4.0 INLET MORPHOLOGY

4.1 General Morphologic Observations – Existing Conditions

Figure 11, following page, depicts a colorized map of the bathymetric depths across the Morehead City Harbor channel and ebb shoal (Beaufort Inlet). The map was prepared from a high-resolution multi-beam survey in June 2005 by Geodynamics LLC. Several physical characteristics of the modern inlet are immediately evident from the survey:

- The navigation channel clearly severs the ebb shoal tidal platform and appears to wholly preclude any significant sand bypassing across the inlet
- Direct sand transport from the beaches and along the shoal/bars and into the channel is evident (1) at the ends of Bogue Banks and Shackleford Banks, (2) across the ebb bar, and (3) at the seaward end of the ebb shoal – consistent with Figure 10, prior page.

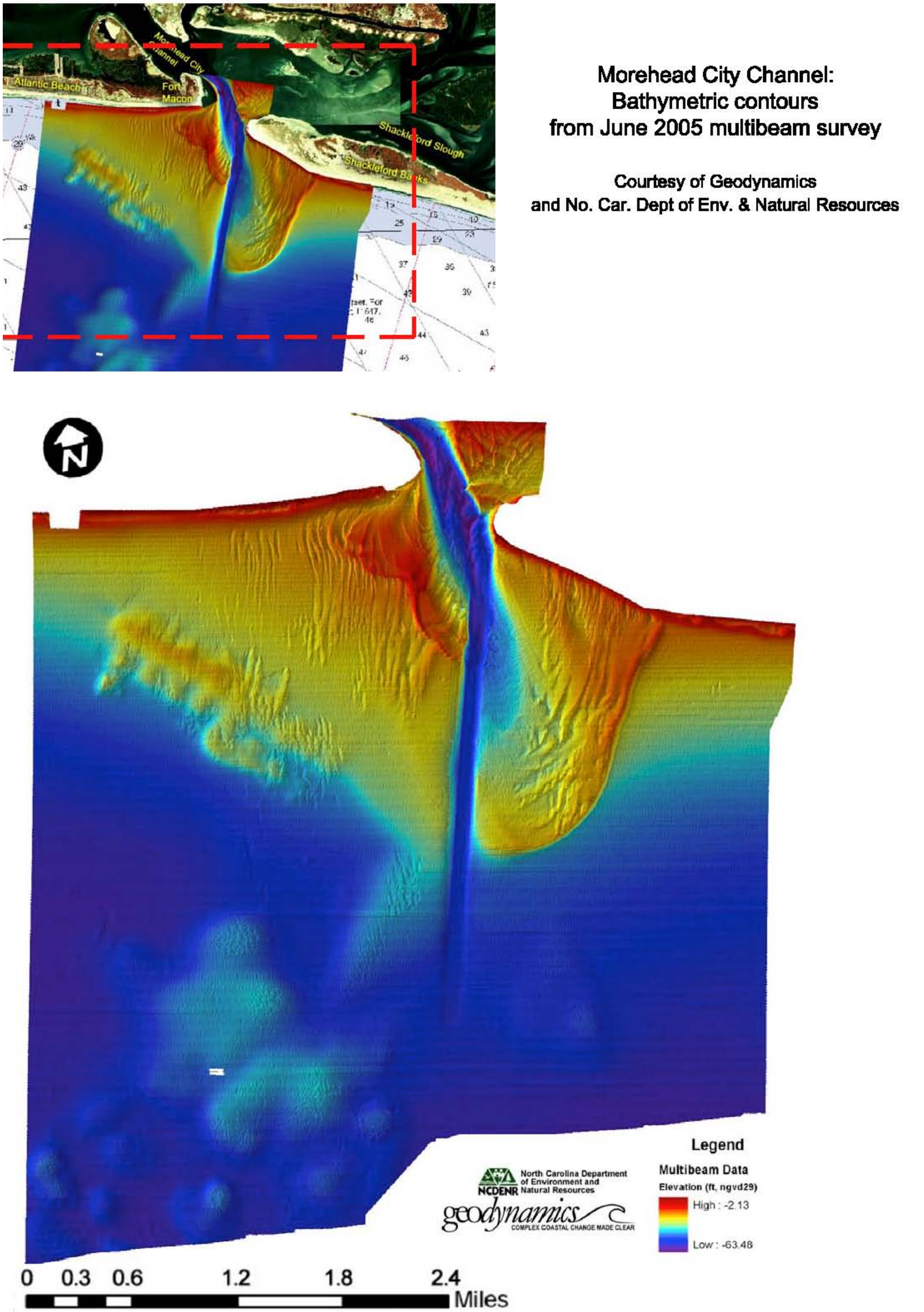

Figure 11: Colorized seabed depths at Beaufort Inlet from 2005 survey by Geodynamics. Red indicates shallowest depths, yellow indicates intermediate depths, blue indicates deepest depths.

- A strong ebb current apparently jets seaward toward the southeast, along the Cutoff channel, and then deflects toward the west near the seaward end of the ebb shoal. This current, confirmed by the Bar Pilots, pushes the eastern lobe of the shoal further seaward, and then carries sand westward from the shoal into the channel.
- The nearshore disposal mounds, evident at middle left, are distinct from the remainder of the ebb shoal platform; they exhibit no littoral connection to the remainder of the system.
- The offshore disposal mounds are evident toward the lower left.

4.2 Pre- and Post-Project Changes in General Inlet Morphology

Figure 12a, following page, depicts the bathymetric contours of the inlet in pre-project conditions (c. 1900) and in existing conditions (c. 2004). In the pre-project, or natural, condition, the inlet was characterized by a broad, quasi-symmetric ebb tidal shoal with a natural ocean bar of about -10 to -15 ft depth. The controlling depth across the inlet's natural channel was about -15 ft MLW or less. There was a well-developed, deep natural channel that was oriented south-southwest, but which broadened -- and fluctuated (based upon other early surveys, not shown) -- across the ebb tidal shoal.

In contrast, in post-project (existing) conditions, the ebb tidal shoal is elongated toward the sea and non-symmetrical. The shoal and ocean bar are wholly severed by the navigation channel. Controlling depth through the inlet is now -45 ft MLW. Depths across the shoal are, overall, deeper than in pre-project conditions.

Figure 12b depicts the change in seabed depths from 1900 to 2004. Differences in vertical datums and sea levels, etc. have been accounted for in the comparison. Areas in red have deepened (lost sand); areas in blue have shallowed (gained sand).

Essentially all of the original ebb tidal shoal platform has dropped in elevation, or "deflated". This includes all of the shoal landward of the existing -20' depth contour; i.e., those depths across which littoral transport principally occurs. The "deflation" of the depth contours continues east and west of the shoal, along the adjacent barrier islands.

Sand has deposited along the outer (seaward) lobe of the original shoal – indicating that the shoal has migrated or been 'pushed' seaward. Some of the apparent deposition is associated with nearshore disposal berms (middle left) and offshore disposal (lower left). The growth of the western end of Shackleford Banks, toward and into the inlet, is also evident (upper-middle right).

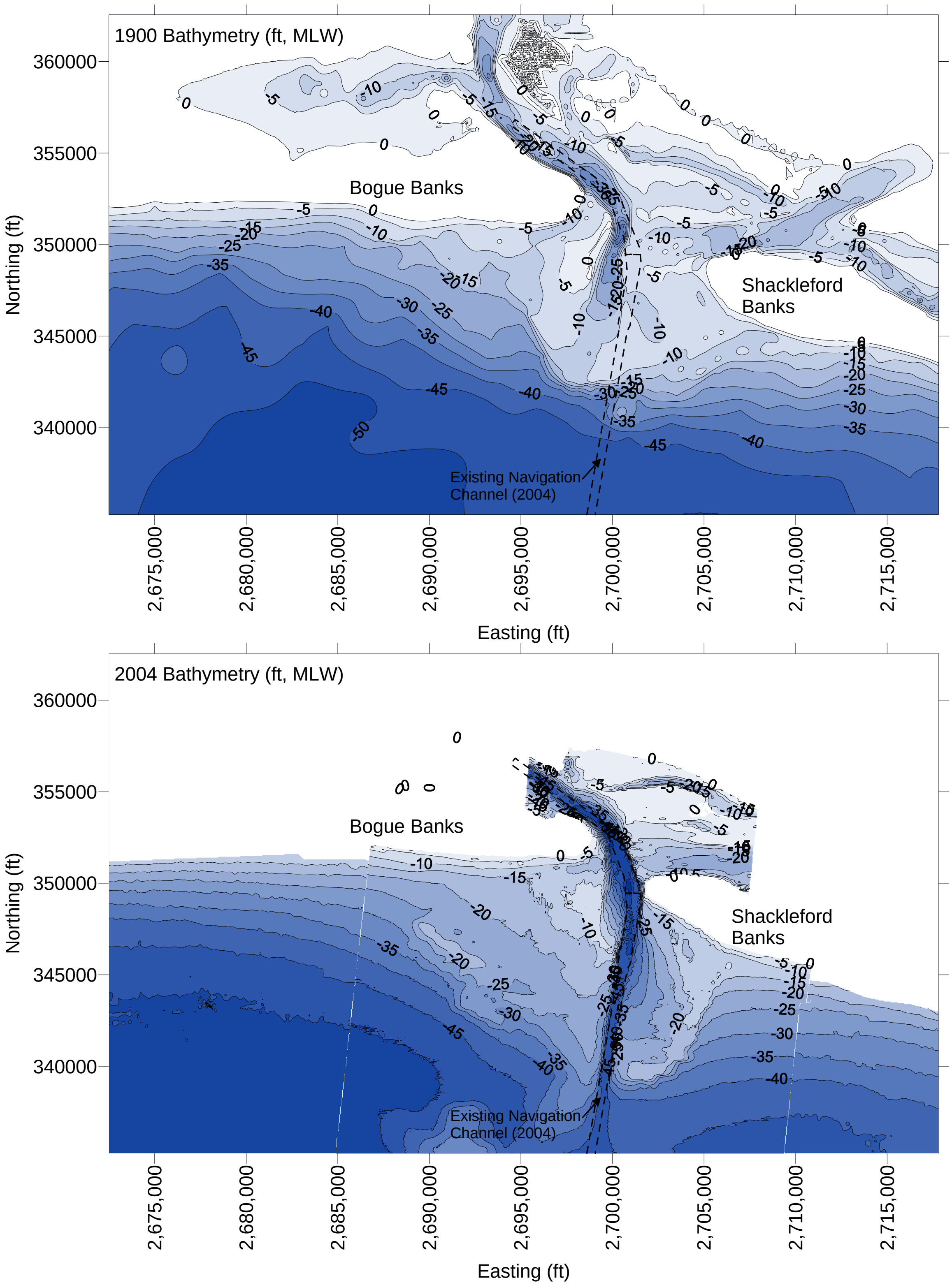

Figure 12a: Bathymetric contours representing conditions near Beaufort Inlet in 1900 (upper figure) and 2004 (lower figure). [In the lower figure, bathymetric data at the far left and right of the image, beyond the limits of the 2004 survey, are from a 1998 survey.]

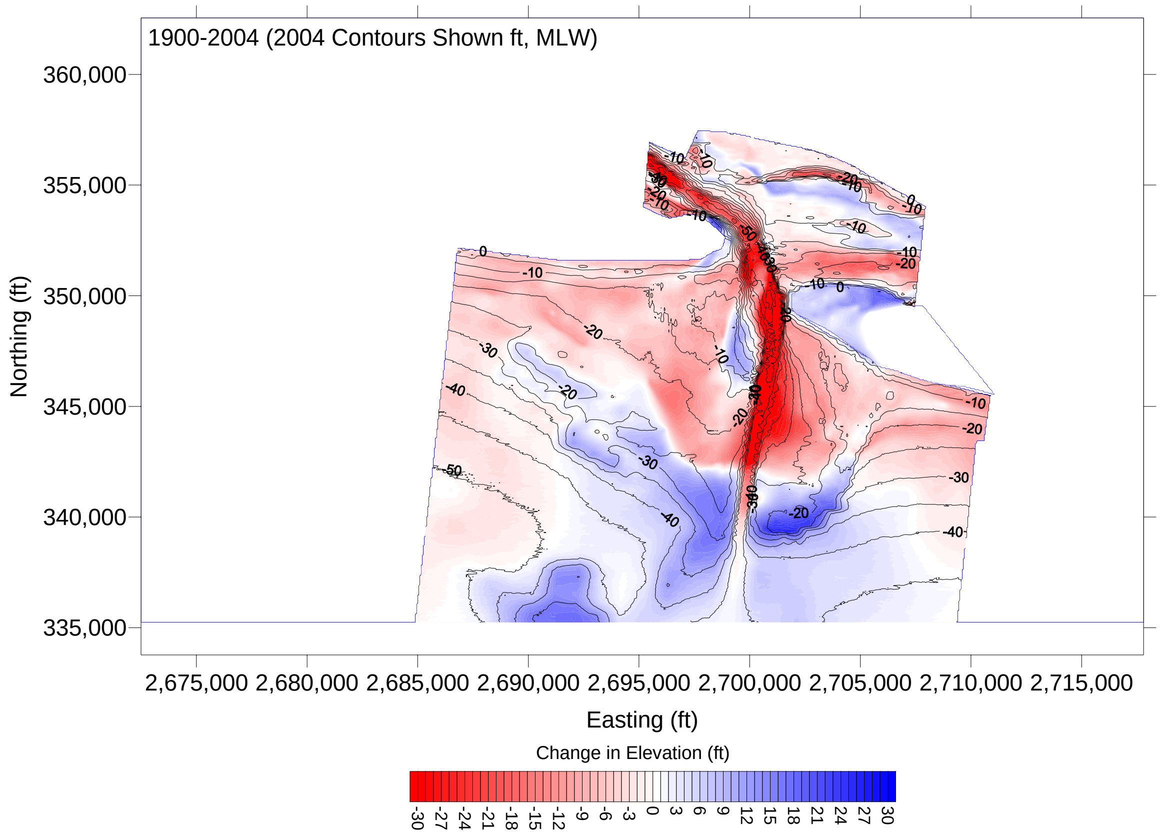

Figure 12b: Change in elevation, 1900-2004. The shorelines and bathymetric contours are from a 2004 survey. Blue shading represents seabed shoaling (accretion) and red shading represents seabed deepening (erosion).

The changes in the shoal elevations and morphology appear to be consistent and ‘ongoing’. ***Figure 13***, for example, illustrates the change in seabed elevation for the periods 1974-1998 and 1998-2004. Both comparisons show a consistent drop in elevation of the inshore portions of the ebb shoal (“red”) and deposition of sand along the outer, eastern lobe of the ebb shoal (“blue”). The former suggests a continuing, steady erosion of the overall shoal that spans the barrier islands. The latter suggests a continuing, steady “jetting” of sand from the nearshore bars to the sea, pushing the ebb shoal further offshore.

The magnitude of the seabed changes over 1974-1998 (upper graphic) is about 3 to 4 times greater than over 1998-2004 (lower graphic). This is consistent with the fact that the 1974-98 period is about 4 times longer than the 1998-2004 period. In these comparative graphics, the dates and spatial limits of the seabed changes are a function of the availability of historical survey data. Quantitative volume changes are presented in ***Appendix D***, and summarized later in these pages.

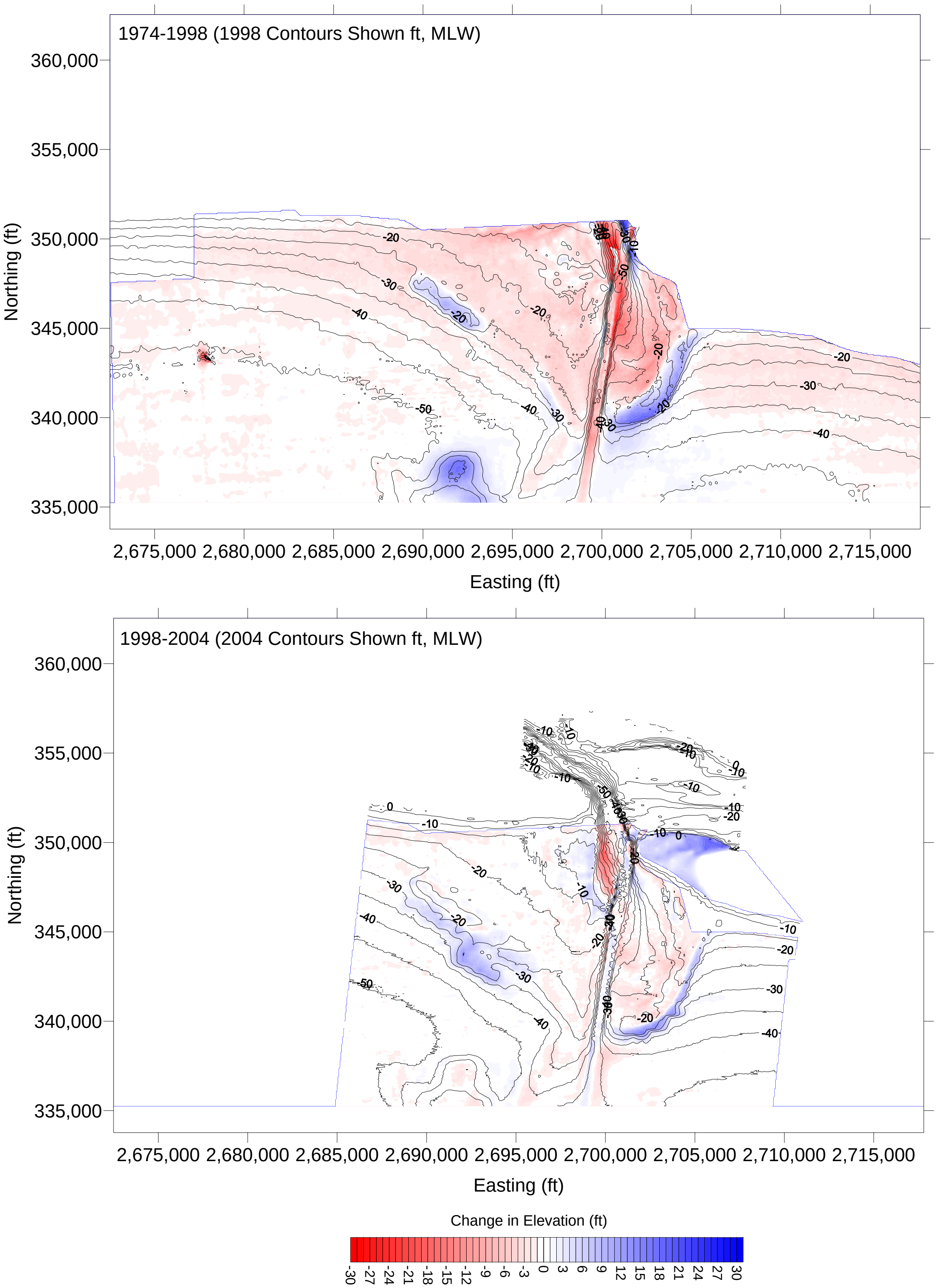

Figure 13: Change in seabed elevations, 1974 to 1998, and 1998 to 2004. Red is erosion (seabed deepening), and blue is accretion (seabed shoaling).

Figure 14, on the following page, depicts the 1900-2004 seabed changes in three-dimensional view. The figure illustrates

- the channel's severance of the original bypassing bar,
- the deflation of the original ebb tidal shoal and deepening of the seabed along the adjacent shorelines,
- the accumulation of sand at the eastern tip of Bogue Banks into the inlet throat and inner channel,
- the growth of western Shackleford Bank into the throat and outer channel,
- the seaward dislocation of the ebb shoal from shallow water into deeper water, and
- the disposal of dredged material beyond the outer edge of the ebb shoal.

4.3 Volume Changes Across Inlet Complex

4.3.1 Overall Change in Pre- versus Post-Project Conditions

Pre-Project Condition. From 1900 to 1933, prior to commencement of significant inlet improvements (c. 1936), the interior flood shoals exhibited minor net volume change: about +1,100 cy/yr on annual average. The east end of Bogue Banks was *advancing* eastward, gaining about +57,300 cy/yr above the low water line; while the west end of Shackleford Banks was *retreating* eastward at a similar rate. The ebb tidal shoal was gaining sand at an average rate of about +208,000 cy/yr. On the whole, the entire inlet complex – including the ocean shorelines within 2.7 miles to the west and 2.1 miles to the east of the inlet -- exhibited a net gain of about +206,400 cy/yr.

Post-Project Condition. The survey interval 1933 to 2004 represents the "post-project" period, with significant channel improvements beginning in 1936. On annual-average, from 1933 to 2004 (and after accounting for new work dredging), essentially all of the inlet's volume changes *reversed* from the pre-project condition:

- the interior flood shoals changed from weakly accretional (+1,100 cy/yr) to erosional (-54,600 cy/yr)
- the east end of Bogue Banks reversed from advancement (+57,300 cy/yr) to retreat (-41,300 cy/yr)
- the west end of Shackleford Banks halted its retreat (-60,000 cy/yr) and advanced significantly toward the inlet (+83,200 cy/yr), and
- the ebb tidal shoal reversed from accretion (+208,000 cy/yr) to erosion (-290,600 cy/yr).
- Overall, the inlet complex changed from *net gains* of +206,400 cy/yr to *net losses* of -303,300 cy/yr, on annual average.

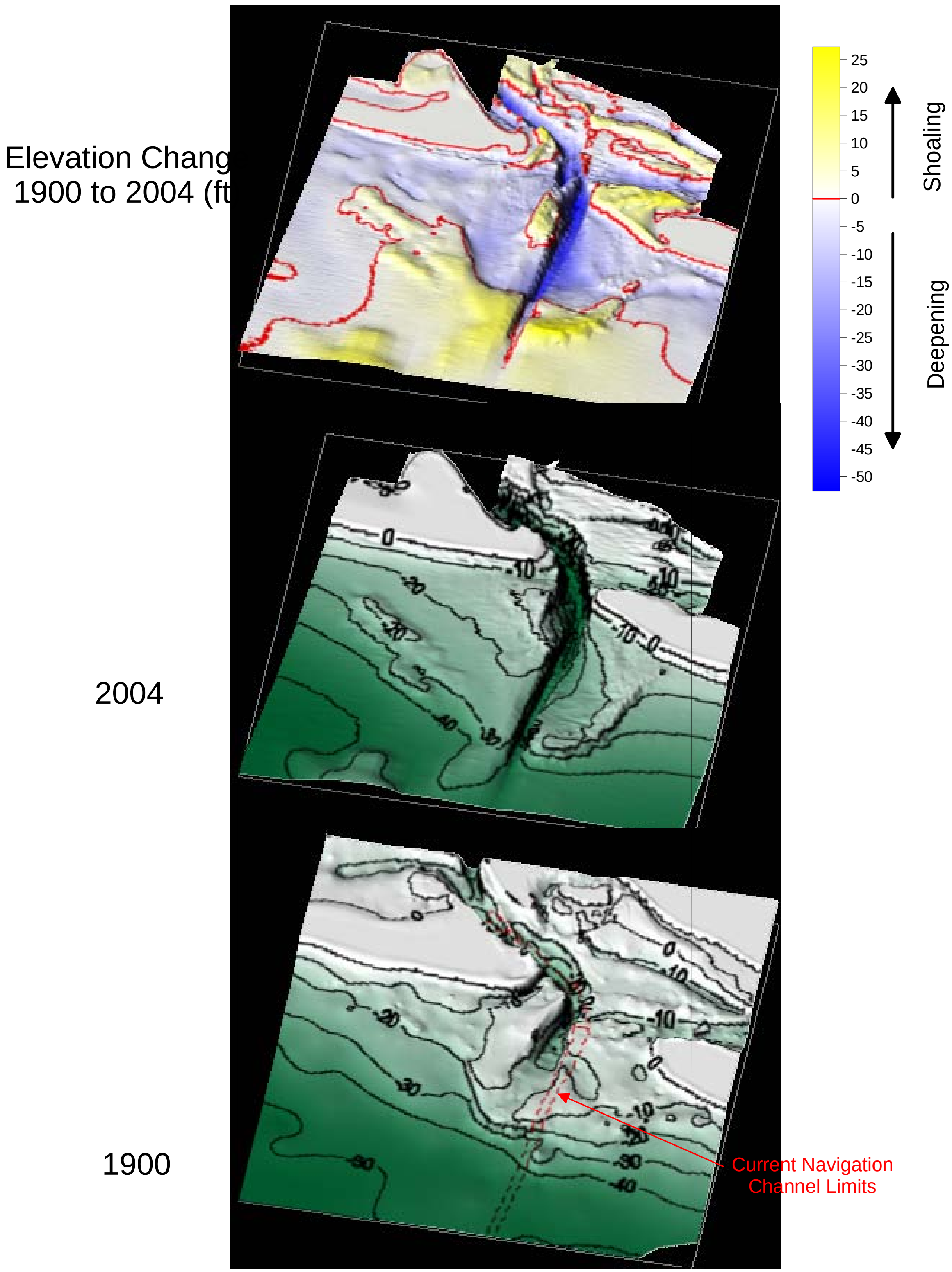

Figure 14: Orthographic view of bathymetric changes from 1900 to present (2004).

4.3.2 Ebb Shoal Changes: West vs. East

Figure 15, on the following page, depicts the changes in the inlet's outer shoal volume from 1900 to 2004. The upper figure considers only changes across the submerged ebb shoal, *below* the modern waterline. The lower figure also includes changes *above* the waterline -- along eastern Bogue Banks and western Shackleford Bank, within the alongshore limits of the ebb shoal platform.

Across the ebb tidal shoal, post-project volume losses were at least four times greater on the *west* side of the navigation channel than on the *east* side. From 1933 to 2004, the submerged ebb shoal lost 21.6 Mcy *west* of the bar channel and 5.0 Mcy *east* of the bar channel.[8] Thus, below the waterline, losses on the west were 4.3 times greater than on the east.

The ratio of west-to-east losses is even larger when one considers that the west shoal was accretional prior to the inlet improvements. That is, from pre-project conditions (1900-1933) to post-project conditions (1933-2004), on annual average:

- the west ebb shoal changed from a *gain* of +265,500 cy/yr to a *loss* of -304,200 cy/yr;
- the east ebb shoal changed from a loss of about -32,700 cy/yr to a loss of -70,700 cy/yr.

Thus, relative to pre-project conditions, the post-project losses on the west side of the channel are 15 times greater than on the east side (-569,700 cy/yr vs. -38,000 cy/yr).

When one includes the gains to Shackleford Banks and the losses to Bogue Banks, above the modern waterline, there were post-project losses of -24.6 Mcy on the west side of the bar channel versus a slight *gain* of +0.9 Mcy on the east side.[9] This broadly implies that *all* of the net inlet volume losses were on the west side.

Figure 15 illustrates a consistent rate of inlet volume losses over the last half-century. After the 1952 survey, both the east and west sides of the ebb shoal reversed from accretion to erosion. Thereafter, each side's erosion trend has continued at a steady rate:

- Considering only the submerged shoal platform (upper graph), net losses after 1952 averaged -534,300 cy/yr *west* of the channel and -146,200 cy/yr *east* of the channel.
- Including the gains to Shackleford Banks and losses to Bogue Banks (lower graph), net losses averaged -550,000 cy/yr *west* of the channel and -67,000 cy/yr *east* of the channel.

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[8] These values do not include losses above the Mean Low Water Line of Bogue Banks or changes to Shackleford Banks. The west-side changes exclude about 3.7 Mcy of nearshore disposal within the west shoal, which otherwise appears as a "false" volume gain in the bathymetric comparison.
[9] This value excludes 3.7 Mcy of nearshore disposal placed to the west shoal after 1996.

Thus, since 1952, both the west and east sides of the ebb shoal platform have eroded at fairly consistent rates. Volume losses were 3.6 to 8.2 times greater on the west side of the channel than on the east side of the channel.

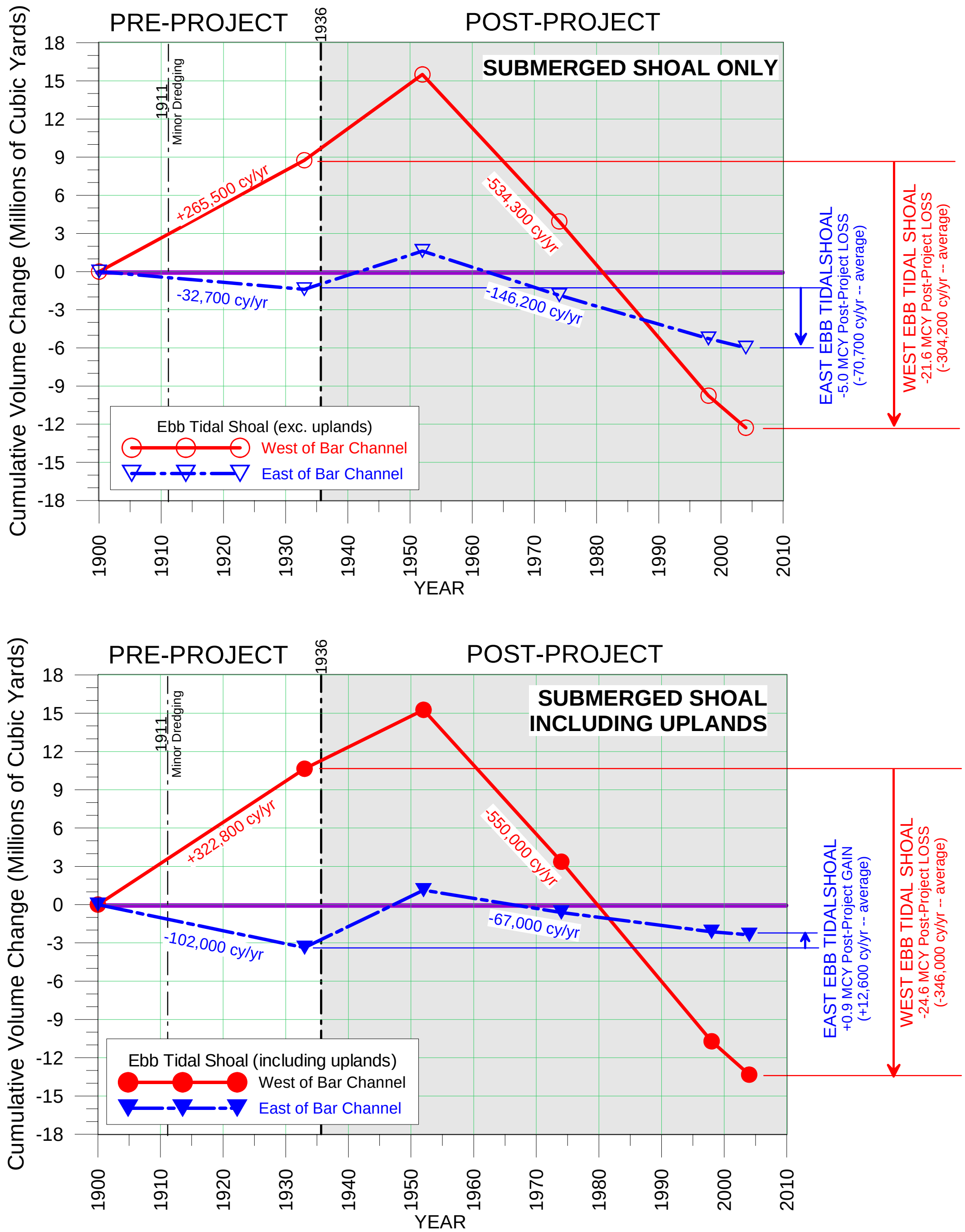

Figure 15: Changes in ebb shoal volume at Beaufort Inlet, 1900-2004. Upper – includes only submerged shoal below existing shorelines. Lower – also includes approximate changes above low water shoreline at eastern Bogue Banks and growth of western Shackleford Banks, within about 2.4 miles west and 2.1 miles east of inlet. Increases in west shoal volume associated with nearshore disposal are excluded. The inlet's volume losses on the west side of the navigation channel are significantly greater than on the east side of the channel.

Figure 16 illustrates the spatial boundaries used in this study to categorize inlet volume changes between available surveys.

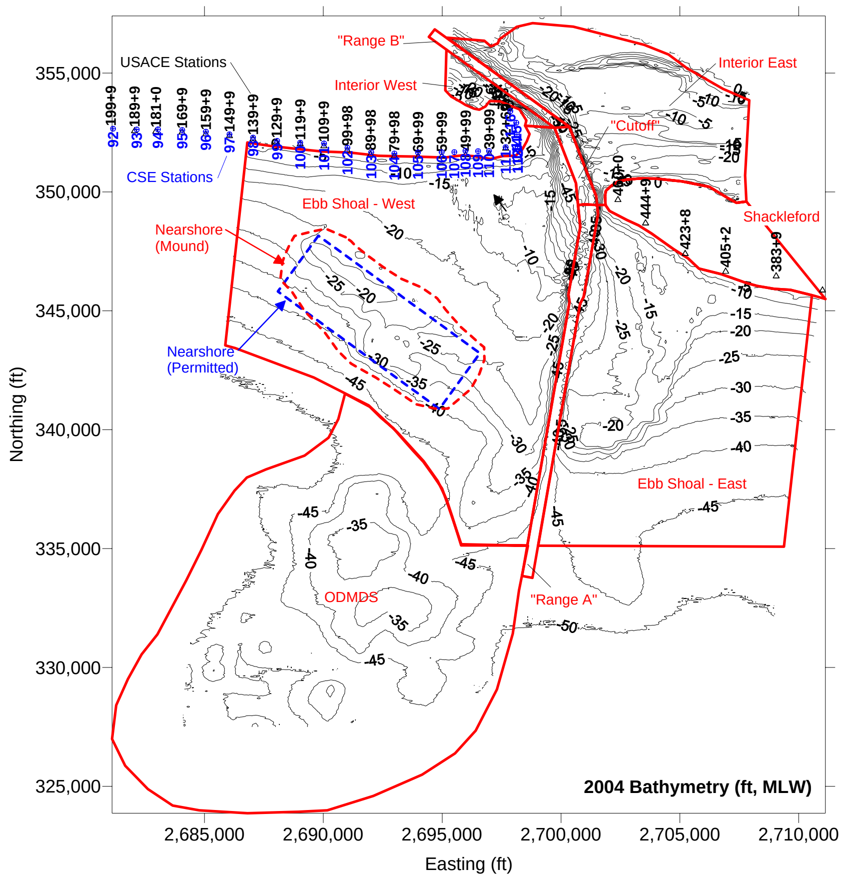

Figure 16: Spatial boundaries used to categorize inlet volume changes in this study.

In sum, depending upon the spatial limits and time-intervals that are considered, post-project volume losses to the inlet's outer shoal complex are between 3.6 and 15 times greater on the west side of the channel than on the east side of the channel. If the gains to Shackleford Banks are included, one could conclude that all of the volume losses are related to the west side of the channel. Classically, with the navigation channel acting as a littoral barrier, this indicates that the dominant drift is from east to west, and that the west side of the inlet is downdrift.

4.3.3 Existing Ebb Shoal Volume versus Historical Rates of Change

From 1952 to 2004, the average-annual net rate of volume losses across the western ebb tidal shoal – above the -20 ft MLW contour – has been -342,000 cy/yr. In comparison, the existing volume of the western shoal, above -20 ft, is 11,938,000 cy.

Simplistically, this suggests that the existing western ebb shoal (above -20 ft depth) would be depleted of sand within the next *35 years*, presuming that the recent historical trends of ebb shoal deflation continue. Likewise, net losses to the eastern shoal above -20 ft depth have averaged -148,000 cy/yr versus an existing volumetric reserve of 6,728,000 cy – suggesting a *45-year* capacity. Combined, this equates to 38 years.

Similarly, measured above the -30 ft MLW depth contour, net historic losses to the western ebb shoal have averaged -427,000 cy/yr versus an existing volumetric reserve of 43,512,000 cy above -30 ft. Net historic losses to the eastern ebb shoal have averaged -198,000 cy/yr versus an existing reserve of 23,307,000 cy above -30 ft. These quantities suggest an existing volumetric life of *102 years* and *118 years* for the west and east ebb shoal lobes, respectively, should deflation of the ebb shoal continue at its historic rates above the -30 ft MLW depth contour. Combined (east & west), this equates to 107 years.

4.3.4 Flood Shoal Changes.

Compared to the ebb shoal, the number, data-density, and spatial limits of flood shoal surveys are very limited. Estimates of volume changes from these surveys is therefore likewise limited, and principally indicate that there has been a net loss in flood shoal volume since 1933, mostly all of which occurred after 1952.

4.3.5 Ebb Shoal Volume versus Inlet Flow Area and Tidal Prism

Available survey data indicate that the existing cross-sectional flow area of the inlet throat is approximately 1.3 to 1.7 times larger than it was in the pre-project conditions of 1900 and 1933, respectively. According to empirical relationships[10], the corresponding tidal prism may have likewise increased by between 30% and 67%, relative to 1900 and 1933. Measured estimates of tidal prism at Beaufort Inlet are limited or of uncertain origin.

From empirical relationships between inlet tidal prism and ebb shoal volume[11], it appears that Beaufort Inlet's pre-project (1900) ebb shoal volume was close to the theoretical equilibrium volume (58.4 Mcy by survey versus 52.6 Mcy predicted). In contrast, because of the increased tidal prism and decreased shoal volume, the existing (2004) ebb shoal volume is significantly smaller than the equilibrium prediction (37.4 Mcy measured versus 72.1 Mcy predicted). This suggests that the inlet is greatly out of hydraulic equilibrium -- and that the theoretical tendency of the inlet's ebb shoal is to "seek" and retain sand from available littoral sources (i.e., adjacent shores) in order to move toward equilibrium.

[10] Jarrett (1976) and O'Brien (1969)
[11] Walton and Adams (1976)

4.4 Gross Changes in Shoreline and Channel Locations

Figure 17, on the following page, illustrates three historical shoreline/channel locations relative to 2004 conditions. (***Appendix D*** includes multiple plates with additional historical data.) These three shorelines, along with the 2004 aerial background, illustrate the fundamental changes in the inlet's planform.

In 'pre-project' conditions, from 1876 to 1933, Bogue Banks advanced seaward and easterly. Its growth toward the inlet is exhibited by the strong recurved spit shown in 1933 (yellow). Simultaneously, Shackleford Banks retreated landward and easterly, with abundant migratory shoals across the inlet. These processes appear steady and consistent in all intervening surveys between 1876 and 1933.

Over the first 40 years of 'post-project' conditions, from 1933 to 1974, the processes had reversed. Bogue Banks retreated rapidly back toward its 1876 location. By 1959 (not shown), and through at least 1974, the shoreline position was held by small groins and structures built to protect Fort Macon. Shackleford Banks advanced westward slowly at first (through 1959), and then very rapidly from 1959 to 1974, approaching its current location.

Over the next 30 years after 1974, the Bogue Banks shoreline advanced as a result of beach fill placement from inner-harbor dredging. Most recently (2003-05), the sand spit at Fort Macon, along the inlet's west bank, has advanced into the inlet. By the summer of 2005, continuous recurved spit growth had encroached upon the Range B channel limits. Meantime, Shackleford Banks consolidated its rapid westerly growth – building in width and elevation -- and ultimately advancing its shoreline toe directly into the eastern channel limits, at the junction of the Cut-Off and Range A channels.

The federal channel location established in 1936 more or less followed the semi-natural channel of 1933 -- except that it followed a straight south-southeasterly seaward alignment whereas the natural, pre-1936 channels all appear to have bent toward the west. (This curved orientation is also suggested by the modern shoal morphology in Figure 11.) The outer channel was shifted eastward in 1978 and the cut-off widener was later pushed westward. Both actions moved the channel banks ultimately closer to the modern shorelines of Shackleford and Bogue Banks, respectively.

Interior channels on the east side of the inlet, ran directly behind and along the western point of Shackleford Banks prior to 1937 (not shown). These channels appear to have decreased in flow and/or permanence after the project improvements. The apparent "collapse" of these channels likely contributed to the significant westerly advance of Shackleford Banks after 1937, as the federal channel was maintained and deepened.

Figure 17: Historical shoreline and channel centerline positions relative to existing (9/2004) aerial photography. Historical conditions were digitized from available nautical charts.