Peace, Colorado, and Mississippi rivers and the −120 m bathymetric contour, representing the approximate low stand of sea level. Modified from Uchupi (1967, Figure 1).

can be tested by examining the timing of sea-level variations compared to that of incision/aggradation of streams near their mouth.

The purpose of this study is to determine if there is a fluvial response by a relatively small stream, the Peace River (Table 1), to sea-level fluctuations and if so, what is the timing and distance upstream of that response. The Peace River was chosen for this study because it is unlike the streams of the northwestern Gulf of Mexico rim that have been studied previously (AUTIN, *et al.*, 1991; BLUM, 1994). First, the drainage basin of the Peace River is within a karst area underlain by limestone, dolostone, and siliciclastics (SCOTT, 1988). Second, the study area is in a tectonically stable area (SCHNABLE and GOODELL, 1968, Fig. 3; HOYT, 1969) with a minimal amount of regional uplift (GABLE and HATTON, 1983). Finally, faulting and compaction are minimal and base-level fluctuations should be dominated by glacioeustatic sea-level variations. The Peace River also has some similarities with other streams that flow into the Gulf of Mexico. Like the Colorado River of Texas but unlike the Mississippi River, the Peace River is south of the Pleistocene ice sheet limit and was not affected by meltwater discharge fluctuations. Because all three rivers (Peace, Colorado, and Mississippi) flow into the Gulf of Mexico (Figure 1), all should have experienced similar sea-level variations.

Timing of sea-level variations is known for the Atlantic and Gulf Coastal Plain. Sea level was at an intermediate (−65 m) (BLOOM, 1983; CHAPPELL and SHACKLETON, 1986) to relatively high elevation (MILLIMAN and EMERY, 1968) 35 ka but was depressed at least 60 m (BLACKWELDER *et al.*, 1979) and probably as much as 121 ±5 m (FAIRBANKS, 1989) to 130 m (CHAPPELL and SHACKLETON, 1986) below modern sea level during the glacial maximum. This lowstand occurred approximately 19–18 ka based on radiocarbon dating or 22 ka based on U-Th ages of Barbados corals (BARD *et al.*, 1990). Since that time, sea level has been rising and was within 3 m of its present level by 3,000 years ago. Sea level may have undergone minor changes (±1 m) in elevation in the past 3 ka (STAPOR, *et al.*, 1991).

The maximum distance inland of the coast that a river responds to changes in sea level is less well known. On the Gulf Coastal Plain stream response to sea-level change is limited to a short distance upstream of the present mouth. Direct influence of late Pleistocene base-level fall and rise on the Mississippi River extends no further than Baton Rouge, Louisiana, approximately 240 km upvalley from Head of Passes in the delta (AUTIN *et al.*, 1991) (Figure 1) (Table 1). BLUM (1994) reports that the smaller Colorado River of Texas (Figure 1) responded to late Pleistocene sea-level changes no more than 90 km upvalley from the modern shoreline, one-third of the Mississippi River response. Along this lower 90 km of the Colorado River, older Pleistocene and Holocene sediments and land surfaces are buried by younger Holocene sediments. The depth of burial increases in a downstream or a basinward direction. In contrast upstream of this limit of stream response, older sediments and land surfaces are higher than younger sediments. These older surfaces form terraces and the Colorado River responds to long-term tectonic uplift, climate change, and/or sediment load variations (BLUM, 1994).

Timing of stream response to base-level change

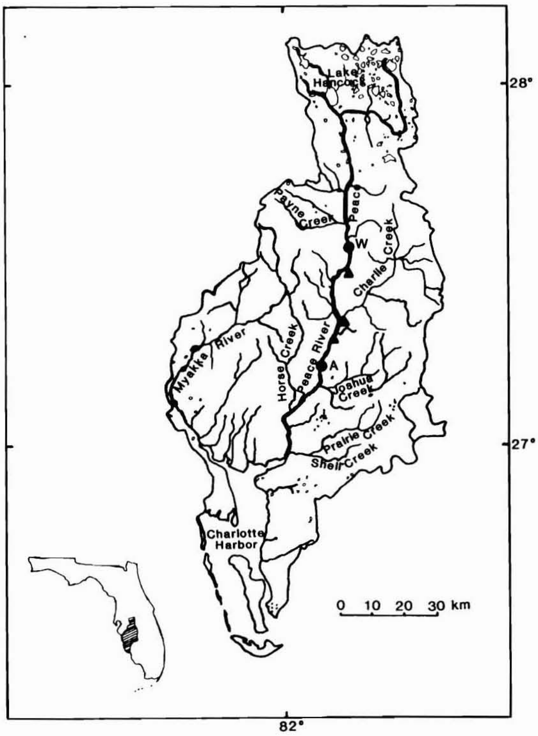

Figure 2. Map of the drainage basin of the Peace and Myakka rivers and Charlotte Harbor, south-central Florida. Site A is Arcadia and Morgan Park, site W is Wauchula. Cross sections of these samples sites are in Figure 3. Additional sites examined but not described in detail are represented by triangles. Modified from Coffin and Fletcher, 1991, Figure 14.

has been studied along the Colorado River. Incision of the river both upstream and downstream of the limit for lowstand fluvial response to sea-level change began prior to 18.6 ± 0.7 ka using radiocarbon dating. (BLUM, 1994). BLUM interprets this incision to be the result of climate/sediment supply changes within the drainage basin rather than sea-level changes. Incision downstream of the limit for lowstand stream response is interpreted as reflecting sea-level change (BLUM, 1994). If so, incision would have occurred at approximately the low sea-level stand, as WOOD's (1992) experimental model predicted for slow base-level fall. Aggradation of the Colorado River began approximately 5 ka and older sediments were buried by 18 ka. Burial resulted from rising sea level and increased sediment supply (BLUM, 1994) and was only slightly lagging behind the high stand of sea level attained about 3 ka.

These examples of large and medium-sized rivers from the northwestern Gulf of Mexico indicate that the inland distance of stream response to sea-level change appears to be related to the size of the stream. Maximum incision of these streams is approximately correlative to the maximum low stand of sea level. Finally, aggradation and burial of older fluvial deposits along the lower portion of these river valleys began approximately 1,000 years after sea level reached its present high stand.

To assess the response of the Peace River to sea-level change, this study determined the depth and timing of river entrenchment and aggradation. Age of entrenchment was determined using radiocarbon dates of organic matter near the base of the fluvial sediment. Age of aggradation was estimated using the degree of soil development and weathering of the flood-plain surface. Three sites, along a 57 km length of the river and 34 km length of the valley (Figure 2), were chosen for detailed study. All three sites exhibited the following criteria. First, the basal channel sediment at each site included organic matter that could be radiocarbon dated. Second, exposures were present to allow study of soil development and landscape stability of the flood plain surface. Finally, the distance between the sites would allow for assessment of time-transgressive nature of incision by knickpoint retreat and aggradation. Three additional sites that did not meet all these criteria were examined but are not discussed in detail in this report.

STUDY AREA

Geology

The Peace River is one of the major streams that drain south-central and southwest Florida. The headwaters of the river are in the central highlands (COOK, 1945; WHITE, 1958) of peninsular Florida (Figures 1 and 2). Here the river is only 37 m above sea level, though the highlands may be as much as 100 m above sea level with relatively high relief. Within the headwaters region all three major tributaries of the stream have lakes formed as solution sink holes along their course. The present mouth of the river is in the drowned estuary of Charlotte Harbor (Figure 2) (WHITE, 1958). During glacial lowstands of sea level, the Peace River would have been only slightly longer than it is today because the fluvial system terminated as an underground stream in the Pine Island Sound karst depression beneath the present Charlotte Harbor (EVANS *et al.*, 1989).

Between the headwaters and present mouth, the Peace River is a straight to somewhat meandering stream (Figure 2) with an exceptionally low gradient, <0.7 m km^{-1}. Along most of the length of the Peace River, there is a distinct flood plain between 0.6 and 2.5 km wide, inset into the surrounding upland. It is 1.75 km wide near Arcadia and Morgan Park, at the downstream study sites and 1.25 km wide at Wauchula, the upstream study site (Figure 3). The present channel of the river is incised 3 to 4 m below the modern flood plain in the study area. Flow persists throughout the year within the study area; but the discharge has varied by three orders of magnitude within the 60 years of record. The mean annual discharge at Arcadia (Figure 2) is 40 m^3 s^{-1}, an order of magnitude less than that of the Colorado River and 3 orders of magnitude less than that of the Mississippi River (Table 1).

The bedrock in the Peace River drainage basin (Figure 2) includes Miocene to Pleistocene limestone, dolostone, sand, and clayey sand (BERGENDAHL, 1956; CARR and ALVERSON, 1959; CATHCART, 1966; SCOTT, 1988; DUBAR *et al.*, 1991). Along the channel, the Miocene Hawthorn Group is exposed. This group consists of a lower, predominantly carbonate unit, the Arcadia Formation and an upper, predominantly siliciclastic unit, the Peace River Formation (SCOTT, 1988).

A series of terraces separated by scarps and subparallel to the modern shoreline are cut into the Miocene and Pliocene bedrock of the region (HEALY, 1975). The lower surfaces are Pleistocene marine terraces. The highest surfaces, above 30 to 50 m, are probably pre-Pleistocene and have been interpreted as subaerial (MACNEIL, 1950).

Climate

Climate changes, indicated by vegetative variations, have occurred during the late Quaternary in central Florida but they were not as extreme as in the higher latitudes (WATTS, 1980; WATTS and HANSEN, 1988). Watts found there is little vegetative evidence for differentiation between middle Wisconsin interstadial and late Wisconsin glacial climates in central Florida. Between 50 and 13 ka the predominant plant cover was pine (*Pinus*) and oak (*Quercus*) woodland, and rosemary (*Ceratiola ericoides*) and hickory (*Carya floridana*) scrub. Dunes were common and many of the shallow lakes were dry, further indicating a depressed water table and cool (Figure 4) but not cold climate (WATTS, 1971, 1975, 1980, KUTZBACH and WRIGHT, 1985). Episodes of abundant pine populations during the middle and late Wisconsin, indicative of more moist environments, correlate with hemispheric cooling events and may represent temperature changes rather than precipitation changes (GRIMM *et al.*, 1993). WATTS and HANSEN (1988) argue that middle Wisconsin interstadial lake sediments (50–25 ka) provide evidence for the greatest reduction of precipitation in the past 50,000 years on the basis of abundant charcoal resulting from natural fires, slightly silty sediment due to deflation, and the sclerophyllus vegetation.

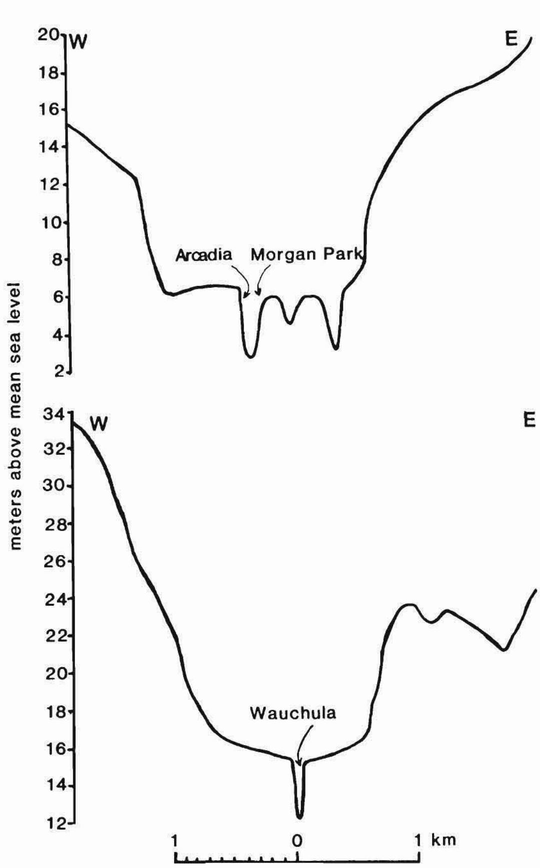

Figure 3. Topographic cross sections of the Peace River, its flood plain and valley walls at Arcadia and Morgan Park (A) and Wauchula (W) sample sites. Location of cross sections is shown on Figure 2.

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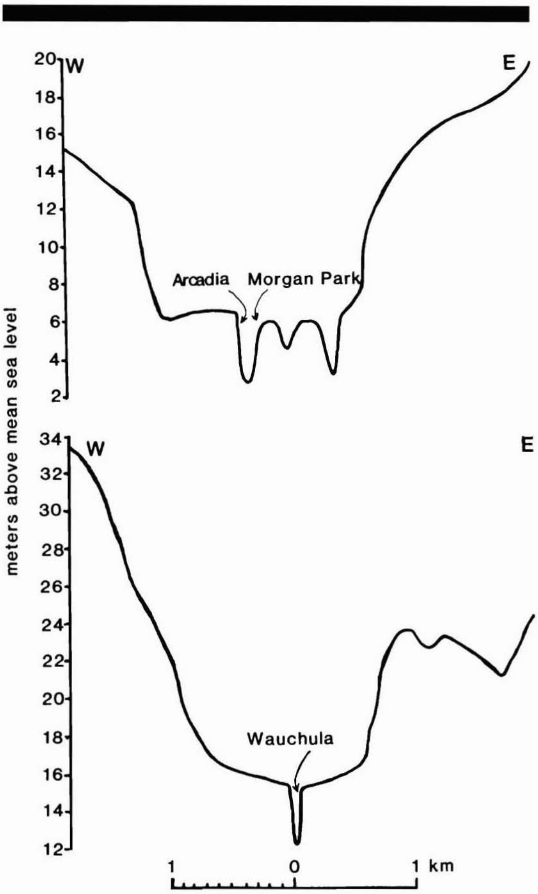

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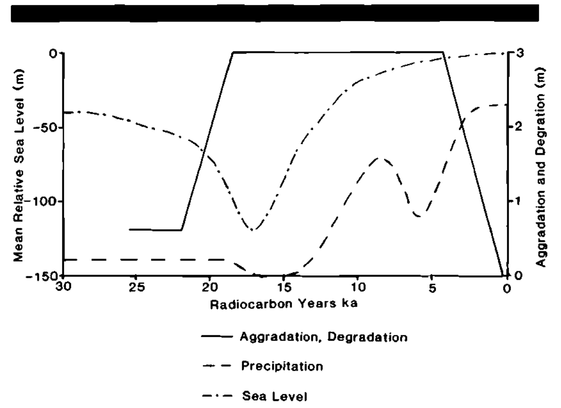

Figure 4. Generalized sea-level curve (modified from Milliman and Emery, 1968; Chappell and Shackleton, 1986; Fairbanks, 1989), unscaled diagrammatic precipitation trend (inferred from Clausen *et al.*, 1979; Kutzbach and Wright, 1985; and Watts, 1971, 1975, 1980; Grimm *et al.*, 1993), and elevation of flood-plain aggradation and channel incision (m) of the Peace River, relative to the present low water level.

changed substantially (Watts, 1971), water has generally been more abundant during the last 13,000 years than it was previously (Figure 4) (Watts, 1980). Rosemary scrub vegetation has been replaced by oak (*Quercus*) woodland with small patches of prairie vegetation (Watts, 1971, 1975, 1980) during the early and middle Holocene. Southwest Florida probably had a similar climate and vegetation, but locally wetter environments were present around deep sinkholes or cenotes in the early Holocene (12 to 8 ka) (Clausen *et al.*, 1979). During the late Holocene, there was more effective moisture in both southwest and central Florida causing pines to increase as oaks decreased in abundance, while charcoal abundance due to fires decreased (Watts and Hansen, 1988).

Water Table

The water table in the region has fluctuated in response to sea-level and precipitation changes (Watts and Hansen, 1988). The level was low between 50 and 13 ka. During the Holocene the total rise in the water table was 26–31 m throughout Florida (Clausen *et al.*, 1979; Watts and Hansen, 1988). The Holocene rise in the water table was not synchronous with the rise of sea level, thus suggesting that precipitation changes also contributed to fluctuations of the water table level (Figure 4) (Watts and Hansen, 1988). Prior to 8500 years ago groundwater levels were still too low to influence lake levels, due to the eustatic depression of sea level (Watts, 1971). Those lakes which were dry during the Pleistocene were still dry. By 8.5 ka water table levels influenced by sea-level rise rose almost to their present levels (Watts, 1971; Clausen *et al.*, 1979). More mesic vegetation during the Holocene compared to that of the Pleistocene (Watts, 1971, 1980; Watts and Hansen, 1988) suggests that increased precipitation also contributed to the rising water table (Figure 4).

During the middle Holocene, between 8.5 and 5.5 ka, the water table was depressed by 8 m along the west Florida coast (Clausen *et al.*, 1979), despite a rise in sea level of 15 m (Blackwelder *et al.*, 1979), 20 m (Chappell and Shackleton, 1986; Fairbanks, 1989) to 25 m (Milliman and Emery, 1968) during that time (Figure 4). Reduced precipitation was probably the main cause of lowered water table levels along the coast. In central Florida, the oak and prairie vegetation was maintained and shallow lakes contained water throughout the middle Holocene. These conditions suggest that reduced precipitation compensated for the rise in sea level and the water table level remained at about the same elevation. During the last 4500 to 5500 years, the increase in pine and decrease in oak in central Florida (Watts, 1980), the rise in the water table in both central (Watts, 1971) and southwest Florida (Claussen *et al.*, 1979), and the increase in cypress (*Taxodium*) swamp vegetation 2.6 ka (Watts, 1980) was most likely due to increased precipitation, because sea-level rise was minimal during this interval (Figure 4).

Perhaps the major effect of this climatic change was the increased rise of the water table compared to the rise in sea level during the early and late Holocene and a lowering or minimal rise of the water table during the middle Holocene. A second effect of the climatic change was changing vegetation with more dune stabilization in the later part of the Holocene compared to Pleistocene and early Holocene. Extensive swamps developed in the late Holocene.

METHODS

To assess the response of the Peace River to sea-level change, this study determined the depth and timing of entrenchment by dating the base of the fluvial sediment and determined the approximate timing of flood-plain aggradation by examining the degree of soil development and

Table 2. *Radiocarbon dating analyses, Peace River, Florida.*

Location	Depth (cm)	C-14 age (years BP)	Lab Number	Material
Arcadia	275–322	21,870 ± 130	Beta-53731	sediment
Arcadia	336–347	>47,300	Beta-53732	wood
Wauchula	266	24,760 ± 920	Beta-55717[1]	organics
Wauchula	304	>39,000	Beta-61414	wood in soil
Morgan Park	347–352	240 ± 60	Beta-57082	wood

[1] Small sample given extended counting time

weathering of that surface. All exposures were described using standard USDA Soil Survey format and procedures (SOIL SURVEY STAFF, 1981); sedimentary structures were noted. Each soil horizon or geologic stratum was sampled. Multiple samples were taken from most horizons or strata >40 cm thick.

Samples were analyzed for particle size, bulk density, and total carbon. Samples came from three sites: Arcadia and Morgan Park (both at A in Figure 2) and Wauchula (W in Figure 2). Fifty-two samples were analyzed for grain size by dry sieving the gravel (>2 mm) and five sand (0.0625–2.0 mm) fractions and by pipette methods for three silt (0.002–0.0625 mm) and one clay (<0.002 mm) fractions (DAY, 1965). Bulk density was determined using the oven-dry weight of a known sample volume. Clay and total silt accumulations in a soil column 1 cm^2 were calculated by multiplying the percent clay and the percent total silt by the bulk density for each horizon and the underlying parent material. The amount of clay and total silt within the parent material was subtracted from the amount in each of the A, E, and B horizons to determine the amounts accumulated/depleted. The accumulation/depletion of each horizon in the pedon was summed. Total carbon content was determined by dry combustion in a Linberg Hevi-duty Tube Furnace (SOIL SURVEY STAFF, 1972). Carbonate minerals were not present in the samples so total carbon is indicative of the total organic carbon and the terms will be used synonymously in this paper. The amount of organic matter accumulated in a soil column 1 cm^2 was calculated using the percent total carbon, bulk density, and horizon thickness for each horizon and summing the total of that fraction in each horizon to determine the amount accumulated in the pedon.

Organic matter within the C horizon or inset within the channel was sampled at the three detailed-study sites (Fig. 2). Organic materials were oven-dried. Wood and organic samples and bulk soil samples were submitted to Beta Analytic Inc. (Miami, FL) for radiocarbon dating (Table 2). One sample (Beta-55717) was small and was given extended counting time.

RESULTS

Outcrops along the Peace River expose two units of stream sediment, each with erosional bases. Only a few tens of centimeters of channel-fill sediment overlie the lowest erosion surface. This unit is a medium to fine-grained quartz and phosphate sand with ripples. The sand is interbedded with clay laminae at Arcadia and medium to coarse sand at Wauchula (Figure 5). Wood within the channel-fill sediment at two sites, Arcadia and Wauchula, had nonfinite radiocarbon dates of >39 ka and >47.3 ka respectively (Table 2), which are considered minimum ages.

In contrast, the complete aggradational cycle of channel and overbank sediment overlie the upper erosion surface (Figure 5). Both the channel-fill sequence and individual beds fine upward (Figure 5). At Arcadia, the basal 0.1 m of fill is a horizontally bedded coarse to granular sand. The middle 0.5 m of the sequence is heterogeneous. It includes ripples with clay drapes and cross-bedded medium to fine quartz and phosphatic sand with laminae of clay and fine organic debris. Disseminated organic matter from the basal channel fill of this unit was dated 21,870 ± 130 yr BP (Table 2). A lag deposit of granules and clay balls occurs along the base of some beds. The upper part of the sequence is a homogeneous, relatively thick-bedded (up to 0.5 m thick) medium to fine sand. At Wauchula the lower 0.9 m of fill above the erosion surface includes beds of medium to coarse quartz and phosphatic sand with basal granules and clay balls interbedded with medium to fine sand (Figure 5). Organics within this unit were dated 24,760 ± 920 yr BP (Table 2). Similar to the Arcadia site, the upper portion of the se-

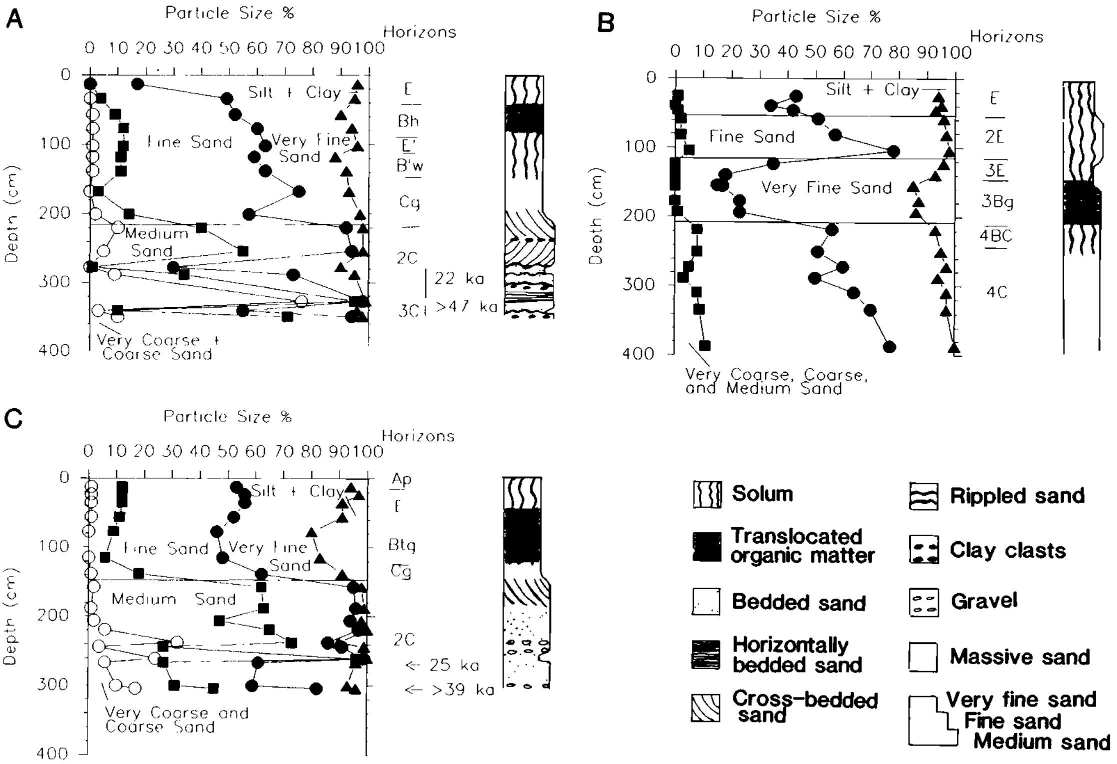

Figure 5. Cumulative particle size of the <2 mm fraction at Arcadia (A), Morgan Park (B), and Wauchula (C) on the Peace River. Soil horizons and a graphic log are also shown.

quence is a more homogeneous medium to fine cross-bedded sand. In contrast to the basal fluvial deposits at the mouth of Charlotte Harbor (EVANS *et al.*, 1989, Figures 10 and 11), the amount of silt is minimal at most of the sites examined and no shells or shell fragments are present at any site.

Overlying overbank deposits 1.5 to 2.1 m thick consist of fine to very fine quartz sand (Figure 5). This unit underlies the flood plain surface and soil-forming processes have modified the deposit at most locations examined. No original bedding is preserved and the material is either massive with infilled root cavities and burrows or extensively altered soil horizons have developed. In contrast to the upper portion of fluvial deposits at the mouth of Charlotte Harbor (EVANS *et al.*, 1989, Figures 10 and 11), silt is almost nonexistent in the study area and soil horizons are well developed.

Within the present incised channel (Figure 3) medium-grained quartz and phosphatic sand is presently being deposited as channel and point bar deposits. Locally fine sand to clay-size, organic-rich channel-fill deposits are aggrading in the slack-water areas of the channel and in inactive channels.

Overbank sediment which underlies the flood plain of the Peace River has been weathered to form a complex of ALFISOLS and SPODOSOLS (ROBBINS *et al.*, 1984; COWHERD *et al.*, 1989). These sandy or loamy soils form on a nearly level landscape, are poorly drained to very poorly drained, and develop in areas where water is within 30 cm of the surface between 1 and 9 months of the year. All three pedons discussed in this study have the spodic property of translocated organic matter (Figure 6), but are classified as an ALFISOL (Wauchula), SPODOSOL (Arcadia) and ENTISOL (Morgan Park) (SOIL SURVEY STAFF, 1992).

Exposures along the Peace River record at least three episodes of incision. The oldest incision documented in this study occurred more than 39 to

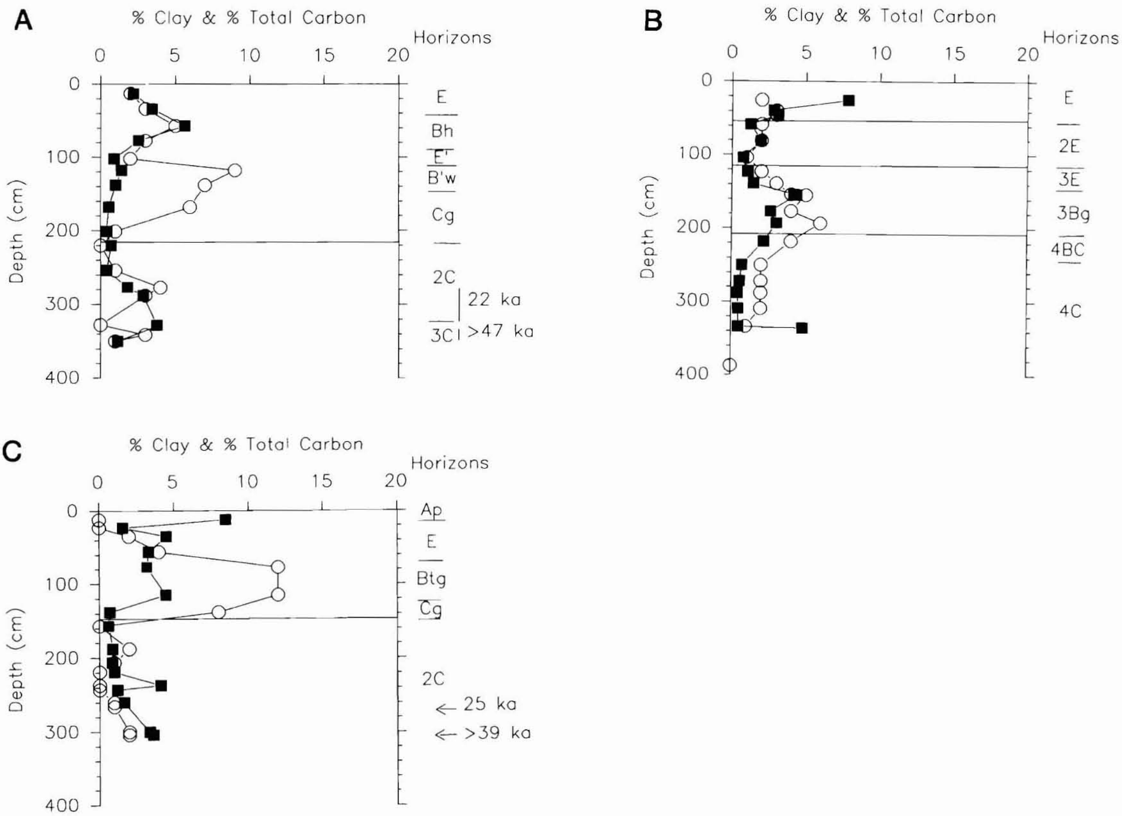

Figure 6. Percent clay of the <2 mm fraction (open circles) and percent total carbon × 10 (solid squares) at Arcadia (A), Morgan Park (B), and Wauchula (C), on the Peace River.

47 ka, during the middle Wisconsin substage (isotope stages 3 and 4) or earlier (RICHMOND and FULLERTON, 1986). The base of the incision is unknown but is probably less than 1 m lower than the present low water level because bedrock is being incised at a number of locations along the stream.

A second incision of the Peace River occurred during the late Wisconsin, slightly more than 22 to 25 ka (Figure 4). This incision was slightly shallower in depth than that of the older channel incision or that of the modern incision.

At sites where bedrock is incised, the third and present incision is the deepest of the three incisions documented in this study (Figure 4). Along other stretches of the river thick sand and gravel deposits are present locally and extend well below the present channel base (BERGENDAHL, 1956).

DISCUSSION

Flood Plain Stability

Aggradation of the modern flood plain and subsequent incision of the present Peace River channel have not been dated absolutely but their age can be estimated, using comparisons with soils that have been dated. HUNT and HUNT (1957) use archeological artifacts within groundwater podsols (spodosols) of west central Florida to establish that considerable translocation of organic matter can occur between 2–3,000 years and 13,500 years (MILANICH and FAIRBANKS, 1980, p. 78; MARQUARDT, 1992, p. 13). By analogy with soils that HUNT and HUNT (1957) described, the soils examined along the Peace River also have translocated organic matter (Figure 6) and probably experienced at least 2–3,000 years of weathering.

In addition to translocated organic matter, the soils encountered in this study have translocated clay forming cambic and argillic horizons (Figures 5 and 6). There are two possible sources for the increased clay fraction. First, weathering of scarce phosphate grains may provide some clay-sized material but the amount is likely to be minimal. Within this uniform parent material at the three detailed-study sites, there are absolute clay increases of 3 to 9% in the B horizon compared to that of the C horizon and at Arcadia 8.76 g cm^{-2} of clay has accumulated. This is a significant amount of accumulation because nearly all of the grains in the parent material are quartz sand. In comparison, temperate region soils with weak argillic horizons require 1800 to 6000 years to form on flood plains in less permeable, finer textured, and more poorly sorted sediment that includes abundant labile grains (GUCCIONE, 1992; GUCCIONE and GUENDLING, 1990). For the more resistant sediment along the Peace River, the duration of weathering needed for measurable clay accumulation by weathering processes is therefore considered to be much greater than 6,000 years.

A second possible source for the clay increase could be addition of clay and silt-sized particles with infiltration of flood water and perhaps recent discharge from upstream mining operations. At the present time, the concentration of suspended sediment decreases with increasing flood stage and is ≤ 9 mg L^{-1} when the water depth is almost high enough to flood the study sites (COFFIN and FLETCHER, 1991). Though the absolute amount of sediment is low, 89% of that present is silt and clay. The amount of silt and clay that might accumulate from infiltration of flood water can be estimated if the following assumptions are made: (1) that the suspended load of floodwater is constant, (2) that flooding is the only source of increased amounts of silt and clay compared to the underlying unweathered flood-plain sediment, and (3) that all of the suspended sediment is trapped in the soil. Based on these assumptions, it would take nearly 19,000 years to accumulate the 11.92 g of accumulated silt plus clay in a 1 cm^2 column of soil if an equivalent of 0.80 m of floodwater covers the flood plain annually. If 1.0 m of water covered the flood plain, only 14,900 years would be required for the same amount of silt-plus-clay accumulation. Flood depths of 1.0 m have been exceeded within historic record (COFFIN and FLETCHER, 1991), but this value may be high for annual flooding events. Depths of 0.80 to 1.0 m may be a more realistic mean equivalent flood water depth prior to incision of the modern channel. Fifteen to nineteen thousand years of flood-plain surface stability between completion of significant overbank aggradation of the overbank sediment and modern channel incision, which probably reduced the infiltration rate, may be realistic. Thus mechanical infiltration may have provided much, if not most, of the silt and clay that has accumulated within the soil. In short, increases of 8.76 g cm^{-2} of clay by both infiltration and weathering to form cambic and argillic horizons in a permeable sand of stable mineralogy would probably require 10^4 years and the observed degree of soil formation and clay accumulation would require most of the 22–25,000 years since deposition began.

The soils examined in this study are probably relict and formed before the Peace River incised into its flood plain 3 to 4 m. Translocation of 40.48 g cm^{-2} of organic matter forming a "spodic" horizon at Arcadia is groundwater related (MCKEAGUE *et al.*, 1983), with the depth of the "spodic" horizon marking a former shallow, fluctuating water table. Present incision of the channel has locally depressed the water-table elevation adjacent to the channel during much of the year, and it is unlikely that these "spodic" horizons would develop under modern conditions. If incision had similarly lowered the water table many millennia ago, organic matter would have been oxidized or been translocated to a greater depth equivalent to the present water table. The age of wood inset into the present channel at Morgan Park is 240 ± 60 yr BP (Table 2), indicating a minimum date of channel incision. Incision of the Peace River in the study area is estimated to have occurred between several millennia and several centuries ago (Figure 4).

Controls on Fluvial Incision

The timing of the incision by the Peace River does not coincide with that of other rivers in the Gulf of Mexico region (BLUM, 1994). Nor does its timing of incision coincide with that predicted from experimental models of base-level lowering (WOOD, 1992). It is difficult to draw any conclusions about the oldest incision episode because of the non-finite nature of the radiocarbon dates. However, the second episode of incision occurred prior to 22–25 ka and coincided with the last glacial cycle (Figure 14). It is noteworthy that incision occurred several thousand years after the beginning of oxygen isotope Stage 2 (Morrison, 1991) and the advance of the Laurentide ice sheet (Andrews, 1987). It is also noteworthy that incision was initiated just prior to or coincident with the initial increased rate of sea-level fall and 5–10,000 years prior to the maximum lowstand or rate of fall (Figure 4) (Milliman and Emery, 1968; Blackwelder *et al.*, 1979).

If incision was due to lowered sea level then there was very little lag time between the initiation of regional sea-level fall and initiation of channel incision (Figure 4). These results are contradictory to the results of Wood's (1992) experimental model. In addition, if the dates accurately record the time of incision, erosion began 2–4,000 years earlier upstream than it did downstream. If the dates are more loosely interpreted, incision was nearly simultaneous across the coastal plain at two sites 49 and 106 km upriver (37 and 71 km upvalley) from the present coastline. This diachronous incision would require a geologically instantaneous knickpoint retreat along a 57 km stretch of the river (34 km stretch of the valley). Finally, further decline of sea level did not cause any additional incision by the Peace River. After sea level dropped below the elevation of the karst depression in Charlotte Harbor (Evans *et al.*, 1989), it may have had little impact on stream incision.

Erosion by the Peace River is unlikely to be directly related to the fall of sea level because: (1) the incision that began prior to 22–25 ka did not lag behind the drop in base level (Figure 5), (2) there was no lag between downstream and upstream incision, and (3) incision may have actually moved downstream rather than upstream. Indirectly, however, a decline in sea level could cause incision of the Peace River. A drop in sea level would result in a significant drop in the water table and thus the depth of incision in a karst area of low-relief and low-elevation. Shallow lakes were dry during the late Wisconsin glaciation and the early Holocene, indicating that the water table was lower during that time (Watts, 1969; Watts and Hansen, 1988). Xeric vegetation in the vicinity of deep lakes that persisted through the middle and late Wisconsin stage suggests that the precipitation was also reduced (Figure 4) (Watts, 1980; Kutzbach and Wright, 1985). During this interval, there are episodes of abundant pine vegetation indicating a more moist environment. These wetter periods may correspond to cooler temperature middle and late Wisconsin intervals rather than increased precipitation (Grimm *et al.*, 1993). Finally, the presence of sand dunes on uplands of central Florida (Milanich and Fairbanks, 1980, p. 51) also supports an interpretation of a dry climate with a low water table.

Depletion of the Floridan Aquifer and a reduction in water table level in response to lowered sea level and low precipitation (Figure 4) may have indeed impacted the hydrology of streams in a karst area such as the Peace River. A water table depressed to elevations within the carbonate strata may have enhanced vertical water flow through solution voids and diminished overland stream flow. For the overland flow that did exist, the potential for incision was greatest from 33 to 13 ka. The maximum depression of the water table and the maximum potential for incision probably occurred during the glacial maximum, between 18.6 and 13.5 radiocarbon years BP (Kutzbach and Wright, 1985). Therefore, river incision that occurred as the Wisconsin glaciation began may have been caused by the low water table which resulted from lower sea level and reduced precipitation. The effect of a lowered water table may have been more critical in the upstream segments of the river, causing erosion to begin there slightly before downstream segments of the river. Incision due to lowering of the regional water table would be a synchronous event, unlike the regional diachronous incision that would be the product of knickpoint retreat. However, in a karst environment such as peninsular Florida, knickpoint retreat may not be a common phenomenon.

Climatic control on incision of the Peace River is an alternative hypothesis to base-level control and will be also considered. In a karst area of low relief such as peninsular Florida, the water table level is an effective control on depth of incision and is strongly influenced by sea level as discussed above (Watts, 1971; Clausen *et al.*, 1979). A second variable impacting the water-table level is climate, specifically effective precipitation. Changes in effective precipitation also influence stream hydrology and vegetation within the drainage basin, which in turn probably affected sediment supply to the Peace River channel.

The present incision of the Peace River probably began within the last few millennia during a high stand in sea level (Figure 4). This erosion, like the previous cycle of erosion and aggradation, is out of phase with base-level change and is unlikely to be a direct result of the rise in sea level. Rising sea level (Scholl *et al.*, 1969) combined with increased precipitation may be the indirect cause of the present incision of the Peace River during the last 5,000 years. Both factors resulted in a rising water table (CLAUSEN *et al.*, 1979; WATTS, 1980) during the last 5,000 years. Vegetation responded to the wetter conditions by the establishment of continuous forests, bogs, and vast cypress swamps (WATTS, 1971). This vegetation and moist ground conditions stabilized the available sediment supply at the same time the discharge was increased, causing the Peace River to erode its own sediments and incise its channel. This should correspond to a period of increased sediment supply in the marine environment and may be responsible for the 1.5 to 6 m of Holocene fluvial-upper estuarine sediment reported in Charlotte Harbor (EVANS *et al.*, 1989).

Controls on Fluvial Aggradation

Aggradation of the Peace River began 22 to 25 ka, during the early low stand of sea level and a dry climate (Figure 4). Well-developed soils with argillic and cambic horizons that have developed in the overbank sediment indicate that areas of the modern flood-plain surface have been stable for a considerable portion of the 22,000 years since deposition began. Thus, aggradation was occurring during the early lowstand and may have been completed by the maximum low stand of sea level.

Aggradation of the Peace River is only partly consistent with net deposition on the coastal plain in the experimental model of WOOD (1992) and along the Colorado River (BLUM, 1994). Aggradation of the Peace River during a low stand of sea level is compatible with WOOD's model and observations by SCHUMM (1993). Upstream segments of the stream may not immediately incise in response to a lowered base level. In contrast to Wood's model and to the response of the Colorado River, the flood plain level of the Peace River continues to be stable during the late low stand of sea level when incision should reach the present coastal plain.

The aggradation since 22 ka is unlikely to be directly related to a rise in sea level for the following reasons. First, initial aggradation preceded the initial rise in sea level. Second, aggradation was probably at its maximum possible level prior to any substantial rise in sea level, and the flood plain remained at an approximately constant level during the rise in sea level (Figure 4). Third, stronger soil development on the flood plain at the upstream site (Figures 5 and 6) suggests that the aggradation may have stabilized there prior to downstream locations. However, changing sea level may have had an indirect influence on aggradation, similar to the indirect affect that sea-level changes had on incision. Lower sea level and less precipitation during late Pleistocene through the middle Holocene caused a depression of the water table and drying of the ground surface, reduction of ground cover, and remobilization of sand dunes (MILANICH and FAIRBANKS, p. 51, 1980). Erosion of the unstable uplands may have provided a more abundant sediment load at the same time lower discharge was unable to transport the sediment resulting in aggradation. Aggradation would begin in the upvalley positions and progressively move downstream (SCHUMM, 1993) as observed by older dates of the channel fill and stronger soil development on the floodplain at the upstream site (Wauchula) compared to the downstream sites (Arcadia and Morgan Park). If most of the sediment load was stored in the floodplain, sediment supply to the marine environment would be reduced during this interval or only become significant after the valley filled. Reduced sediment transport to the marine environment during valley filling may be represented by a Pleistocene-Holocene unconformity in Charlotte Harbor (EVANS *et al.*, 1989).

Additional episodes of incision and subsequent aggradation may have occurred during the late Pleistocene and Holocene. Several sites along the flood plain of the Peace River (Figure 2) have floodplain sediment with varying amounts of translocation of organic matter and clay accumulation but less soil development than the sites discussed in this report. Unfortunately, the sediments could not be dated, but these areas of the floodplain appear to be younger than that at the locations discussed in this report. Because of the very low elevation of peninsular Florida, the amount of accommodation space for aggradation is limited and strata repeatedly aggrade to the same level over a long period of time, perhaps 20,000 years or more. During this interval the Peace River slowly reworks its floodplain sediment, resulting in local areas of various ages and numerous stages of soil development on a single geomorphic surface.

CONCLUSIONS

Incision and aggradation of the Peace River within the study area are not synchronous with falling and rising sea level, the expected lag time associated with sea-level variations (WOOD, 1992) or with those relationships observed from the Colorado River (BLUM, 1994). The tectonically stable nature of the Peace River drainage basin, its distance from the glacial margin and lack of access to glacial meltwater eliminate tectonic movement or increase in meltwater discharge as mechanisms for Peace River incision or aggradation. Climatic, vegetative, and hydrologic changes are more reasonable explanations for late Quaternary variations in the regime of the Peace River. However, vegetative and hydrologic changes are partially dependent on sea-level change and its impact on water-table level fluctuations. Thus, base level is indirectly responsible and climatic change is directly responsible for alternating episodes of incision and aggradation. Direct influence of fluctuating sea level is limited to areas downstream of Arcadia, a point which is 37 km upvalley from the present shoreline. The maximum distance of upstream impact of sea-level change on the Peace River is less than half the distance of sea-level impact upstream from the mouth of the Colorado River (BLUM, 1994) and less than 15% of distance of impact along the Mississippi River (AUTIN *et al.*, 1991). This supports the hypothesis that the distance of sea-level impact on a stream is dependent on its size.

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