The Terminal Groin Controversy

William J. Cleary
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Terminal Groins

In their 2009 article Pilkey and Neal contend that if Figure Eight Island is allowed to build their proposed "jetty" North Topsail Beach would soon follow with its own "jetty". They further contend that *the term "terminal groin" is a minomer apparently intended to allay the fears of opponents who are aware of the price paid elsewhere for stabilization of inlets by jetties. "Terminal groin" in textbooks and manuals is defined as the groin at the downdrift end of a groin field.* Certainly any knowledgeable reader is fully aware of the dramatic distinction between a terminal groin and a jetty (see section below for further discussion). They also assert that *the significance of the societal debate centers around that fact that were the jetty allowed, it would be the end of the state's anti-hardening laws. The law allowing the jetty to be constructed passed the state senate but failed to pass the house. Stay tuned.*

The facts are a bit different than that mentioned above. During the 2007 NC Legislative Session the, a bill was passed by the NC Senate that would allow the construction of a terminal groin as a "pilot" project at an unspecified inlet. The bill stated the groin installation would be evaluated in an Environmental Impact Statement and must be approved by the NC Coastal Resources Commission (CRC). The bill was moved to the NC House of Representatives but no action was taken before the 2008 Legislative Session ended. A similar bill (SB 832) was introduced in the NC Senate, but the bill did not pass the senate. However, House Bill 709 was signed into law that directed the CRC to conduct a feasibility investigation to determine if the use of terminal groins would be an effective erosion control structure near inlets. The CRC and the NC DCM sponsored report was completed in the Spring of 2010. The study focused on the two existing terminal groins in North Carolina (Beaufort Inlet and Oregon Inlet) and three terminal groin sites in Florida. The CRC report determined that there was no conclusive evidence to support or prohibit the installation of terminal groins.

In 2011 Senate bill 110 was passed by the legislature after several compromises. The bill became law without the governor's signature in June 2011. The SB 110 would allow the

CRC to permit four terminal groins near inlets. In order for the permit to be granted the applicant needed to provide the CRC poof 1) that the shoreline is imminently threatened by erosion and other mitigation solutions are impractical, 2) that the EIS met certain requirements, 3) that notification of property owners and local governments that could be affected by the project had occurred, 4) that a plan is in place for the construction and maintenance of a terminal groin by a professional engineer, and a management plan has been formulated for the inlet and adjacent shoreline that includes monitoring the project impacts, provides mitigation measure and plans to remove the terminal groin if the negative impacts cannot be mitigated, 5) of financial assurance to undertake the project and tasks stated above.

As of the date of this review (24 September 2014), there were four sites (inlets) where the local towns have plans for a terminal groin. All four are nearing the completion of their EIS. Several are close to submission of a draft EIS. The four communities are Figure Eight Island, Bald Head Island, Holden Beach and Ocean Isle. North Topsail Beach has chosen not to pursue the terminal groin option as a management tool for the mitigation of inlet-related shoreline erosion.

Terminal groins are constructed at the end of sediment cells (littoral cells) for the purpose of mitigating erosion and conserving sand along the terminus of a barrier (Fig. 1 A and B). They extend into the nearshore zone (surf zone) and interrupt the longshore sand transport. They are usually constructed on the downdrift end of a barrier (updrift margin of an inlet). However, because sand enters the inlet throat along both inlet margins due to wave refraction, they can be placed on the downdrift margin of the inlet as well (Fig.2). In the case of Figure Eight Island, the focus of most media attention, the terminal groin will be constructed on the downdrift margin of the inlet or the updrift end of the barrier island. The groin will extend seaward of the HTL a distance of ~ 180 ft and upon completion, beach fill will be added so that the groin does not impound sand from the local reservoir (Fig. 3). When the fillet is full to its capacity, sand is transported around or over the terminal groin into the inlet such as that depicted in Figure 1A and B for the terminal groins at both Beaufort Inlet and Oregon Inlet.

Although a terminal groin has the capability to impound sand they are very dissimilar to a jetty (Fig. 1C and D). A jetty or jetties are constructed as part of a navigation project at an inlet margin with the intention of preventing sand from entering an inlet and thereby helping to maintain navigation depths in the main channel. The jetties at Masonboro Inlet, NC (Figs. 1C and 3) and Murrell's Inlet, SC (Fig. 1D) are thousands of feet long and in almost all cases lead to erosion along the adjacent barriers. Jetties confine the ebb flow within the deepened inlet throat and eventually lead to a steepened and elongated ebb-tidal delta that extends well into deep water. In the case of Masonboro Inlet natural by-passing of sand to the downdrift barrier has stopped. The fillet in the lee of the southern rock jetty has been trapping sand since its construction in 1981. Sand moving northward along Masonboro Island has been impounded by the long rock jetty that has resulted in significant progradation of the northern portion of the island (Fig. 1C).

There has been a heated debate about the impact of the proposed terminal groins on the adjacent beaches as well their impact on the barrier where it is constructed. Most of North Carolina coastal scientists believe that terminal groins will harm the coast downdrift and place property at risk. The group further asserts that the structures at the end of an island near an inlet will cause negative impacts to an adjacent island. In the case of the proposed groin at Rich Inlet on the northern end of Figure Eight Island (F8I), the negative effects would occur on Hutaff Island located to the northeast. In addition, these scientists, as well as the environmental groups, believe that the proposed structures on F8I as well as Ocean Isle (OI), that are on the downdrift side of inlet, will block the flow of sand onto the island where the structure is located and will cause increased oceanfront erosion.

The group spearheading this opposition to terminal groins included Dr. Orrin H. Pilkey, Dr. Robert Young and Dr. Stanley Riggs among others. These individuals maintained that the beaches in vicinity of existing terminal groins at both Beaufort Inlet and Oregon Inlet have required huge volumes of beach nourishment for decades. They concluded that the structures at the above inlets had no impact on the stability of the island adjacent to the terminal groin and at worst have caused downdrift erosion that has necessitated massive renourishment. They provided no data to substantiate their claim. In the case of the Oregon Inlet terminal groin they contend that Dr. Stanley Riggs has published detailed analyses that indicated the terminal groin at Oregon Inlet, located at the northern end of Pea Island, has impacted the stability of Highway 12 on the Outer Banks. The impact has resulted in constant maintenance of NC Highway 12.

It is difficult to understand how coastal scientists can believe that shoreline erosion along Atlantic Beach (Beaufort Inlet) and Pea Island (Oregon Inlet) are related to the terminal groins. In both areas the adjacent inlets have been modified extensively through long-term channel maintenance (dredging and disposal). In addition, Pea Island is a storm-dominated barrier where shoreline change is rapid and ever changing due to their impacts. The information that follows are overviews of the variables, both natural and human-induced, that influence the oceanfront shoreline changes adjacent to the two existing terminal groins at Beaufort Inlet and Oregon Inlet.

Beaufort Inlet and Fort Macon Terminal Groin

Beaufort Inlet (Figs. 4 and 5) located between Bogue Banks on the West and Shackelford Banks on the East. Fort Macon situated on the eastern end of Bogue Banks was constructed in early 19th century and was acquired by the State of North Carolina in 1926. The terminal groin built to protect the fort was completed in 1965 (Figs. 1B, 5 and 6). Between 1965 and 1970, ~ 200,000 cy of sand was placed along the updrift (west) shoreline within 1.3 miles of the groin. Additional nourishment events have occurred since 1970, two of which are depicted in Figure 7. Bypassing of sand beyond the groin has been occurring since 1968 and continues to date (Fig. 6).

Beaufort Inlet was a dynamic inlet whose entrance was constantly changing prior to major modifications. Early 20th century maintenance operations dredged the ship channel to 29 ft and by 1933 the navigation channel was deepened to 30ft. Subsequently it was again deepened to 35 ft by 1960. Presently the navigation control depth is 47 ft. The cumulative impact of over a century of dredging has had a profound negative effect on the shoreline changes along the Bogue Banks shoreline. The eastern end of Bogue Banks was highly progradational from 1851 to 1933 but highly erosional from 1933 to 1946 (Fig. 8). This period marked the large-scale dredging of the navigational channel and significant shape changes of the ebb-tidal delta. Shoreline erosion was the norm between 1946 and 1974 but significantly less than between 1933 and 1946 (Fig. 8). Accretion along the shoreline west of the groin was dominant between 1974 and 1984 while erosion has generally been the norm since 1984.

The above shoreline changes were related to occasional beach fill operations and more importantly the dredging operations involving the inner and outer bar channel. As part of the Morehead City Harbor Federal navigation project the entrance channel was gradually deepened from 20 ft to 30 ft and widened from 300 ft to 400 ft in 1933 and subsequently increased 42 ft deep and 450 ft wide in 1978. In 1994 the bar channel was dredged to its present depth of 47 ft and 450 to 600 ft wide. Since 1970, ~20 million cy of dredged material have been disposed of in the offshore area (ODMDS). Beginning in 1995, some of the dredge material was placed in a nearshore site on the western segment of the ebb-tidal delta (Figs. 9 and 10) under the assumption that the shoaling waves would ultimately transport the sand landward and eventually onshore. Approximately 0.830 million cubic yards of material was placed in the nearshore site (~25 ft) before the site was abandoned in 1997 when it was determined that that site was to deep for shoaling waves to redistribute the sand.

The progressive deepening and widening of the ship channel has led to an increased tidal exchange that resulted in a larger equilibrium cross-sectional area of the entrance channel. Olsen and Associates (2006) demonstrated that since dredging began in 1933 the cross-sectional area of the inlet increased by 1.3 to 1.7 times. The larger tidal prism (67% greater) which should have increased the volume of the equilibrium sized ebb-tidal delta failed to do so due to the extensive dredging that occurred since 1933. In essence the large volume of sand extracted from the inlet system was the primary factor in the depletion of the ebb-tidal delta (Fig. 10), Since large-scale dredging began (1933) the ebb-tidal delta has been depleted of ~ 26.6 million cubic yards of sand. Both lobes of the segmented ebb-tidal delta lost significant volumes of sand. Sediment by-passing has also been impacted by the segmented outer bar. The deep ship channel prohibits the transport of sand around the periphery of the outer bar from one segment to the other. Due to the a combination of the above factors, the western lobe that fronts Bogue Banks (Atlantic Beach) lost 21.6 million cubic yards of sand while the eastern segment that fronts Shaclkleford Banks lost 5.0 millin cubic yards (Fig.10). In brief, more material was dredged from the inlet system than was delivered to it by the longshore transport along its margins.

The increased tidal prism and the resulting tidal flow had a significant impact on the depth and shape of the ebb-tidal delta surface and the wave sheltering effects along the shoreline. The strong ebb tidal flow asymmetry eventually led to an increased transport farther offshore which in turn elongated the shoal extending it into deeper water. The cumulative effects produced an ebb-tidal-delta whose surface (platform) is steep which allowed incident waves to break closer to the oceanfront.

The primary reason erosion is occurring along the eastern end Bogue Banks is not due to the placement of the terminal groin in 1965, but rather the long-term dredging of the ship channel that resulted in a steeper and deeper ebb-tidal delta platform. The steeper gradient of the outer bar has resulted in less attenuation of wave energy particularly during storms and the greater susceptibility for oceanfront erosion.

Oregon Inlet.

Oregon Inlet (Fig. 11) is one of four inlets along the Outer Banks of North Carolina (Fig. 4). The inlet opened during 1846 hurricane and since that time the inlet has migrated ~2.5 miles in southerly direction (Fig.12). The inlet separates Bodie Island to the north and Pea Island to the south. In 1963 the NC DOT constructed the ~2.0 mile long Herbert C. Bonner Bridge (Fig. 12). Within two decades, the migrating inlet threatened the southern terminus of the bridge on Pea Island. In order to mitigate the potential erosion a 3,127ft long rubble mound revetment and terminal groin (Fig. 13A) were constructed (1989-1991) on the northern end of Pea Island.

In the mid 1980s an ebb-tidal delta breaching episode occurred that eventually led to the large-scale spit development along the Bodie Island inlet margin (Fig. 14). Figure 15B-D depicts the abandonment of the former location of the ebb channel and the commencement of spit growth due to the enlarged flood channel along the Bodie Island margin (Fig. 16). Between 1987 and 2002, when the spit reached its southern most extension, the updrift inlet shoreline had shifted southward ~ 3,610 ft (Figs. 14-17B). The surface area of the 2002 spit covered ~8.9 E+06 square feet. The subsea portion of the spit platform contained an undetermined enormous volume of sand that was not by-passed downdrift to Pea Island.

The southerly extension of the Bodie Island spit caused the ebb channel to shift southward, and by 2002, the inlet width narrowed to 1,830 ft (Fig. 12 Insert). The constricted inlet throat led to an increase in the tidal flow velocities, a scouring of the navigation channel and the seaward extension of the ebb channel which in turn promoted the seaward displacement of the platform and apex of the ebb-tidal delta (Figs. 17-18). Figure 17 shows the elongated ebb-tidal delta during the period 2001-2014. During this 13 year period the ebb channel was initially aligned in a near-shore normal alignment (50-55 degrees) but with time assumed a more NNE orientation (~30 degrees). Figure 17A depicts a time when the ebb channel alignment favored progradation along the Pea Island oceanfront shoreline in vicinity of the terminal groin fillet due to the welding of swash bars. With time as the inlet widened and the ebb channel shifted to the northeast, the marginal flood channels assumed more important roles in dictating shoreline erosion (Fig. 17D-F) along both Bodie Island and Pea Island.

Oregon Inlet is situated along a relatively high wave energy storm dominated coast. The dominant direction of wave approach is from the NE quadrant that resulted in a high sediment transport rate in a southerly direction. The annual littoral transport estimates ranged from 0.5 to 1.5 Million cy. Figures 19 and 20 depict ebb-tidal delta configurations and the dominant manner in which breaking waves transport sand around the outer bar periphery. As waves approach the ebb-tidal they refract (bend), and as they break, the wave-induced current transports sand toward the Pea Island shoreline. A portion of the sand volume that is transported toward the southern terminus of the ebb-tidal delta (yellow circle) passes through a zone where the angular approach of the waves drives a portion of the sand in a northerly direction. This zone where the sand moves opposite the regional transport direction is termed the zone of sediment transport reversal.

During the rising tide, flood tidal currents augment the wave-related transport toward the inlet and terminal groin. Figure 19A shows the Pea Island northern shoreline segment prior to the construction of the terminal groin. The nodal point (yellow dot) lies well south of the future location of the terminal groin. Inspection of Figures 16-19 shows that the terminal groin has always been located north of this sediment transport reversal zone and thus, had no impact on the portion of the by-passed sand moving southward of the transport reversal zone. The longshore sediment transport has fed sand to the groin fillet when it was not filled to capacity, and if filled, it was transported beyond the groin and into the inlet. Figure 16 B-C depicts evidence of the incremental filling of the groin fillet while Figures 16 D, 17 and 18 show sand deposition (beach) on the inlet side of the groin.

Erosion along the Pea Island oceanfront shoreline has been the norm for the past century. The migration of the inlet since its opening in 1846 has been a long-term factor in depriving sand from the downdrift Pea Island shoreline. During its southerly migration the inlet has impounded large volumes of sand during spit development as well as through the development of additional lobes of the extensive flood-tidal delta (Fig. 12). Additional factors that are instrumental in the erosion scenario are the numerous extra-tropical and tropical storms that impact this region and the effects related to maintenance dredging of the inner navigation channel and the outer bar channel.

Information from the USACE indicates that the 14 ft control depth of the navigation channel has been exceptionally difficult to maintain due to the large longshore transport.

Therefore, dredging activities have been relatively frequent. Figure 21 depicts the current depths of the navigation channel located west of the bridge while Figure 22 depicts the throat and outer bar channel depths. The throat segment of the channel is significantly deeper (25-47ft) than the 14 ft control depth whereas the 4,000 ft long segment extending seaward from the inlet proper has depths that ranged 26 ft to 14 ft. The remaining 3,000 ft long channel segment, which extends to the edge of the ebb-tidal delta platform, shoals in a seaward direction (10-14 ft).

Figure 14 depicts a map of Oregon Inlet (2007) and a small segment of the enormous flood-tidal delta that has formed in the sound since 1846. This feature represents an enormous sand sink for the littoral transport. Dredging the navigation channel in the area west of the bridge has the potential to increase the tidal prism that in turn can lead to a larger volume of material retained in the ebb-tidal delta. During the period from 1989 to 2010 ~15.7 million cubic yards of sand has been dredged from the interior channel and placed offshore Pea Island. This material tended to be finer grained sand than that from the outer bar channel. Most of the ~ 10.8 million cubic yards of sand extracted by dredging the bar channel (1993-2010) was placed on Pea Island (Fig. 13B-D) south of the terminal groin (Fig. 14 Insert).

The long-term and large-scale dredging of the various channel segments of the system have affected the hydraulics of the inlet, which, in turn, has directly and indirectly affected the natural by-passing of sand to Pea Island. Furthermore, on the occasion when dredging operations cut the channel through the outer bar platform, in effect bisecting the shoal, the wave-induced by-passing of sand to Pea Island temporarily ceased.

The last and perhaps the most important factor that controls the shoreline erosion and morphology of Pea Island are the occurrence and frequency of hurricanes and nor'easters. The extra-tropical storms are more frequent and generally have a longer duration, but are generally less intense that hurricanes. However, there are notable exceptions and include the higher class storms such as The Ash Wednesday Storm (March 1962), The Halloween Storm (October 1991) and The Veteran's Day Storm (September 2009). The cumulative impact of the lower class storms, and there are as many as 25 per year, can be substantial. Nonetheless, hurricanes are the agents of major, far reaching shoreline change. Between 1950 and 2013, 40 tropical storms and hurricanes passed within 75 statute miles of Oregon Inlet. Seventeen of the 21 hurricanes were Category 1 and 2 storms. During the past 13 years (2000-2013), four hurricanes (H1-2) and four tropical storms passed within 75 miles of the inlet. Hurricane Sandy (2012) that had a significant impact on Pea Island passed the Outer Banks more than 340 statute miles offshore.

Figure 23A depicts the erosion related to Hurricane Isabel along the Pea Island shoreline immediately south of the terminal groin fillet. Massive dune erosion occurred along the barrier and where the dune line was destroyed major washover fans extended across Highway 12 well into the marsh. Widespread overwash occurred along the PINWR shoreline testifying to the low elevation of the barrier and the lack of a protecting dune system. The Veteran's Day Storm of 2009 similarly impacted Pea Island but to a lesser degree. Figure 23B shows the effects of the erosion along the fillet of the terminal groin and the new storm-related washover topography. Inspection of the image shows that within several days shoreline recovery was occurring as evidenced by the landward migration of a number of longshore-bars.

Several erosion hot-spots occur along Pea Island where erosion is excessive and overwash is commonplace. One of these is located near Rodanthe (Fig. 24) where a segment of Highway 12 is termed the "S" curve. This road segment has been relocated several times due to the impassability during high water and overwash events. On 27 August 2011 Hurricane Irene a Category 1 storm made landfall near Cape Lookout, NC and produced a 1.9-2.1m storm surge in Pamlico Sound as it tracked northward. These elevated water levels and the associated storm waves breached Pea Island in two places, one along the PINWR and another in the Mirlo Beach area near Rodanthe. Figures 25 and 26B show the latter breach site. Figure 26 depicts the evolution of the breach between March, 2011 and January, 2014.

An examination of the aforementioned figure shows that the breach never truly evolved into a viable inlet despite being open for 1.5+ years. The large quantity of material moving alongshore overwhelmed the apparently very small tidal discharge associated with the narrow and shallow sound side feeder channel that was the focus of the breach (Fig. 26 white arrows). In brief, the scour channel filled in rather quickly. Although the breach closed the roadway remained vulnerable and a result the NC DOT armored the shoreline with large sand bags and eventually workers completed a two-mile long $20 million project (September 2014) that entailed placing ~ 1.7 million cubic yards of sand along the shoreline segment armored with huge sand bags (Fig. 27). The intent of the nourishment project was to buy time with a buffer between the highway and the ocean until a permanent solution was found.

Farther north along the PINWR shoreline Hurricane Irene breached the shoreline in two very closely spaced locations (Fig. 28). The southern breach closed naturally within several months while the northern breach locally known as New Inlet remained opened until late 2013 (Fig. 29). The NC DOT quickly built a temporary steel bridge connecting the two severed segments of Pea Island. Although the breach is closed (as of January 2014), the bridged channel is likely to open again in a major storm. Plans are currently being discussed for a permanent solution.

Despite the fact that Hurricane Sandy (10/27/12) tracked northward ~340 miles offshore the storm had a significant impact on the Pea Island shoreline (Figs. 30 and 31). Figure 30A-D depicts the massive destruction of the post-Irene remaining dunes and the formation of small washover fans extending across Hwy. 12 into the ponds along the PINWR shoreline. The storm waves on top of the elevated water levels lowered the elevation of the backshore area by as much as 11.5 ft and in sites where washover fans developed, the elevation increased by as much as 2.9 ft (Fig. 31).

Researchers at NCSU have been monitoring the shoreline changes along Pea Island to determine the impact of the terminal groin since the early 1990s. Their summary report (Overton et al 2009) for the past 20 years concluded that erosion rates along northern Pea

Island are much less than historical rates (pre-terminal groin) along the 1st four miles of the barrier downdrift of the terminal groin while along the 5th and 6th miles of Pea Island the rates are mostly below the historical rates. These findings would validate the statements that the key factors responsible for the erosion along the northern portion of the Pea Island are storms and the maintenance dredging of Oregon Inlet.

Although storms played a key role in the erosion along the Atlantic Beach shoreline adjacent to Beaufort Inlet their role is magnified when dealing with the erosion along the Pea Island shoreline. The storm-related Pea Island shoreline changes are exacerbated by the sequestration of sand in the Bodie Island spit and in the flood- and ebb-tidal deltas of Oregon Inlet. In addition, the dredging of the bar and the sound side navigation channels as well as the manner of material disposal also directly and indirectly impacted the volume of material by-passed to Pea Island.

Aerial photographs clearly demonstrate that wave-refraction around the ebb-tidal delta (Fig. 32) delivered sand to the Pea Island northern shoreline. Analyses of several scores of historic photographs also validated the premise that the terminal groin does not interfere with sand by-passing to Pea Island. The terminal groin located at the inlet's southern margin is located far to the north of the zone of sediment transport reversal. While this zone does shift, in accordance with the outer bar's configuration, it never migrated closer than 2,500 ft south of the terminal groin. The most important impact the terminal has had on the PINWR shoreline has been the stabilization of the southern margin of the inlet. If the groin were not in place the inlet would have continued its southward migration at the expense of Pea Island. Sand would have been lost due to the sequestration in the flood-tidal delta thereby lessening sand delivery to this storm-dominated barrier. In brief, the Oregon Inlet terminal groin has not had a negative effect on the adjacent shoreline but rather a positive effect in stabilization of a once eroding reach of shoreline along the northern portion of Pea Island (Fig. 32).

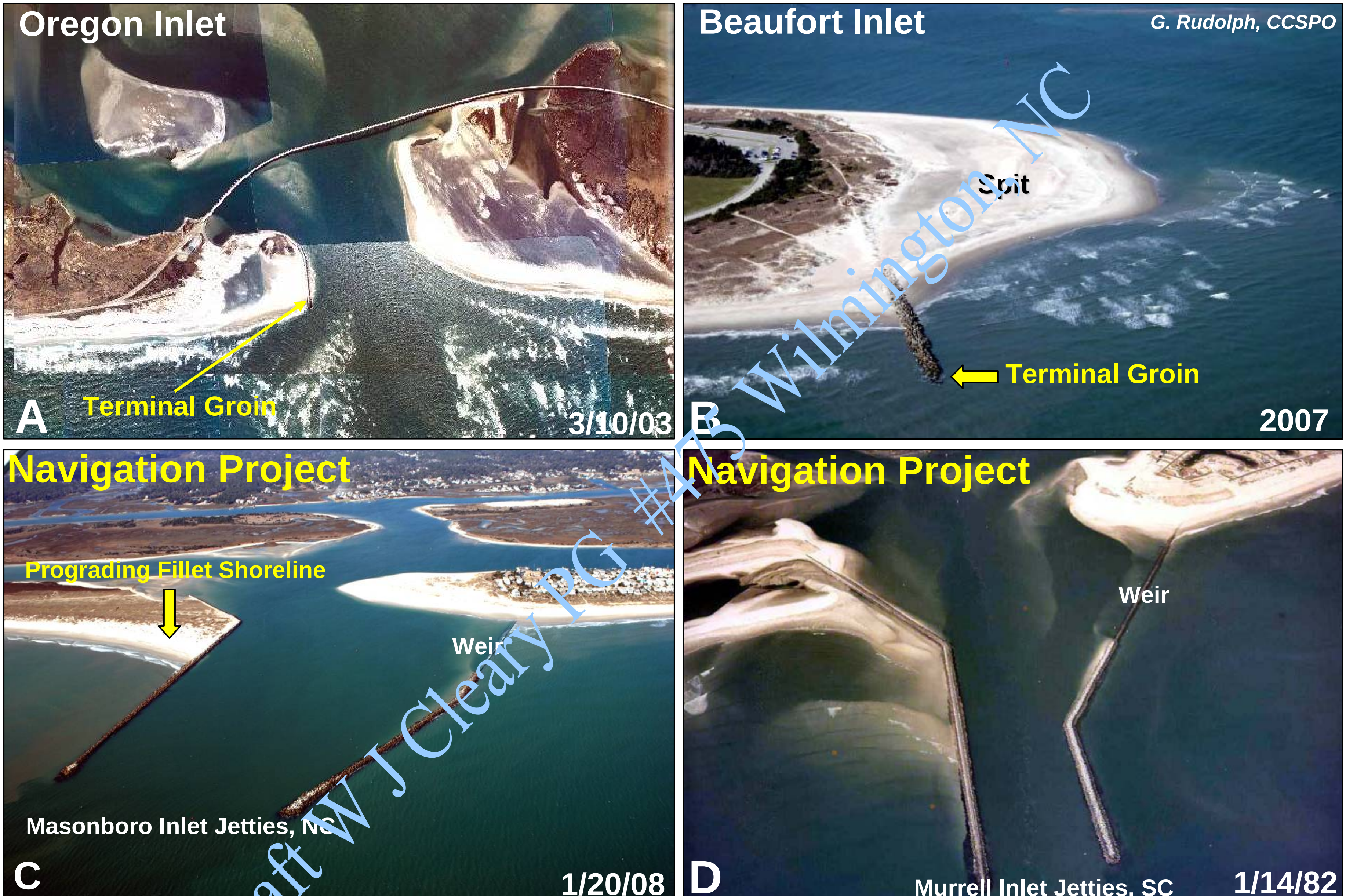

Figure 1. Aerial photographs depicting terminal groins and jetties. A. Vertical photograph (3/10/03) of Oregon Inlet and the terminal groin on the downdrift margin. B. Oblique photograph (2007) depicting the terminal groin at Beaufort Inlet. Note the location of Fort Macon. C. Oblique aerial photograph (1/20/08) depicting the dual jetties at Masonboro Inlet, NC. D. Vertical photograph (1/14/82) depicting the dual jetties at Murrell's Inlet, SC. The jetties imaged in C. and D. were built as part of navigation projects. The jetties confine the ebb flow leading to a steepened and elongated ebb-tidal delta that extends into deep water.Note no waves are breaking in vicinity of the structures. Note also in "C" that the south jetty fillet's shoreline has prograded while in "D" the newly constructed rock jetty is capturing sand.

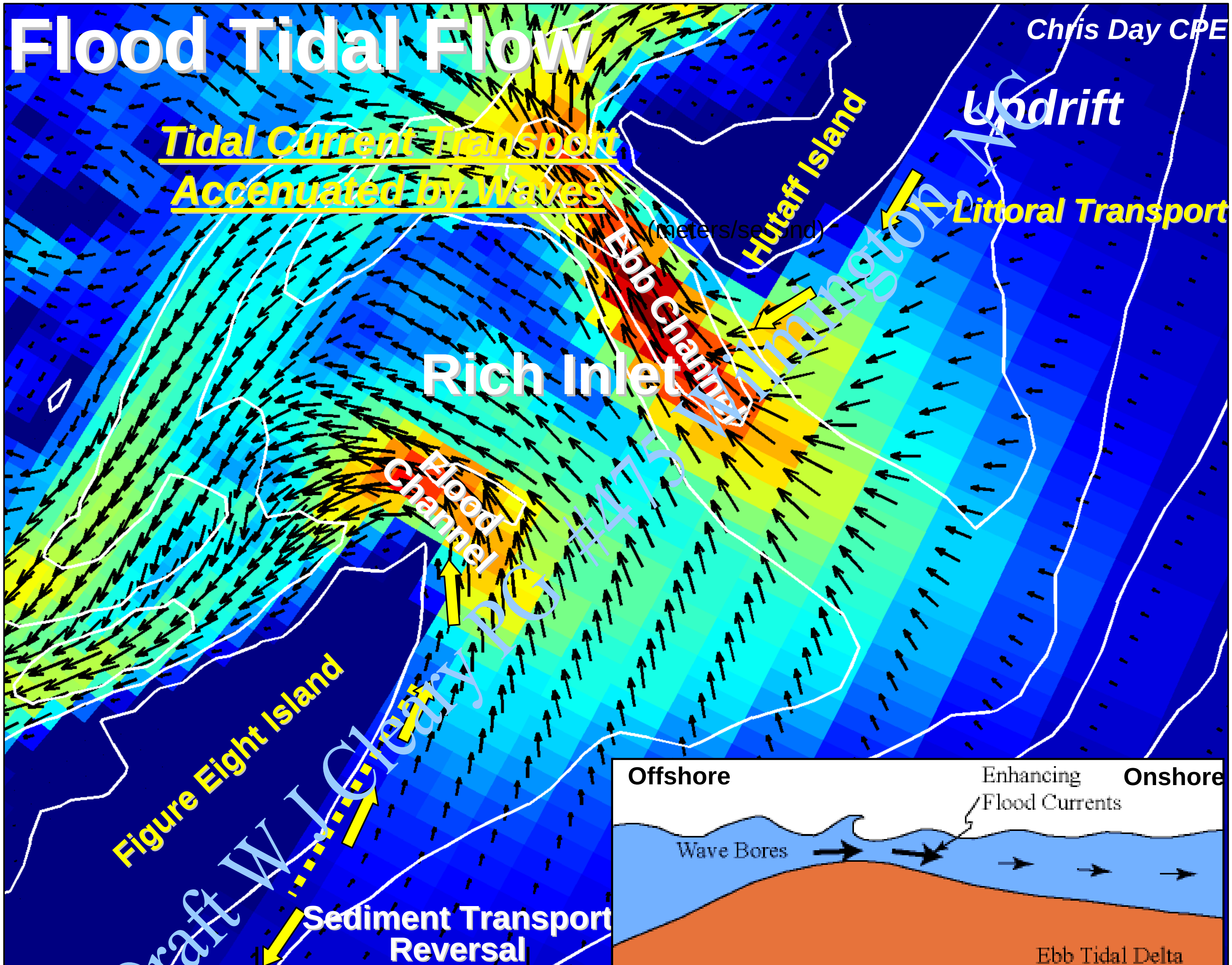

Figure 2. Map depicting the flood-tidal flow at Rich Inlet (2005) modified after C. Day CPE. Note that along the F8I oceanfront downdrift of the inlet (bottom left) the tidal flow becomes negligible and ultimately flow is directed away from the inlet. As waves approach the ebb delta from the upper right of the image refraction occurs, ultimately setting up a zone of sediment transport reversal. In essence, the wave-generated current set up by breaking waves augments the tidal flow (Insert). On the F8I oceanfront sand is transported toward (NE) the inlet along a portion of the shoreline fronted by the ebb delta while along the remaining shoreline incident waves transport sand to the southwest.

Figure 3. Aerial photograph (7/2009) depicting the dual jetties at Masonboro Inlet, NC. The jetties imaged were built as part of a navigation project. The red colored line located near the landward terminus of the weir-portion of the north jetty depicts the distance the proposed terminal groin at Rich Inlet extends seaward of the HTL.

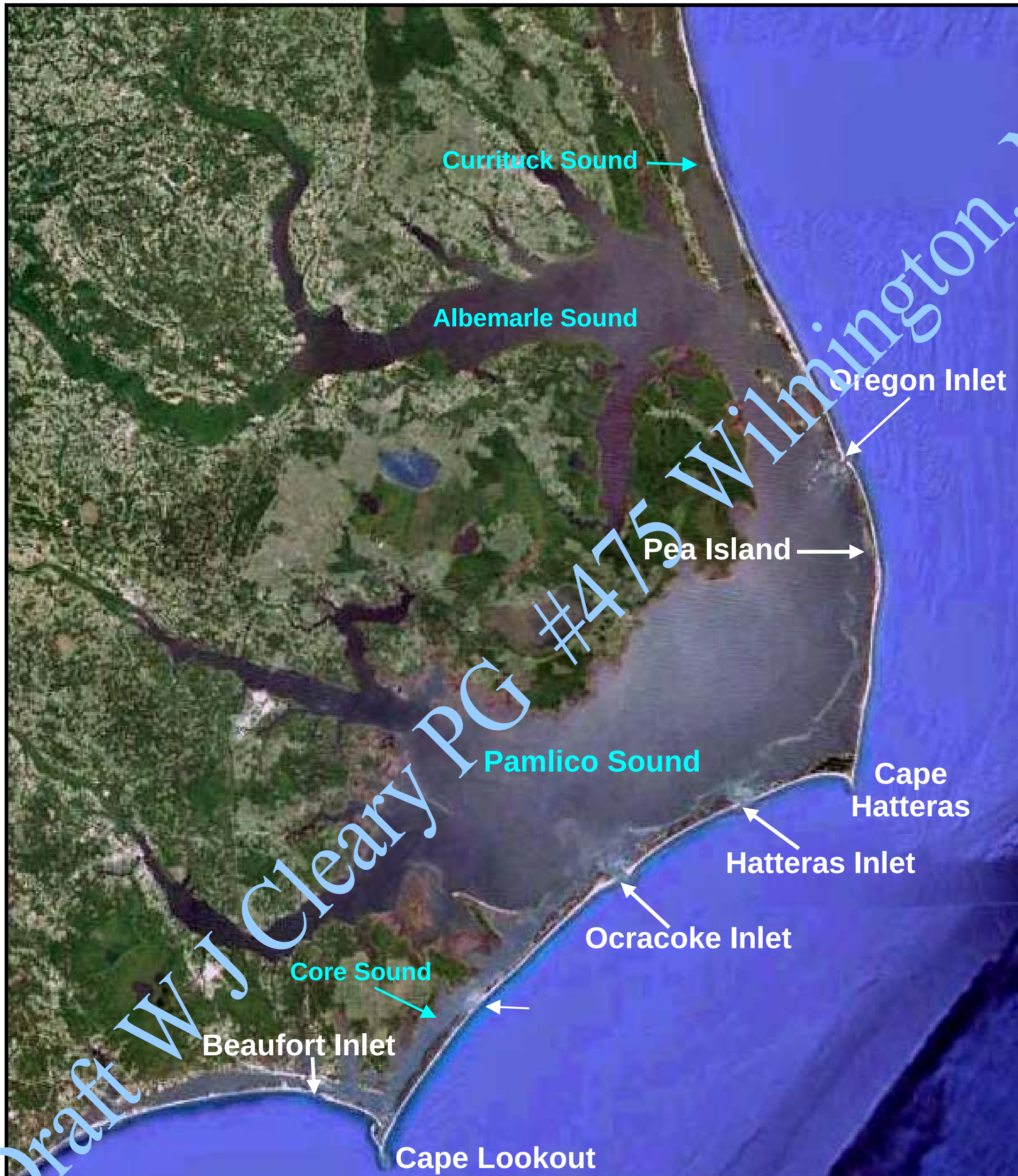

Figure 4. Satellite image of northeastern NC showing major inlets and capes.

Figure 5. Aerial photograph (7/2009) of Beaufort Inlet, NC depicting the adjacent barriers and the location of the terminal groin on the western margin of the inlet. Note that incident waves approaching and crossing the outer bar are not breaking due to the water depth in the nearshore area over the surface of the ebb-tidal delta. The longshore transport direction is from west to east along Atlantic Beach.

Figure 6. Views of the Beaufort Inlet terminal groin that was constructed in 1965. A. Seaward view (3/16/06) of the groin and the inlet margin beach. The terminal groin controls sand loss due to wave-induced and tidal currents. B. Inlet view (3/16/06)of terminal groin depicting sand movement over and around structure ultimately forming a beach. C. Vertical photo (7/09) the terminal groin and the beach inside the inlet. THe presence of the beach indicates that sand is moving around structure

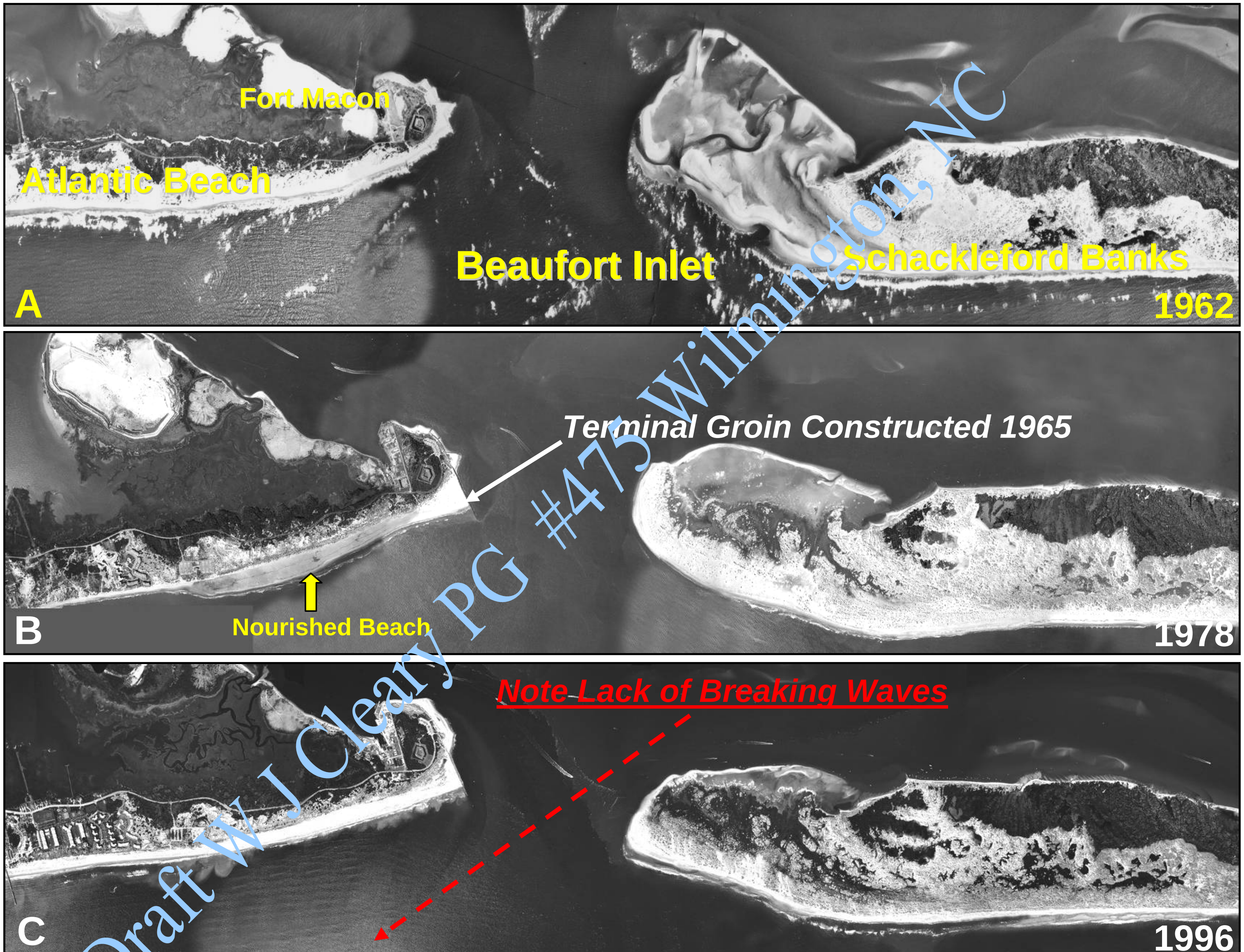

Figure 7. Aerial photographs of Beaufort Inlet. Note the location of Fort Macon. A. Aerial photograph (1962) of Beaufort Inlet. B. Vertical photograph (1978) depicting the terminal groin on the western margin of the inlet seaward of Fort Macon. Note the recently nourished beach along Atlantic Beach. C. Aerial photograph (1996) of Beaufort Inlet. Note the lack of breaking waves across the ebb-tidal delta due to the deepened and steepened platform.

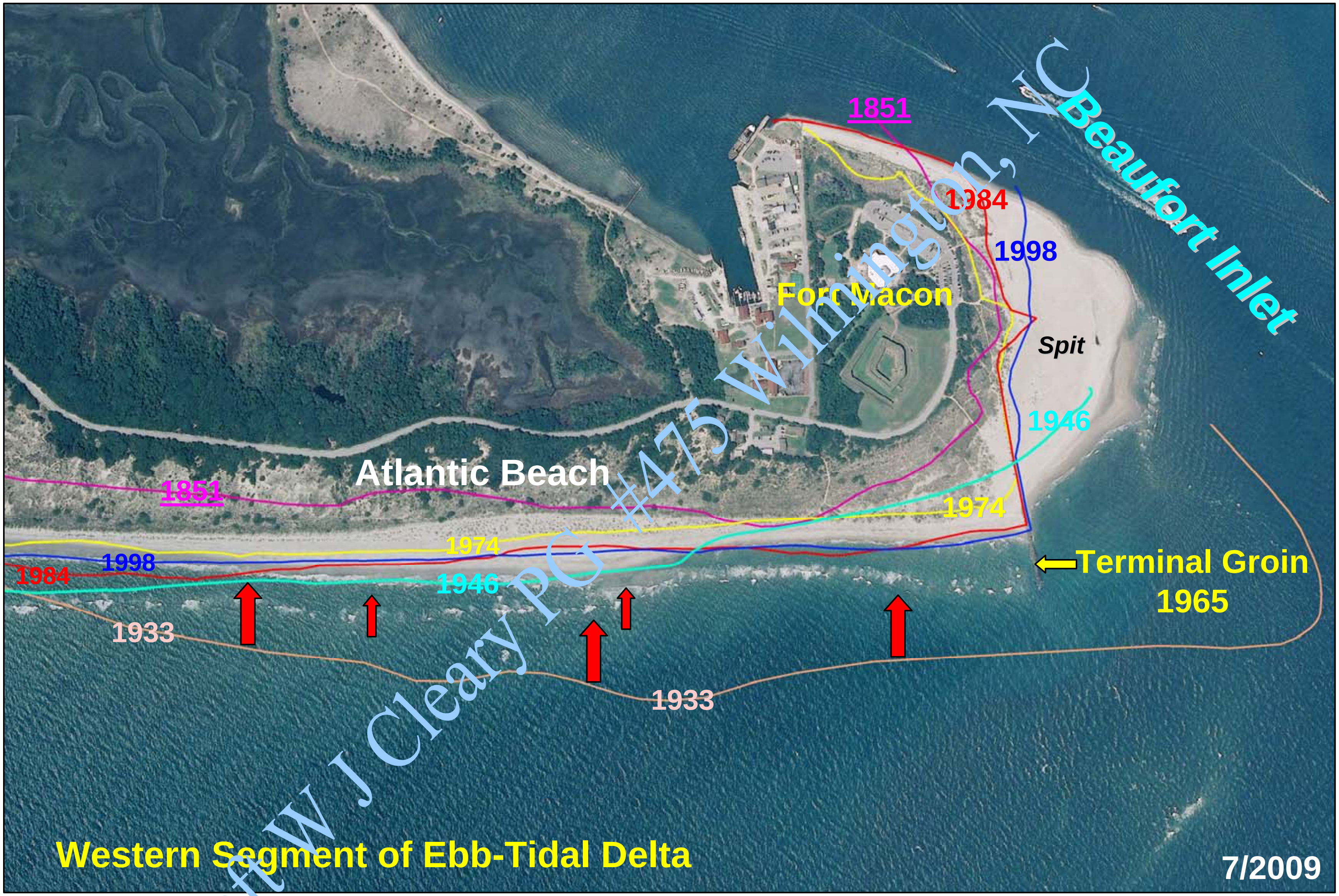

Figure 8. Map depicting selected historic shoreline positions along the western margin of Beaufort inlet. Note the degree of shoreline progradation between 1851 and 1933 followed by shoreline retreat from 1933 to 1946, the period when channel maintenance operations began and have continued to date. Large spit on inlet side of terminal groin indicates that sand by-passing has occurred

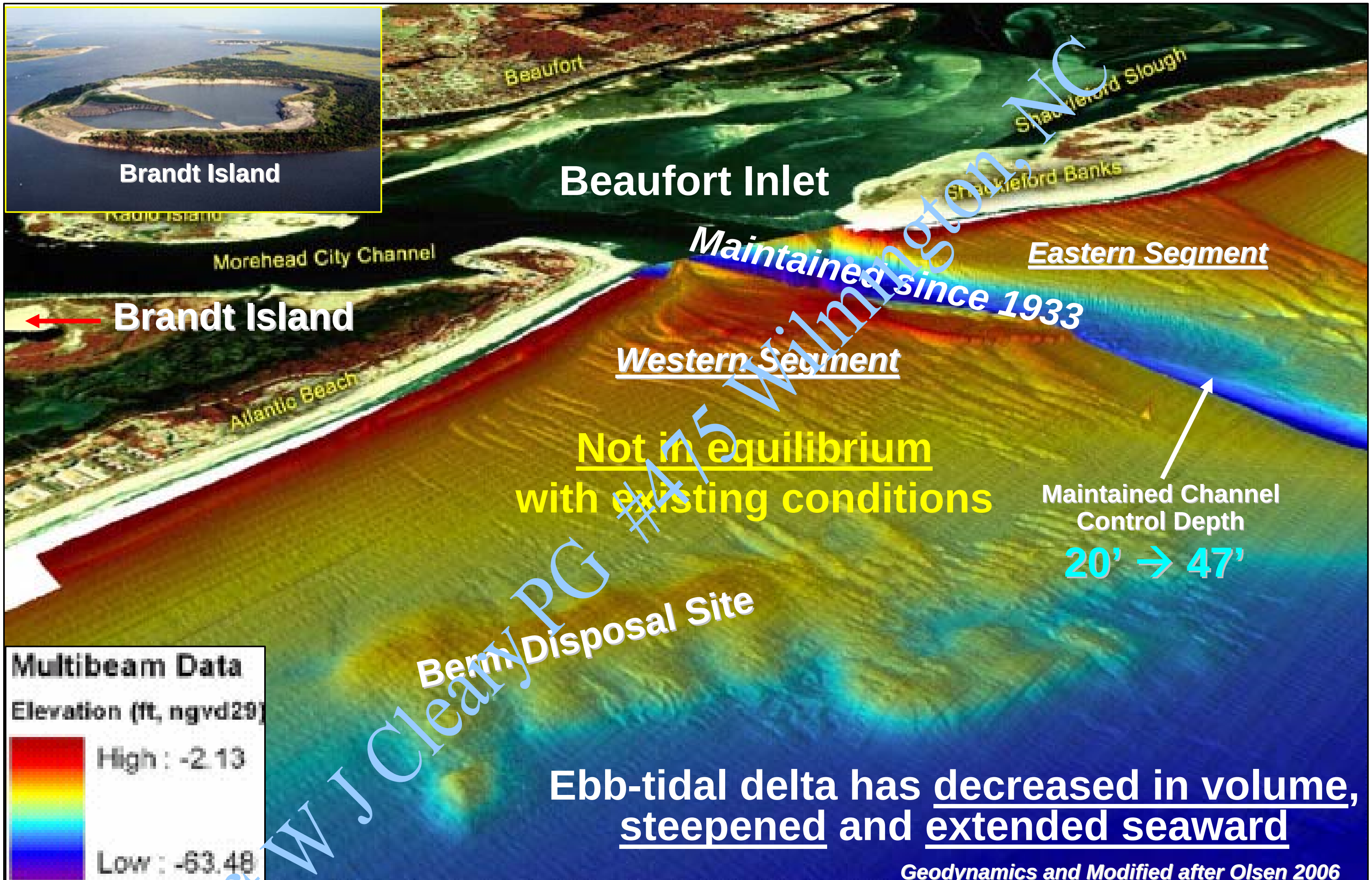

Figure 9. Digital elevation model (DEM) depicting the dredge disposal site (ODMDS) used in maintaining the navigation channels for Morehead City and Beaufort Inlet. The depth of ship channel (ebb-channel) has been dredged extensively since 1933 and as a consequence the ebb-tidal delta (segment sand volumes) is not in equilibrium with the inlet conditions (Ac and Tp).

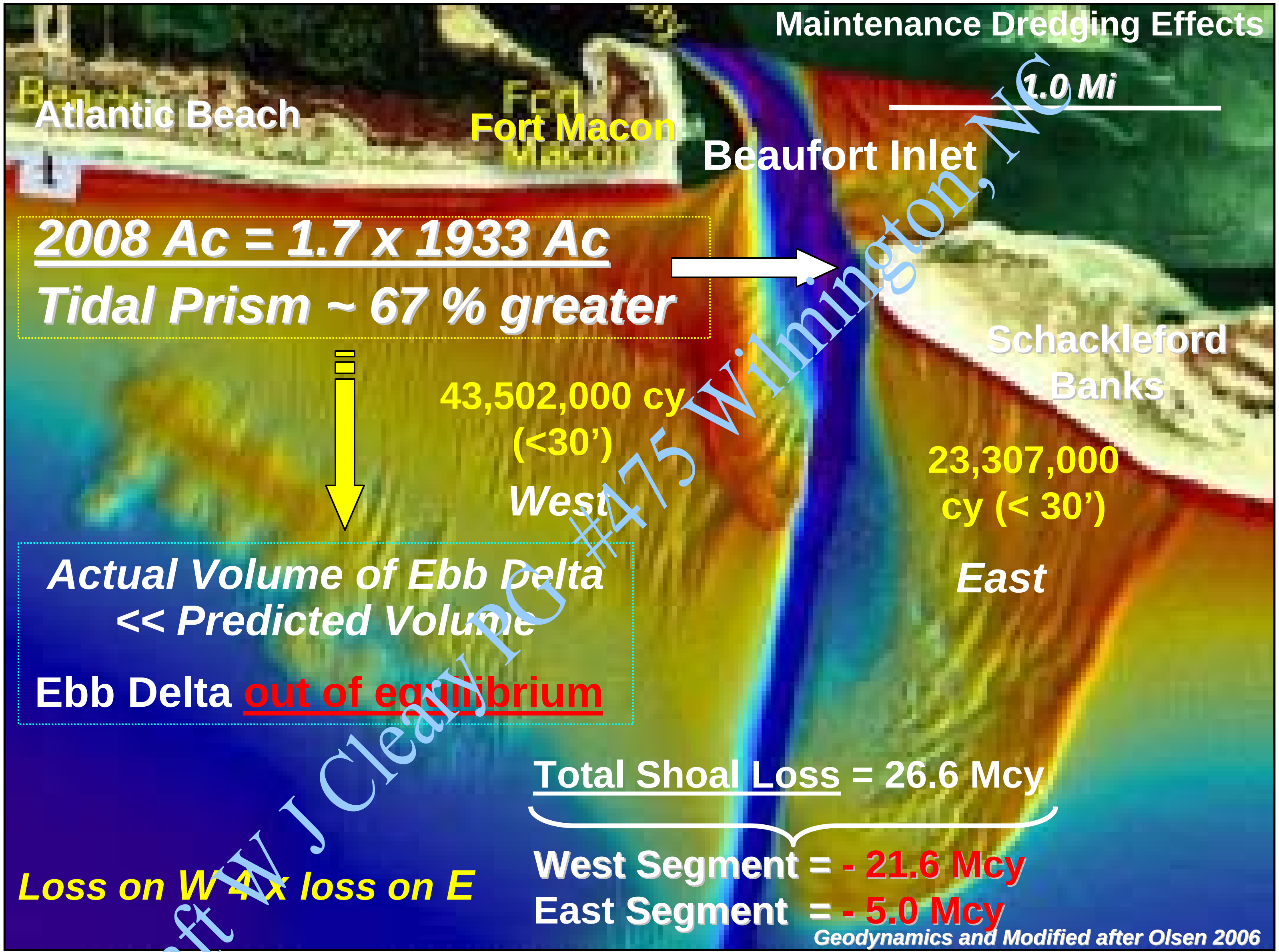

Figure 10. Digital elevation model (DEM) depicting the ebb-tidal delta (east and west segments), the deep ship channel and the dredge disposal site (ODMDS) for Beaufort Inlet. The ship channel (ebb-channel) has been dredged extensively since 1933 and is presently maintained to a depth of 45 ft. No sand by-passing occurs. The channel cross-sectional area (Ac) in 2008 was 1.7 times greater than the 1933 Ac and as result the sand volume of the 2008 ebb-tidal delta should be 67 % greater than it was in 1933. In fact it is significantly less and therefore it is not in equilibrium with the inlet conditions (Ac and Tp). The volume difference is attributed to the maintenance channel dredging and not the terminal groin.

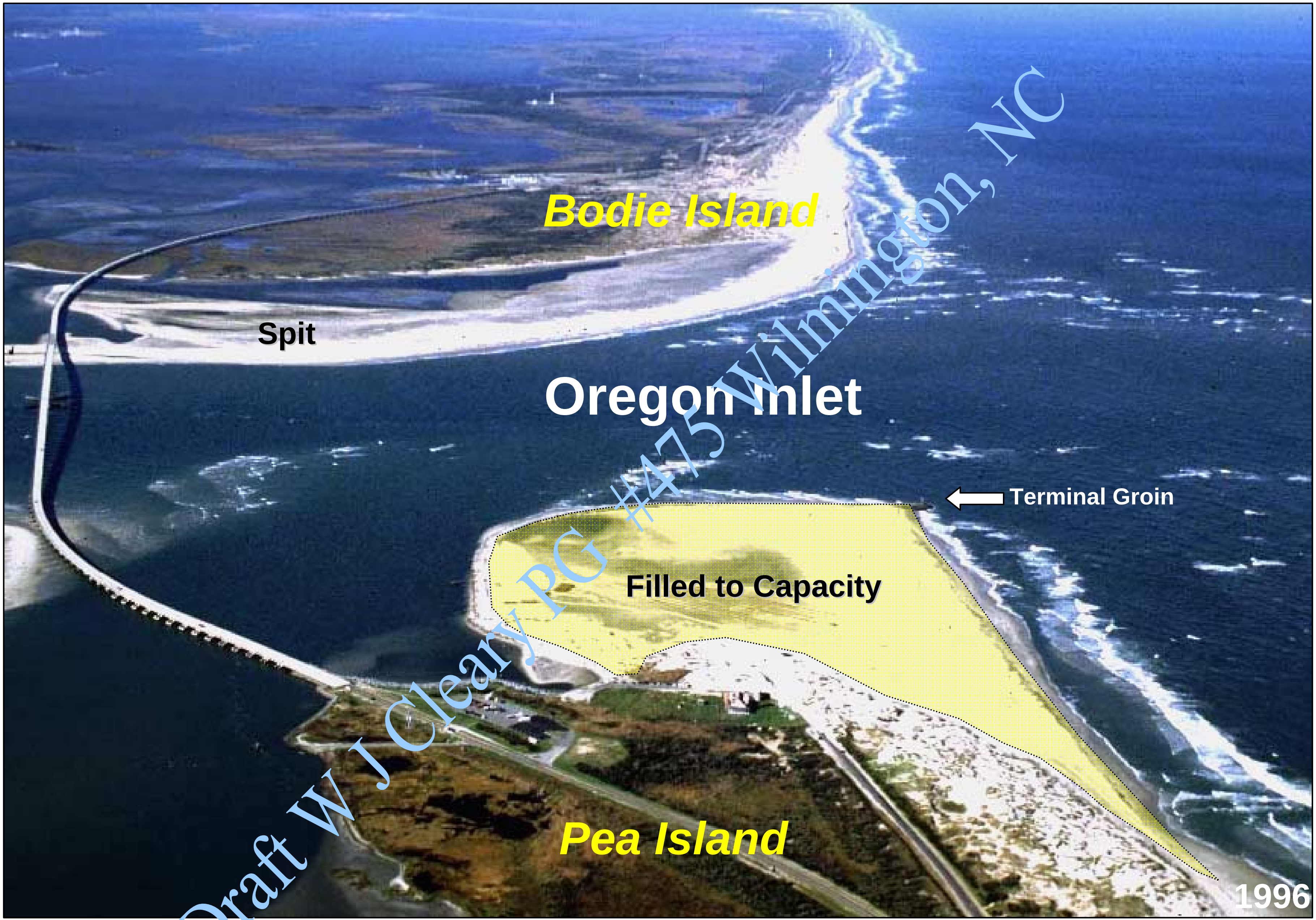

Figure 11. Oblique aerial photograph (undated 1996) of Oregon Inlet depicting the terminal groin and groin fillet.

	Width Ft
1949	3019
1980	3928
1997	2927
1998	2795
2002	2098
2004	2445
2006	2977
2007	2975
2008	3295
2009	3025

Figure 12 Map (2009) aerial photograph of Oregon Inlet depicting positions of selected historic shorelines. The insert lists the width of the inlet between 1949 and 2009. The terminal groin has halted inlet migration. The enormous flood-tidal delta is a sand sink for the littoral transport. The navigation channel and the bar channel are evident. Note the orientation of the elongated ebb-tidal delta and the location of where it merges with Pea Island. The terminal groin is located ~2,750 ft to the northwest of this nodal point cannot interfere (block) sand by-passing the inlet.

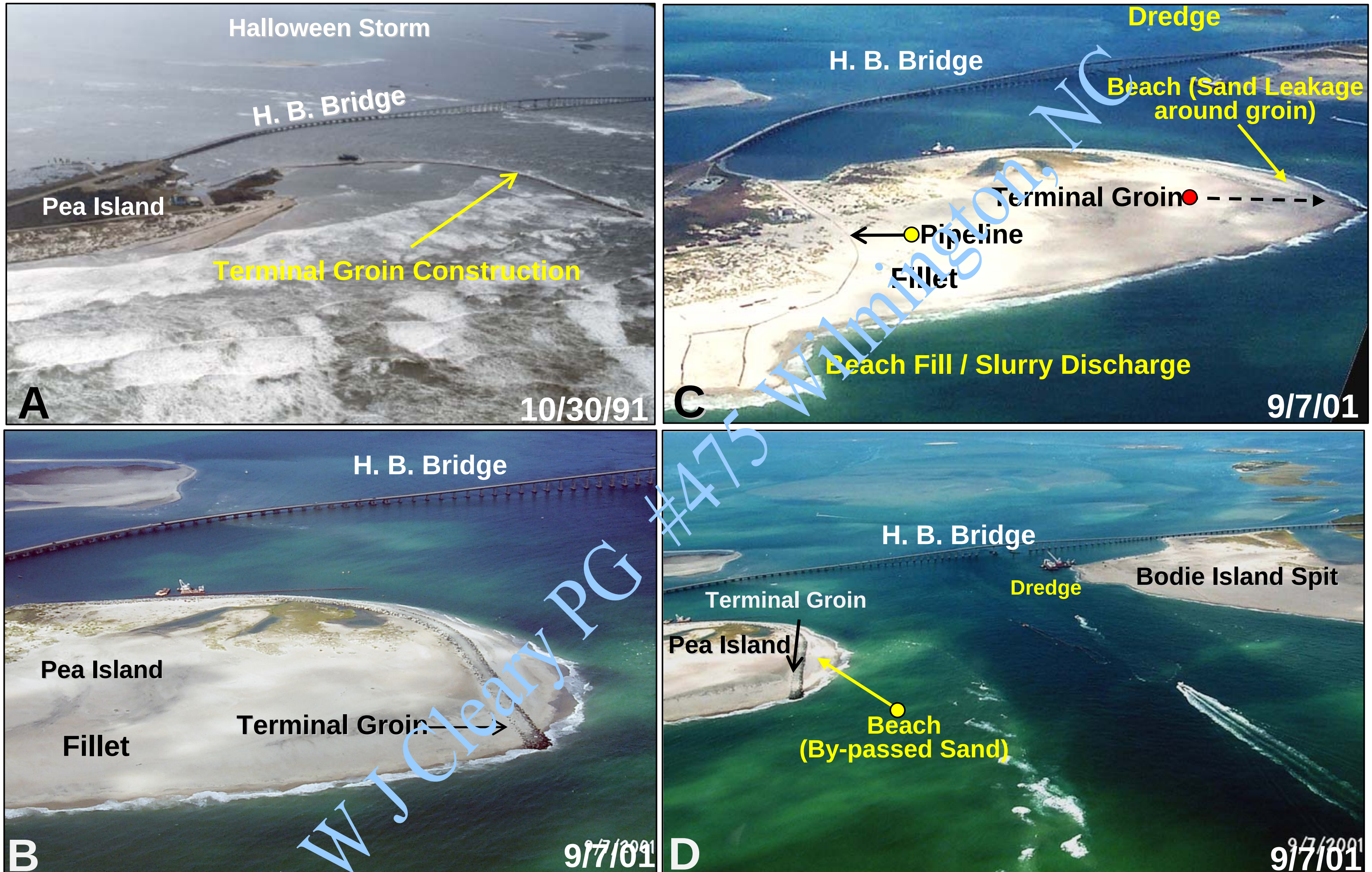

Figure 13. Oblique aerial photographs of the Oregon Inlet terminal groin (courtesy of Bill Birkemeier [USACE FRF]). A. Landward view (10/30/91) of terminal groin construction in the aftermath of Halloween Storm. Compare with "B". B. Landward view (9/7/01) of terminal groin, beach on inlet side of groin and the fillet filled to capacity. C. Landward view (9/7/01) of terminal groin, the beach along the inlet margin and dredge material placement along Pea Island shoreline near nodal point. D. Landward view (9/7/01) of groin, ebb channel and beach along inlet margin. Note the narrowed inlet due to the encroachment of the Bodie Island spit.

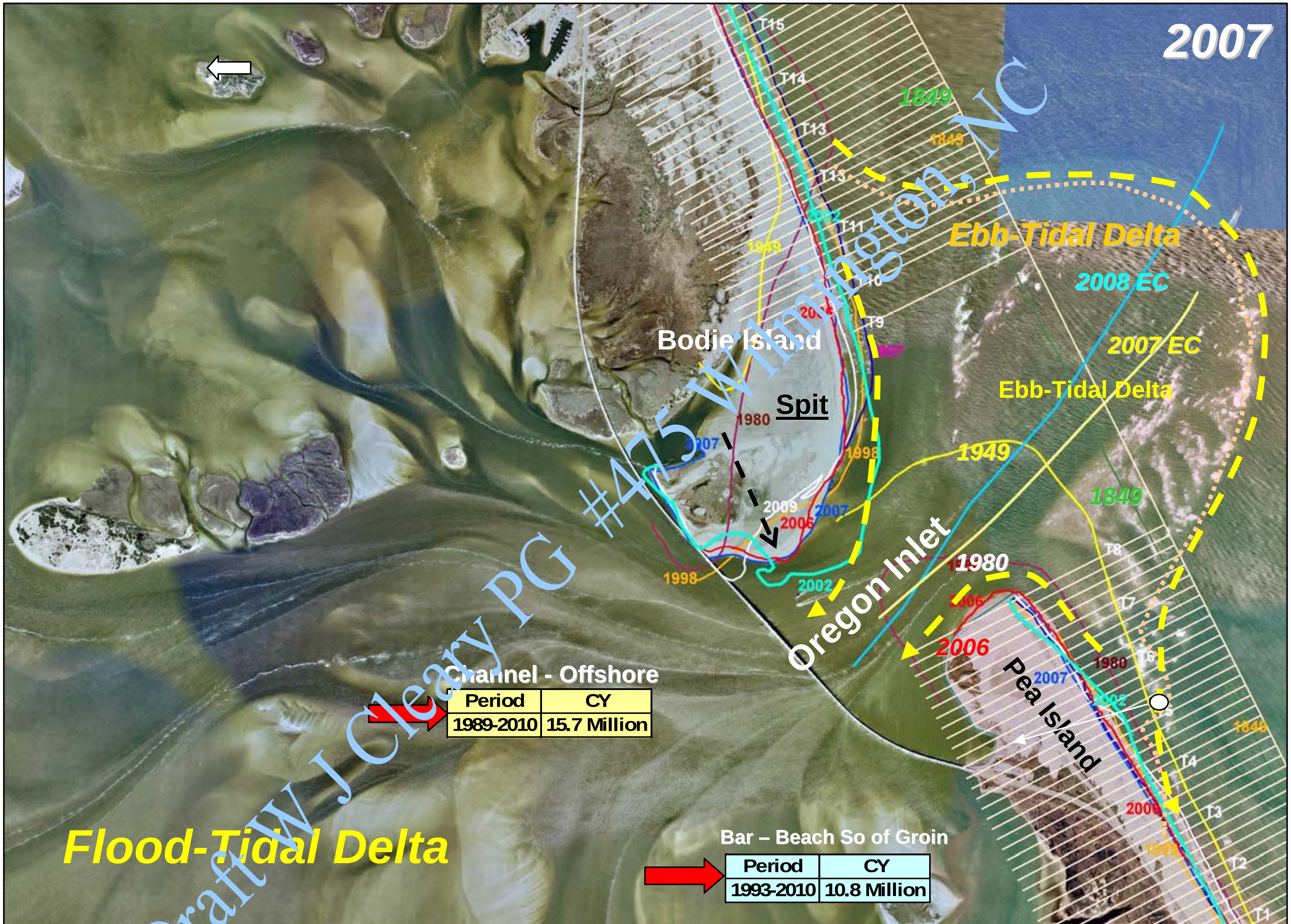

Figure 14. Map with 2007 aerial photograph of Oregon Inlet depicting the positions of selected historic shorelines. The Bodie Island spit began to rapidly prograde southward in 1987 and reached its maximum extent in 2002 The terminal groin halted inlet migration thus, the channel x-section changed leading to increased a channel efficiency, tidal flow velocities and eventually an elongated ebb-tidal delta. The small inserts (red block arrows) lists the volume of sand dredged from various channel segments and the disposal locations.

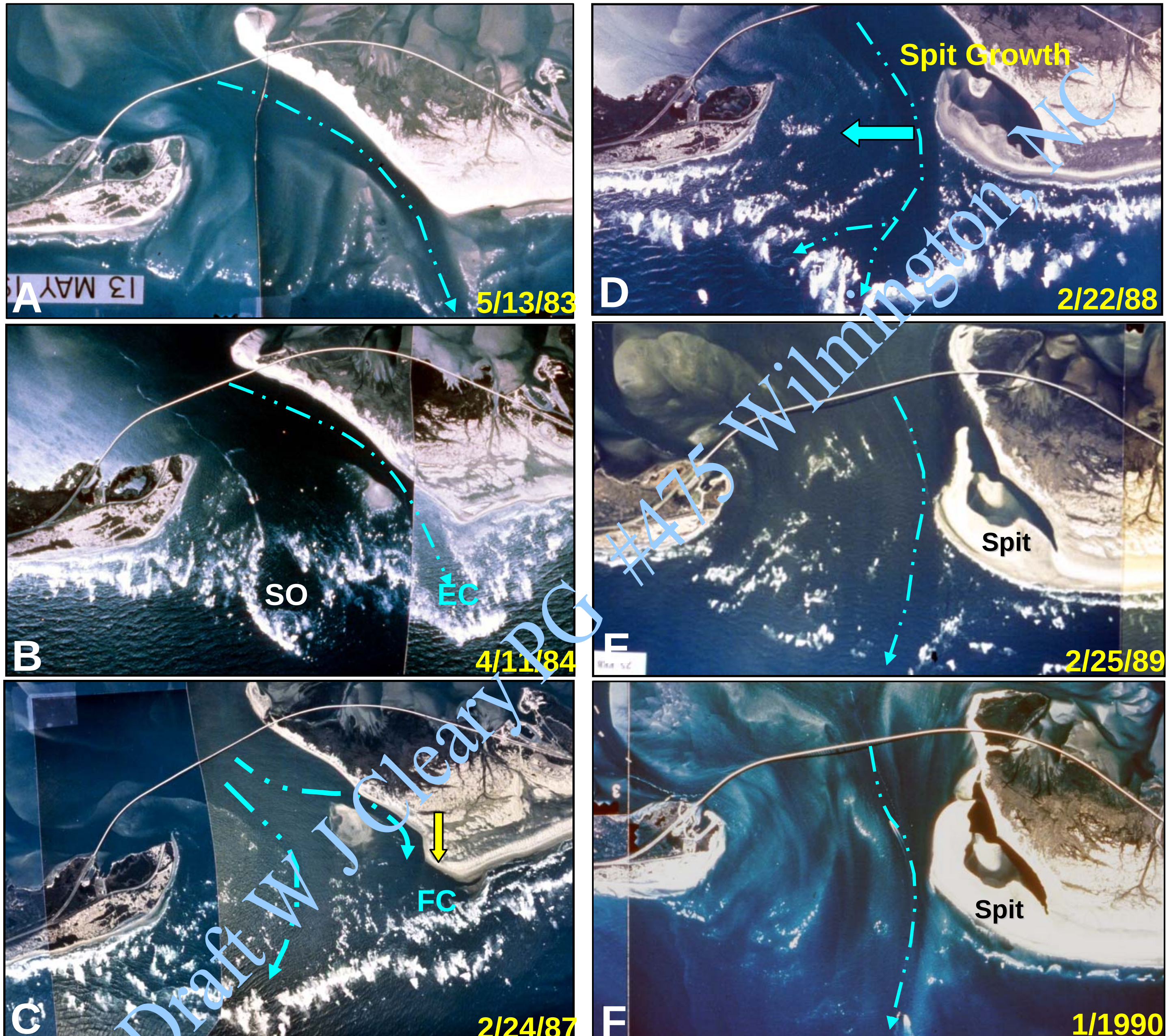

Figure 15. Aerial photographs of Oregon Inlet (ORI) 1983 to 1990. A. View of ORI (5/13/83) depicting the ebb channel along Bodie Is. B. View (4/11/84) of ebb delta breach (SO). C. View (2/4/87) of ebb channel in mid-throat position. Incipient spit on Bodie Is. Margin. D. View @2/22/88) of spit growth and inlet narrowing. E. View(2/25/89) and F. View (1/1990) depict continued spit development.

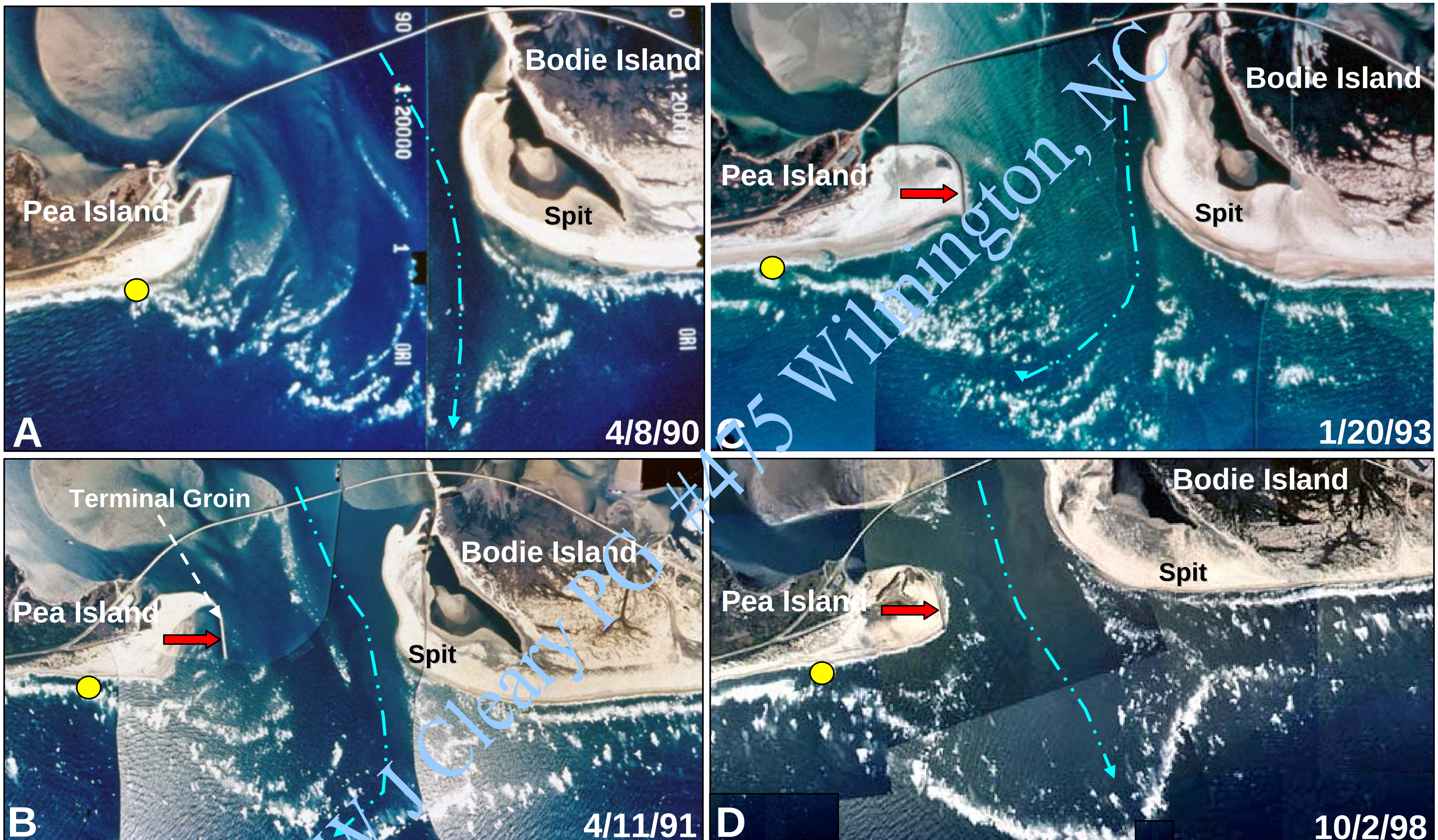

Figure 16. Aerial photographs of Oregon Inlet (ORI) 1990 to 1998. A. View of ORI (4/8/90) depicting the ebb channel in a near shore normal alignment and narrow flood channel along the Bodie Island margin. B. View (4/11/91) of the partially filled terminal groin fillet. The newly constructed groin is filling to capacity in "C" and "D". C. View (1/20/93) of outer bar channel deflection. The Bodie Island spit extends to bridge. D. View (10/2/98) of continued spit growth and inlet narrowing. The ebb channel has shifted to mid-throat position and the outer bar channel is aligned to the northeast. A small beach has developed along the inlet margin adjacent to the terminal groin indicating that sand has been bypassed beyond the groin. Note that in all of the above images the nodal point is located south of the terminal groin

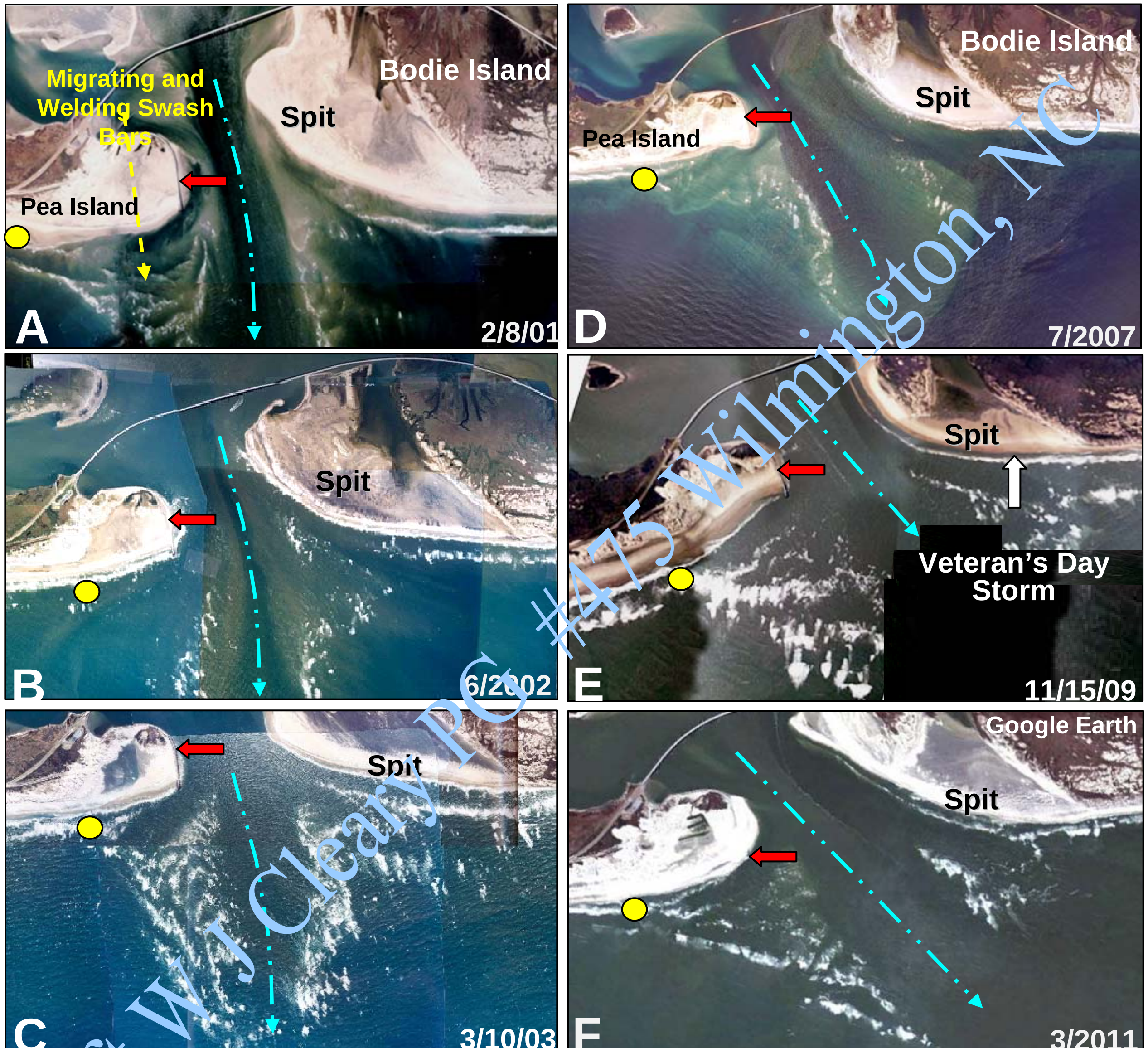

Figure 17. Aerial photographs of Oregon Inlet (ORI) 2001 to 2011. A. View of ORI (2/8/01) depicting the ebb channel in a near shore normal alignment within the very narrow throat. Note swash welding bars along the fillet B. View (6/02) of the narrowed inlet and the symmetric ebb-tidal delta. C. View (3/10/03) of elongated outer bar near LT. Note throat remains constricted . D. View (7/07) of the the deflected outer bar channel and the reconfigured outer bar. Reorganization of bar morphology has led to a widened inlet as the Bodie Is. margin eroded. E. View (11/15/09) of erosion related to the Veteran's Cay Storm. Note slight widening of inlet. F. View (3/11) of continued erosion along the Bodie Island spit. In all the images, with exception of "E", a beach of varying extent is present along the inlet margin adjacent to the terminal groin. Its presence indicates that sand has been bypassed beyond the groin. Note that in all of the above images the nodal point is located south of the terminal groin.

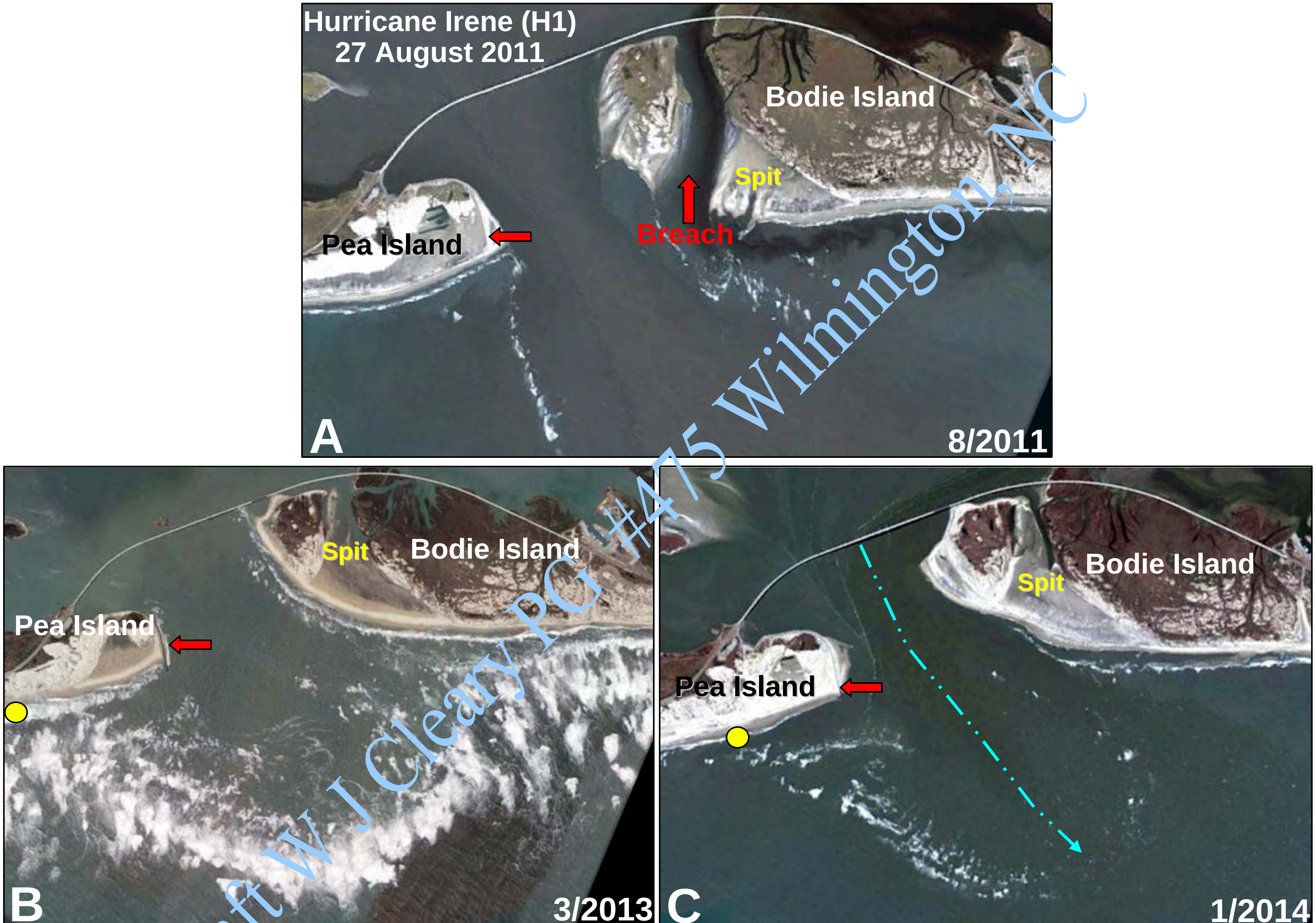

Figure 18. Aerial photographs of Oregon Inlet (ORI) 2001 to 2014. A. View of ORI (8/11) depicting the Hurricane Irene related breach along the Bodie Island spit and erosion along the groin fillet on Pea Island. B. View (3/13) of the symmetric ebb-tidal delta and the closed breach along the Bodie Island spit shoreline. C. View (1/14) of the elongated outer bar and zones of accretion and erosion along the Bodie Island spit. Note that the terminal groin fillet has again filled to capacity.

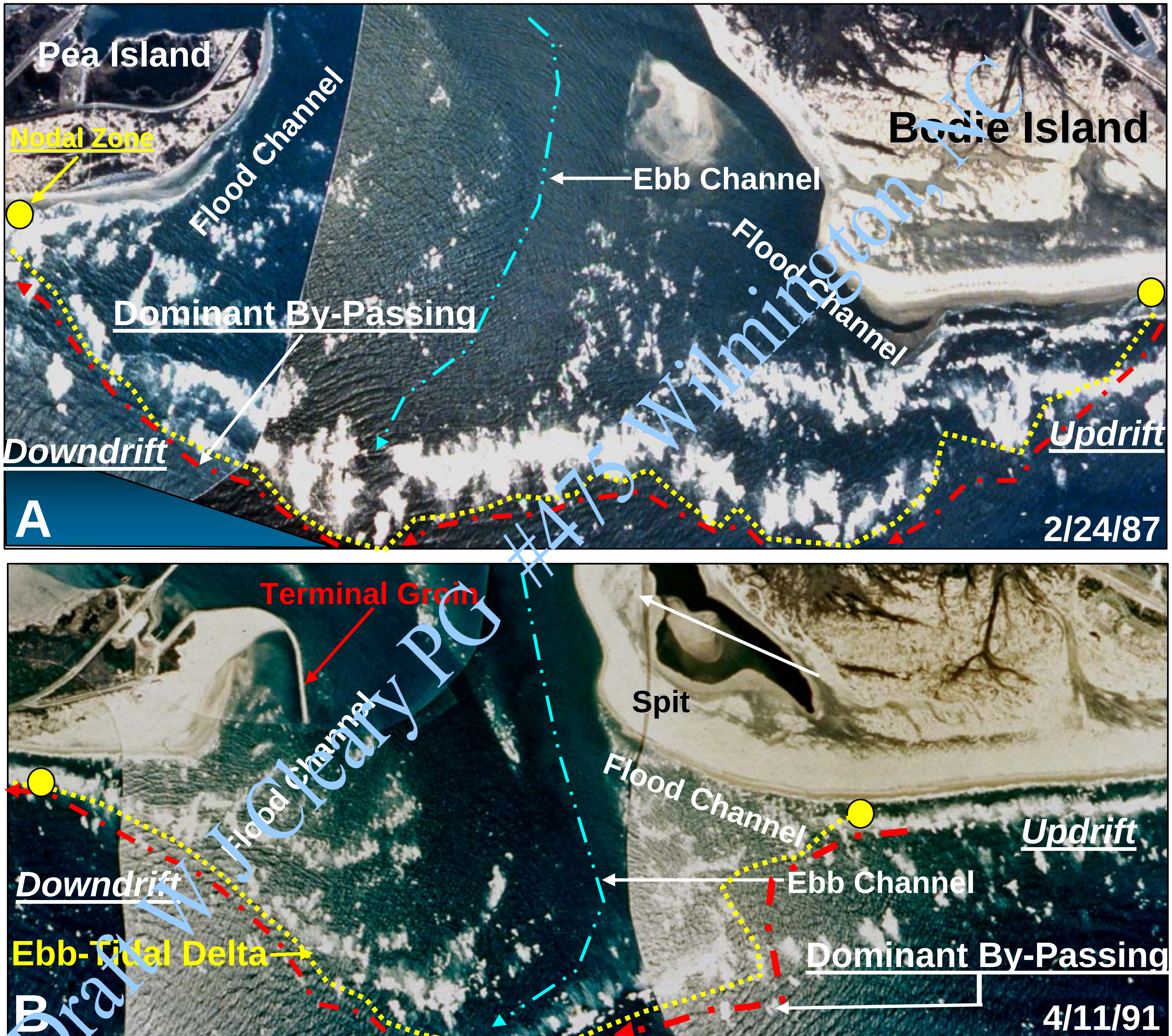

Figure 19. Aerial photographs (1987 and 1991) of Oregon Inlet. A. Photograph (2/24/87) of the inlet prior to construction of the terminal groin. Note the erosion along Pea Is. Red colored dashed line refers to dominant manner of sand by-passing around periphery of ebb-tidal delta. B. View (4/11/91) depicting the recently constructed terminal groin and swash bars migrating toward the "fillet". Note positions of the nodal points. Also note the narrowed inlet due to the growth of the large Bodie Island spit.

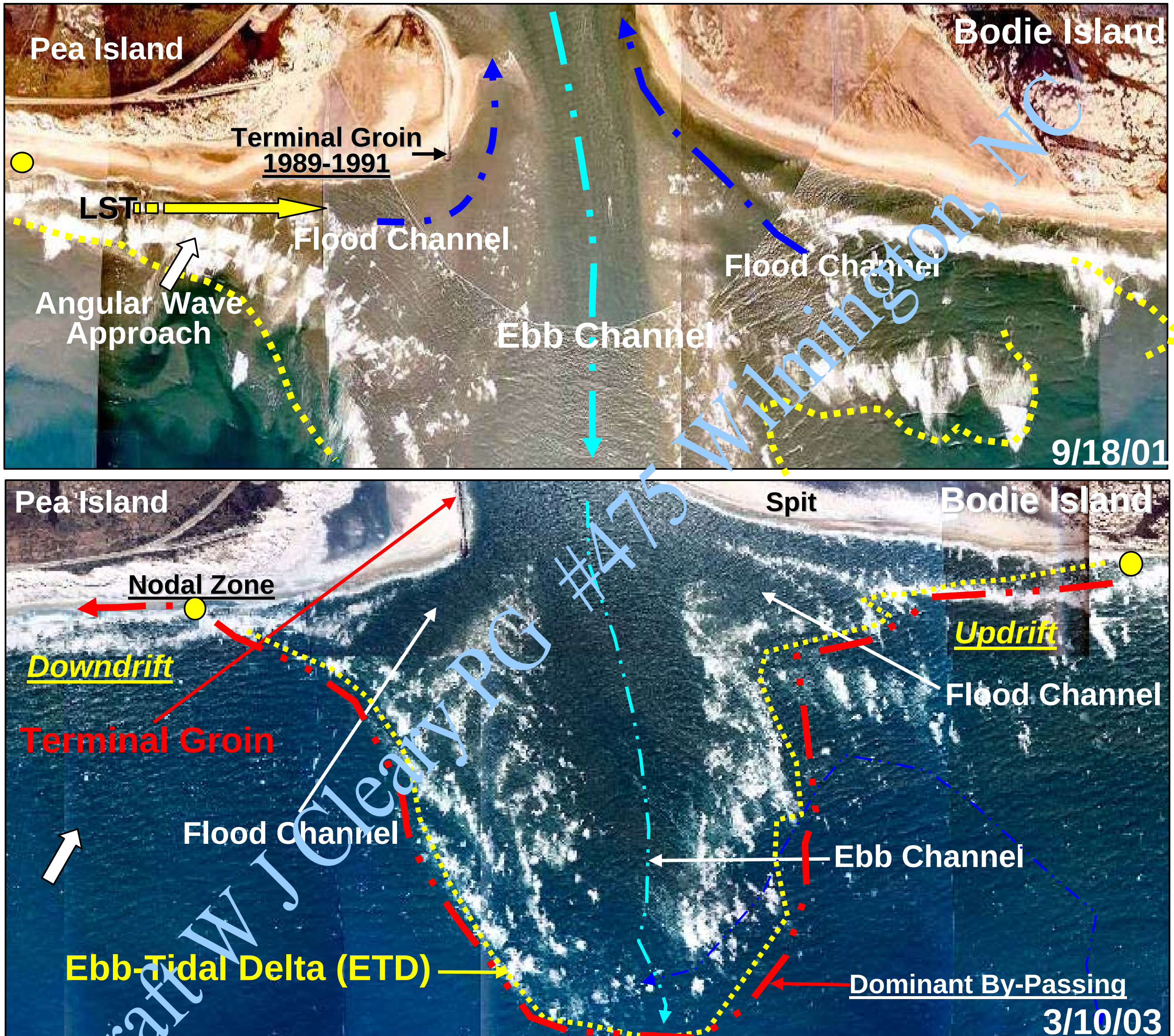

Figure 20. Aerial photographs of Oregon Inlet. A. Partial view (9/18/01) of inlet and ETD and wave refraction around ebb-tidal delta producing northerly sand transport (LST) along the Pea Is. shoreline (TG fillet). Beyond the nodal point the LST is directed southward. Note leakage of sand around the TG and formation of a beach. B. Photograph (3/10/03) of symmetric elongated ETD and dominant manner of by-passing sand from updrift to downdrift barrier. Note nodal zone has shifted toward inlet due to ETD shape change.

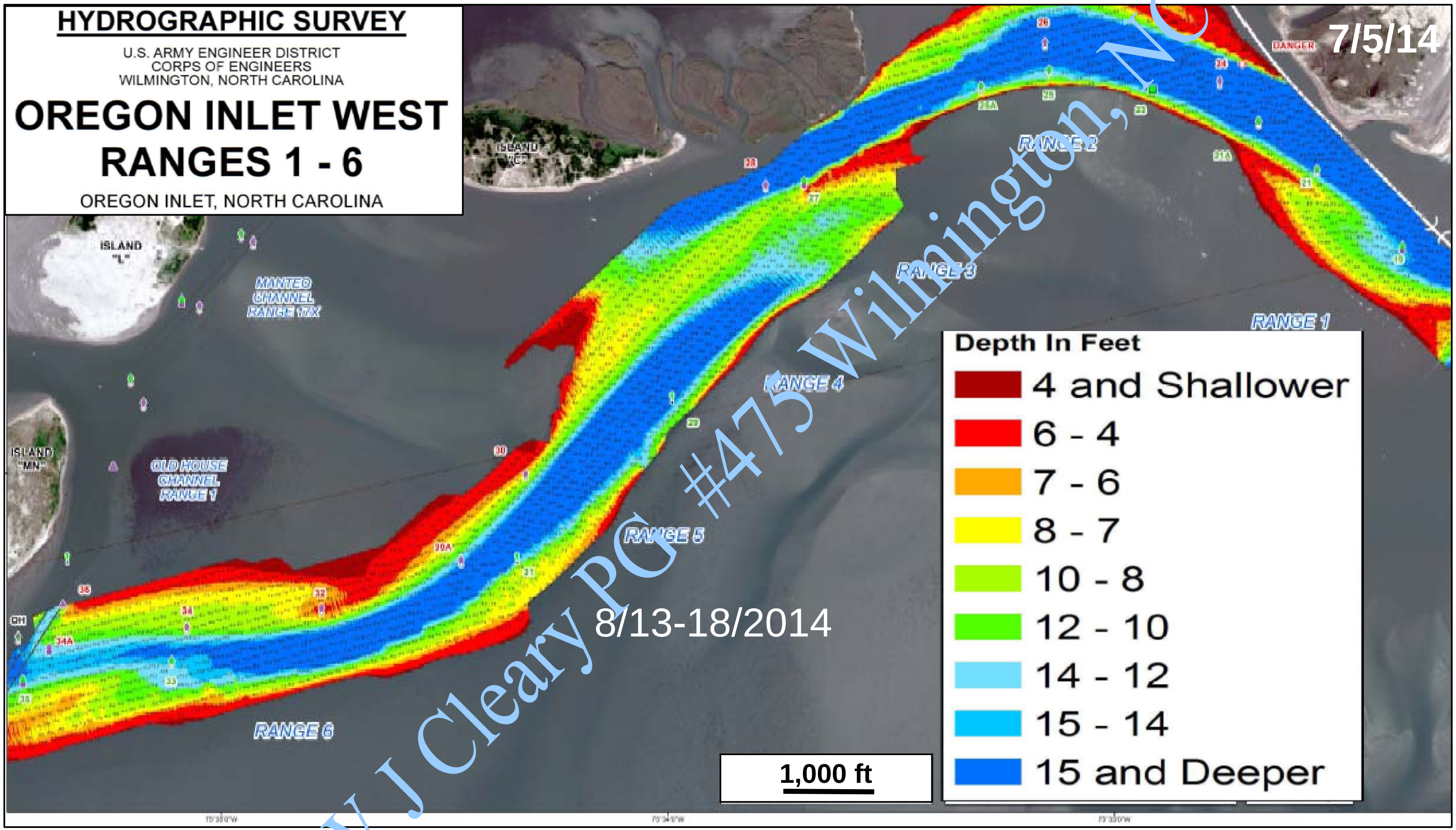

Figure 21. Hydrographic survey (8/13-18/2014) of the navigation channel west of the bridge showing the problem shoaling areas.

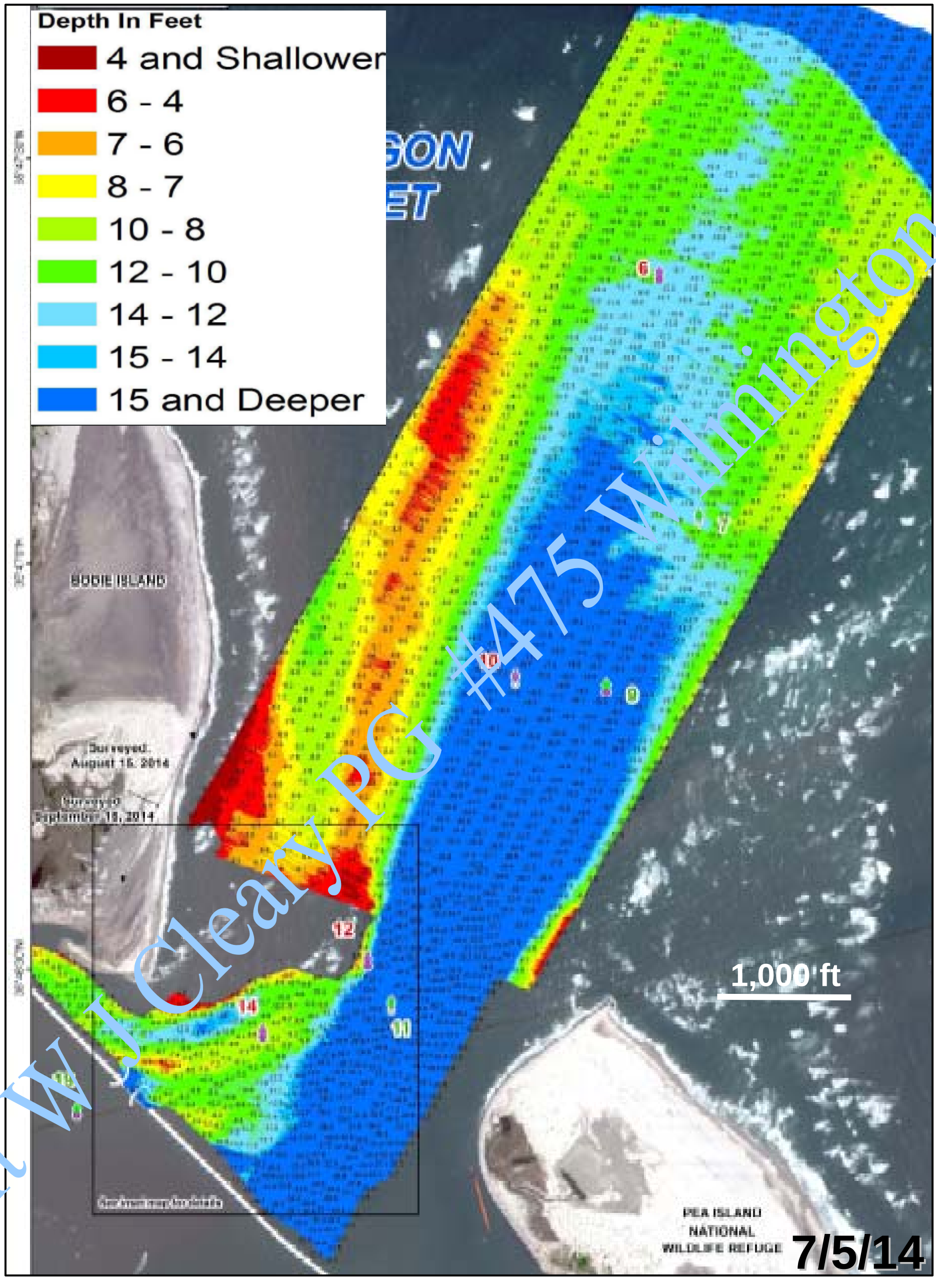

Figure 22. Hydrographic survey (8/13-18/2014) of the navigation channel (bar channel) east of the bridge showing the shoaling areas across the outer ebb-tidal delta..

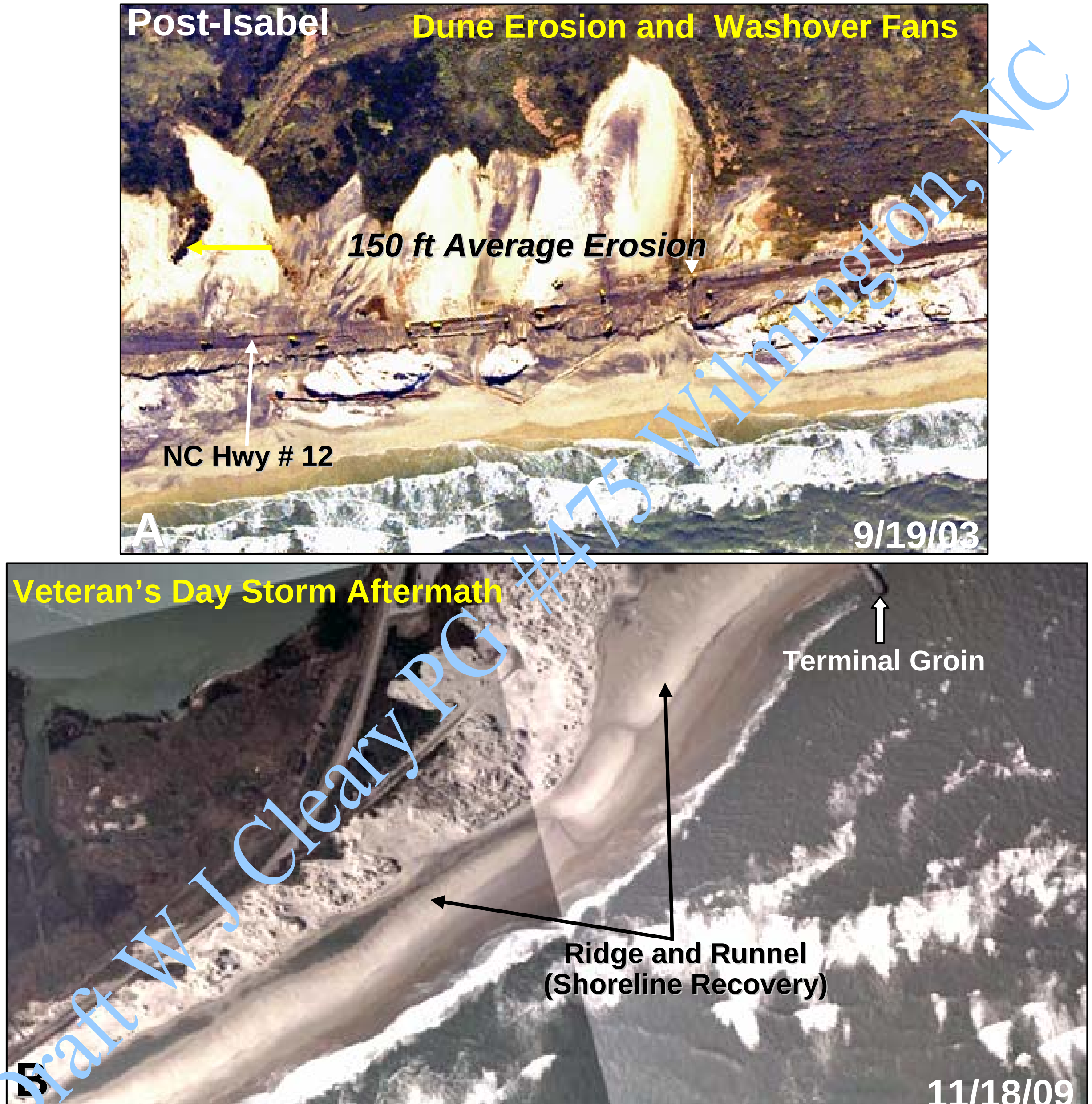

Figure 23. Erosion along Pea Island shoreline in vicinity of Oregon Inlet terminal groin. A. Photograph (9/19/03) depicting the erosion and washover topography related to the Hurricane Isabel's (H2) 6-8 ft surge. B. Photograph (11/09) depicting erosion and washover fans related to the Veteran's Day Storm.

Figure 24. Post-Isabel photograph (10/2003) showing the “S” curved portion of Highway # 12 north of Rodanthe . Note the presence of extensive washover fans and road crews with heavy equipment used in road scraping. Rodanthe is located ~12 miles south of the terminal groin. Insert depicts area on 12/4/09 (Post Nor’Ida**)**. Note washover fans have revegetated and the shoreline has retreated slightly.

Figure 25 .Views of Irene Breach Rodanthe, NC. A. Oblique aerial photograph (8/30/11) looking south along Hwy 12 toward Rodanthe, three days after landfall of Hurricane Irene. B. Landward view of Irene breach. C. North view of Irene breach. Higher tide levels allow the filling of the scoured region behind homes. Note the road is line with large sand bags some of which failed during the storm.

Figure 26 . Photographs of the opening and closure of the Hurricane Irene Breach updrift of Rodanthe. A. View (3/12/11) of a small tidal channel (white arrow), likely the corridor for bayside opening. B. View (8/27/11) of the Hurricane Irene breach and road scour. Note seaward excursion of surf line. C. View (3/9/13) of in-filled breach, the sand bag armored breach site and the area fronting the roadway (red arrows). D. View (1/11/14) of repaired Hwy. 12 and closed breach and beach fill.

Figure 27. Beach nourishment along the Irene Breach (Rodanthe, NC). A. Nourishment shortly before project completion. B. Completed project involved 1.5 million cu yds. of sand placed along a two mile-long shoreline segment.

Figure 28. Aerial photographs of Hurricane Irene (breach) inlet along the Pea Island shoreline. A. Northward view of two breaches along the barrier . The southern and smaller breach closed naturally while the northern breach is a viable inlet. B. Vertical view of the NC DOT construction of a temporary steel bridge. Note the southerly breach is closed. A viable ebb-tidal delta has yet to form. C. Oblique landward view of the new inlet showing the washover sediment filling the small breach and large longitudinal bars immediately offshore.

Figure 29 . Photographs of the opening and closure of the Hurricane Irene Breach downdrift of the ponds on the PINWR. A. View (3/11/11) of a small tidal channel (white arrow), likely the corridor for bayside opening. B. View (8/27/11) of the Hurricane Irene breaches and road scour. Note seaward excursion of surf line due the small tidal flow. C. View (3/9/13) of breach shoaling, spit development on the inlet margins and a small flood-tidal delta. A temporary steel bridge connects the repaired roadway. D. View (1/11/14) of the closed breach and washover deposition filling scoured areas. Flood-tidal has increased in area and it is likely that wave runup and overwash at higher tide levels its size during the previous year.

Figure 30. Post-Hurricane Sandy (27 Oct 2012) oblique aerial photographs of the PINWR shoreline. A. Seaward view of the Oregon Inlet terminal groin fillet depicting washover sands filling the eroded the scour hole. B. Northward view (10/31/12) depicting the island wide erosion and the near complete destruction of the dunes. C. Southward view of eroded dunes and the heavy mineral lag (black sand) along the barrier. Note the washover features cover Hwy. #12 and most extend into the adjacent pond. D. Northward view of PINWR breach. Note washover fans extending into a former breach south of the inlet. A small ebb-tidal delta now fronts the inlet throat. See Figure 30.

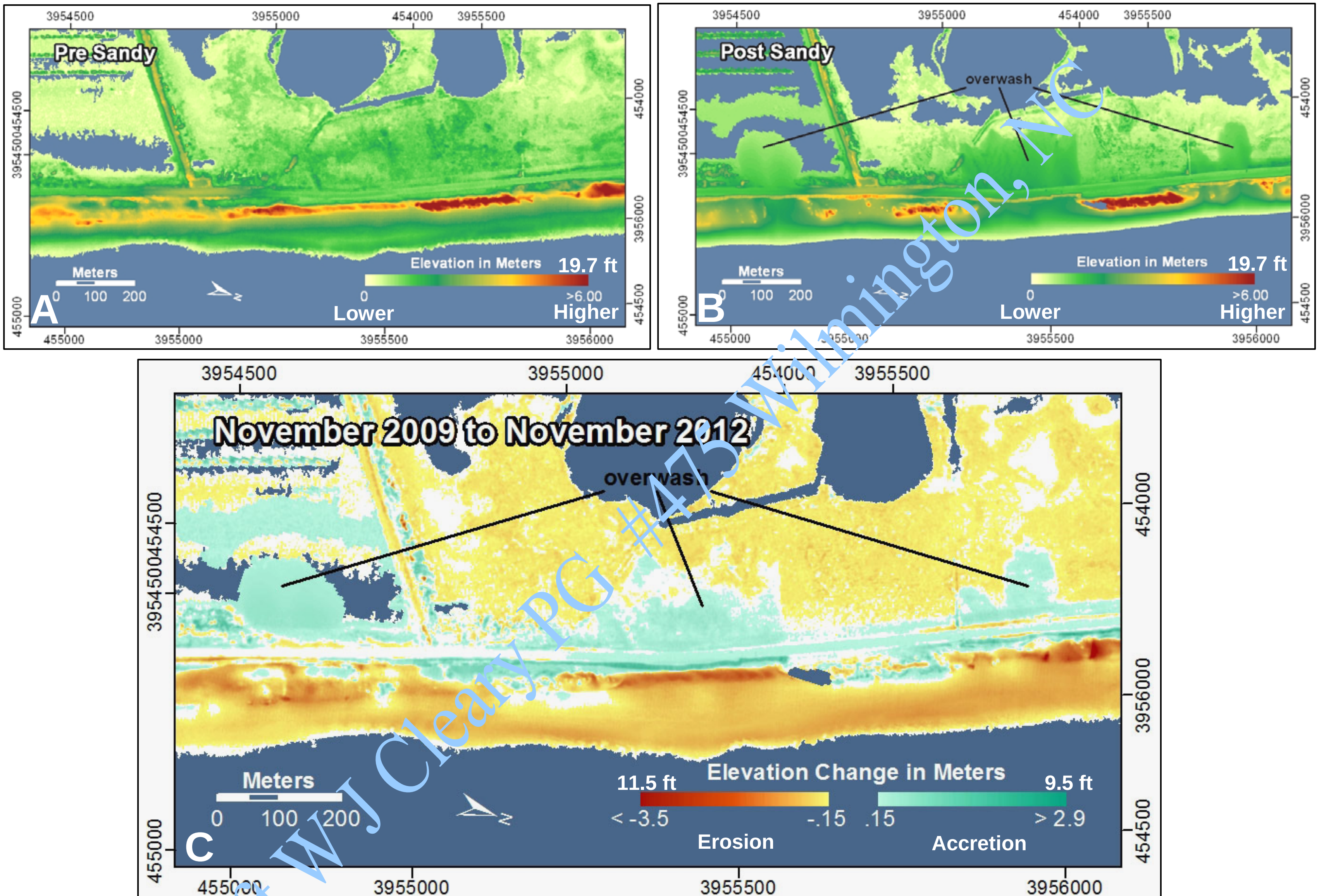

Figure 31. Digital elevation maps depicting the shoreline changes related to Hurricane Sandy along the PINWR shoreline. A. Pre-Hurricane Sandy elevation map (Nor'Ida Nov 2009) showing a continuous dune line of varying elevation. B. Post – Hurricane Sandy elevation map depicting the topographic change related to the storm-related erosion and deposition. C. Post-storm elevation difference map. The orange - red color denotes erosion while blue - green color signifies accretion. Basically the map depicts a lowering of the foreshore and an increase in elevation along portions of the backshore and in the pond due to washover sand deposition. An additional storm struck the area between the two surveys so the post storm maps shows the cumulative effect of several storms. After the USGS, http://coastal.er.usgs.gov/hurricanes/sandy/lidar/northcarolina.php

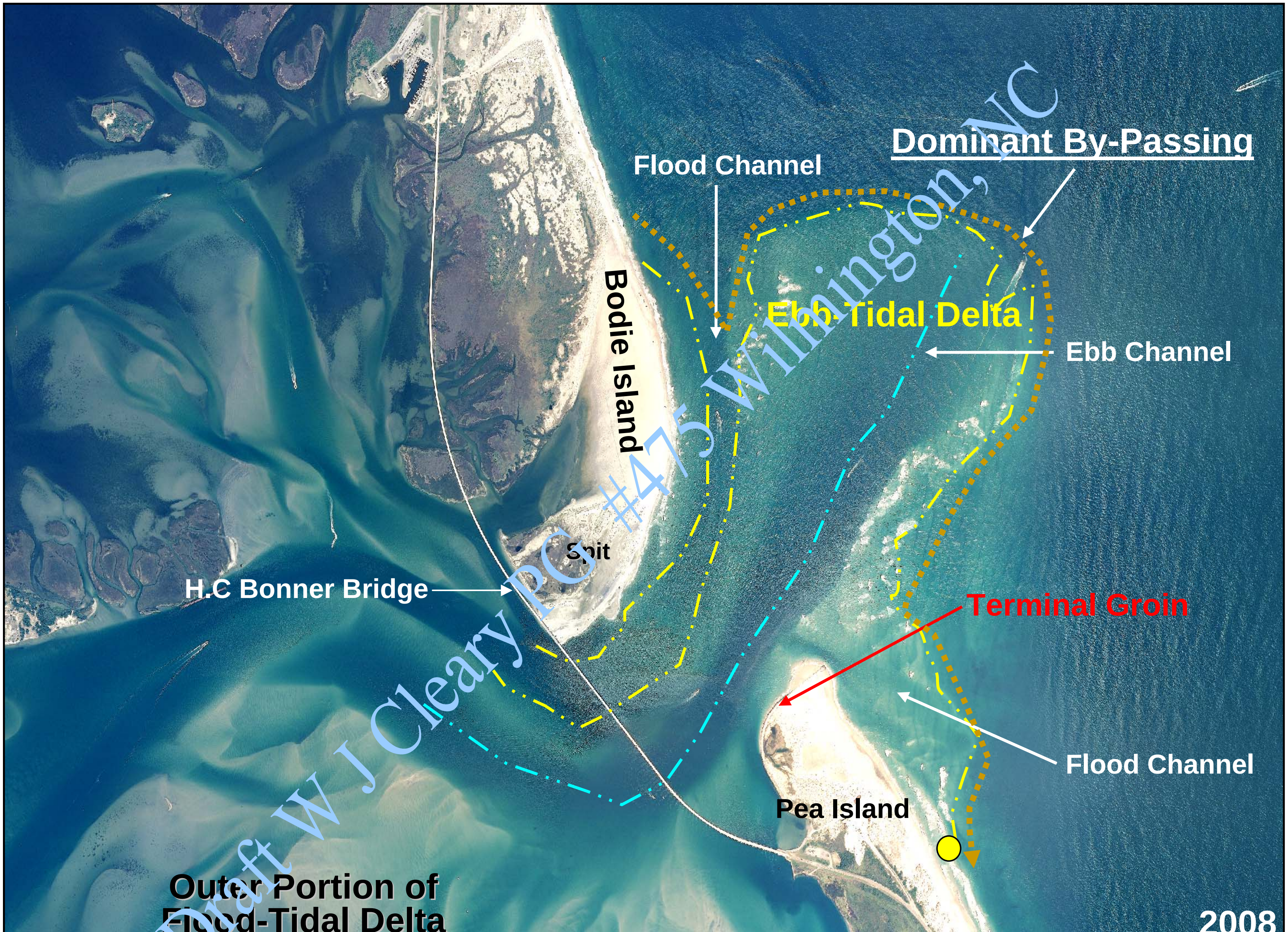

Figure 32 Map with 2008 aerial photograph of Oregon Inlet showing the ebb-tidal delta, a small portion of the flood-tidal delta and the terminal groin. The light brown colored dashed line refers to the dominant manner in which d=sand by-passes an inlet in a wave-dominated setting such as Oregon Inlet. Regardless of the alignment of the ebb channel and the symmetry of the shoals by-passing occurs around the periphery of the swash platform (yellow colored dashed line). By-passing ceases if the terminal lobe is bisected by a dredged and deepened outer bar channel.