THE NORTH CAROLINA OUTER BANKS BARRIER ISLANDS: A FIELD TRIP GUIDE TO THE GEOLOGY, GEOMORPHOLOGY, AND PROCESSES

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NORTH CAROLINA ITINERARY

Thursday October 29

0800	***Leave Hotel***
0830-0930	***Waties Island (northern Long Bay Barriers Waties Architecture)*** ***(LEADS: Wright)*** ***Waties Island Architecture- Mid Holocene Core-accrete-erode***
0930-1330	***Bus Transit to Cedar Island - Lunch on Bus***
1400-1630	***Ferry Transit to Outer Banks*** ***(LEADS: Riggs, Culver, Mallinson)*** ***Discussion of barrier island geomorphology and evolution; post-glacial development of the Outer Banks (OBX)***
1930	***Arrive Hotel in Ocracoke- Dinner in town***

Friday October 30

0800	***Leave hotel –***
0815-0845	***Stop 1: Ocracoke beach*** ***(LEADS: Riggs, Culver, Mallinson)*** ***Discussion of the geomorphic evolution of Ocracoke and Portsmouth Islands, Holocene barrier collapse and antecedent geologic controls on modern system***
0930-1030	***Ferry transit to Hatteras Island***
1045-1145	***Stop 2: Isabel Inlet*** ***(LEADS: Riggs, Walsh)*** ***Discussion of the role of inlets in barrier island evolution, coastal vulnerability mapping, and management practices***
1200-1300	***Stop 3: Old Hatteras Lighthouse location*** ***(LEADS: McNinch, Riggs, Mallinson)*** ***Discussion of cuspate foreland development, coastal hardening effects, long-term management strategy*** ***Box Lunch***
1400-1430	***Stop 4: New Inlet*** ***(LEADS: Riggs)*** ***Observation of old flood-tidal delta; discussion of role of inlets, inlet history, shoreline erosion rates at S-curves, shoreface morphology***
1500-1545	***Stop 5: Oregon Inlet (south jetty)*** ***(LEAD: Riggs)*** ***Discussion of Oregon Inlet history, management practices, future options***
1615-1645	***Stop 6: South Nags Head*** ***(LEAD: Riggs)*** ***Observation of actively eroding shoreline, discussion of processes, rates, and management issues***

1715-1830 Stop 7: Sand Point
(LEADS: Kemp, Corbett)
Observation of wind-tide dominated marsh system, discussion of sea-level curve construction, geochronology, and Holocene sea-level history

1900 Dinner

Sat. Oct 31: 0800 – Leave hotel

0830-0845 Stop 8: Erosional hotspot at Kitty Hawk (brief observational stop – discussion will be held at Duck-FRF)

0915-1100 Stop 9: Duck-FRF
(LEAD: McNinch)
Further discussion on the role of shore oblique bars, antecedent geology, management practices, etc.

1100 Shuttle departs for airport in Norfolk

I. BACKGROUND

General Geologic Framework of the North Carolina Coastal System

The shallow geology of the North Carolina coastal plain can be subdivided into the geologically distinct northern and southern zones (Figures 1 and 2). North of Cape Lookout, the coastal zone is characterized by a thick Quaternary sequence (up to 90 m; Mallinson et al., in review) that fills a regional depositional basin centered under northern Pamlico Sound to eastern Albemarle Sound and called the Albemarle Embayment (Popenoe and Ward, 1983; Popenoe, 1985; Ward and Strickland, 1985; Mallinson et al., 2005, in review; Culver et al., 2008). Seismic and drill core data suggest that the Quaternary section has filled the last remnants of the Aurora Embayment, a pre-Miocene depositional basin northwest of the Cape Lookout High. This Oligocene to Pliocene paleotopographic high divided North Carolina into two depositional embayments (Snyder et al., 1982; Riggs et al., 1990). The Pleistocene section within the northern zone represents a complex record of multiple cycles of coastal deposition and erosion in response to numerous glacial-eustatic sea-level cycles (Riggs et al., 1992; Sager and Riggs, 1998; Riggs et al., 2001; Parham et al., 2007; Mallinson et al., 2005, in review). During each glacial episode, fluvial channels severely dissected previously deposited coastal systems. The subsequent transgression sequentially backfilled the valleys with fluvial and estuarine sediments and then produced a ravinement surface that migrated landward. Shoreface erosion truncated large portions of previously deposited coastal sediments. Holocene sea-level rise has produced a modern sequence of coastal sediments deposited unconformably over the eroded remnants of these Pleistocene sequences (Figure 3). Thus, the modern barrier island system is stacked on top of numerous highly dissected, partially preserved lithostratigraphic units with irregular, erosional geometries and composed of sediments ranging from compact peat and mud to unconsolidated to semi-consolidated sands, gravels and shell beds.

South of the Cape Lookout High, the coastal zone is dominated by Tertiary and Cretaceous units (Figure 2). The older and more lithified, offlapping stratigraphic sequences wrap around the Carolina Platform (a.k.a., the Cape Fear Arch), a major basement structural feature that occurs south of Cape Fear, and crop out across much of the continental shelf in Onslow and Long Bays (Snyder, 1982; Riggs et al., 1990). These Tertiary and Cretaceous stratigraphic units, along with local, remnant Quaternary sediment units, form a basal platform with variable topography upon which many of the modern barriers in the southern province are perched.

Controls on Barrier Island Geomorphology

This section on barrier island types is mostly excerpted from a paper by Riggs, Cleary, and Snyder (1995) in *Marine Geology* entitled "Influence of inherited geologic framework on barrier shoreface morphology and dynamics" and Riggs et al. (in press) "Barrier island dynamics and geomorphic evolution of the Outer Banks, North Carolina".

This summary statement sets the stage for our field trip on the North Carolina Outer Banks.

Along continental margins with limited sand supplies, such as the U.S. Atlantic coast, the shoreface and associated subaerial island is not an infinitely thick pile of sand. Rather, it is a thin, dynamic accumulation of sand perched upon a pre-existing and highly-dissected geologic framework (Figure 4). Holocene sea-level rise has produced a modern transgressive barrier island, estuarine, and fluvial sequence of coastal sediments that are being deposited unconformably over irregularly preserved remnants of pre-existing stratigraphic sequences consisting of sediment and rock units of variable ages, origins, and compositions. It is the complex variability in this underlying geologic framework, in concert with the physical dynamics of each specific coastal system, that ultimately determines the three-dimensional shoreface morphology, the composition and texture of beach sediments, and the shoreline recession rates.

Based upon the pre-modern geologic framework, there are several general categories of coastal geologic/geomorphic and barrier island systems that occur along the North Carolina coast. Headlands are morphological features that rise above the active ravinement surface and are composed of semi-indurated to indurated, Pleistocene or older sediment units. Subaerial headlands are emergent features characterized by the active incisement of a wave-cut platform and cliff into Pleistocene or older stratigraphic units with an associated perched beach. Submarine headlands are submerged morphological features composed of Pleistocene or older stratigraphic units that have been incorporated into the modern shoreface and upon which the barrier island-estuarine system is perched. Pre-Holocene sediments crop out on the eroding shoreface and commonly occur on the inner shelf as bathymetric highs seaward of the modern shoreface and thus, modify incoming waves and currents. Non-headland areas are characterized by the occurrence of fluvial or tidal inlet channels in the subsurface, that have been filled during late Pleistocene to Holocene sea-level rise and barrier island migration. Channel-fill sediments crop out along the shoreface, and influence sediment types on adjacent beaches, as well as shoreface morphology which controls wave energy impacting the beach.

Barrier islands dominated by Holocene processes and sediments can be divided into three classes.

1) Simple overwash and inlet-dominated barrier islands that are sediment poor. These barrier islands are low and narrow and generally are characterized by transgressive shorefaces. The minor amounts of sand generally overly compact estuarine peat and mud deposits or sand-filled channel deposits that extend from the modern estuary, under the barrier sand, and crop out within the surf zone and upper shoreface.

2) Simple overwash-dominated barrier islands that are sand rich. The large volume of available sediment builds extensive overwash plains, often containing multiple sequences of low ridge and swale structures, that result in a regressive shoreface generally composed of unconsolidated sand. These barrier island segments are often associated with inlets and cape structures and are dominated by progradational geometries.

3) Complex barrier islands. These occur when a simple barrier segment migrates into and welds onto an older barrier island segment that formed in response to a different set of conditions (e.g., western Ocracoke Island), or when a regressive beach ridge

complex begins to erode, resulting in shoreline recession (e.g., Kitty Hawk Woods). These island segments tend to be relatively wide and high and often contain back-barrier dune fields and associated maritime forests.

In North Carolina, most shoreline features are controlled by the pre-Holocene stratigraphic framework of the shoreface; the beaches are perched on top of pre-existing Pleistocene, Tertiary, and Cretaceous sediments. Superimposed upon this regional stratigraphy is an ancient drainage system resulting in a series of fluvial valleys filled with younger coastal sediments separated by large interfluve areas of older stratigraphic units (Figure 4).

The composition and geometry of the headland and nonheadland areas influences the shoreface dynamics and resulting profiles in two ways. First, a shoreface composed of compact muds, limestones, or sandstones has a greater effect upon the morphology of barriers and the shoreface and inner shelf than a shoreface composed of unconsolidated sands and soft muds. Second, along many parts of the coastal system, shoal features occur on the inner shelf. These features modify incoming wave and current energy, thus affecting patterns of sediment erosion, transport, and deposition on the adjacent beaches.

Thus, the basic structural, stratigraphic, and geomorphic characteristics of the pre-barrier land surface interacts in a complex way with modern coastal processes to determine the morphology, shoreface dynamics, and rates of shoreline recession. Consequently, the concept of a common equilibrium profile for all shorefaces is neither realistic nor adequate when considering detailed processes along any given coastal segment.

The trunk streams (Roanoke, Tar, and Neuse Rivers) occupy major shore-perpendicular fluvial valleys (Figures 3 and 4) with a series of shore-parallel tributaries flowing into the trunk rivers. With sea-level rise, the drowning process floods up the drainage systems to produce the complex network of drowned river estuaries and ultimately floods across the upland interfluves. The North Carolina Outer Banks are perched on top of a late Pleistocene interfluve with the paleo-fluvial valleys associated with Pamlico Creek, the Tar-Pamlico River, the Neuse River, and the Roanoke River west of the interfluve forming the basins that comprise the Albemarle-Pamlico Estuarine System (APES).

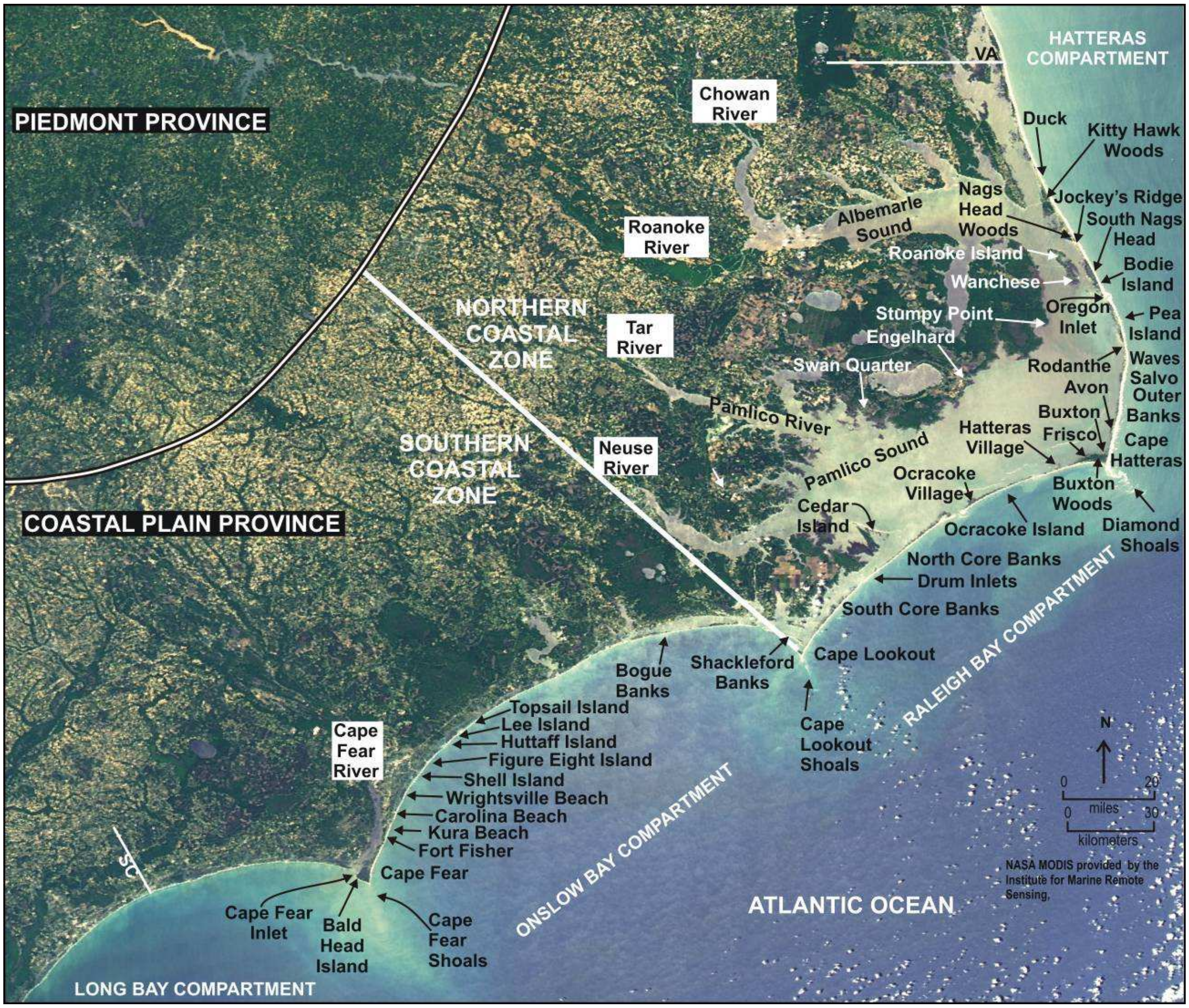

Figure 1. MODIS satellite image illustrating the location of the two primary coastal zones within the North Carolina Coastal Province, and other geographic terms referred to within the text.

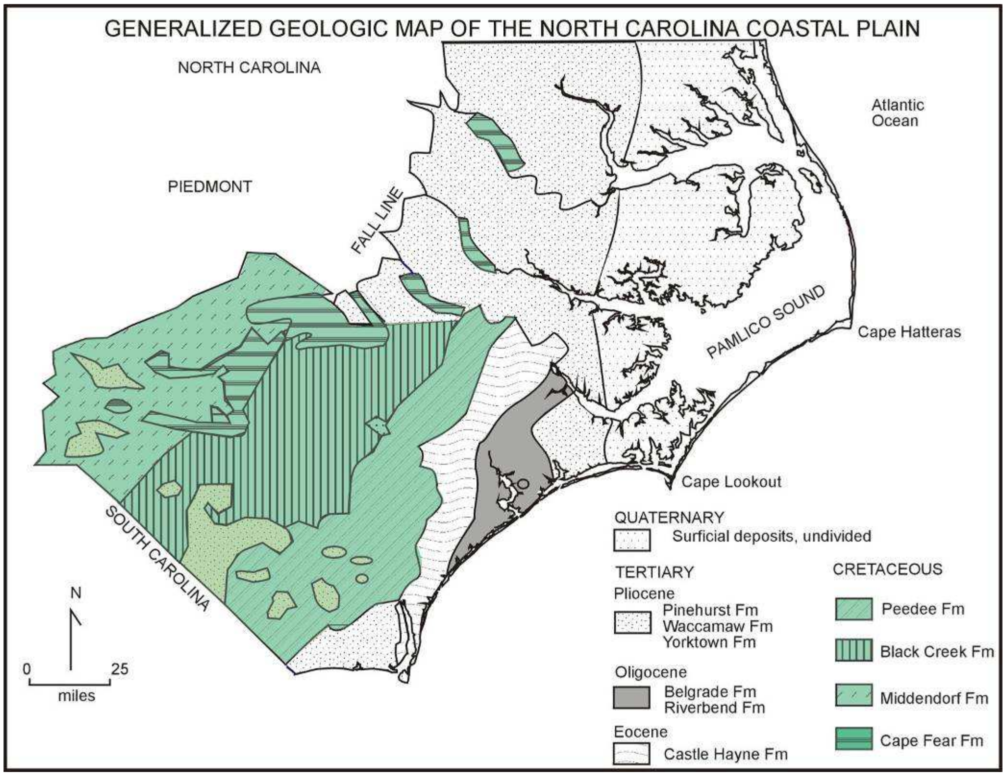

Figure 2. Generalized geologic map of the North Carolina Coastal Plain illustrating the regional outcrop/subcrop patterns of the various stratigraphic units. Note the occurrence of old (Mesozoic and Tertiary) units in the shallow subsurface south of Cape Lookout, and Pliocene and Quaternary units north of Cape Lookout.

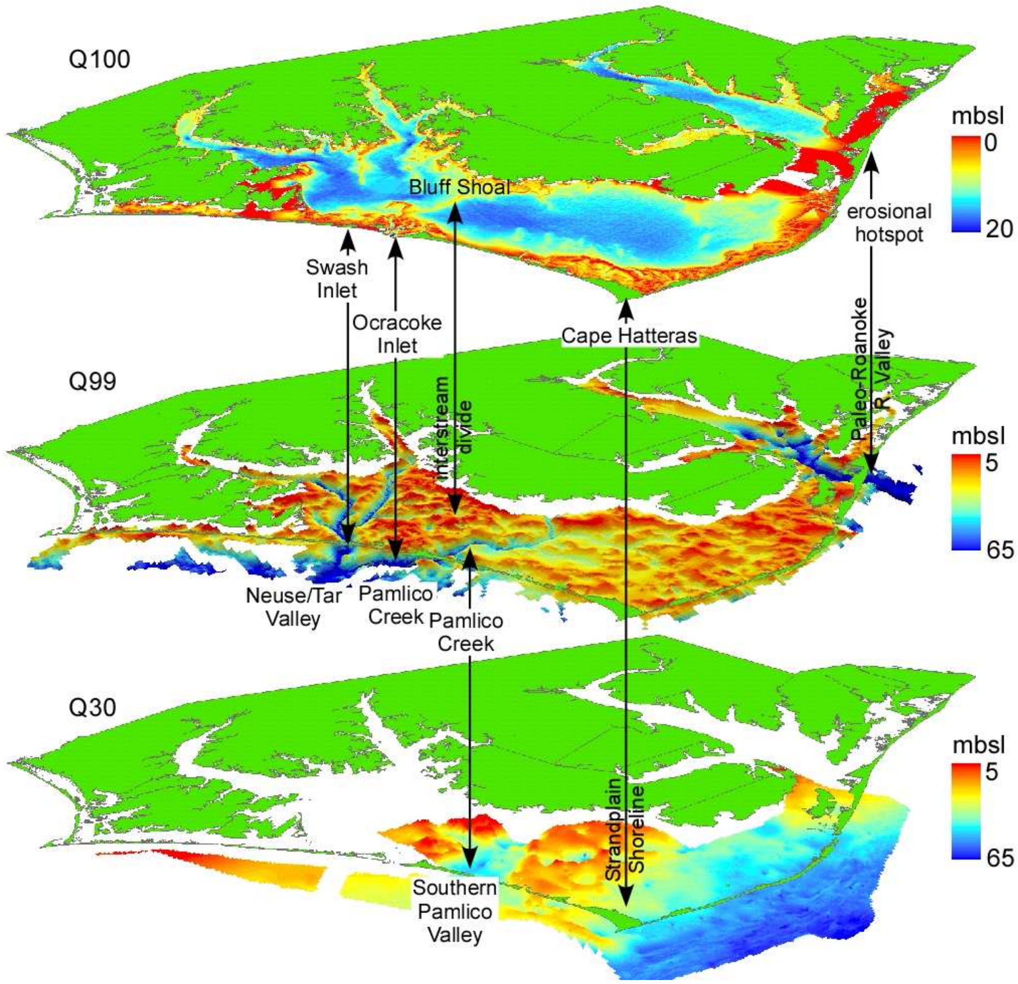

Figure 3. Oblique view of the study area (from the southwest) showing the relief associated with seismic reflections Q30 (mid-Pleistocene), Q99 (late Pleistocene; LGM surface), and Q100 (the modern bathymetric surface). Features are indicated that represent antecedent topographic controls. Note the different depth scale for the Q100 surface (to emphasize the shallow features), as opposed to the other two surfaces (from Mallinson et al., in review).

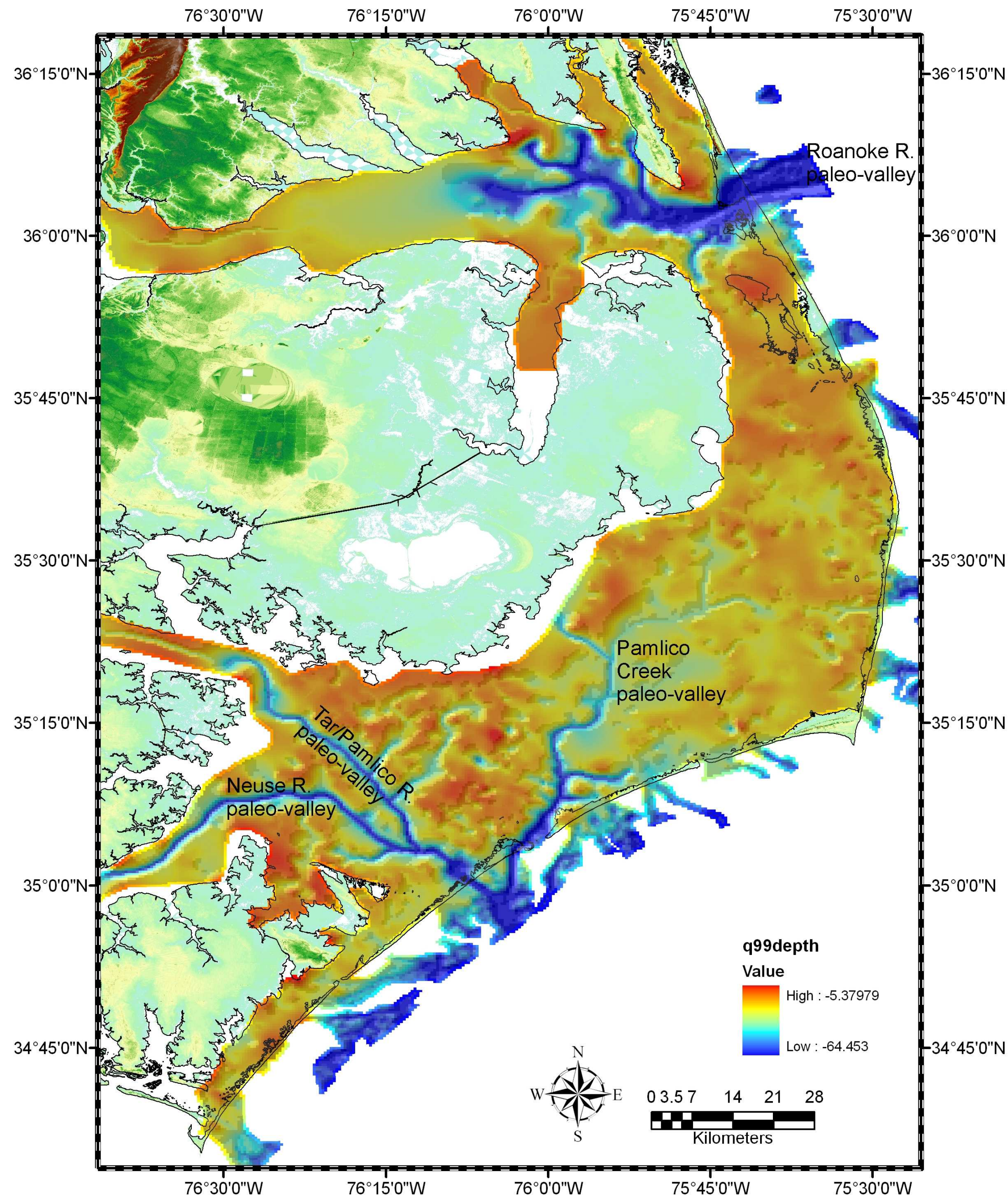

Figure 4. Color-coded and shaded surface structure map of the Last Glacial Maximum (LGM) unconfomity, based upon seismic data. Depths are in meters below mean sea level (m bsl). Modified from Mallinson et al. (in review).

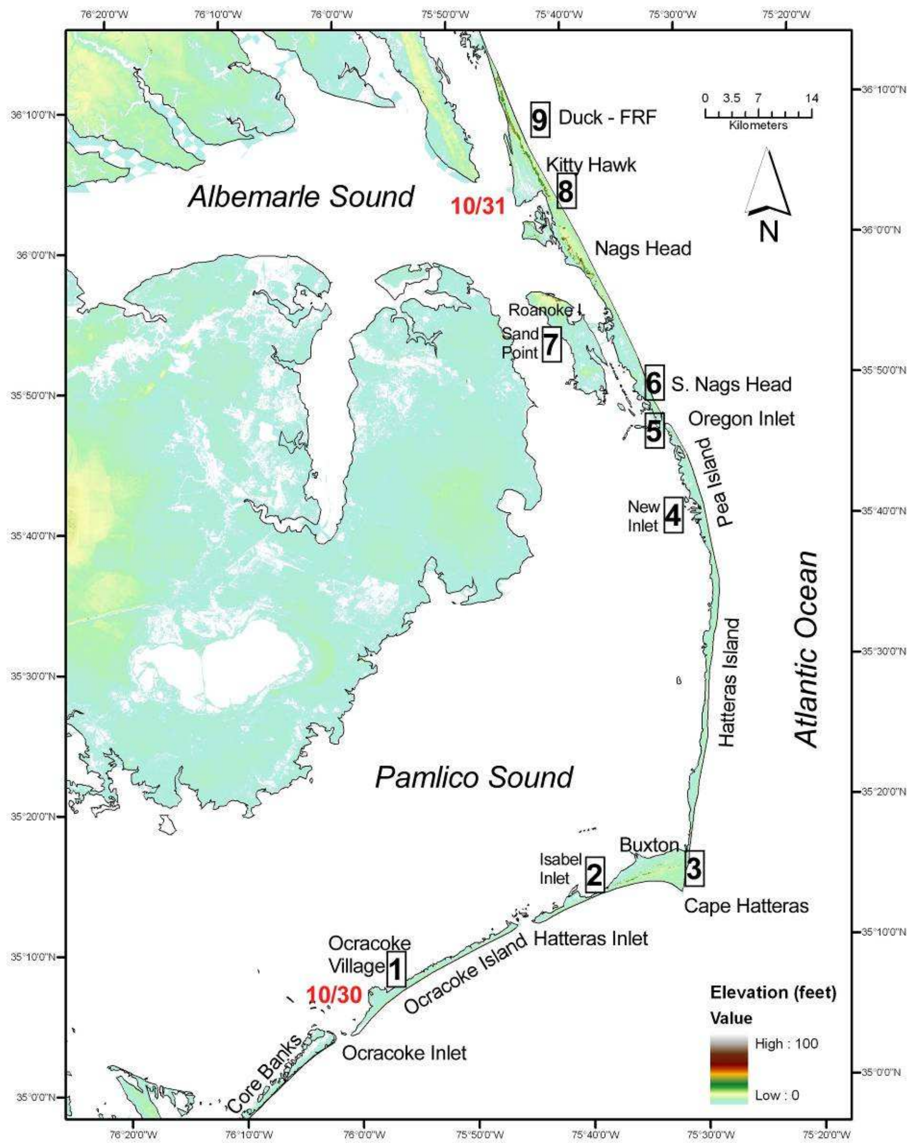

Figure 5. Field trip stops along the Outer Banks.

II. FIELD TRIP STOPS (Fig. 5)

STOP 1: OCRACOKE BARRIER ISLAND AND BARRIER DUNE RIDGES (Fig. 6a)

Ocracoke Island is situated on an interstream divide between Pamlico Creek (the riverine system occurring beneath Pamlico Sound during the Last Glacial Maximum) and offshore paleo-watersheds. The Pamlico Creek valley extends beneath Ocracoke Inlet (Fig. 6b), making this inlet the most stable and long-lived in the Outer Banks system. Ocracoke Inlet is the only inlet that has remained open throughout historic times (i.e., since 1590 – the first map of the Outer Banks). Several smaller tributary creeks occur beneath the shallows (Hatteras Flats) behind Ocracoke Island. Culver et al. (2007) identified a collapse of the Outer Banks barrier islands in this region (widespread erosion below sea level) occurring at approximately 1100 yBP, and existing until ca. 500 yBP (Fig. 7). They hypothesize that the collapse was due to the impact of a single category 4 or 5 hurricane or several category 1 to 3 hurricanes in short succession. Consistent with this premise is the recognition by Mann et al. (2009) that tropical cyclone activity reached a peak during the Medieval Warm Period at ca. 1000 yBP, followed by a lull. Further, Kemp (2009) identified an increase in the rate of relative sea-level rise in NC at this time.

The Ocracoke Village area is a complex barrier island, consisting of multiple sets of regressive beach ridges. No dates yet exist from this complex, but by comparison with other progradational components of the Outer Banks, we can speculate that this section began to form ca. 3000 yBP, at the same time as the Kitty Hawk beach ridges (Mallinson et al. 2008). The remainder of the island is <1000 years old, having reformed following the Medieval Warm Period collapse. Most back-barrier marsh flats are <500 years old.

An important event in modern barrier island history that substantially changed natural barrier island processes began in the late 1930's. At this time the CCC/WPA programs used sand fencing and bulldozers to build dune-ridges down the entire length of the Outer Banks from the Virginia line to Ocracoke. Zig-zag sand fences were built along the entire coast, with dense shrubbery brought over from the mainland. The fencing successfully trapped sand and built a continuous dune ridge along the coast. The ridge was up to 20 feet high and often consisted of multiple rows of dunes. The resulting barricade was like a fort wall standing against the ocean waves providing a false sense of security that facilitated the rapid sale of ocean-front property to summer visitors who didn't understand coastal storms, overwash, and coastal change. Barrier dune-ridges altered the natural equilibrium and dynamics of these overwash barriers. In addition to providing a barrier from the ocean for human development and economic growth along the beach front, the dune ridges essentially eliminate the overwash process, greatly modify the type and abundance of vegetation across the barrier, and alter the effects of the back-barrier estuarine processes.

As you drive along Ocracoke Island, notice the extensive constructed dune ridge system. These dune ridges have been rebuilt many times since their initiation during the late 1930's. As you drive along Hwy 12 notice that almost every curve in the road represents a location where the road was moved back from the shoreline due to beach recession. The latest relocation of this "going-to-sea" highway occurred as recently as

2003. Today, about 40 km (25 miles) of Hwy 12 is in serious jeopardy of collapsing as the ocean shoreline continues to recede. You will notice extensive areas where the dune ridge has just been rebuilt, now with sandbag cores, to keep the barrier secure. Keep your eyes open and you will see dune ridges in every stage of destruction by natural processes and reconstruction by humans.

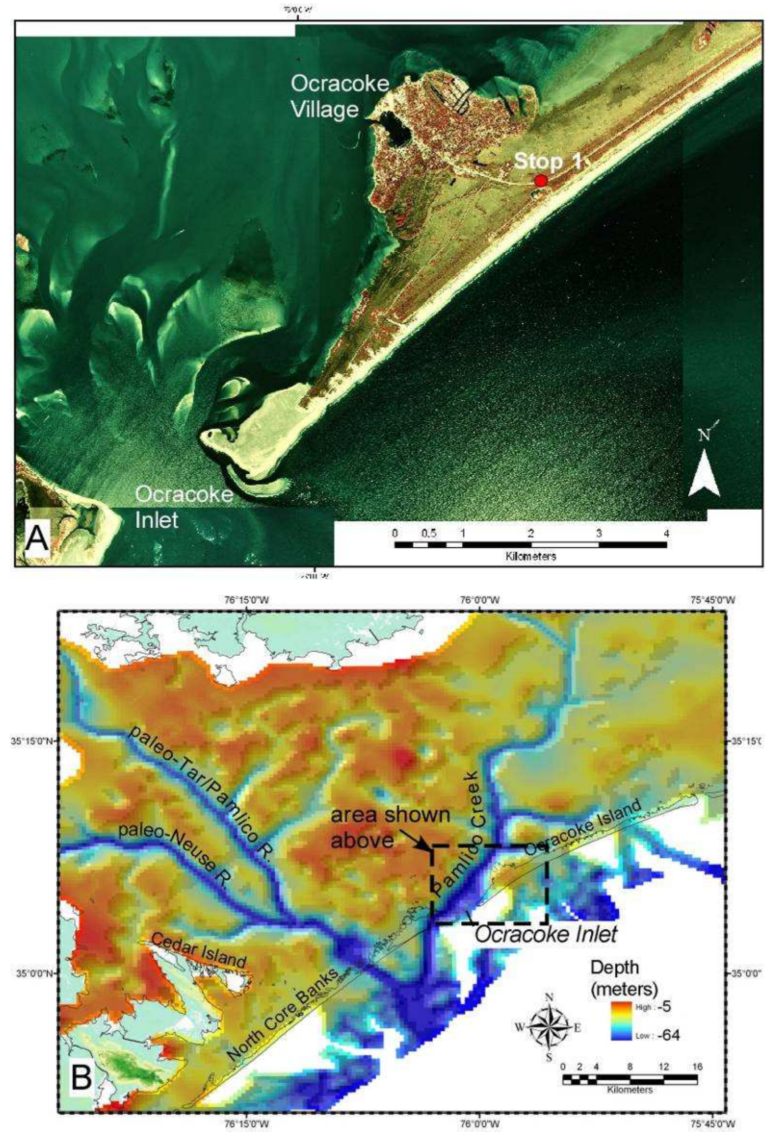

Figure 6. A) Aerial photograph of Ocracoke Inlet and Ocracoke Village. B) A map showing the topography of southern Pamlico Sound and the Ocracoke Inlet area as it appeared during the last glacial maximum approximately 20,000 years ago when this area was dry land (based upon seismic data; Mallinson et al., in review). Ancient river channels (blue) were mapped beneath the modern southern Pamlico Sound and the inner continental shelf. Note that Ocracoke Inlet occurs where Pamlico Creek passes beneath the modern barrier island trend, and Ocracoke Island occurs on an interstream divide. The modern day coastline is included for the purpose of spatial orientation.

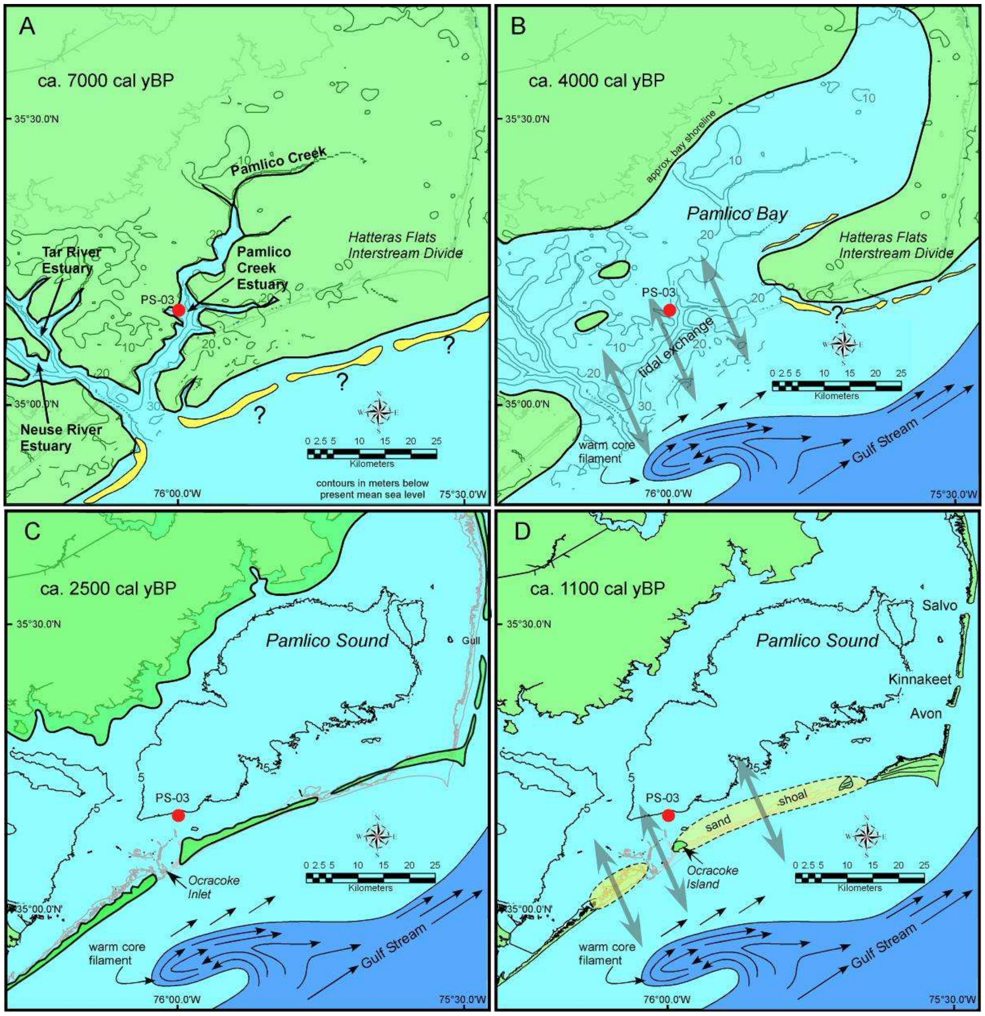

Figure 7. Diagrams illustrating environmental conditions in the southern Pamlico basin during four Holocene time slices. A) Sea-level rise flooded the fluvial paleo-valleys producing estuaries ca. 7000 cal yBP. B) By ca. 4000 cal yBP, flooding of sections of the Hatteras Flats Interstream Divide adjacent to the paleo-drainages allowed normal salinity waters into the southern Pamlico basin. Grey arrows indicate tidal exchange. Contours indicate the depth (meters below present mean sea level) to the Pleistocene surface and define the paleotopography that controlled the timing of flooding and morphology of Pamlico Bay. C) Barrier islands formed by ca. 3,500 cal yr BP and persisted until at least 1500 cal yBP. D) Barrier island collapse along the southern margin of Pamlico Sound at ca. 1,100 cal yr BP resulted in a shallow, submarine sand shoal over which normal salinity waters, derived from northward migrating Gulf Stream warm-core filaments, were advected into the southern part of the Pamlico basin in response to wind-forcing. Contours indicate modern bathymetry (meters below mean sea level) within Pamlico Sound (modified from Culver et al., 2007).

Hatteras Inlet

Hatteras Inlet is one of only three major inlet/outlet systems that drain the entire Albemarle-Pamlico estuarine system (Fig. 1). This inlet was opened in its present location by an 1846 hurricane. During the ferry ride across Hatteras Inlet we will be pointing out and discussing the inlet features including: 1) A small, well developed ebb-tide delta on the ocean side; 2) a vast region of shallow sandy flats on the estuarine side that constitutes the flood-tide delta; 3) extensive spoil piles indicating actively migrating channel complexes; and 4) a very long prograding spit on the northeast side of the inlet with increasing degree of development of vegetation away from the inlet. The latter indicates that the inlet/outlet system has been actively migrating towards the southwest through time.

Paleo-Inlets of Hatteras and Pea Island

Upon crossing Hatteras Inlet, you will arrive on southern Hatteras Island. Traditionally, the northern end of Hatteras Island, between Oregon Inlet and Rodanthe is called Pea Island (Fig. 1). Although no inlets currently occur along this section of the Outer Banks, numerous inlets have dissected Hatteras and Pea Islands episodically during the past (Fig. 8) (Stick, 1958; Fisher, 1962; Smith, 2006; Mallinson et al., in review). The first map of northeastern North Carolina was made in 1590 and illustrates numerous inlets along the northern Outer Banks (Fig. 8a).

GPR data have been used to define the locations and characteristics of old inlet channels (paleo-inlets) from Oregon Inlet to Ocracoke Inlet (Fig. 8b) (Smith, 2006). Based upon these data, sediment cores were collected to provide sediment for determining the age of inlet activity and defining the role of inlet formation in barrier island evolution.

GPR data in combination with geomorphic and historic data reveal that paleo-inlet channels constitute up to 75% of Hatteras and Pea Islands between Oregon Inlet and Cape Hatteras. Two main types of paleo-inlet channels (non-migrating and migrating) were classified based on geometry and fill patterns (Fig. 9). The paleo-inlet channels are cut into older flood-tide delta (FTD) deposits that correspond to older inlet activity when barriers existed further seaward. Flood-tide delta deposits are generally overlain by marsh peat and storm overwash sediments. Channel-fill sediments occur under the widest portions of the island, whereas narrow portions of the island are underlain by the FTD and overwash sediments. This relationship is attributed to the successional stage of island evolution in response to rising sea level, and indicates that the narrow island segments are now in need of new inlets and deposition of new FTD's to increase island width.

Optically stimulated luminescence (OSL) dating of the inlet channel-fill sediments indicates that inlet activity declined following the Little Ice Age (LIA), ca. 500 yBP (Smith, 2006). These ages are in agreement with the early maps, such as the White-deBry map of 1590 (Fig. 8b), which show greater numbers of inlets along the Outer Banks. The occurrence (during and prior to the LIA) and subsequent decline of these inlets suggests a "healing-phase" of barrier reorganization following major disruption of barrier continuity during the Medieval Warm Period (Culver et al., 2007), or greater extratropical cyclone activity during the LIA.

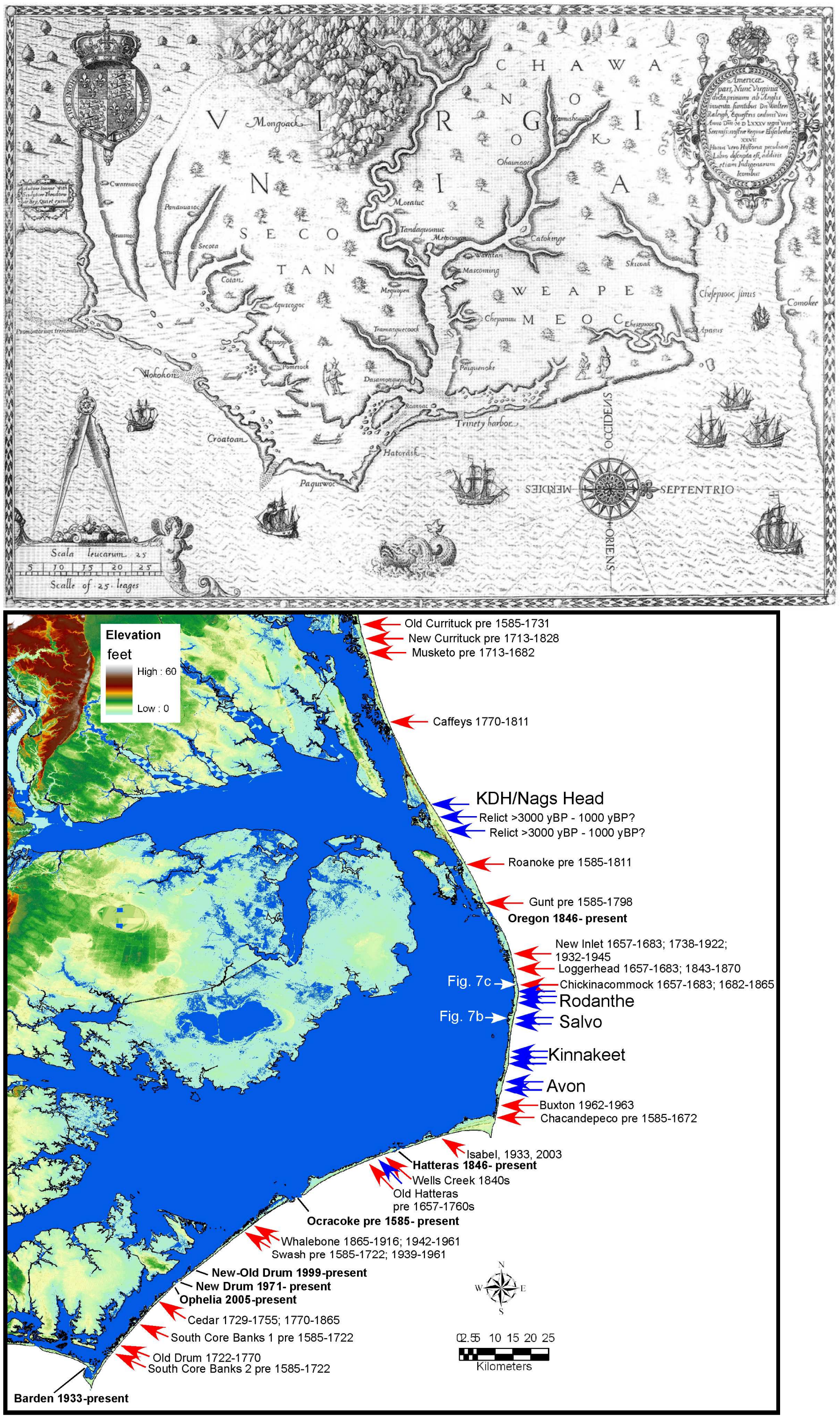

Figure 8. (A) Top panel. The White-deBry map was made in 1590 and shows numerous inlets along the NC coast. (B) Bottom panel. Map illustrating the approximate locations and dates of existence of documented historic inlets (red arrows) and previously undocumented inlet channels (blue arrows) discovered using ground-penetrating radar data.

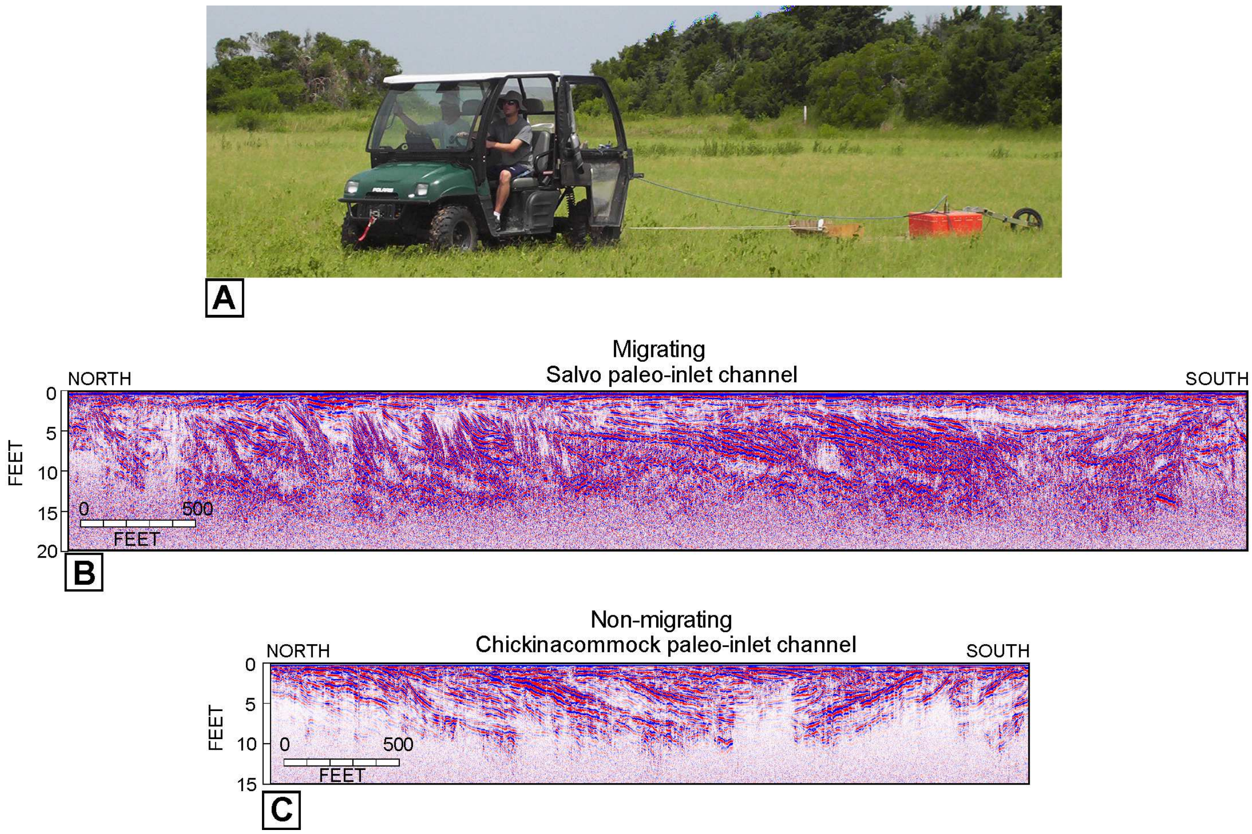

Fig. 9. (A) A photograph showing the process of collecting ground penetrating radar data using an all-terrain vehicle. The GPR antenna is the orange box being pulled across the ground surface. (B) GPR data illustrating a migrating inlet channel (from Salvo). (C) GPR data illustrating a non-migrating inlet channel (Chickinacommock Inlet north of Rodanthe).

STOP 2: HATTERAS VILLAGE AND ISABEL INLET (Fig. 10)

Hurricane Isabel (Figs. 10-13), a category 2 storm, came ashore in the vicinity of North Core Banks and Ocracoke Inlet on September 18, 2003 with sustained winds of approximately 85 knots (NOAA-NWS web site). The storm tracked NW across southern Pamlico Sound, westernmost Albemarle Sound, and W of the Chowan River estuary (Fig. 1). As the storm approached Pamlico and Albemarle Sound, strong NE and E winds produced major, but highly variable storm surges that reached an estimated 7 to 10 feet above MSL at the mouth of the Neuse and Pamlico River estuaries and 5 to 7 feet above MSL in western Albemarle Sound and up into southern Chowan River estuary (NOAA-NWS web site). The resulting storm surge caused severe ocean shoreline erosion and extensive barrier island overwash, while estuarine storm surge caused shoreline erosion along segments of the mainland shoreline and flooding of the adjacent lowlands. Isabel Inlet opened in response to the storm surge in an area that had previously been opened (in 1933) by a hurricane. This site demonstrates the vulnerability of certain segments of the barriers, and the inevitability of continued inlet formation, regardless of human efforts.

Figure 10. DOQQ showing Hatteras Village and the narrow portion of the island where Isabel Inlet opened in September 2003 during Hurricane Isabel.

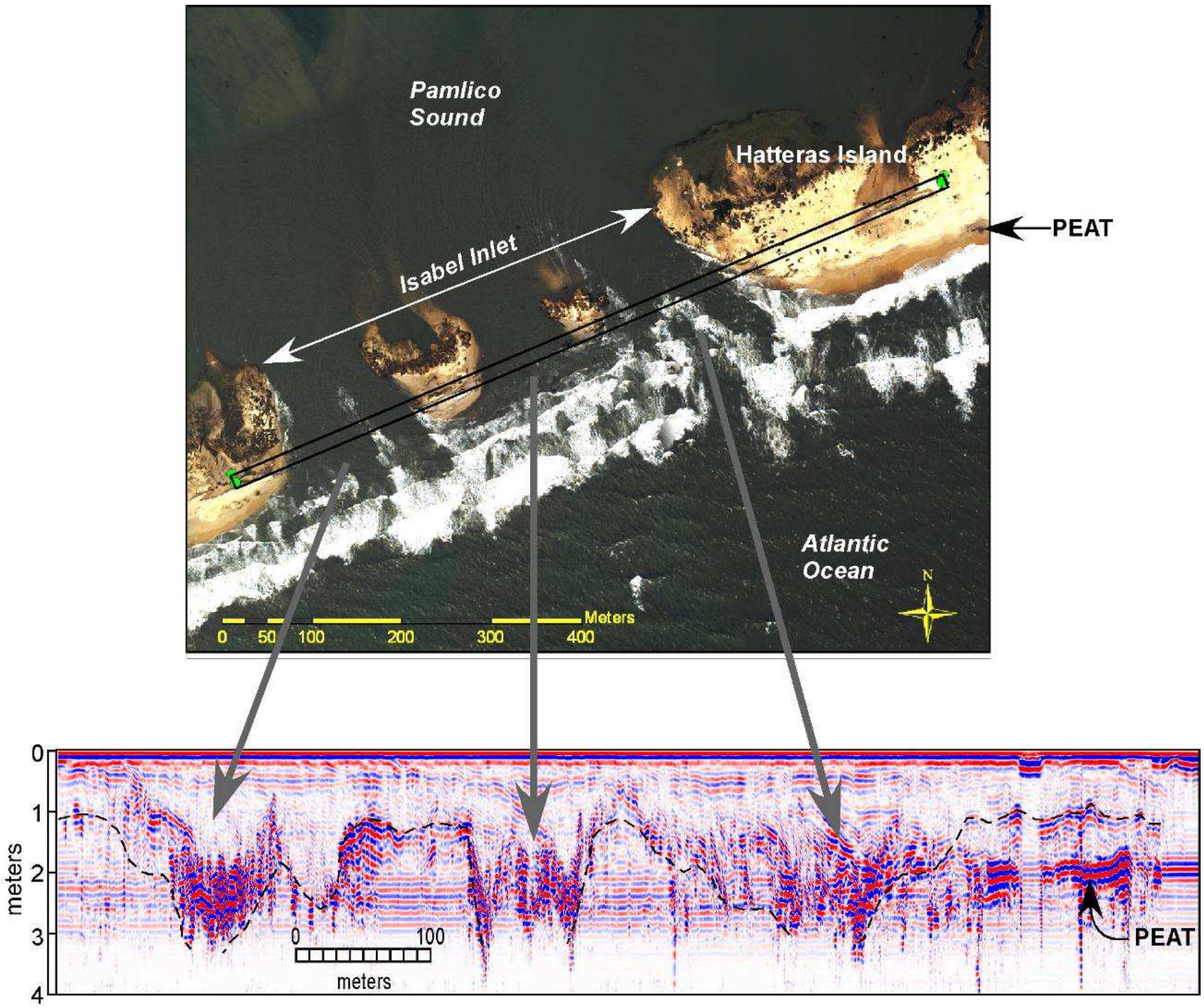

Figure 11. (A) An aerial photograph of Isabel Inlet indicating the location of the ground penetrating radar survey following filling of the channels, shown in B) (NC State Database). Note the location of three channels that developed, which are also seen within the GPR data. For clarity, channel flanks are delineated with a dashed black line. Also, note the occurrence of peat in the subsurface, and exposed on the shoreface (from Mallinson et al., 2008b).

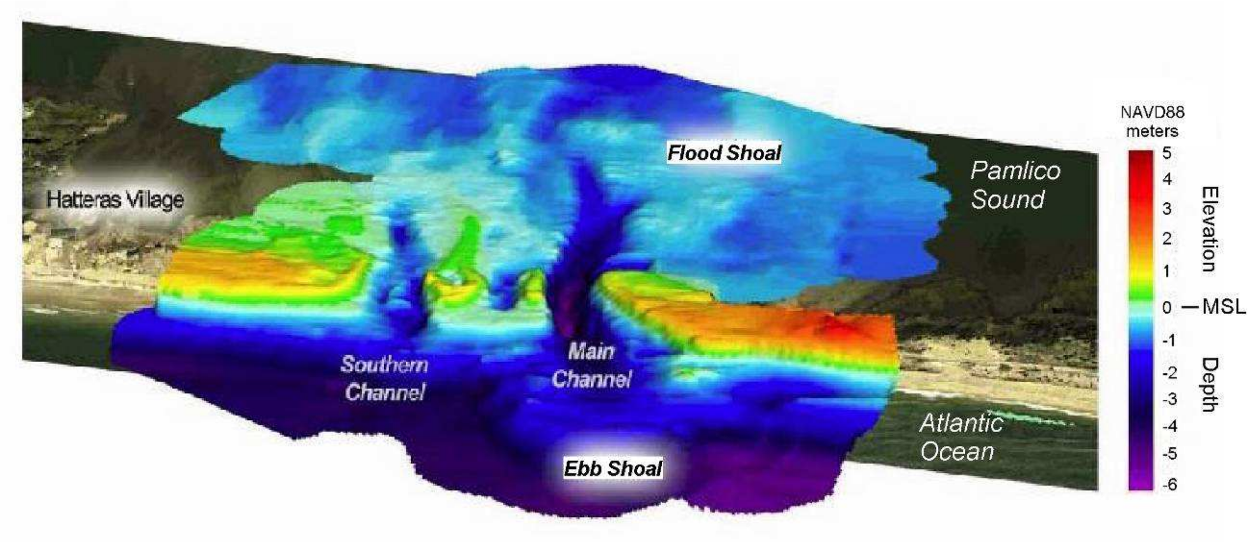

Figure 12. Figure showing the digital elevation model of Isabel Inlet that was made by Geodynamics, Ltd. (modified from Freeman et al., 2004) showing the beginnings of a flood-tide delta (Flood Shoal) and ebb-tide delta (Ebb Shoal) formation, and channels scoured to 6 meters (20 feet) below sea level. The inlet was filled by the USACE before a significant flood-tide delta could form.

Figure 13. A photograph looking northeast across the newly formed Isabel Inlet. Notice the pilings in the water which are the remains of a bridge built in 1933. Photograph courtesy of Gary Owens.

STOP 3: BUXTON BEACH RIDGES AND CAPE HATTERAS LIGHTHOUSE (Fig. 14)

Buxton Woods

Between Frisco and Buxton, you will be driving in Buxton Woods, the largest maritime forest on the Outer Banks. The road crosses many of the east-west beach ridges and swales that make up the bulk of Buxton Woods (Figure 14a). The swales contain extensive freshwater ponds and marshes, locally called sedges, with an abundance of wildlife.

Notice the abundance of broken and dead pine trees occurring within the Buxton maritime forest, which was impacted by Hurricane Emily in 1994. Note that the broken trees that are still standing point in a S to SE direction. All of the damage from Hurricane Emily was from N and NW winds and the resulting sound-side flooding as the eye of the hurricane passed along and slightly offshore of the barrier island. Not only were many of the pine trees broken off by the storm, but subsequently, insect infestations have killed most of the pines that survived, but were stressed by the storm. The original hardwood forests were heavily logged for ship timbers during past centuries, and so pines have dominated this maritime forest most recently. Hardwoods couldn't compete with pines until Hurricane Emily trimmed back the pine canopy. This allowed the hardwoods, the normal climax growth, to compete in this coastal habitat during the past few years.

New optically stimulated luminescence (OSL) data indicate that the oldest preserved ridge on the north side of Buxton Woods is ca. 1630 ± 200 years old (McDowell, in prep.). The ridges have built southward, fed by sediment from the north, as Hatteras Island north of Buxton receded westward. The ridges form sets bounded by extensive erosional surfaces. A major erosional boundary occurs just north of the highest beach ridge in the system, on which Highway 12 in Buxton is located. The erosional boundary is a major ravinement surface separating the 1600 year old NE-SW trending ridges from the <1000 year old E-W trending ridges. This regressive coastal system did not form in response to falling sea level, but formed in response to variations in sediment supply and the wave energy field, during Holocene sea-level rise. Thus, it is a normal regressive unit, as opposed to a forced regressive unit. This has been demonstrated by evaluating the elevation of paleo-berms as defined in cores and GPR data, to reconstruct sea-level index points (McDowell, in prep.).

Cape Hatteras

Cape Point is one of the most popular surf fishing spots in the US. The Point is a high energy system that is highly mobile and responds dramatically to changing energy regimes. As a result, the Point changes character daily and seasonally. The infamous Diamond Shoals extend 15 km seaward from Cape Point. Each of North Carolina's Capes has a similar cross-shelf shoal system that creates the dangerous conditions that led to coastal Carolina being dubbed the "graveyard of the Atlantic".

The Cape Point and Diamond Shoals system separates two major ocean currents and biological regimes. These two water masses control the local water conditions, species of fish in the water column, types of shells on the beach, and the storm patterns for the Outer Banks. To the north is the Labrador Current and associated cold water fauna and flora while to the south is the tropical Gulfstream and associated warm water fauna and flora. The interaction of these two currents over the Diamond Shoals results in an awesome display of dynamic interplay between waves, currents, winds, and the sand shoals.

To the west of Cape Point is one of the very few accretionary or progradational beaches on the Outer Banks. Only local and relatively small segments of the North Carolina shoreline are presently characterized by regressive shoreface conditions. These areas generally occur on the flanks of cape structures and headlands and represent temporary episodes of coastal progradation that usually alternate with episodes of longer-term truncation as the headland recedes. However, during episodes of regression, these shorefaces are relatively stable, are characterized by progradational geometries, beach ridge accretion, dune ridge development, and have the potential for approximating the idealized "profile of equilibrium". Hatteras Island, southwest of Cape Hatteras, as well as portions of Portsmouth Island, Cape Lookout, Shackleford Banks, and Bald Head Island are examples of regressive shorelines.

Cape Hatteras Lighthouse

The old Cape Hatteras lighthouse was built in 1802 between 1000 and 1200 m from the shoreline. The present lighthouse was built in 1872 near the base of the old lighthouse approximately 500 to 750 m from the shoreline. By 1935, erosion had progressed to the point where the lighthouse, awash in the surf zone, was abandoned and replaced by a steel tower one mile to the northwest. However, extensive sand fencing and grass planting by the Civilian Conservation Corps and the National Park Service in the late 1930's formed a series of barrier dune ridges; by 1950 the lighthouse was declared safe and the light was returned.

Since 1966, the CHNS was involved in a battle to "save the lighthouse". This has included construction of three groins (and rebuilding them on several occasions), carrying out several major beach nourishment projects, setting numerous layers of large rock revetments, deploying many layers of nylon sand bags, planting artificial seaweed, and even tearing up and dumping the asphalt from the adjacent parking lot onto the beach. There were also several engineering studies carried out to design structures that would allow the lighthouse either to stand as an island within the encroaching ocean or be picked up and moved inland on tracks. In 1999 the lighthouse was successfully moved 900 m to its new location 500 m inland from the encroaching sea. Retreat from an eroding shoreline and rising sea level is a critical management response for the healthy maintenance of a dynamic barrier island.

At this stop we will observe and discuss the history of this shoreline and attempts to protect the lighthouse, as well as the processes associated with cuspate foreland development.

Figure 14. Aerial photographs of the Buxton Beach ridges and Hatteras Lighthouse areas. A) Buxton Beach ridges which represent southward progradation of the shoreface as the barrier islands north of the cape migrate westward. The oldest beach ridge (at the far north end of the complex) has been dated to ca. 1600 yBP using OSL techniques (McDowell, thesis in progress). B) appearance of the Lighthouse area in 1998. The yellow circle is centered on the lighthouse and the structure and shadow can be seen. C) The appearance of the lighthouse area in 2009, following relocation of the lighthouse structure (centered within the yellow circle). Note (in B and C) the inflection in the shoreline caused by the construction of a groin field (arrow) in this area in 1969 and 1975 in an attempt to protect the lighthouse, to no avail.

Wimble and Kinnakeet Shoals

The Cape Hatteras to Oregon Inlet segment of the Outer Banks (Figure 1) is perched on a ravinement surface cut into the nose of the Dare Headland which defines the basic geometry of this portion of the Outer Banks. Four coastal features define this area. 1) Changes in barrier island orientation occur at Cape Hatteras and at Rodanthe. 2) Bathymetric highs on the inner shelf intersect the lower beachface at acute angles (Wimble Shoals from Rodanthe to Salvo and Kinnakeet Shoals from Kinnakeet to Avon). 3) Two minor cape structures (minor seaward excursions of the shoreline) occur on the barrier beach at Rodanthe and Avon (associated with Wimble and Kinnakeet Shoals) with rapidly receding beach segments occurring between them. 4) In Pamlico Sound, the backside of the barrier island is characterized by the Hatteras Flats, a broad and shallow platform bounded on the west by a high angle slope up to 3 m high.

Wimble and Kinnakeet Shoals are ridges that are oriented NNE-SSW at about 25^{o} to 30^{o} angles to the barrier (Figure 15). These offshore Pleistocene hardbottom features have up to 6 m of relief and rise up to between 7 and 9 m below sea level. High-resolution seismic and side scan sonar data demonstrate that they are erosionally scarped hardbottoms (Thieler, personal communication). Vibracores in these hardbottoms (Boss and Hoffman, 2000), demonstrate that they are Pleistocene, carbonate-cemented sandstones and mudstones. Thus, these shoal features are relict erosional features and not constructive depositional sand bars as inferred by Swift et al. (1973). Wimble and Kinnakeet Shoals have dramatic impacts upon the energy regime affecting the adjacent beaches through wave refraction and wave setup (Cox, 1996), and account for the large-scale behavior of this coastal segment. Bathymetric charts suggest fairly steep and deep shoreface profiles occur directly off the two cape features, whereas, in the adjacent receding portions of the beach, shoreface profiles are relatively broad and shallow.

The Hatteras Flats occur on the west side of the barrier islands between Oregon Inlet and Ocracoke Island (Figure 15). This broad and shallow platform is between 4 and 6 km wide and generally less than 1 m deep. From Oregon Inlet south to Rodanthe, the flats slope gradually into Pamlico Sound. However, beginning near Rodanthe and continuing southward to Avon, the western side of these flats is characterized by a high-angle slope that drops from 0.5 m or less into 3 to 4 m water depth.

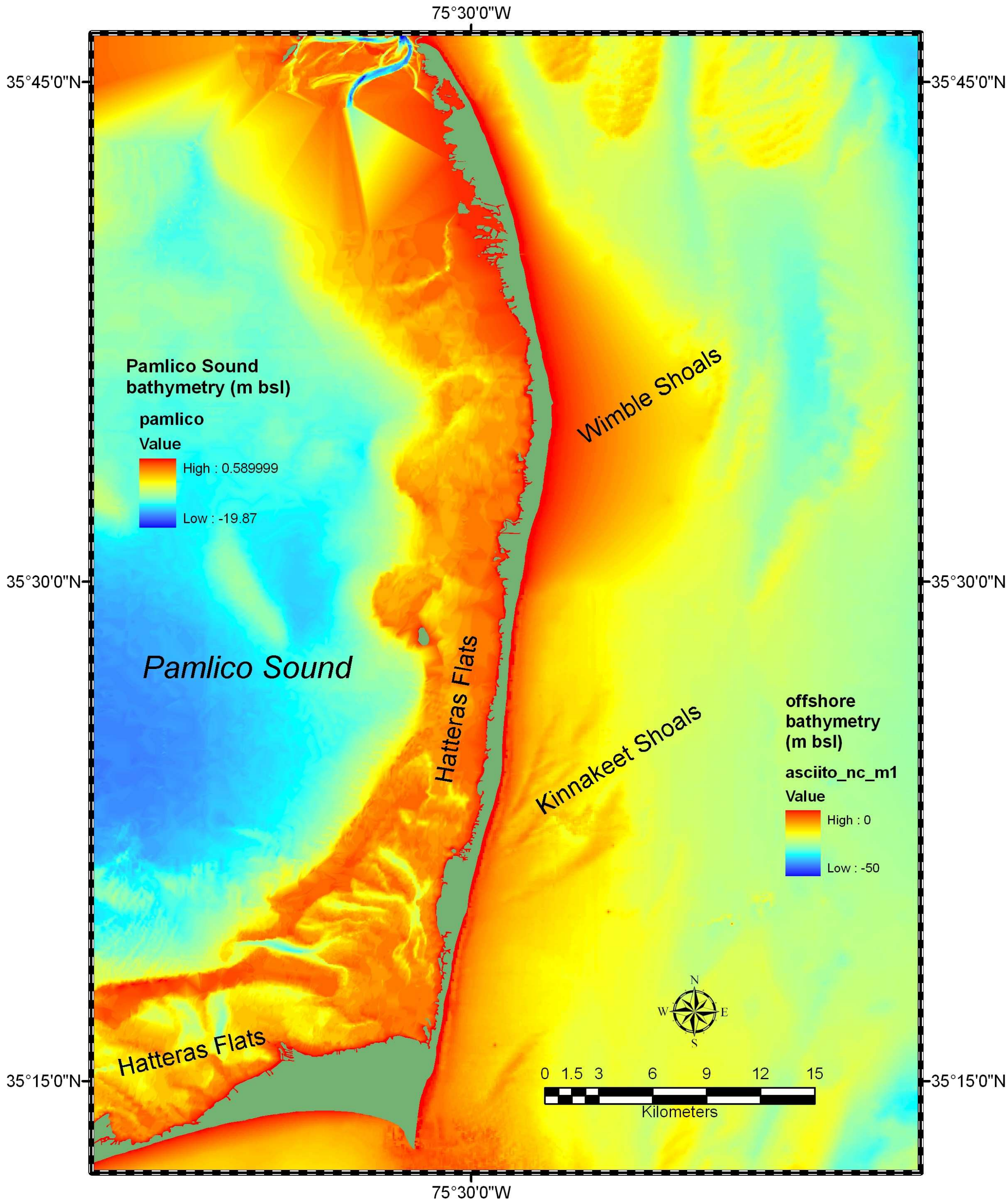

Figure 15. Bathymetry of the estuarine and marine environments adjacent to the Outer Banks. Note the different color scales (to accentuate relief in the estuary) for the Pamlico Sound and offshore data.

Pea Island "Going-To-Sea" Highways

About half of the 12 mile length of Pea Island National Wildlife Refuge is threatened by coastal recession and island narrowing. Highway 12 has a fixed right-of-way. Consequently, there are three areas where the NC DOT maintains the road at an extremely high cost. Every curve in the road represents a "going-to-sea" highway that has been rebuilt to the west. Miles of sandbags along the old road stand as a monument to an incredible economic investment in trying to preserve a fixed object on a moving barrier island. Notice that the barrier dune-ridge is in various stages of destruction. Numerous steep, straight, knife-edged sections of constructed barrier dune-ridges occur between the irregular and higher ridges. These knife-edged portions occur in areas where the dunes have been breached by overwash and subsequently rebuilt with bulldozers, sand fencing, and grasses. Driving along this section, you can get a feel for the major cost of building and maintaining a barrier dune-ridge along the entire length of Cape Hatteras National Seashore.

Due to the great and ever expanding economic importance of coastal tourism to the state of North Carolina, the State has decided to "hold the line" with respect to the processes of coastal erosion. The recent establishment of this unofficial position is largely driven by the Department of Transportation (NC DOT), and Highway 12 has been rebuilt and relocated for decades at incredible cost. The road is the sole vehicular hurricane evacuation route.

In a study for the NC DOT, Stone et al. (1991) concluded that 20 miles of Highway 12 between Kitty Hawk and Ocracoke "are now particularly vulnerable or will be vulnerable in the near future". They recommended that the road be relocated along the Kitty Hawk and Kill Devil Hills sections, and that all other sections, including the Oregon Inlet to Rodanthe sections be managed through beach nourishment projects.

DOT's efforts are all very short term fixes for a very large scale problem. During the past two decades more and more sections of the road system have been subjected to increasing amounts of erosion (averaging up to 16 feet per year at Rodanthe; Benton et al., 1993), shoreline recession, and overwash.

If a viable coastal highway system is to be maintained, long portions of it will have to be relocated. In many places, the barrier is already too narrow to accomplish this on land. We must consider other options such as an estuarine causeway or an extensive water taxi system between villages. The long-term costs for quick-fix repairs could be as great as the initial cost for a back-barrier causeway system that is probably inevitable in the long-term. Do we really need to maintain a paved road that allows the public to speed through this beautiful coastal system at 70 mph? Why not maintain the vulnerable portions of the highway as temporary, gravel-based segments that will allow both the movement of traffic, occasional overwash, and less-costly rehabilitation and relocation until an alternative system can be developed. In high energy, physically dynamic coastal areas, we must begin to build in harmony with the natural processes.

STOP 4: NEW INLET AND ITS BRIDGE TO NOWHERE (Fig. 16)

New Inlet is within the Pea Island National Wildlife Refuge, north of Rodanthe (Fig. 1). This is the site of a series of inlets that first appeared on maps in 1738. Apparently they were relatively small, ephemeral, and little used by boat traffic during the colonial period since the nearby, larger, and longer-lived Roanoke Inlet was open until about 1817. After Roanoke Inlet closed, a series of major inlets opened in the vicinity of the present Oregon Inlet and provided the primary flow through the barrier islands. By the time the present Oregon Inlet opened during a 1846 hurricane, New Inlet was almost closed, and it finally closed completely in 1922. An unsuccessful attempt was made in 1925 to open New Inlet artificially. New Inlet reopened in 1933 as a result of hurricanes and remained open until 1945. The wooden bridge was built during this period and stands as a monument to the dynamic nature of inlets and the vulnerability of anthropogenic structures.

Figure 16. Aerial photograph of the New Inlet area showing the flood tidal delta (FTD) shoals, some of which have developed into marsh, adding width to the island and a platform for island migration. Also noted is the long-abandoned New Inlet Bridge which stands as a testament to the ephemeral nature of most inlets in this area.

STOP 5: OREGON INLET-SOUTH SIDE (Figs. 17 and 18)

The various inlets through the Outer Banks might better be called outlets since their primary function is to allow fresh water draining off the land and estuarine water piled up in the sound during storms to escape through the barrier island into the sea. Inlet/outlet systems are natural, self-adjusting safety valves. During storms or floods they open up by flushing sand out. Between storms they close down by shoaling to minimal-sized channels. Sometimes during storms new inlets will open where needed to accommodate the increased tidal prism. When the storm or flood has passed, these temporary inlet/outlet systems may close up naturally. Without outlets the barrier islands would act as dams, and storm damage due to flooding would increase.

Oregon Inlet formed during an 1846 hurricane about 4 km north of its present location. In the distance to the north you will see the third Bodie Island lighthouse, which was built on the north shore of the inlet in 1872. The inlet has migrated to the south (Figure 17b), taking with it the sites of both of the original lighthouses, built in 1848 and 1859 on the south side of the inlet, and the original lifesaving station. Until 1989, the inlet continued to migrate southward at rates between 60 and 90 m per year destroying campgrounds, parking lots, roads, and finally threatening the US Coast Guard station and the end of the Oregon Inlet bridge. In 1989 the NC DOT built the rock jetty to stop the southward migration of the inlet. However, the constrained location of the south bank, and the continued southward spit growth on the north bank caused Oregon Inlet to narrow and deepen. The narrower throat channel resulted in rapid scour beneath the central bridge pilings. As a result, rocks were emplaced beneath the free-hanging pilings.

Oregon Inlet is an extremely dynamic inlet which, under natural conditions, would continue to migrate southward. The high energy and dynamic character of the inlet conflict with the static human infrastructure (bridge and road), often pitting management policies and local interests against natural coastal dynamics. Continually shifting sand shoals and channels have necessitated increased dredging to maintain navigability for commercial and recreational vessels from nearby ports.

At this stop we will be discussing the dynamics of this system, impacts of these stabilization attempts, as well as the ongoing controversy regarding placement of a new bridge.

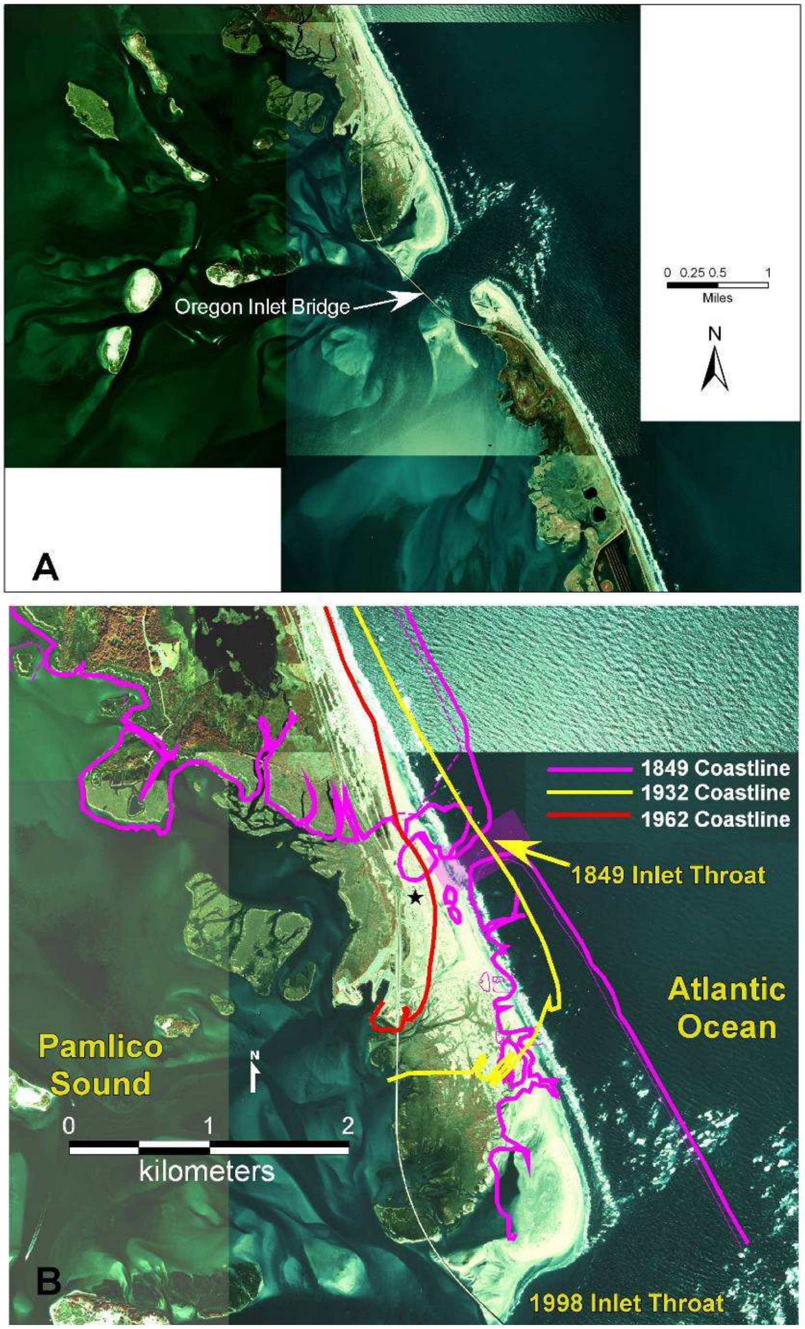

Figure 17. (A) Figure shows a 1998 aerial photograph of Oregon Inlet (NC State Database). (B) The 1998 aerial photograph of Oregon Inlet showing superimposed shorelines from 1849, 1932, and 1962 (following the 1962 Ash Wednesday storm), illustrating the large degree of shoreline variation and inlet migration (from Mallinson et al., 2008b).

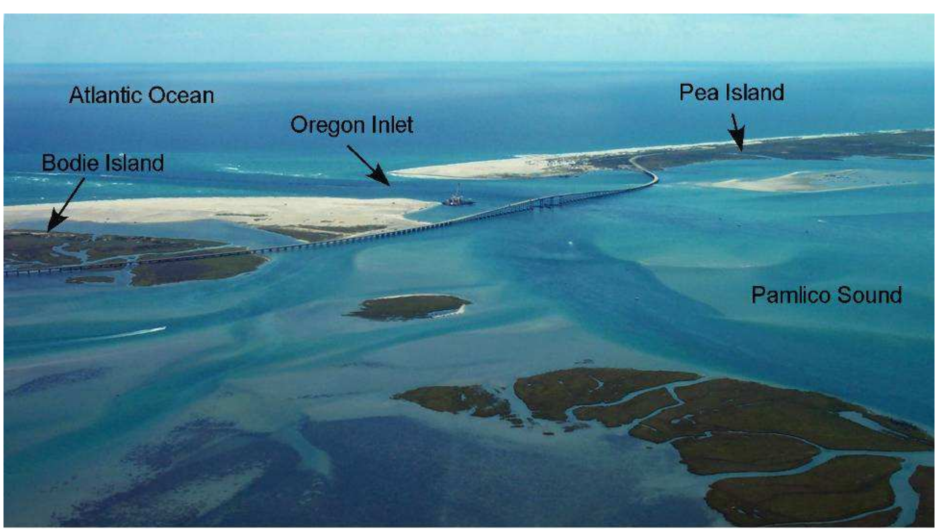

Figure 18. An oblique aerial photograph of Oregon Inlet and the Oregon Inlet Bridge. Courtesy of the U.S. Army Corps of Engineers, Field Research Facility in Duck, NC.

STOP 6: SOUTH NAGS HEAD "GOING-TO-SEA" (Figs. 19 and 20)

This stretch of the beach is one of the most rapidly eroding shorelines on the Outer Banks (Fig. 20). Shoreline recession rates range from 3 to 5 m per year (Benton and Bellis, 1993). Most of the development of South Nags Head has taken place since the 1980s and 90s; consequently all of the houses met the setback code at the time they were built. However, since then shoreline recession has taken some ocean front houses resulting in second tier houses in the checkerboard developments acquiring an ocean front location. All of the "ocean-front" houses along this beach segment are now in front of the storm beach and waiting their turn to make the front page of the news as they disappear into the sea. In the desperate efforts to buy a little more time, extensive and expensive bulldozing and sandbagging follow every storm (Fig. 20).

The serious consequences of this approach to development are loss of the public beach, remnants of destroyed structures littering the beach, and septic tanks exposed and broken during each storm. The houses are immediately condemned, but septic tanks are repiped and quickly buried again and the houses are ready for rental. This is good for the neither coastal system nor the tourist industry.

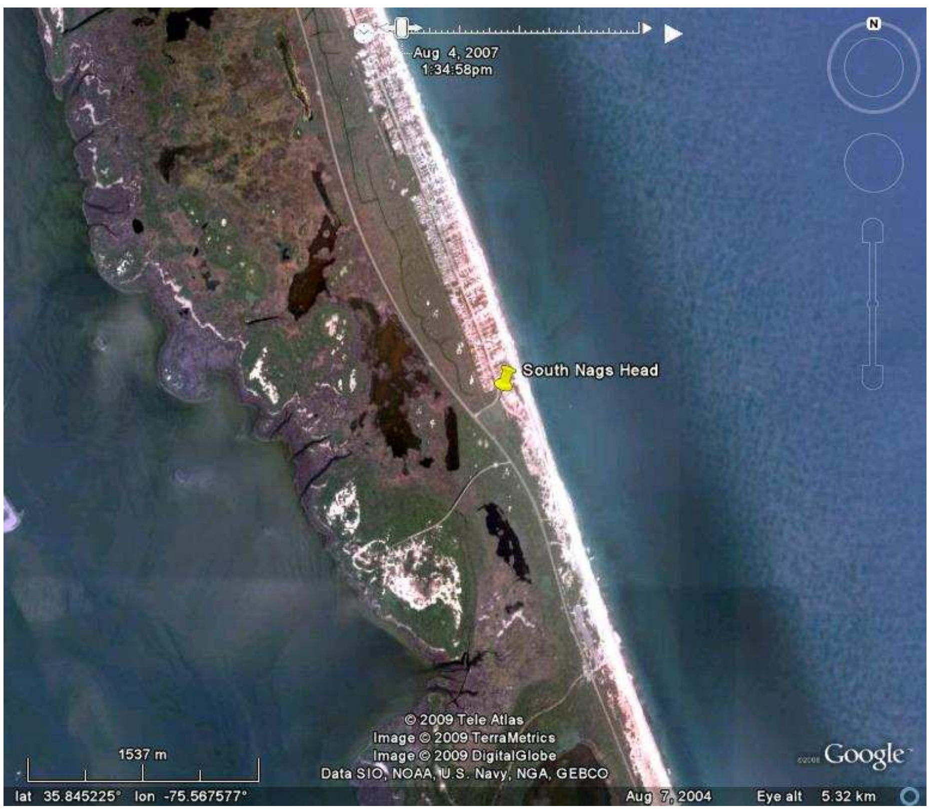

Figure 19. Location of South Nags Head.

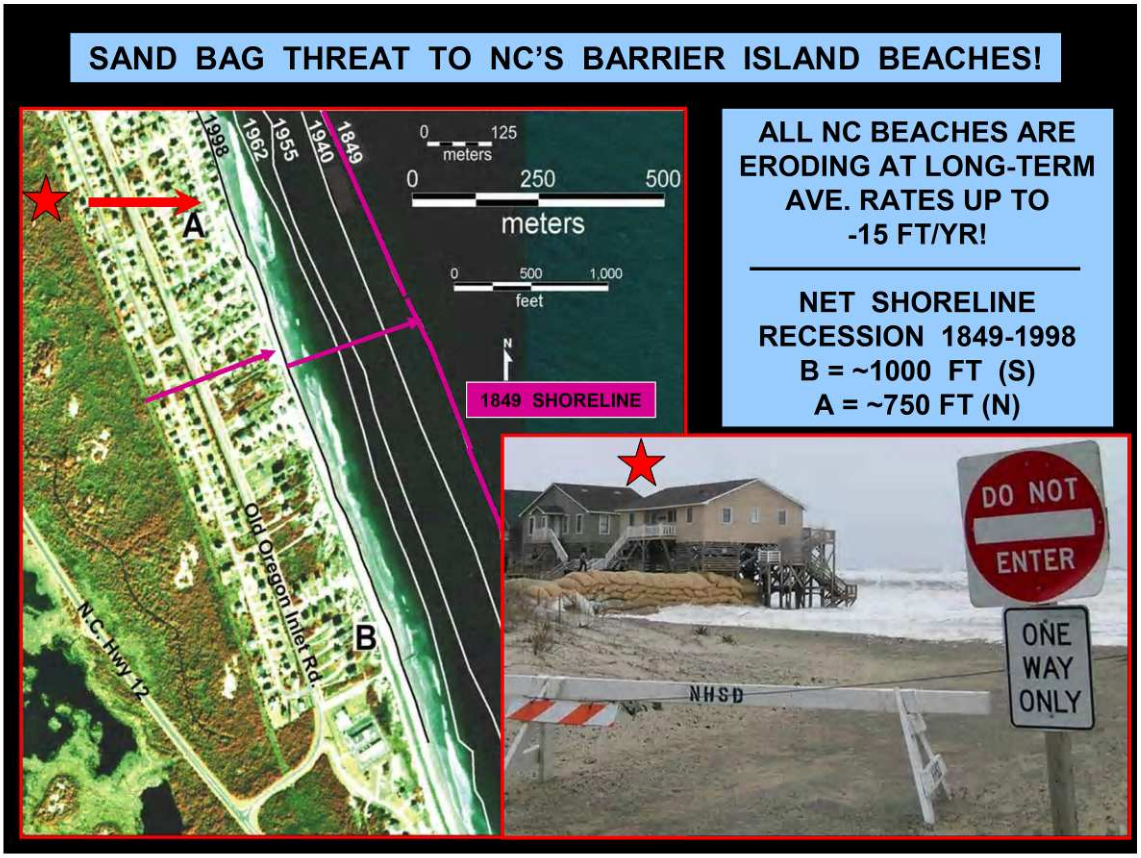

Figure 20. Erosion and sandbag issues at South Nags Head (from Riggs et al., 2008).

Whalebone Junction: Paleo-Roanoke Inlet

At Whalebone Junction the highway 158 causeway, which connects Roanoke Island with Outer Banks, joins highway 12. This is the general location of the old Roanoke Inlet through which Sir Walter Raleigh's ships probably passed in 1585 to establish the "Lost Colony" on the north end of Roanoke Island (Figure 8). This inlet opened during pre-historic times and closed about 1817. The former salt marsh islands on which the Roanoke Island causeway and all associated development occur are part of the flood-tide delta for the paleo-Roanoke Inlet.

As you travel north, look at your map and the barrier upon which you are traveling and notice the following: 1) no outlets occur north of Oregon Inlet to drain the largest river system in North Carolina, the Roanoke River and its tributaries; 2) a 55 mile fetch occurs down the length of Albemarle Sound; and 3) the barrier island between Whalebone and Jockeys Ridge is extremely narrow. A major hurricane storm surge from Albemarle Sound against the back side of this narrow barrier island could possibly open a new outlet. Until 1817 there were numerous inlet north of Roanoke Island; since then the entire Roanoke, Chowan, Albemarle drainage system must flow around Roanoke Island to exit through Oregon Inlet.

STOP 7: SAND POINT PLATFORM MARSH

This site represents a classic platform marsh which is typical of the micro-tidal estuaries in NC. Kemp et al. (2009) produced records of relative sea level from two salt marshes in North Carolina (Sand Point on Roanoke Island and Tump Point on Cedar Island; Fig. 21) since AD 1500 to complement existing tide-gauge records and to determine when recent rates of accelerated sea-level rise commenced. The two study sites provide an ideal setting for producing high-resolution records because thick sequences of high marsh sediment are present and the estuarine system is microtidal, which reduces the vertical uncertainty of paleosea-level estimates. Reconstructions were developed using foraminifera-based transfer functions and composite chronologies, which were validated against regional 20th century tide-gauge records. The measured rate of relative sea-level rise in North Carolina during the 20th century was 3.0 to 3.3mm/yr, consisting of an isostatic background rate of c. 1mm/yr, plus an abrupt eustatic increase of 2.2mm/yr, which began between AD 1879 and 1915. This acceleration is broadly synchronous with other studies from the Atlantic coast. The magnitude of the acceleration at both sites is larger than at sites further north along the U.S. and Canadian Atlantic coast and may be indicative of a latitudinal trend (Kemp et al., 2009). We will discuss these findings, marsh dynamics, and the significance of the sea-level record in this area.

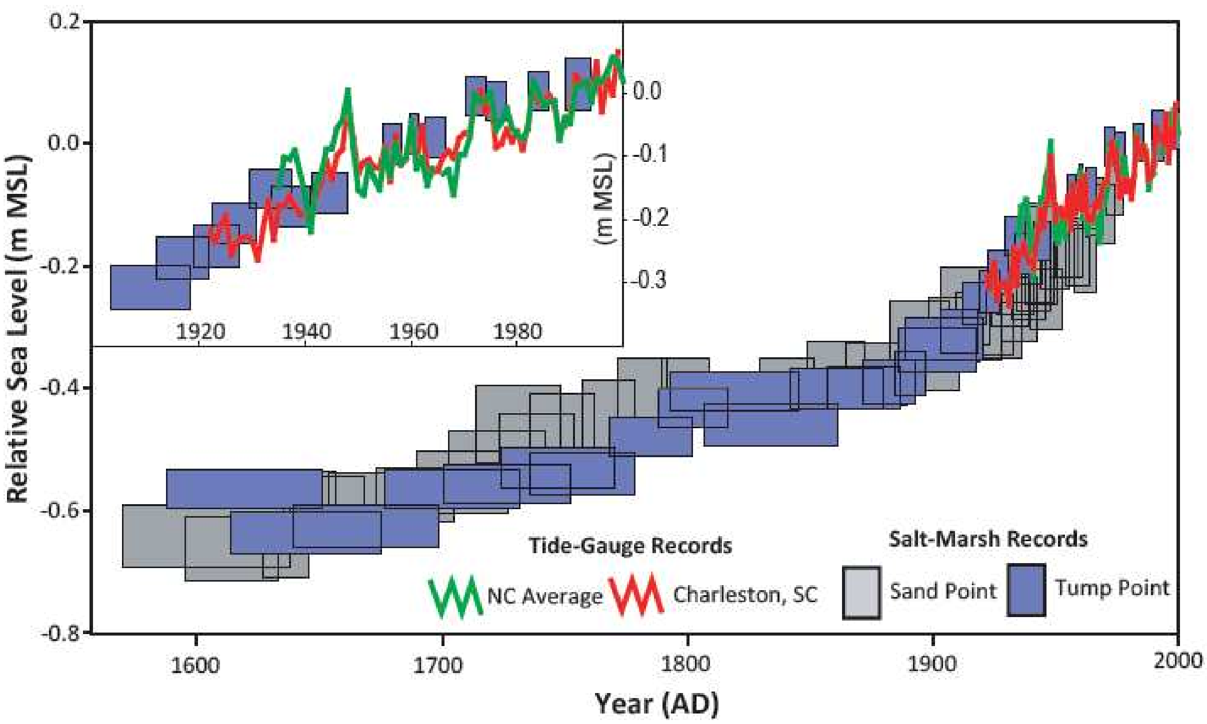

Figure 21. Reconstructions of relative sea level (meters above mean sea level, MSL) at Sand Point (gray boxes) and Tump Point (blue boxes) for the period since AD 1500. An average tide-gauge record from North Carolina (green) and the record from Charleston, SC (red) are also shown. (Kemp et al., 2009).

Old Nags Head

The era of modern tourism and associated development on the Outer Banks began slowly after the Civil War, boomed after WWII, and has become an economic driving force since the early 1980s. Prior to this time, most villages on the Outer Banks were situated in maritime forests on the estuarine side of wide portions of the barrier. These villages included Ocracoke, Buxton, Avon, Rodanthe, Old Nags Head, and Kitty Hawk. The active portion of the barrier islands were low and flat with a sparse vegetative cover that consisted dominantly of grasses. All of the Outer Banks were characterized by wide beaches, low berm crests, and only scattered dunes along the beach. The process that dominated these very low, high-energy barriers was overwash, which was not conducive to beach living. Consequently, there were no inhabitants on the active portion of the barrier island until outsiders began to acquire parcels of this land for fishing shacks and small summer cottages; the locals were all too happy to sell this high-energy, overwash-dominated land to the inlanders. But even then, the islanders acquired properties that were long in the shore perpendicular direction so they could move their cottages landward as the beach receded. With today's checkerboard developments, designed to maximize the profits, development cannot move with the migrating barrier beaches.

In the Nags Head portion of the Outer Banks, most of the original inhabitants lived deep inside Nags Head Woods, a maritime forest on an extensive back-barrier dune field along the Roanoke Sound shoreline. Only fishing and beach combing would bring them out of the woods and onto the ocean beach. After the Civil War, hotels were built near the ferry landing south of Nags Head Woods and facing Roanoke Sound. These hotels were built to accommodate the first tourists who retreated to the Outer Banks during the summer malaria season. Soon the locals began migrating out of Nags Head Woods to develop the support system for the early tourist industry south of Jockeys Ridge. In the meantime, the tourists began migrating towards the beach. The old Cape Cod style houses along the beach southeast of Jockeys Ridge were built during the late 1800s on deep lots with plenty of room to move with the retreating shoreline. Notice the new piles and chimney bases under most of these older houses reflecting previous moves.

Back Barrier Dune System

Jockey's Ridge, a massive sand dune field, is part of a much larger system of "back barrier dunes" that include the former Seven Sisters Dunes, Nags Head Woods, Run Hill, Colington Island, Kill Devil Hills, and Kitty Hawk Dunes. This back barrier dune system represents at least three different types of dunes with substantially different geologic ages and processes of formation. All of them are being severely impacted by anthropogenic modification. For example, the Seven Sisters and Kitty Hawk dunes have been completely developed, Jockey's Ridge became a NC State Park in 1974 with over a million visitors annually, a large portion of Run Hill was mined for construction sand, and Kill Devils Hill was stabilized with grass in the 1920s for construction of the Wright Brothers monument.

Dunes are high energy, storm dependent systems. A dune is the end product of the type, direction, intensity, duration, frequency, and the wet/dry character of each wind event. A dune must have continuing winds to maintain itself. Temperate coastal dunes are more complex than dry climate wind dunes, in that they are also dependent upon water and vegetation, which play equally important roles in their development. Water binds sand grains in wet dunes. This not only changes the mobility of the dunes and associated sands, it leads to the encroachment of vegetation which can rapidly stabilize the dune and its sand. Subsequent destabilization events such as fire, storm overwash, or human modification then become important in dune history.

Humans aid gravity in the downhill transport of sand. Everyday during tourist season, thousands of feet and bodies impact Jockeys Ridge, and are likely to be partly responsible for the decrease of dune elevation over the last several decades. Perimeter vegetation systematically encroaches up an active dune mass to eventually stabilize the feature. However, the trampling of many feet plays a role in killing encroaching vegetation. Barrier island modifications have indirect impacts upon vegetation growth. This includes such changes as draw-down of the water table, land clearing, perimeter construction, and construction of dune ridges, buildings, and roads along the active ocean beach. These modifications change the patterns of wind transport, storm overwash, and salt spray. The initiation of the constructed barrier dune ridge system in the 1930s probably had the greatest impact upon the vegetation and dune systems on the Outer Banks.

The morphology of Jockeys Ridge is controlled by the combined interaction of wind and sediment supply. Since the 1940s, the dune's location and shape appear to be little changed. The dune's elevation, however, has decreased substantially from 138 ft above MSL on 1953 USGS quad map, to 110 ft in 1974, to 87.5 ft in 1995 (pers. comm. 1995, NCDPR). This concerns park managers and local citizens of the Outer Banks who worry that they are losing a key tourist attraction. The State Park and public response reminds us of the 1995 movie set in Wales entitled "The Englishman who went up a hill but came down a mountain". The local mountain of a prideful community suddenly became a hill as a result of a political definition and survey crew's measurement. The incensed town people promptly built their landmark back into a mountain by hand carrying enough rocks to build a rock cairn on top that exceeded the critical height limit. The map was changed and everyone lived happily ever after. If the million plus people who go to the top of Jockey's Ridge annually were given a bucket of sand to transport back to the top, the dune might also return to "mountain" status.

Nags Head Woods Back-Barrier Dune Field

Northwest of Jockeys Ridge is the Nags Head Woods back-barrier dune field with a maritime forest that stabilizes a series of blowout dunes. The dunes are up to 75 feet high with steep slopes that greatly exceed the angle of repose. Their bases are eroded below the water table resulting in abundant fresh water ponds. The high diversity maritime forest was the original location of Old Nags Head Village complete with its own water supply, farms, sawmills, schools, churches, and estuarine fishery. Today, most of Nags Head Woods is preserved as a natural area by The Nature Conservancy.

Run Hill and Wright Brothers Dunes

At the north end of Nags Head Woods is another active dune field known as Run Hill. Run Hill is a spectacular, back-barrier dune system that is over-riding the maritime forest and estuarine marsh system. Large portions of this dune to the east and north were mined during the 1970s. The remaining dunes developed abundant vegetation that has terminated the natural sand source and changed the wind flow patterns. From the top of Run Hill, you can see the Wright Brothers monument to the north on top of a similar sand dune that was stabilized with grass in the late 1920s.

The Wright brothers took more than 150 well documented photographs of the 11 mile segment of the Outer Banks from Nags Head to Kitty Hawk during the period between 1900-1911. All of these images demonstrate very clearly that the seaward portions of the barrier islands were dominated by storm overwash processes with only a minor cover of salt-tolerant grasses and microbial mats. The general profile of equilibrium for this entire stretch of the coast consisted of very wide and gentle beaches, a low berm crest with small scattered dunes, and a flat back-beach surface that sloped gently towards the sound. The island surfaces had a grass cover with no woody vegetation (shrubs or trees); all maritime forest vegetation was restricted to the back side of the wider portions of the islands, often behind dune fields (Frost, 2000). Active dunes were unvegetated and so differed from the vegetated dunes of Nags Head Woods and the beach ridges of Kitty Hawk Woods. Small fishing shacks were scattered along the beach to house fishing nets and other gear. Only a few houses were located on the beach in the Nags Head area. The water table was close to the surface resulting in extensive standing rain water and a hard packed sand surface that supported microbial mats and allowed vehicular traffic.

10/31/09

<u>STOP 8: KITTY HAWK EROSIONAL HOTSPOT / SHORE OBLIQUE BARS / PALEO-ROANOKE RIVER VALLEY (Fig. 22)</u>

This site is situated directly over the paleo-Roanoke River Valley (Fig. 22b), which incised to a depth of ca. 35 m during the LGM. The valley is backfilled with fluvial, estuarine, baymouth, inlet and barrier island deposits (Mallinson et al., 2005; Culver et al., 2008). Valley-fill sediments crop out on the shoreface directly seaward of the stop, and produce shore-oblique bars (Fig. 22c) that affect wave patterns in the area (McNinch, 2004; Schupp et al., 2006). The high rates of erosion can be directly attributed to the occurrence of this valley in the subsurface.

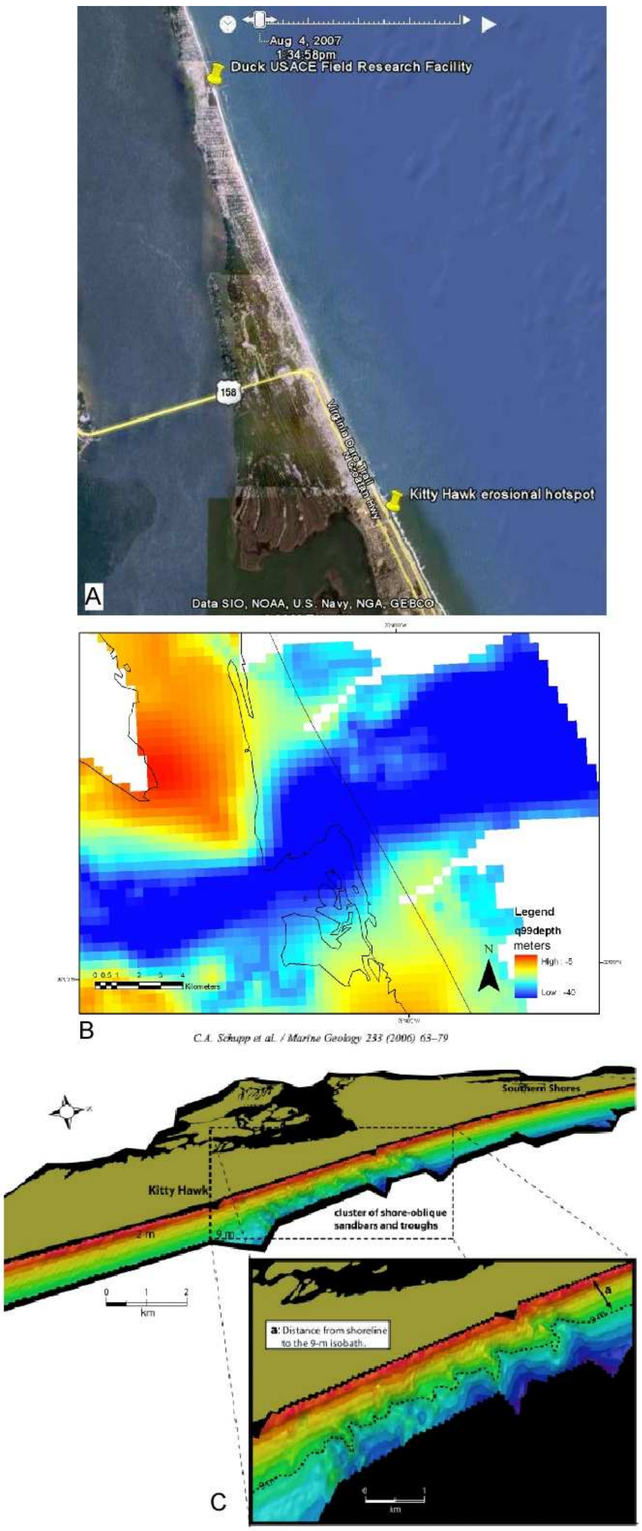

Figure 22. A) Map showing the general location of the erosional hotspot area within Kitty Hawk and Kill Devil Hills. B) The location of the paleo-Roanoke River valley based upon seismic data. C) The location of the shore oblique bars identified along the shoreface (McNinch, 2004).

STOP 9: DUCK PIER FIELD RESEARCH FACILITY (Fig. 23)

The final stop is the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck, NC. We will tour the facility and discuss the importance of shoreface geology and geomorphology in controlling wave energy and coastal erosion.
For more info on the FRF, visit: http://www.frf.usace.army.mil/

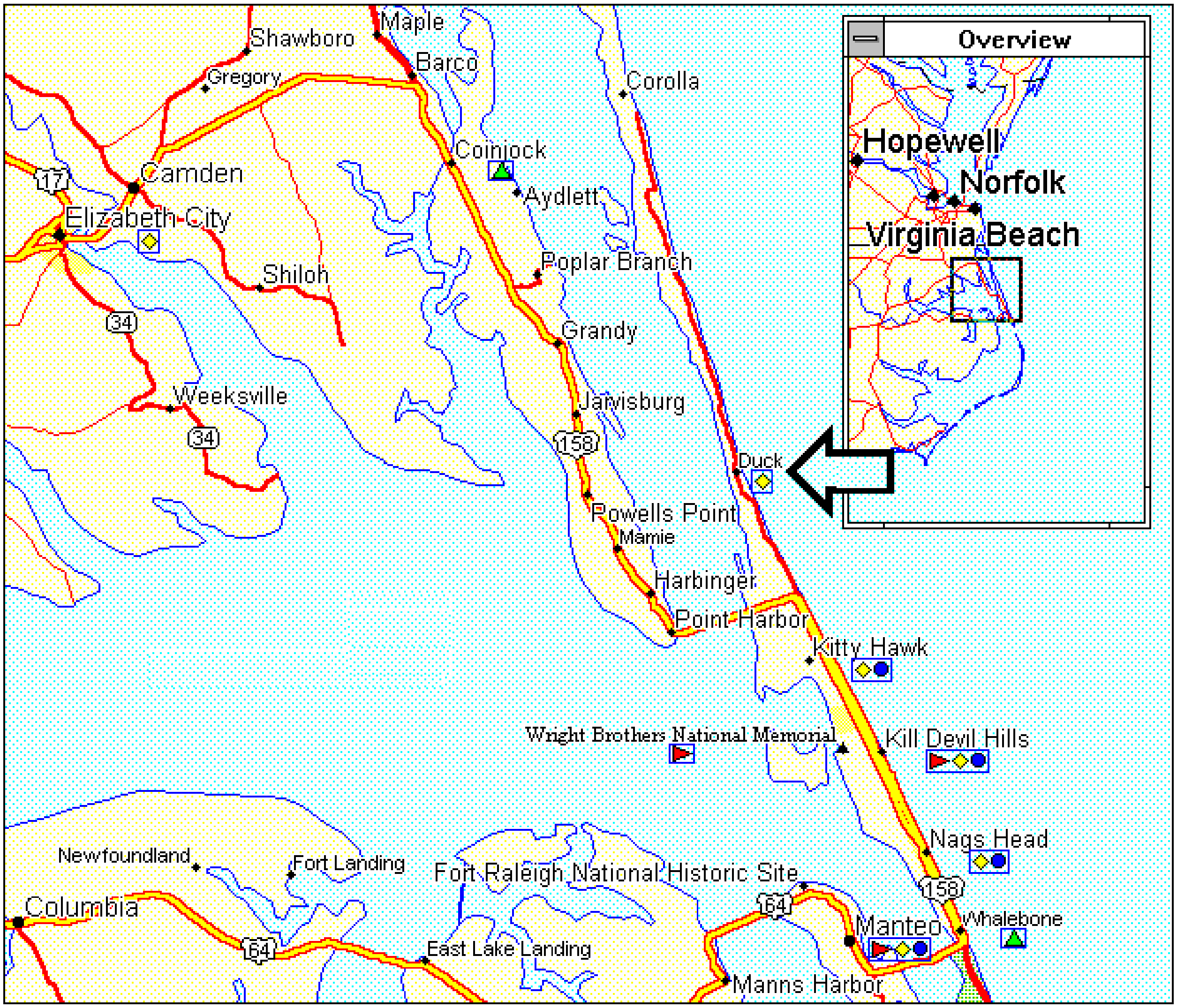

Figure 23. The location of the U.S. Army Corps of Engineers Duck Field Research Facility.

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