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Louisiana Barrier Island Erosion Study: Correction for the Effect of Relative Sea Level Change on Historical Bathymetric Survey Comparisons, Isles Dernieres Area, Louisiana

by

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"In studying successive hydrographic surveys for possible changes in the underwater topography, it is just as essential to bring them to the same sounding datum before comparisons as it is to bring them to the same geographic datum. This is basic."

Shore and Sea Boundaries
Schalowitz, 1964

Introduction

For the past several hundred years, hydrographers have surveyed the coastal waters of the United States to facilitate the safe navigation of ships by charting underwater topography and hazards. The U. S. agency charged with this duty is the National Ocean Survey (NOS), formerly the United States Coast and Geodetic Survey (USCGS). The USCGS was established in 1807 and made its first chart of coastal waters in 1835 (Schallowitz, 1964). The early bathymetric surveys by the USCGS are, in general, detailed high-quality representations of the underwater topography with as many as several hundred depth soundings in each square kilometer of seafloor surveyed. The original sounding data were plotted on charts known as smooth sheets. Although some of the earliest sheets have degraded with age, most are still in good shape. These sheets are a valuable resource which can be used to construct a history of the underwater topography in U. S. coastal waters.

Before evaluating seafloor changes between successive surveys, the charts reference systems, or datums, must be correlated. The information to correlate geographic datums is provided on most USCGS smooth sheets in the form of notes and markings of standard latitude/longitude graticules. The information can be used to shift depth sounding locations to a common geographic datum. Currently the datum most often used is the North American Datum of 1927. No guidelines are given for correlating the vertical reference level for soundings; known as the sounding, survey, or chart datum; because their relationships are complicated and depend on the local sea level conditions during the time of surveying as well as sea level changes between surveys.

Correlating sounding datums requires an understanding of how the datums were determined. Before correcting to a common vertical reference, depth soundings taken during hydrographic surveys measure the distance from the seafloor to the surface of the sea, which fluctuates with the rise and fall of the tide and the disturbing effects of the wind and weather (Marmer, 1951). After completion of a survey, these fluctuations are removed from the sounding value by subtracting the difference between the sea level at the time of sounding, measured at a tide gage in or near the survey area, and a vertical reference plane, usually a tidal plane. The assumption implicit in this procedure is that the water level in the entire survey area fluctuates as the water level at the tide gage. In general, the vertical datum for depth soundings is the mean-low or mean-lower-low water level because soundings reduced to these planes show expected average minimum depths for navigation (Marmer, 1951, Hicks, 1985, Schallowitz, 1964, and Adams, 1942). A datum is calculated for each survey by averaging the appropriate readings from a large number of water level measurements that were taken frequently (every hour or less) for the duration of surveying from a tide gage in or near the survey area. Most likely, the datum for two different surveys are not precisely the same because of natural fluctuations in the average sea level.

The correlation of sounding datums is influenced by conditions during the surveys that affect the average sea level and are a function of the distance between tide gages used to compute the datums, the time of year the surveys were made, how much time it took to complete the surveys, and how much time passed between surveys. For instance, the differences in the reference tidal planes for surveys using tide gages at different locations would depend on differences in wind conditions or river discharge, both of which can affect sea level (Komar, 1987). The reference tidal plane also is sensitive to the duration used for averaging the tide measurements and to when the series was taken because meteorologic and oceanic conditions change on daily and seasonal scales resulting in changes to sea level (Komar, 1987, Hicks, 1968, 1972, and Hicks and others, 1983). For example, the reference tidal plane follows the yearly cycle of higher sea level during summer months and lower sea level during winter months caused by the thermal expansion and contraction of the water column (Komar, 1987). On longer time scales, the plane will rise with rising eustatic sea level, and with subsidence of the land at the tide gage station.

When comparing surveys from different regions and/or from different times the relationship between the tidal planes used to reduce the soundings must first be established. The latter comparison, the comparison of the seafloor in the same region through time, is the case in this study. After correcting the chart datums to a common datum, a series of charts can be used to find the sequential history of the magnitudes and spatial patterns of erosion and accretion. In this way, historical charts can be an excellent source of information for understanding the processes of seafloor evolution.

The Necessity of Correlating Vertical Datums

When comparing surveys bracketing a period of sea level change the differences in sounding datums will result in errors if the datums are not correlated. Consider Figure 1, which schematically shows the influence of a change in sea level between successive surveys on sounding depths. In this figure, the seafloor has not undergone either erosion or accretion, but because of local subsidence, global sea-level rise, or both, the sounding in the later year's survey is deeper. The depth sounding taken during the later survey indicates a greater depth because the reference, the mean-low-water level, has risen higher with the rise in relative sea level. This results in an apparent erosion for the example in Figure 1 and a bias toward erosion in a comparison of actual surveys of a region where both true erosion and accretion has occurred. The erosion is an artifact of a changing datum, with the amount of apparent erosion equal to the rise in the datum.

In the case of Louisiana surveys, which this paper addresses, a correction for the large relative sea level rise between surveys must be made before patterns of erosion and accretion can be interpreted. Without this correction, errors on the order of several hundred thousand cubic meters of sediment for every square kilometer of seafloor will exist in seafloor change volume calculations. In historical seafloor change digital analyses (see Jaffe and others, 1988, List and others, 1990, or Sallenger and others, 1990 for a description of the methodology), commonly thousands of square kilometers of seafloor are compared which would result in billions of cubic meters of apparent erosion if datums were not correlated. The datums must be correlated to determine actual values, volumes and patterns of erosion and/or accretion between these surveys.

The purpose of this paper is to develop an objective methodology for establishing the changes in chart datums of historical surveys of Louisiana coastal waters. We first explore whether datum changes between surveys can be accurately determined using measurements of sea level rise and subsidence in Louisiana. Finding that measurements were taken neither for a long enough period nor near enough to the study area, we propose a new method for finding datum changes based on historical bathymetry data. In the final section, we discuss the significance of applying the datum change and the use of historical bathymetry data for extending the recent history of sea level.

Description of Historical Bathymetric Surveys and Their Vertical Datums

The geographic region considered here encompasses about 1750 km^2 of seafloor and extends from the Isles Dernieres barrier chain to the western end of Timbalier Island, an area located about 120 km west of the modern Mississippi River delta (Figure 2). In addition, the case is made for applying the results to a much larger coastal region extending from Timbalier Island to Sandy Point.

The study area was surveyed four times from 1853 to 1986. The United States Coast and Geodetic Survey (USCGS) made three surveys from 1853 to 1936. The USGS contracted to have a fourth survey of the area made in the summer of 1986. The following sections briefly describe each survey and the plane of reference for soundings.

Historical Surveys by the U. S. Coast and Geodetic Survey

1853

The U.S. Coast and Geodetic Survey made the first detailed bathymetric survey in the study area in 1853. This survey, comprised of about 9,000 soundings taken from April 3 to May 7, 1853, explored only the western half of the Isles Dernieres and concentrated on the Gulf seafloor. The purpose of the survey was to chart the waters near Ship Shoal, which was along the shipping route from New Orleans to Texas, and to select a suitable site on the shoal to locate a light house to help avoid another ship wreck like the one that had recently happened to the steamer Galveston (USCGS Superintendents Report for 1853).

Cartographers noted on the charts that soundings were referenced to mean low water observed during the survey from April 5th to May 5th; however, they did not note the location of the tide gage. In the 1853 Report of the Superintendent a likely location for this tide gage is indicated in that tide measurements were made for "two lunations" in 1853 near Raccoon Point at the western end of the Isles Dernieres (Table 1). Because the tide station was temporary, constructed specifically for the survey as was the practice at that time (Shallowitz, 1964), a different location was used to set the datum for surveys later in the 1800s.

1890s/1906

USCGS teams made the first complete survey of the study area about 40 years later. This survey was done in two stages. They surveyed seaward of the barrier islands and the backbay behind the western half of the barrier arc, Caillou Bay, from 1889 to 1891. The backbay behind the eastern half of the arc, Lake Pelto, was surveyed 15 years later in 1906. Both surveys were more detailed than the 1853 survey, with over 40,000 soundings taken in the area.

Again, the vertical plane of reference for soundings was mean low water (MLW). Four tide gages, measuring during different years and seasons at different locations, were used to define the MLW datums in the study area. It is, therefore, highly unlikely that the datums used to reduce the soundings are the same, and that small changes in depth from one part of the area to another could be caused by differences in datums.

Tide gage locations and the interval used to calculate the MLW datum are given on each chart from this period. Tide stations at Southwest Light, Ship Shoal Lighthouse and Timbalier Light House were used to determine the MLW datum for the 1889-1891 portion of the survey (Table 1). In the west, the datum area was calculated from four months of measurements (February to June, 1889) from a tide gage at Southwest Light. The datum for the middle portion of the survey area, by far the largest portion of the study area, was defined from measurements taken for a different 5 month period (December 1889 to May 1890) at a tide gage at Ship Shoal Light House. In the eastern part of the study area, the datum was calculated from measurements taken for about one month (March to April 1891) at Timbalier Light House. A piece of information not noted on the chart was that this datum was elevated by a piling up of water near land caused by high winds during the survey (page 60, The 1891 Report of the Superintendent of the U. S. Coast and Geodetic Survey):

> "The tide gage was established at Timbalier Light-house. For nearly one-half of the time occupied in the survey there was an extraordinary persistence of south-easterly winds, producing unusually high tides on the coast and in the bays; hence the plane of reference obtained for the soundings was probably somewhat above normal."

The elevated datum was observed in our seafloor comparisons in this area.

Information about the datum used to reduce soundings in the 1906 survey of the bay behind the eastern Isles Dernieres, Lake Pelto, is printed on the hydrographic chart. These notes indicate that a tide station at Round Bay, located north of the center of the Isles Dernieres, was used to reduce soundings. Again, the datum was most likely calculated as the average low water levels during the surveying, May 21 to June 11, 1906 (Table 1). Considering that there was 15 years between this survey and the others, and that the land was subsiding and sea level rising, this datum is likely higher than the 1890s survey datums.

1930s

The USCGS surveyed the area a third time from 1934 to 1936. This survey has the greatest density of soundings of the four surveys, with over 120,000 soundings taken in the study area. Again, soundings were referenced to mean low water. Cartographers did not note on the charts the location of tide station(s) used to establish the datum. Two of the charts, however, show tide gage stations. Tide stations were located behind the western tip of the Isles Dernieres and Wine Island, the island between the Isles Dernieres and Timbalier Island (Table 1, Figure 1).

Several references provide more detailed information about USCGS surveys in the Isles Dernieres area. Jaffe and others (1988) describe the surveys and show plots of sounding locations and bathymetric contour maps of USCGS surveys in the area. Surveying methods used by the USCGS during this period of time are covered in Shallowitz (1964) and Adams (1942). For a summary of the error criteria for USCGS surveys and how it changed through time, see Sallenger and others (1975).

The 1986 Survey

From June through August, 1986 over 100,000 depth soundings were taken in the study area. These soundings were reduced to a standard mean-lower-low water datum established during the 1960 to 1978 tidal epoch at a National Ocean Survey (NOS) tide gage located about 75 km east of the center of the study area at Grand Isle, Louisiana (Figure 2 and Williams and others, 1989). This plane is 20 cm lower than the MLW level during the three months of surveying, but is only 3 cm lower than MLW at the Grand Isle gage during 1986. It is worth noting that because the tide gage was not in the study area, the tide measured there might not have have been representative of the tide influencing the soundings. Lags between the times of high and low water at the tide gage and the study area have been predicted, which could affect the accuracy of correcting soundings to the distant tide station (NOAA Tide Tables, 1986).

Summary

In summary, bathymetric surveys were made during four periods in the study area in the past 135 years. The first three periods of surveying by the USCGS reduced soundings to MLW during the time of the surveying. The time period used to determine the mean low water, however, varied from one month to several years, and as many as four tide gages, each with a different tidal plane for reducing soundings, were used during each surveying period. The USGS reduced soundings of the 1986 survey to the mean lower low water during the 1960-1978 tidal epoch, which coincidentally is also within 3 cm of MLW for 1986.

Although soundings for all four survey periods were reduced to depth below mean low water, they were not referenced to the same vertical plane because the elevation of mean low water was rising rapidly relative to land in the study area because of subsidence and eustatic sea level rise. An added complication is that the averaging time for each MLW chart datum was not the same- seasonal fluctuations in water level cause short-term (several months) averages to be different from longer term (one year) averages. This sensitivity to averaging time must be accounted for in addition to the general trend of rising sea level.

Determining Datum Change Using Direct Measures of Sea Level and Subsidence

Ideally, vertical datum changes between hydrographic surveys are corrected using direct measures of the relative sea level rise between surveys. Penland and others (1988) used three types of data to find relative sea level change in Louisiana: 1) tide gage data, 2) geodetic leveling data, and 3) stratigraphic data. As will be shown below, a variety of factors prevent this direct method of datum correction from being used in this study.

Tide Gage Data

Tide gages measure water level after filtering out, either mechanically or electronically, short period motions such as waves. It would be relatively simple to determine the history of the chart datums if tide gages operated in the study area during the entire survey period, 1853 to 1986, and the type of tidal plane used as the chart datum and the period tidal measurements were averaged over to establish the plane were known for each survey. We could relate surveys to each other by calculating the difference in the appropriate average water level through time. However, a very limited amount of tide data was collected in the study area because the USCGS used temporary tide gages to determine the MLW datum for each survey.

Can the existing tide gage data be used to determine survey datum changes accurately enough for our purposes? Tide measurements are made in Louisiana by two government agencies, NOS and the U. S. Army Corp of Engineers (USACE). Figure 3 shows the location of tide gage stations in Louisiana. These monitoring programs have two major deficiences for use in establishing the history of chart datum changes in this study: 1) no tide gage stations exist in the study area, and 2) water level series from stations near the study area started only about 40 years ago, while the first detailed surveys were done about 135 years ago (Table 2). To use this data for ascertaining changes to survey datums, we must determine if we can relate relative sea level changes outside and inside the study area and also accurately extrapolate changes back in time to the earliest survey.

An accurate prediction of relative sea level rise inside the study area based on distant tide gage stations requires predictable spatial gradients in the rates of relative sea level rise. Geodetic leveling data shows that the subsidence component of relative sea level rise decreases with inland distance from the coast (Figure 4 and Ramsey and Moslow, 1987). In as much as the surveys are of coastal waters, it seems reasonable that the subsidence offshore would be more similar to rates at the coast than inland, so only tide stations along the coast will be examined for defining alongshore variations in relative sea level rise. Table 2 gives the relative sea level rise rates of the 5 tide stations from 3 locations along the coast of Louisiana (Figure 3). These rates are similar even though the gages rest on sediments deposited at different times- the data, admittedly sparse, does not support differential relative sea level rise along the coast near the study area during the period of operation of the gages, the 1930s to present. This is in contrast to the hypothesis of Ramsey and Moslow (1987) where spatial gradients of relative sea level rise along the coast (their Figure 9) are controlled by differences in geologic histories of the sublobes of the Mississippi Delta. Much of the data supporting their hypothesis, however, were from interior regions, not the coastal regions. It could well be that away from the coast the rate of subsidence, and therefore the rate of relative sea level rise, is affected to a greater extent by the geologic history. In addition to the coastal tide gage data, the limited geodetic leveling data (Figure 4) also suggests that coastal Louisiana has small longshore gradients in subsidence, and, since the eustatic contribution does not have gradients, we would expect similar rates of relative sea level rise along the coast.

Assuming that the rate of relative sea level rise is similar to rates outside the study area, we can use water level series from tide gages near the study area to calculate the rate of relative sea level rise experienced by the study area. Figure 5 shows the behavior of sea level at the Grand Isle NOS tide station. This station is selected because NOS gages record water levels more frequently than USACE gages (6 minutes versus 1 hour) and this gage is not as effected by large flood events as the Eugene Island gage, the other NOS gage.

Figure 5a shows the annual mean sea level at the Grand Isle NOS gage from 1947 to 1987. The line through the series is a linear regression best fit and has a slope of 1.04 ± 0.06 cm/yr, r^2=0.88. Using a linear regression model implies that the process of sea level rise is linear, which is not the case as excursions from the linear trend lasting 5 or more years are obvious when examining figure 5a. These excursions strongly affect trends for shorter series. Penland and others (1988) report linear regressions of 0.30 ± 0.22 from 1942 to 1962 and 1.92 ± 0.19 from 1962 to 1978. The deviations of annual sea level from a linear trend are related to fluctuations in meteorologic or oceanic conditions, which can persistent for several years. For instance, the Gulf Stream affects water level on both sides of the flow by altering the geostrophic balance (Maul and others, 1985 and Bruun, 1962). Even though there are reasons why the rise in sea level might not be linear, assuming a linear model allows the calculation of extrapolation errors using annual sea level data. Because of nonlinearities, the actual errors are likely to be greater.

For the datum correction problem, we are interested in finding the difference in elevation of two tidal planes measured a number of years apart. We must know the range of values that a predicted sea level will fall within. Errors in a linear regression occur because of uncertainty in the slope of the trend, the intercept, and the variability of the data (Ferguson, 1977). The minimum uncertainty is at the center of the data and increases with distance from the center forming an envelope bounded by two hyperbolae symmetric about the trend line (Figure 6). The uncertainty that annual sea level will be at the value predicted by the linear fit increases as we attempt to predict the historical values further back in time. Applying the formula for the standard error of prediction (page 32, Meyers, 1986) to the Grand Isle tide measurements, we are 95% confident that the annual mean sea level will be within ±10, ±14, ±18 cm of the value predicted by extrapolating the linear trend to 1935, 1890 and 1853, respectively.

But the datums can be, and likely are, different from annual sea level during those years. Not only is the annual MLW level different than the annual mean sea level, but the mean-low-water datums used for the surveys are not the average of a full year of measurements. At Grand Isle, monthly mean sea level fluctuates more than 20 cm during a year, mainly due to sea water temperature fluctuations and fresh water discharge from streams (for example, see Grand Isle data in Figure 5b). The short averaging time used to compute the MLW datum could cause up to an additional 10 cm difference between an extrapolated annual mean low water and the survey datum if the averaging time coincided with either seasonal highs or lows in water level.

In summary, it is likely that simply extrapolating an annual rate of sea level change from a nearby tide gage back in time could cause uncertainties on the order of 25 cm for extrapolation to the 1930s. This uncertainty increases as you extrapolate further back in time because the large variability of the tide data results in an increase in errors and the assumption of linearity- that the rate of relative sea level rise is the same as a linear fit to annual sea level measured during the last forty years- becomes more tenuous. The problems associated with the available tide data make it desirable to develop another method to find the history of sounding datum elevations.

Geodetic Data

Another method of finding sounding datum changes between surveys uses geodetic leveling data to determine the portion of relative sea level change due to land elevation changes and adds the eustatic component of change.

Holdahl and Morrison (1974) used geodetic leveling lines to determine the rates of subsidence for the Gulf coast (Figures 7a and b). Their isopleths of elevation change were computed from the difference between levelings. The first levelings were made at some time from 1897 to 1934. The relevelings were done from 1955 to 1973. There are no isopleths of elevation change in the study area because the leveling net did not have transects near the study area (Figure 7a). The closest isopleth, about 25 km north of the study area, shows 0.5 cm/yr of subsidence.

The same problems that made it difficult to use tide data to determine the chart datum changes also make it difficult to use the geodetic leveling data. Because there are no data in the study area, a scheme for extrapolating rates from outside the study area must be developed. Also, although the geodetic data span a longer time interval than the tide data, the leveling surveys did not coincide with hydrographic surveys so we must extrapolate and interpolate to match the survey dates. The errors inherent in the spatial and temporal extrapolations and interpolations are greater than for the tide data. Geodetic data cannot be used to obtain a precise value for datum changes between surveys.

Stratigraphic Data

Radiometric dating of an organic horizon thought to be at mean sea level during deposition, in conjunction with information about its present elevation, gives a rate of relative sea level change. Penland and others (1987) used carbon-14 to date in-situ peat deposits from 67 vibracores collected throughout the Terrebonne Parish delta-plain region. The Isles Dernieres study area is part of this region. Using only the 11 layers they dated as younger than 150 years, a linear regression gives a relative sea level rise rate of 0.84 ± 0.44 cm/yr. The large standard error of trend, 0.44 cm/yr, and the possibility of the rate varying during the 150 year period used to determine the rate, make the stratigraphic relative sea level rise rate unsuitable for determining precise changes in sea level during the past 135 years in the study area.

Summary

Although the direct measures of sea level change described above cannot be used for an accurate vertical datum correction, they provide rough estimates of the area's sea level change trends. These estimates are useful for substantiating a potentially much more accurate measure of the vertical datum change employing hydrographic survey data in sedimentologically inactive areas. This alternative method is described below.

Finding Chart Datum Changes using the Hydrographic Surveys

A comparison of soundings from different surveys can potentially gives us information about changes in the chart datum if we choose the proper area. The difference between depth soundings at the same location between two surveys is caused by erosion or deposition of the seafloor and changes in the vertical datum. This statement is formalized as:

$$\Delta Z_{surveys} = \Delta Z_{sediment\ transport} + \Delta Z_{vertical\ datum} \qquad (1)$$

where $\Delta Z_{surveys}$ is the difference in depth sounding values between two surveys, $\Delta Z_{sediment\ transport}$ is the change in depth caused by net erosion or accretion to the seafloor between the surveys, and $\Delta Z_{vertical\ datum}$ is a change in depth caused by the vertical plane of reference changing between the surveys. As Figure 1 shows, with a chart datum tied to relative sea level, stable seafloor will appear erosional when sea level rises or the land subsides. We can invert this problem to find the datum change if an area of stable seafloor can be identified in the study area. That is, if we know that an area has undergone neither net accretion nor erosion between two surveys, then the change in the depth sounding value is caused by a difference in the vertical datum between the surveys. Although a totally stable area might not exist in the study area, a region where the net seafloor change is small would give us the approximate changes in chart datum. As a working hypothesis, we postulate that there was a region with minimal net seafloor change during the period of surveying and that we can find datum changes between surveys by finding the apparent seafloor change to this region. The region could experience cycles of erosion and deposition between surveys and still be useful for determining datums changes if the amounts of erosion and deposition nearly balanced over time. In the following sections we first pose the question of what identifies a region with a stable seafloor, then we test for whether our predictors are successful by examining the spatial variation of change in the region.

Finding a Region with Minimal Net Seafloor Change

Two approaches, one based on the energy available to transport sediment and the other on the morphology of the seafloor, are used to identify a region with a stable seafloor.

The first approach to defining the region is based on energy arguments; three cases likely to produce a region with little net seafloor change are proposed. The trivial case is if a region of seafloor exists where the energy is too low to transport sediment. Obviously, there would be neither erosion nor accretion because there would be no sediment transport. It is not likely such a region exists in our study area because several major hurricanes and hundreds of cold-front storms passed through the study area between each set of surveys. The second case, a less stringent energy requirement, is that the energy distribution in the region results in small spatial gradients in transport. There still can be sediment transported; but, since the seafloor change is proportional to the transport gradients, the transport would result in little seafloor change. Sediment could be transported through the region, but would not be deposited or entrain additional sediment which would result in erosion. It is possible that such regions exist. The third case, the least stringent energy requirement, is when the energy distribution allows redistribution of sediment with equal transport into and out of the region. Again, the possibility of such a region existing is high, but it would be difficult to define. To define a region with a stable seafloor solely on the basis of energy would take substantially more knowledge of waves and currents in the area than is presently known. Energy arguments; however, do rule out obvious high-energy areas with large gradients in energy such as the shoreface (the steeply sloping portion of the profile near the islands) and tidal inlets from inclusion in the region.

The seafloor morphology can be used to define a region likely to have no net seafloor change. The region should have no geomorphic indicators of gradients in transport, such as sharp breaks in slope like those at channels or shoals. Geomorphic arguments rule out the shoreface and tidal inlets from inclusion in the search for region as did energy arguments. An additional area excluded as a stable seafloor Ship Shoal, a broad shoal located about 10 km offshore of the Isles Dernieres (Figure 2). The geomorphology of a stable region is likely to be gently sloping seafloor that maintains its slope through time.

We can more rigorously define a potentially stable region using profiles normal to the shoreline. Figure 8 shows profiles near the two ends of the Isles Dernieres that extend from the barrier island to seaward of Ship Shoal. These profiles were constructed using 1934 bathymetric data, but the general profile shape holds for any of the surveys in this study, the difference from other surveys being the position of the shoreface which moves landward as the islands erodes (Jaffe and others, 1988). Two profiles were necessary to define the depths at the base of the shoreface and/or Ship Shoal because of a westward shallowing trend. This trend follows the westward shoaling of the crest of Ship Shoal which is probably controlling the depth of the base of the shoreface through shielding of wave energy. The gently sloping seafloor present in both profiles between Ship Shoal and the shoreface is the region that we hypothesize is most stable. To be conservative in delineating this region from areas known to be changing, the chosen section is separated by several kilometers from the shoreface and Ship Shoal. A definition of the region by 1986 depths simplifies the computations that follow in the paper. This region covers 187 km^2 and is encompassed by the 6- and 9 m isobaths (Figures 9 and 10). The region does not extend into the eastern part of the study area because of inlet effects and a sand body migrating into the study area from the east (Jaffe and others, 1989).

Depth Changes in the Stable Region and Their Cause

Depth changes in the hypothesized region of minimal net seafloor change were calculated by differencing computer generated grids that represent seafloor surfaces for each of the survey periods. The average change ranges from 27 cm between the 1890's and 1934 surveys to 45 cm between the 1853 and 1890's surveys (Table 3). A

33 cm change between 1934 and 1986 is intermediate.

To statistically assess the confidence in the average change between surveys, we examined the depth change at selected points (grid nodes) on the seafloor. The grids had a node spacing of 1000 m in the longshore and 200 m in the on/offshore to insure that each node was supported by soundings in all 4 periods of surveying. For the 1890s, 1930s, and 1986 there were 554 nodes in the region, but only 441 nodes for 1853 when only the western Isles Dernieres was surveyed. Figure 11 shows histograms of change in these subareas for all three periods. Although the range of depth change values was large (over a meter), the estimate of the mean change in the region, $\overline{\Delta Z_{surveys}}$, is close to the true mean change of the region because of a small standard error ($\frac{s}{\sqrt{N}}$, where s is the standard deviation of the depth differences at grid nodes, and N is the number of grid nodes). The magnitude of the standard error of estimate is controlled by the large number of comparisons which cause the deviations from the mean to tend to cancel, although the small standard deviations also keep it low (16, 22, and 20 cm for 1930s-1986, 1890s-1930s, and 1853-1890s; respectively). At the 95% confidence level, the true mean depth change, μ_z, falls within the interval (from pg. 114, Bendat and Peersol, 1971):

$$\overline{\Delta Z_{surveys}} - \frac{s t_{n;\alpha/2}}{\sqrt{N}} \leq \mu_z < \overline{\Delta Z_{surveys}} - \frac{s t_{n;\alpha/2}}{\sqrt{N}} \qquad (2)$$

where $t_{n;\alpha/2}$ is the student t variable for the 95% confidence level with the degrees of freedom, n, which in this case is the number of grid nodes - 1. The mean depth change for all years fall within 2 cm of the true mean depth change for the region at the 95% confidence level. The confidence interval is smaller for change between the more recent surveys, when survey technique was improved.

We qualitatively examined whether these depth changes were consistent with a chart datum change by comparing contour maps. After adjusting the datums to the 1986 datum, contours from earlier maps shifted downslope (deeper to account for the rise in the datums with time) and roughly overlied the contours on the 1986 map. Had there been changes in the seafloor morphology or if the magnitude of datum corrections were wrong the contours would not have overlain.

To more rigorously evaluate whether the depth changes were due to a changing datum, to sediment transport, or to sounding errors, we examined the spatial variability of the depth change. What we expected to find follows this reasoning. If there were no sounding errors or gradients in sediment transport, then the change in depth between surveys would be constant throughout the hypothesized region, with the amount of change equal to the difference between the survey's vertical datum elevations. If depth change, however, was not constant then the patterns of change would indicate whether sounding errors or spatial gradients in transport caused the change. If there was a random pattern of depth change between surveys, it likely was due to random surveying errors because the forcing for transport is not random. If there was a systematic pattern to depth change, it can be caused by spatial gradients in transport causing erosion/deposition or by systematic survey error.

Figure 12 shows the spatial distribution of the average change in depth from 1934 to 1986 for 26 2 km by 2 km subareas within the hypothesized region of minimal net change. We chose this size to insure that, for all surveys, the surface representation was supported by more than one sounding trackline and more than 30 soundings. The subareas correspond to 20 of the grid nodes used in determining the accuracy of the mean depth change earlier in this section. This reduces the effects of random sounding error by averaging before comparing the depth change. It also is easier to examine the spatial distribution of change in 26 samples than in the complete 544 samples (the number of grid nodes in the "stable" region). All depth changes are negative (apparent erosion) and there is no systematic longshore variation in depth changes throughout the region. A box to the west of another box is just as likely to have greater erosion as less erosion (each case occurred 12 times). There is also no systematic on/offshore variation in depth change.

A more detailed analysis of the on/offshore variation was made to test whether there was a transport of sediment from the shoreface into the region. If sediment was moving offshore from the shoreface into the region, then as the forces driving the offshore transport decreased seaward of the shoreface, less material would be transported resulting in offshore deposition. Again, the calculation is made easier by using depth limits, with an increase in depth corresponding to a greater distance offshore of the shoreface. Table 3 gives the average changes by depth range. From 1934 to 1986, there was less than 2 cm difference between change averaged over 1 m depth intervals from 6 to 9 m. This suggests on/offshore gradients in transport were small for this time period and, unless seafloor change was caused by longshore gradients in transport, the hypothesized area is well chosen. The on/offshore variation in depth change was greater for the earlier survey comparisons; 5 cm from 1853 to 1890's and 12 cm from the 1890's to 1930's (Table 3).

Another check on the bathymetric comparison method for finding datum change is a comparison with stratigraphic and tide gage rates. Figure 13 shows the datums relative to the 1986 datum. The datums derived by a bathymetric comparison method are consistently above the value estimated from extrapolating the tide gage data for mean annual sea level. All three values from bathymetric analysis fall close to the short-term stratigraphic rate for relative sea level change. An even sedimentation in the hypothesized region would explain this observation. An alternate explanation is that the rate of sea level rise calculated from a linear regression of annual mean water level from 1947 to 1987 is not representative of rates from 1853 to the 1930s because of non-linearities in the trend or an increase in the rate of sea level rise during the past 40 years. We do not expect there to be an exact correlation because of reasons mentioned in the section about tide and stratigraphic data. It is reassuring; however, that the bathymetric method gives estimates for datum changes that are in qualitative agreement with the other two methods.

Summary

On the basis of energy and geomorphic arguments, we hypothesized there existed a region away from tidal inlets, offshore of the shoreface, and landward of Ship Shoal with little or no net change to the seafloor between surveys. We then calculated average depth changes in this region between surveys and checked the validity of our hypothesis using the pattern and amount of variation in depth change. From the variability analysis we found: 1) there was little on/offshore variation of depth change in 6 to 9 m water depth suggesting the region was not receiving appreciable amounts of sediment from the shoreface or offshore, 2) there is no systematic longshore variation between the surveys in this region suggesting there were no significant longshore gradients in transport, and 3) the 95% confidence intervals about the mean depth change, calculated using gride nodes in the hypothesized region, are less than 0.02 m. The low variability and random spatial distribution of depth change values are consistent with a mean change caused by a rise of survey datums, overprinted by random changes due to sounding errors. It should be pointed out that a portion of the mean change could be due to erosion or deposition that was evenly distributed over the entire area. However, this material would have to leave/enter the region, and we would expect there to be some indication of sink/source transport paths shown by gradients of depth change. These systematic variations were not large in the region that was hypothesized to have minimal net change. The low variability and apparently-random patterns of change are consistent with the interpretation that there was little net seafloor change in the region caused by sedimentation during the period of surveying. We conclude that the changes in this region measured by bathymetric surveys were primarily due to a changing vertical datum, which rose as eustatic sea level rose and as land subsided. As a further check, we compared the rates found using the bathymetric method to rates derived from stratigraphic and tide gage methods. The results of the three methods were in qualitative agreement.

Application of Datum Correction

Qualitatively, Figure 14 shows the effects of using the derived datum correction on a comparison between 1934 and 1986 surveys. The top plate, a comparison before making the datum correction, shows areas of apparent erosion greater than 0.5 m lightly shaded and areas of apparent accretion greater than 0.5 m in a darker shading. The 1986 islands are shown in black. The bottom plate shows the result of correcting the vertical datums to a common datum. Regions that appeared erosional before the correction, for instance places offshore of Ship Shoal and landward of islands, are no longer erosional at the 0.5 m level. This is because the erosion was fabricated, it was the result of the 1986 survey datum being higher than the 1934 datum, not the result of physical erosion. Another consequence of this correction is that the elongate accretional body entering the area from the east is now one continuous body with more than 0.5 m of deposition.

Not correcting soundings to a common datum has a huge effect on a sediment budget. Neglecting a 0.33 m datum change, the datum change between the 1934 and 1986 surveys, would result in over 500 million cubic meters of apparent erosion in the study area. This number is arrived at by multiplying the size of the area (1750 km^2) by the amount of datum correction (0.33 m). Even if the budget was confined to a smaller region adjacent to the barrier islands, the apparent erosion would be significant. For instance, if the sediment budget area was confined to a strip 5 km wide including the shoreface, islands, and backbays near the islands; the apparent erosion due to uncorrected survey datums between 1934 and 1986 would be about 75 million cubic meters and would mask real changes.

Because each survey datum was determined from the average of the MLW level during the survey, the numbers for datum change are related, but not equivalent, to long-term rate of relative sea level change. The changes in datum elevations are not average sea level rise rates for the entire time period between surveys, but rates between two short periods in time when mean sea level could have been either below or above normal. The long-term average rate will differ from bathymetric comparison rate as the expected mean sea level differs from mean sea level during surveying. The rates of relative sea level rise in the Isles Dernieres area of Louisiana derived from survey datums over the past 135 years range from 0.67 ± 0.10 to 1.23 ± 0.21 cm/yr, with a linear regression fit of 0.76 ± 0.09, r^2=0.97.

Application of Results to an Extended Study Area

In this section, we make the case for applying the datum correction derived in the Isles Dernieres area (Figure 10) to the much larger study area shown in Figure 15. Bathymetric data exists in this area for the same time periods as in the Isles Dernieres area, except for the 1850s surveys. Because this study area extends over 100 km to the east of the seafloor used to derive the datum correction, it is uncertain that the corrections are valid in this area.

However, in addition to the same problems as in the Isles Dernieres area-- namely the lack of long term tide records or other accurate direct measures of sea level rise-- this study area has no large seafloor areas that clearly meet the criteria for a bathymetric datum correction. Nevertheless, tide gage measurements over the last 40 years demonstrate that sea level rise rates lack a spatial gradient along this part of the Louisiana coast (Table 2). This implies that datum corrections derived in the western part of the study area should apply to the eastern part of the study area.

Comparisons of seafloor change maps with and without datum correction in the eastern part of the study area show differences similar to those in Figure 14. With the datum correction, patterns of erosion and accretion become more coherent, and random patterns of erosion in sheltered regions, such as bays, are minimized.

Summary and Conclusions

Historical charts are a rich data source for understanding the history of seafloor erosion and deposition. The Louisiana Barrier Island Study examined four bathymetric surveys taken in the Isles Dernieres area of Louisiana during the past 135 years. Each of these surveys had a different vertical datum. The vertical datum was the MLW during the period of surveying- as the land subsided and sea level rose, the datum rose relative to land. A direct comparison of soundings from different surveys without correcting soundings to a common datum introduces a bias towards erosion. The available tide gage, geodetic leveling, and stratigraphic data are too spatially and temporally limited to use to correlate the chart datums. We developed a method using comparisons of depth soundings to find datum change between surveys.

The method starts by defining a region of seafloor with little net change on the basis of energy and geomorphologic considerations. The stability of seafloor in the region is then tested using the spatial distributions and statistics of change between soundings from different surveys. In the Isles Dernieres area of Louisiana, such a stable region apparently existed during the past 135 years offshore of the shoreface and onshore of a shoal. The datum changes between surveys were: 1853 to 1890- 0.45 ± 0.02 m, 1890 to 1934- 0.27 ± 0.02 m, and 1935 to 1986- 0.32 ± 0.01 m.

Correcting vertical datums to a common datum is necessary to accurately determine seafloor change between surveys. For example, if the correction was not made for a comparison of the 1934 and 1986 surveys, the excess erosion introduced in the study area would exceed 500 million cubic meters. Excess erosion would be greater when comparing surveys taken over a longer time interval.

The datum correction procedure proposed here suggests relative sea level rise in the Isles Dernieres area since 1853 range from 0.67 ± 0.10 to 1.23 ± 0.21 cm/yr . These are not average rates for the entire time period between surveys, but rates between survey pairs. The average long-term relative sea level change rates will differ from these rates if the surveys were taken when mean sea level was either below or above the long-term average sea level. A least square fit of the bathymetry derived datum changes suggest a relative sea level rise rate of 0.76 ± 0.09 cm/yr, r^2=0.97.

The method for finding datum and relative sea level change described is only applicable if two surveys covered a common region with little net seafloor change between surveys. Additional applications of bathymetric survey data to determine relative sea level change in other areas should shed light on the general utility of this method. In particular, more work needs to be done on finding objective criteria for determining stable regions of seafloor. With further development of the method, our ability to separate sedimentological seafloor changes from datum induced seafloor changes will improve and we could possibly extend our knowledge of sea level history back to the first detailed hydrographic surveys.

Acknowledgements

The computer processing of the bathymetric surveys was an enormous undertaking which involved many people over the last five years. We wish to thank Greg Gabel, Thang Phi, Graig McKendrie, Rob Wertz, Carolyn Degnan, Clint Steele, Tracy Logue, Dorothy Hopkins, and Keith Dazeil. We also thank Shea Penland, Randy McBride, Matt Hiland and others of the Louisiana Geological Survey, who provided part of the shoreline information. We thank Karen Ramsey, also of the Louisiana Geological Survey, who provided compilations of NOS and USCACE tide gage data.

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TABLE 1

CHART DATUM AND TIDE GAGE INFORMATION					
REGISTER #	**YEAR**	**SURVEY DATES**	**GAGE LOCATION**	**TIDE OBSERVERS**	**CHART DATUM NOTES**
H-360	1853	April 3 to May 7	Bayou behind Raccoon Point	Mr. G. Wurdeman	"The curve of reference is mean low water observed during the survey from 5th April to 5th May"
H-1831	1888 1889	May 15 to May 25 Feb. 14 to June 8	S. W. Light	G. Johnsen, O. Anderson A. Nilson, S. Olsson	"Soundings ... refer to Mean Low Water"
H-2014	1889	Dec. 17,'89 to May 15,'90	Ship Shoal Light House	S. Olsen and O. Anderson	"Mean Low Water, Plane of Reference" on the chart, and in the Report of the Superintendent of the USCGS, 1890, "Observations of day tides at Ship Shoal Light House between January 6 and May 15" and "the range and the times of high and low water were much influenced by the wind"
H-2015	1889	Dec. 17,'89 to May 15,'90	Ship Shoal Light House	S. Olsen and O. Anderson	same as H-2014
H-2016	1890	Jan. 11 to April 28	Ship Shoal Light House	S. Olsen and O. Anderson	same as H-2014
H-2069	1891	Mar. 13 to April 24	Timbalier Light House		In the Report of the Superintendent of the USCGS, 1891, "tidal observations, which were begun March 13, and continued without interruption (from 6 a.m. to 6 p. m.) to the close of the season [April 24]... For nearly one-half of the time occupied in the survey there was an extraordinary persistence of south-easterly winds, producing unusually high tides on the coast and in the bays; hence the plane of reference obtained for the soundings was probably somewhat above normal."
H-2070	1891	Mar. 13 to April 24	Timbalier Light House		same as H-2069
H-2071	1891	Mar. 13 to April 24	Timbalier Light House		same as H-2069
H-2812	1906	May 21 to June 11	Round Bay		"Soundings show the depth at Mean Low Water, the plane of reference"
H-5479	1934	Feb. to May			Mean Low Water, chart shows tide gage in 5 to 6' depth about 200m behind west end of Wine Island
H-5537	1934	May 15 to Aug. 15			Mean Low Water, chart shows tide gage in 7 to 8' depth about 400 m behind Raccoon Point
H-5827	1935	March to April			Mean Low Water
H-5938	1935	Aug. to Sept.			Mean Low Water
H-6154	1936	April to June			Mean Low Water
H-6184	1936	June to Aug. 8, Oct.			Mean Low Water
USGS	1986	June to Aug.	Grand Isle	NOS	MLLW for tidal epoch 1960-78, which is 3 cm above MLW for 1986

TABLE 2

Relative Sea Level Rise Rates at Coastal Louisiana Tide Stations				
Station	#	Series	Rate (cm/yr)	Distance to Isles Dernieres (km)
NOS Stations				
Eugene Island		1939-1974	1.19±0.17	55
Grand Isle		1947-1987	1.04±0.06	75
USACE Stations				
Eugene Island	10	1944-1986	1.10±0.10	55
Grand Isle	14	1949-1986	1.11±0.08	75
Southwest Pass	15	1944-1988	0.94	140

is the tide station number in figure 3b

TABLE 3

Average Depth Change in "Stable" Region (m)				
Years of Surveys	Water Depth			
	6 to 7m	7 to 8m	8 to 9m	6 to 9m
1930s to 1986	-0.34	-0.32	-0.34	-0.33
1890s to 1930s	-0.21	-0.33	-0.29	-0.27
1853 to 1890s	-0.42	-0.47	-0.47	-0.45

- Using 1986 contours to define depth limits
- 1853 area smaller than the area used for other years because data only exists for west of the middle Isles Dernieres

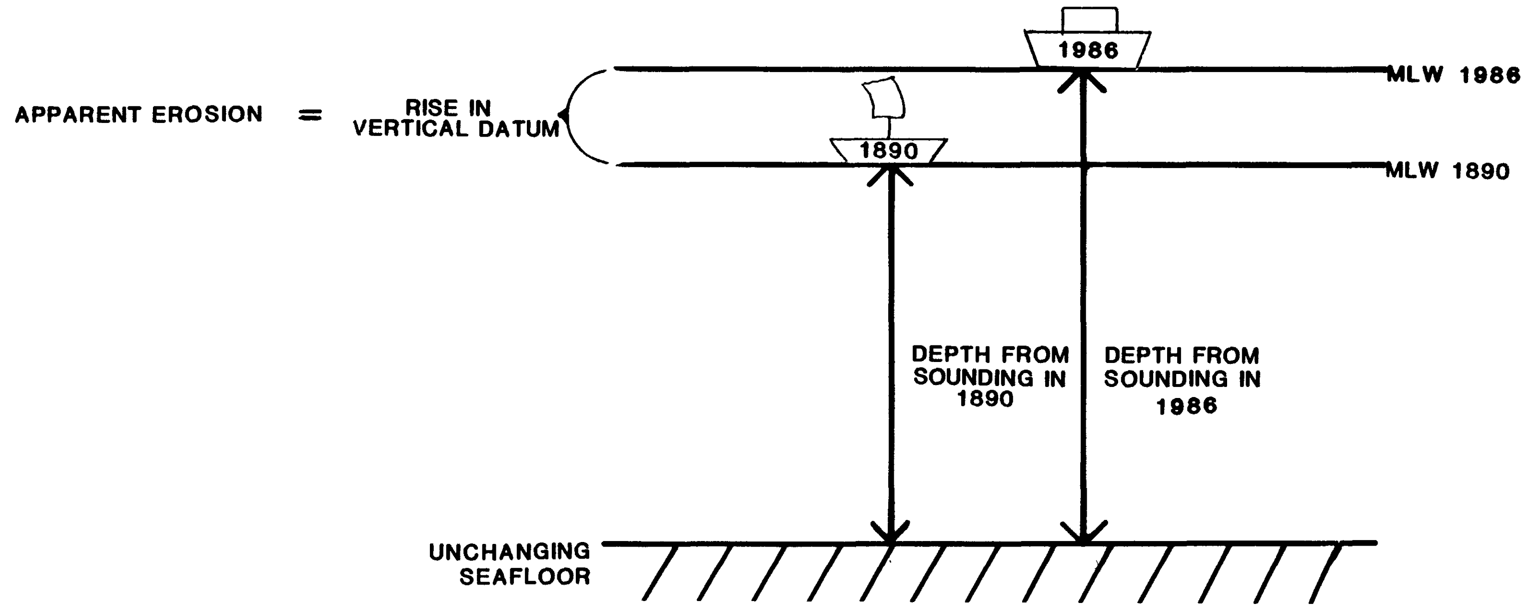


Figure 1- Schematic showing the effects of a rising vertical datum on a comparison of depth soundings of the same area of stable seafloor. The vertical datum can rise because of a combination of eustatic sea level rise, local subsidence, or differences in the short-term sea level during the averaging time used to establish the datum.

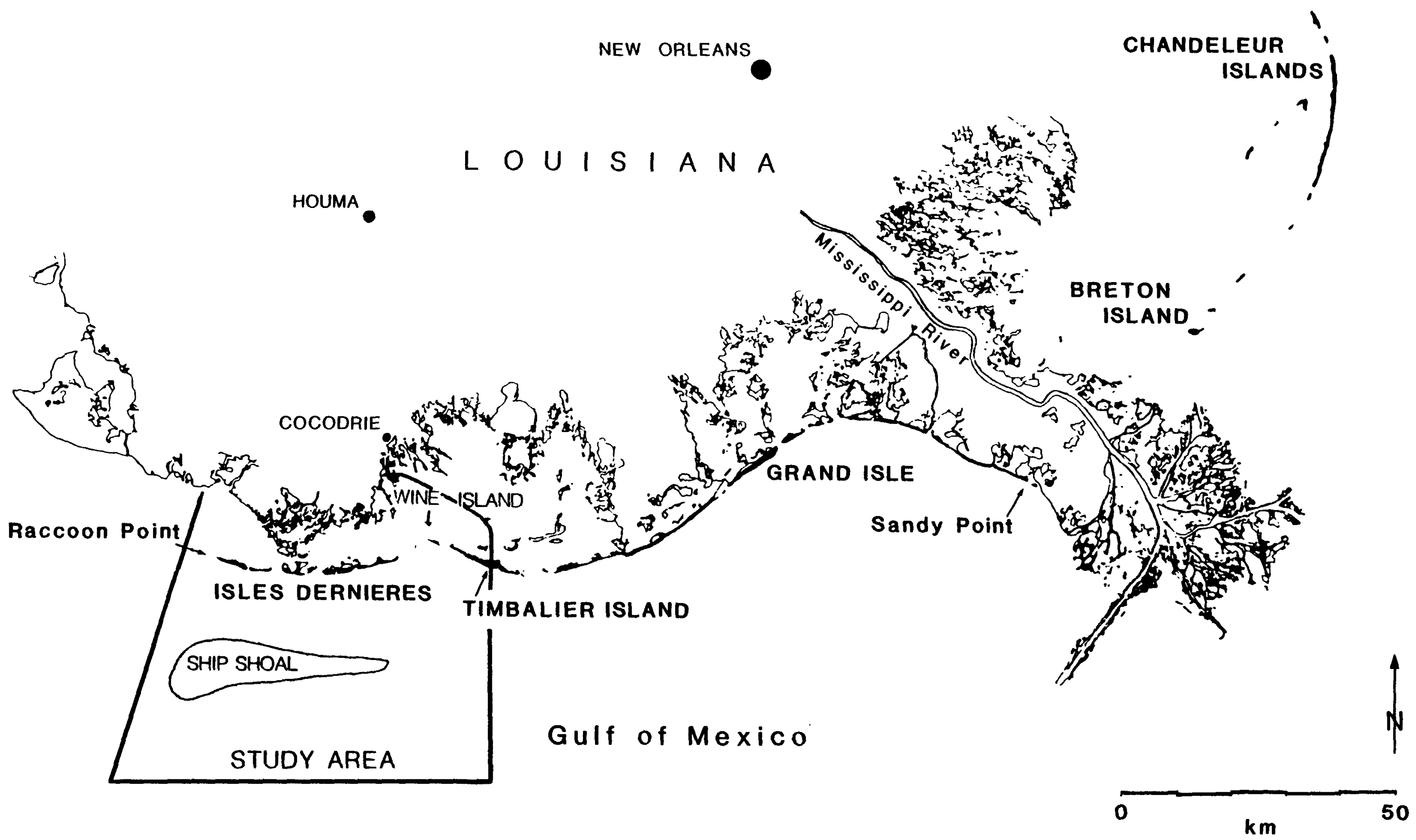


Figure 2- Location map showing study area in central Louisiana.

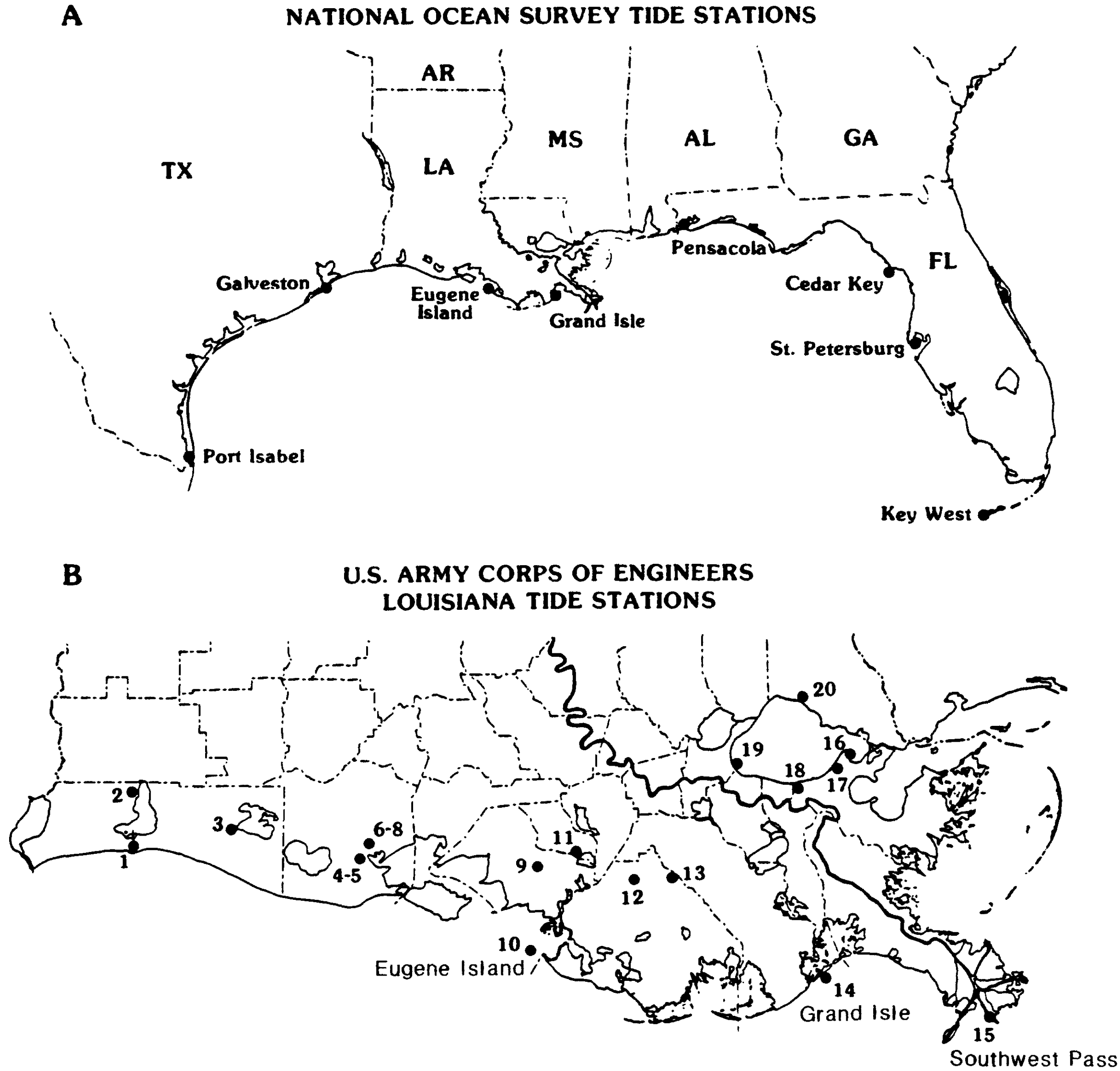


Figure 3- (A) Location of NOS tide gage stations in the Gulf of Mexico (Lyles and others, 1987, from Penland and others, 1988), (B) Location of U. S. Army Corps of Engineers tide gage stations in Louisana (USACE, 1931-1986, from Penland and others, 1988).

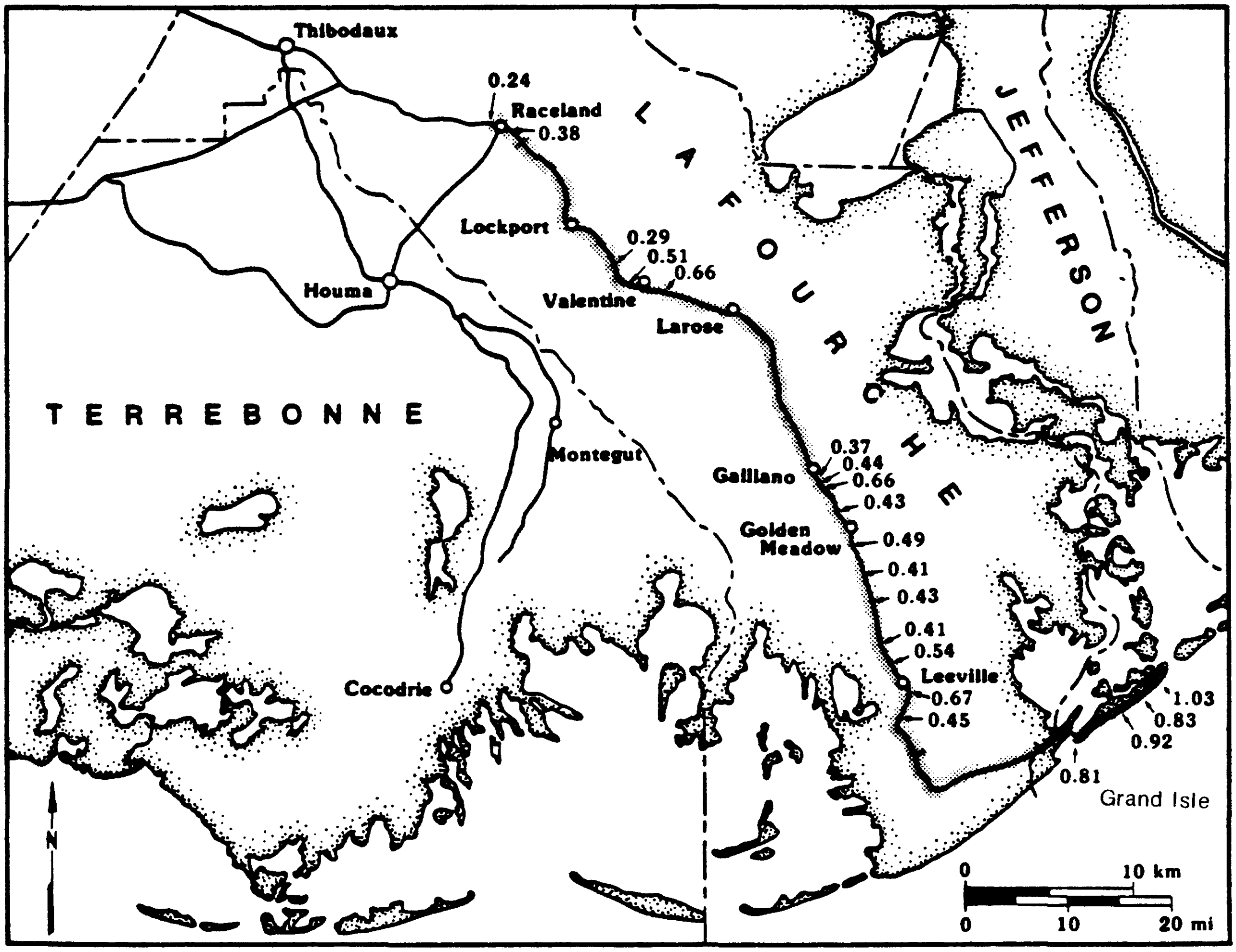
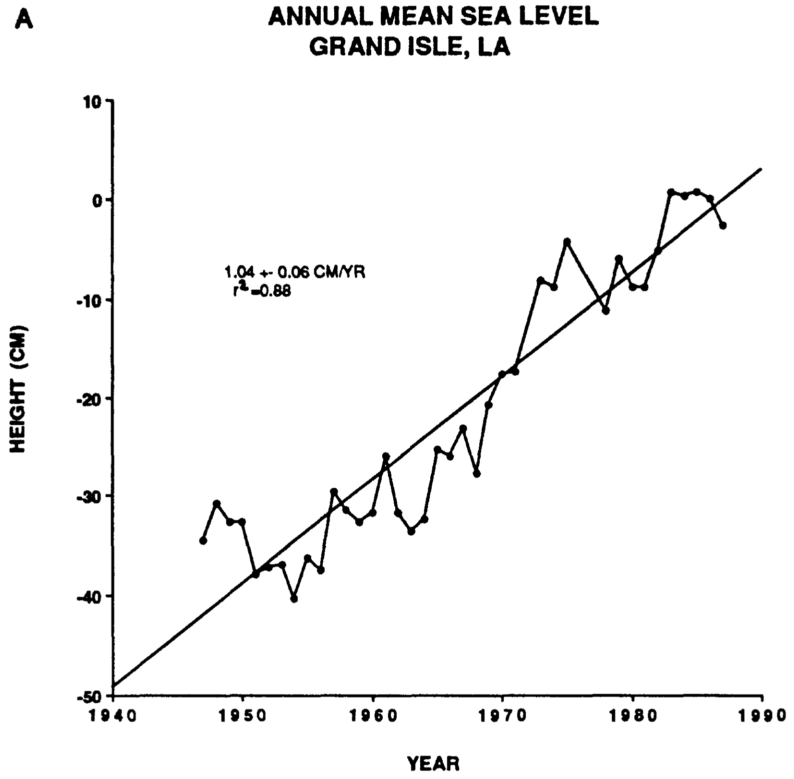


Figure 4- Subsidence rates (cm/yr) determined from geodetic leveling data taken in 1965 and 1982 (from Penland and others, 1988). Note the inland decrease in subsidence rates with distance from the coast.



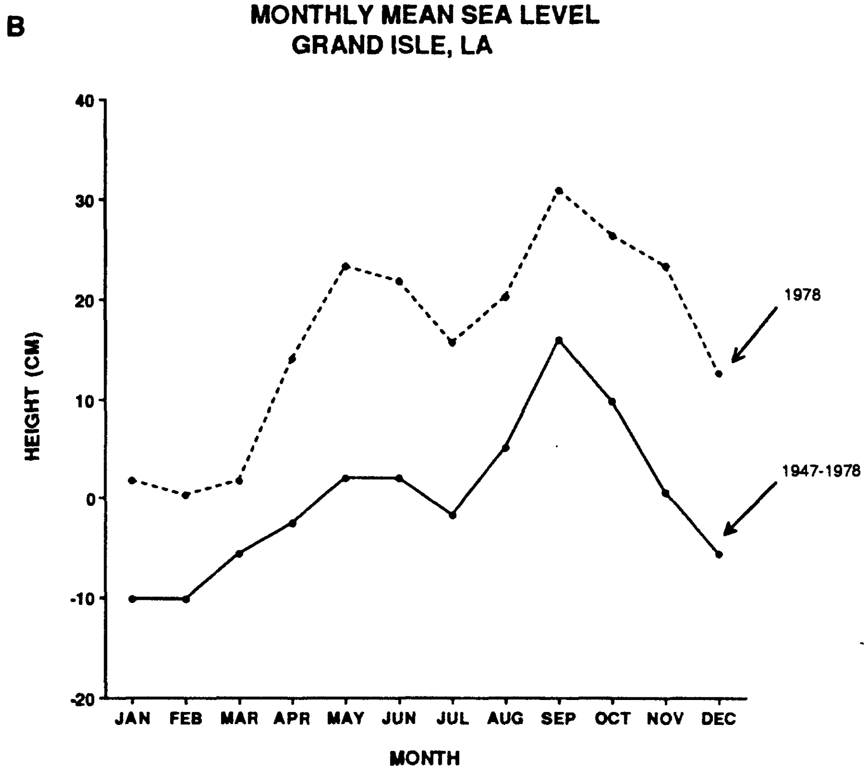


Figure 5- A) Annual mean sea level measured at Grand Isle NOS tide gage. The linear fit to the series is 1.04 ± 0.06 cm/yr, $r^{2=0.88}$. B) Monthly mean sea level for 1978 and averaged from 1947 to 1978 at Grand Isle NOS tide. Data from Hicks and others, 1983.

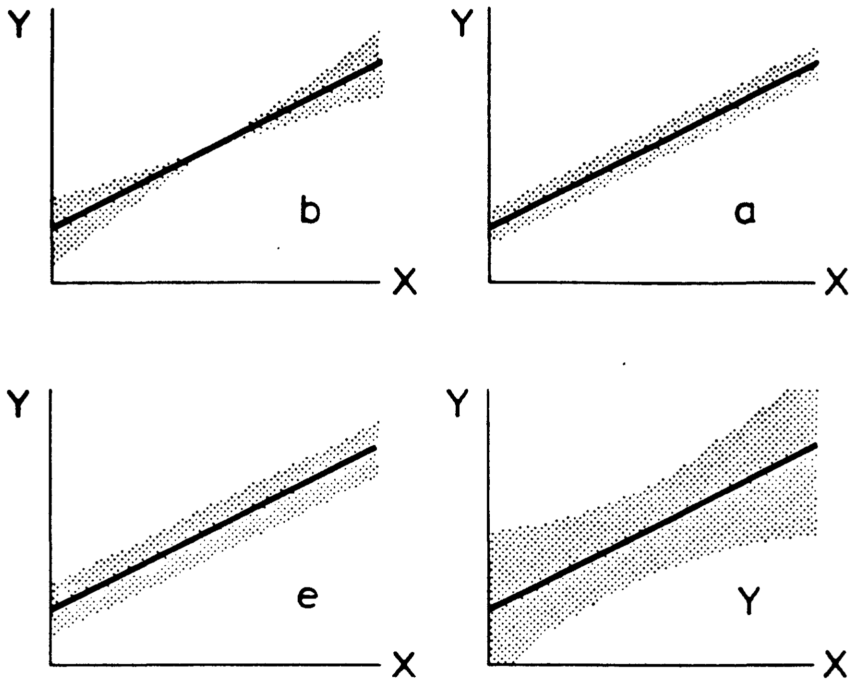
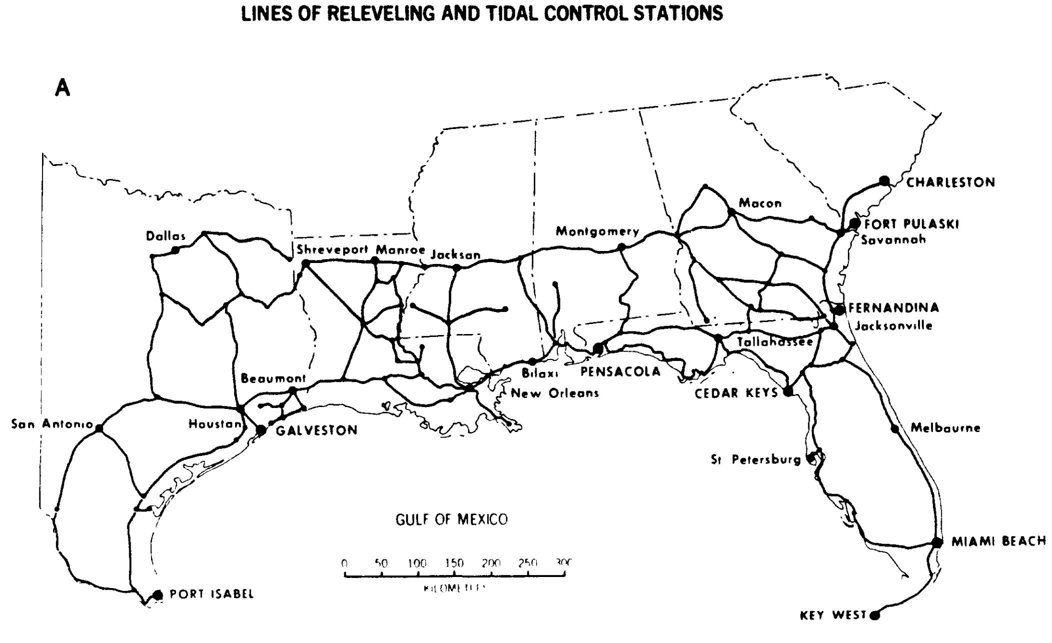


Fig. 6- Uncertainty in linear regression (from Ferguson, 1977). The dependent variable (Y, which in our case is annual sea level) may depart from the fitted trend because of uncertainty in slope (b) and intercept (a) as well as inherent scatter about trend (e).



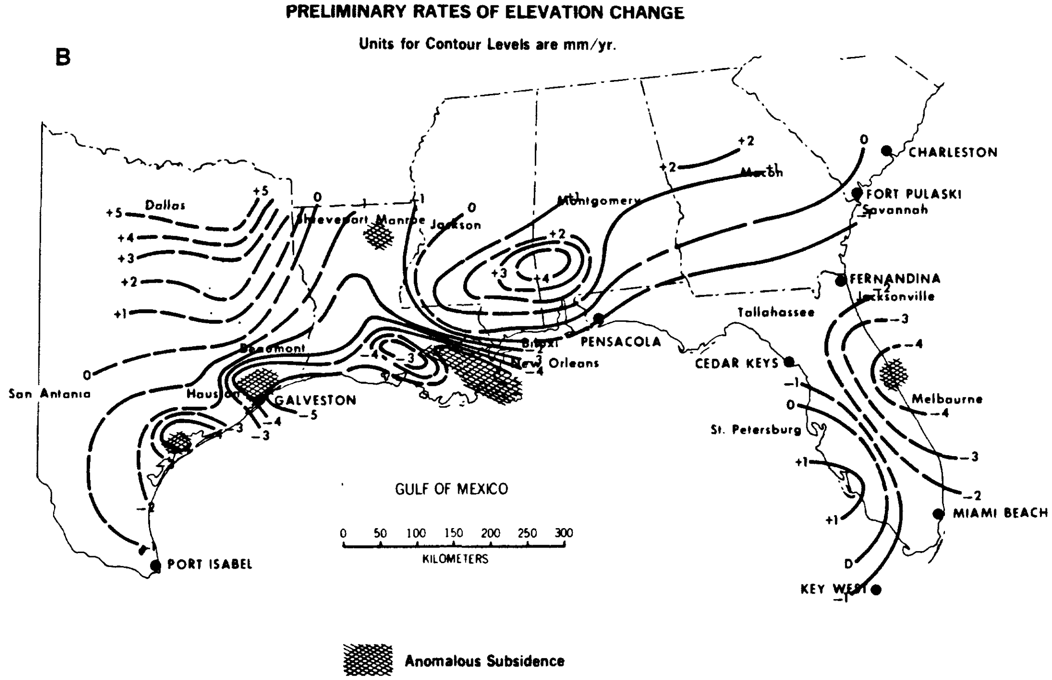


Figure 7- (A) Lines of releveling and tidal control stations in the Gulf of Mexico and southeastern United States (B) Preliminary rates of elevation change. Contours in mm/yr (from Holdahl and Morrison, 1974)

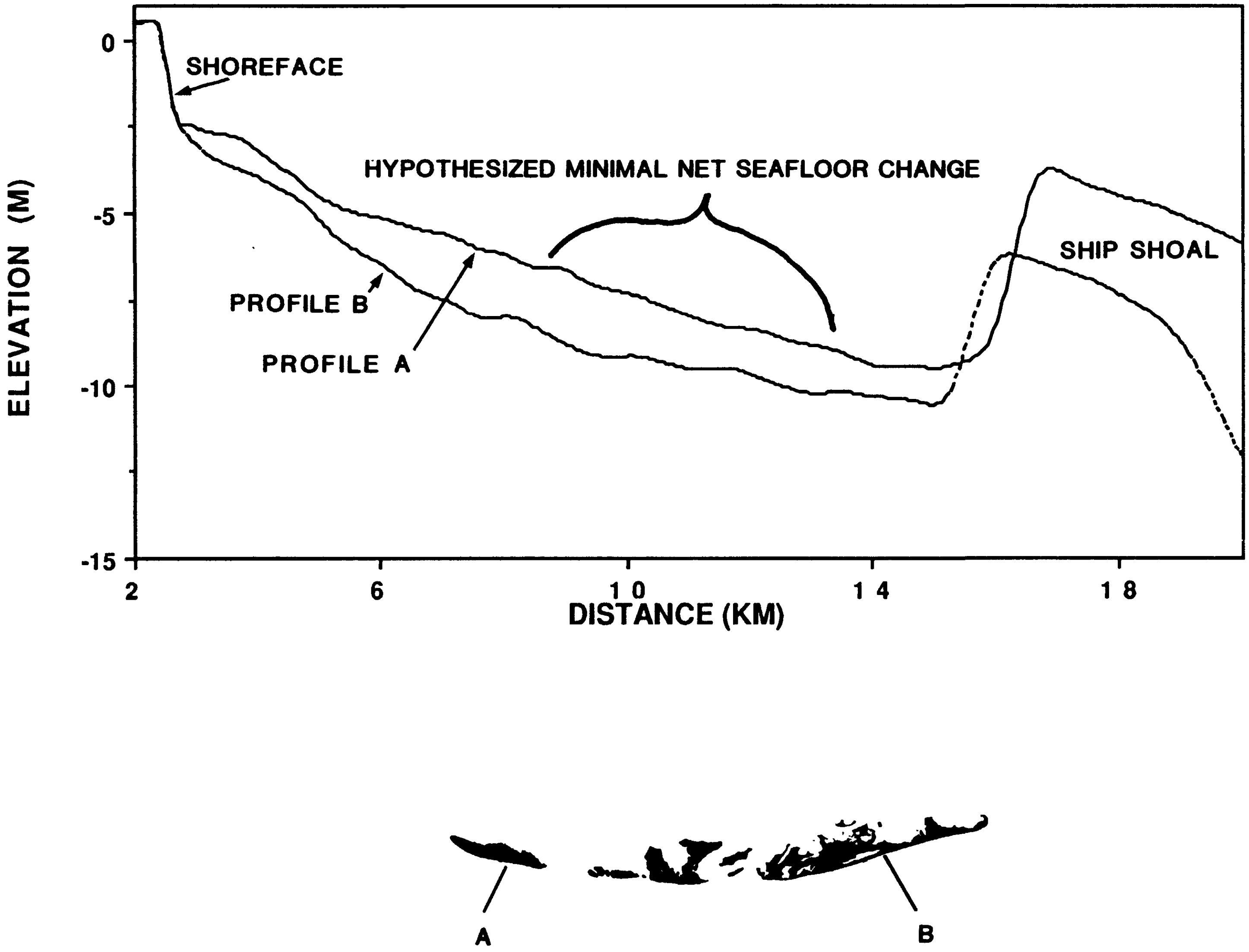


Figure 8- Shore-normal profiles off western (A) and eastern (B) Isles Dernieres showing on/offshore position of the hypothesized section with minimal net seafloor change. The section meets the geomorphic and energy criteria in that it is seaward of the shoreface, has a gently sloping seafloor, and is landward of and protected by Ship Shoal.

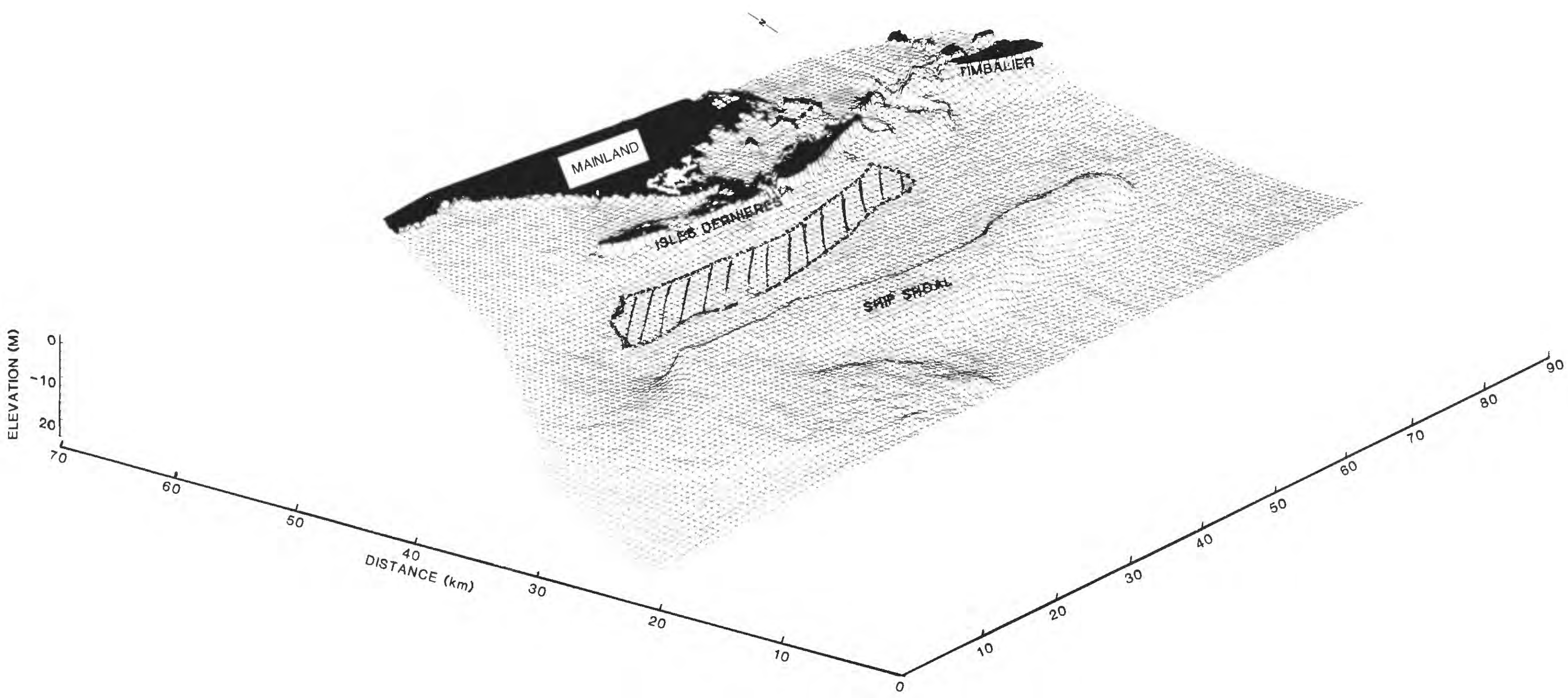


Figure 9- Mesh perspective view of the 1930s seafloor in the study area showing the area selected using geomorphic and energy criteria as having minimal net seafloor change during the period of surveying.

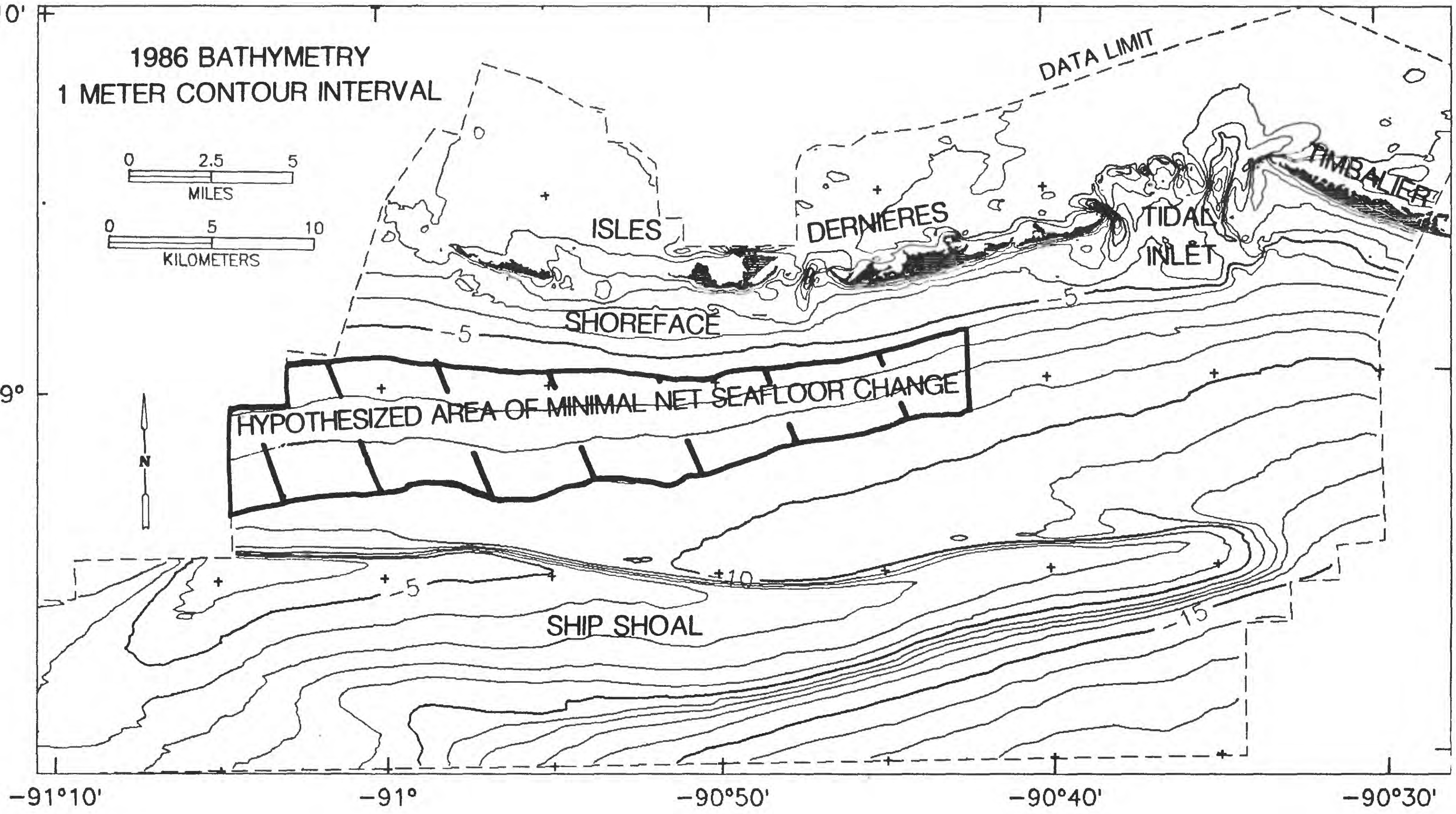


Figure 10- 1986 bathymetry showing hypothesized area of minimal seafloor change in the gently sloping region between Ship Shoal and the shoreface of the Isles Dernieres.

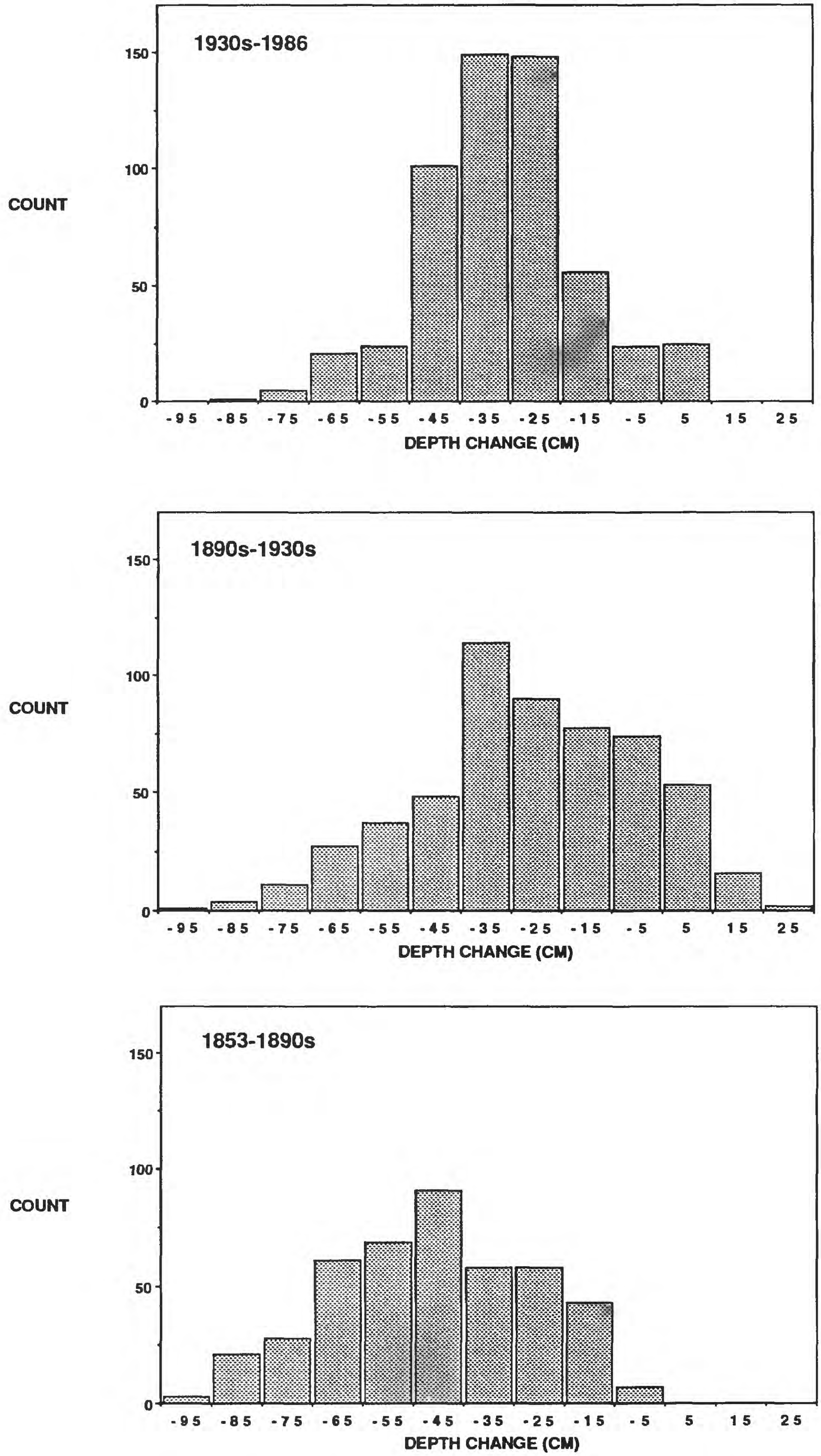


Figure 11- Histograms of depth changes between historical bathymetric surveys at grid nodes within the hypothesized stable region.

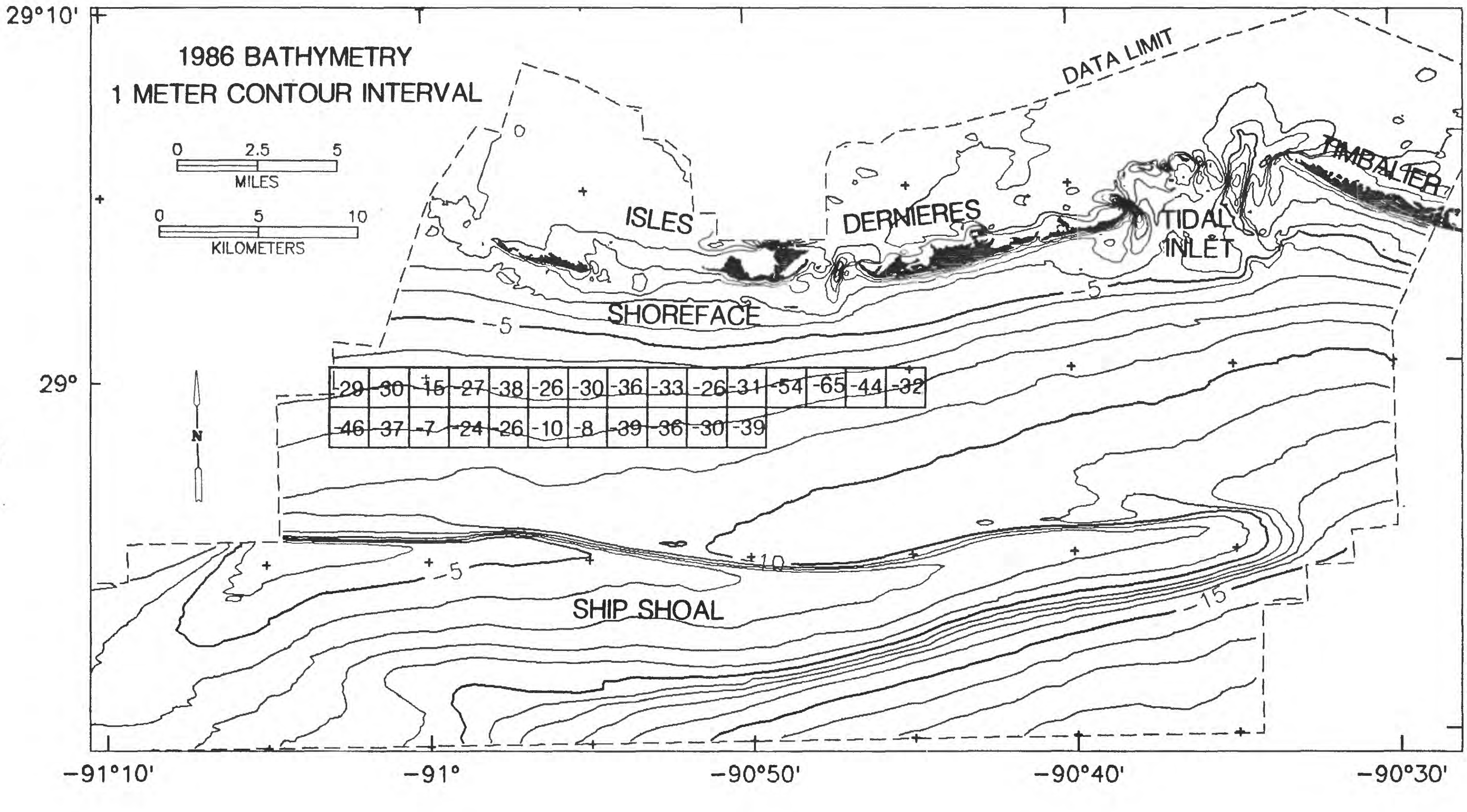


Figure 12- Variability of average depth changes (in centimeters) between 1930s and 1986 for 2 km by 2 km subregions.

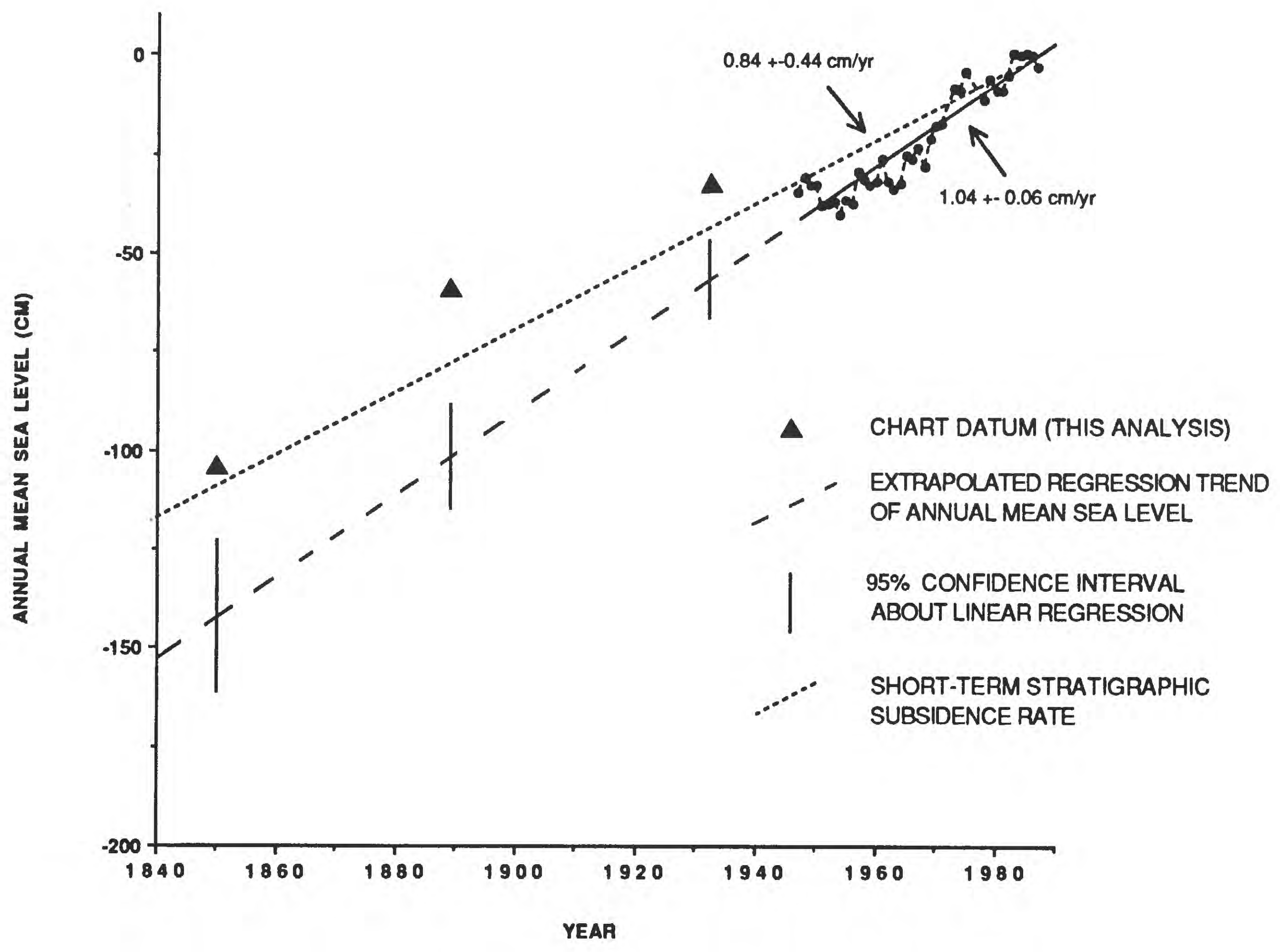
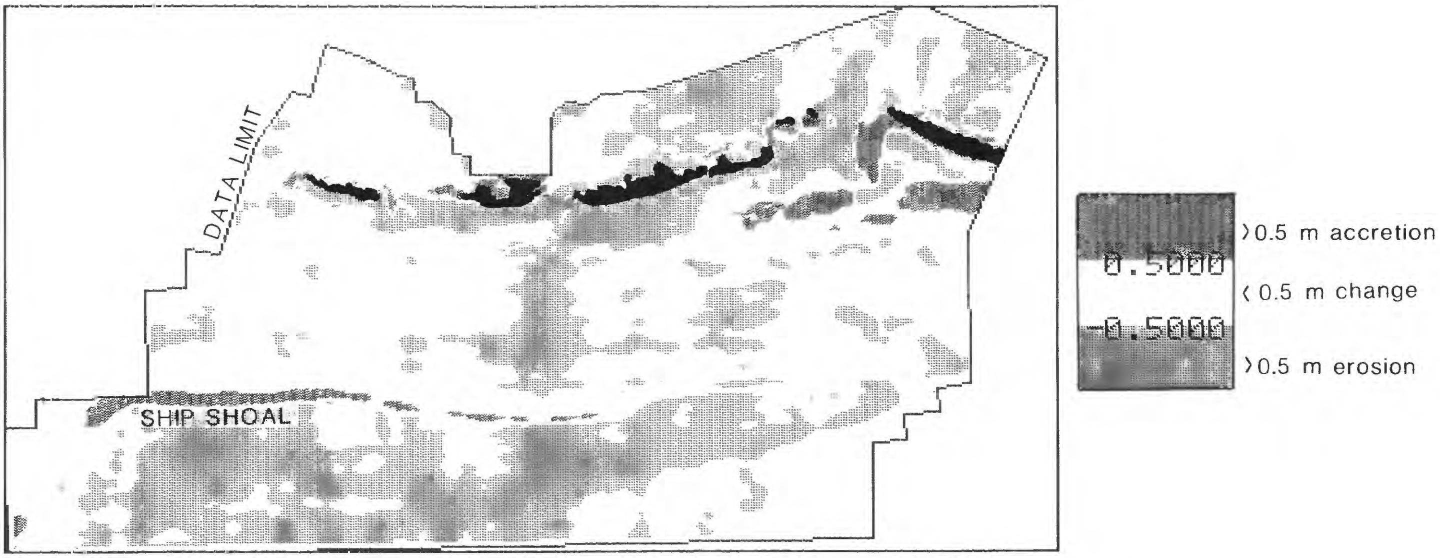
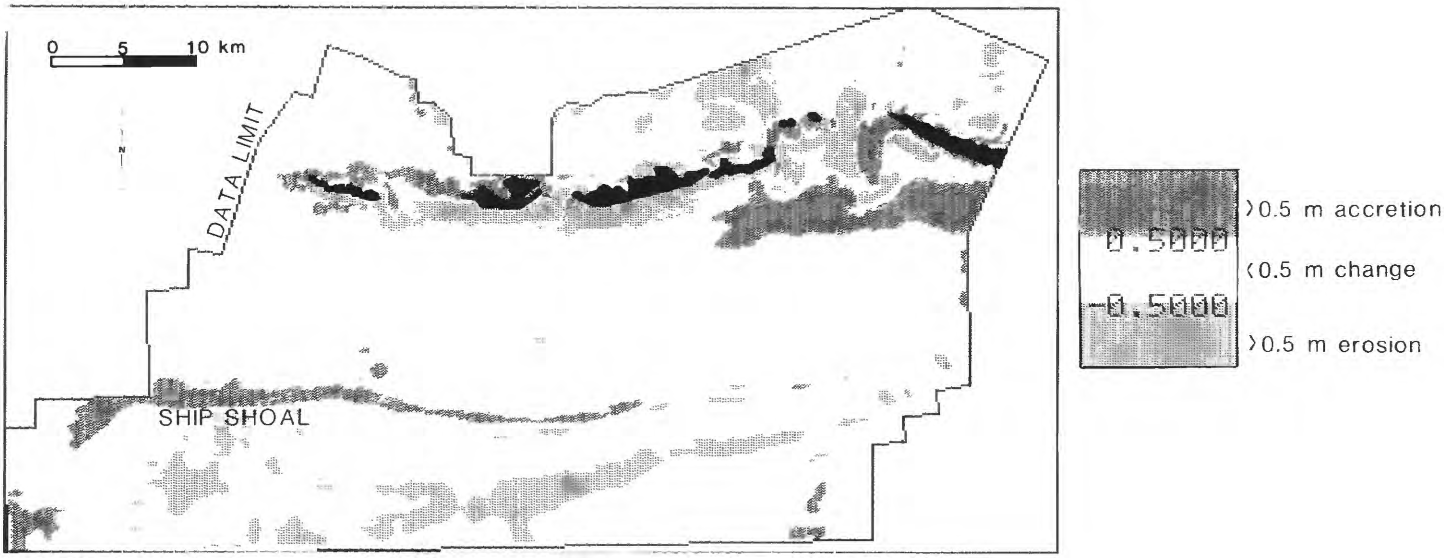


Figure 13- Comparison of chart datum changes determined from this analysis with the current rate of relative sea level rise from the Grand Isle tide gage extrapolated back in time. Note that the 95% confidence interval about the regression of the tide data increases with longer extrapolations. The rate of relative sea level rise from a stratigraphic analysis is also shown for comparison.



SEAFLOOR CHANGE FROM 1934 TO 1986, BEFORE VERTICAL DATUM CORRECTION



SEAFLOOR CHANGE FROM 1934 TO 1986, AFTER VERTICAL DATUM CORRECTION

Figure 14- Seafloor changes from 1930s to 1986 before (top) and after (bottom) making correction to bring chart datums to a common datum. Areas of apparent accretion greater than 0.5 m are lightly shade and areas of erosion greater than 0.5 m are in a darker shading. The 1986 islands are in black. Note that patterns of erosion/accretion with greater than 0.5 meter vertical change are clearer after correlating datums.

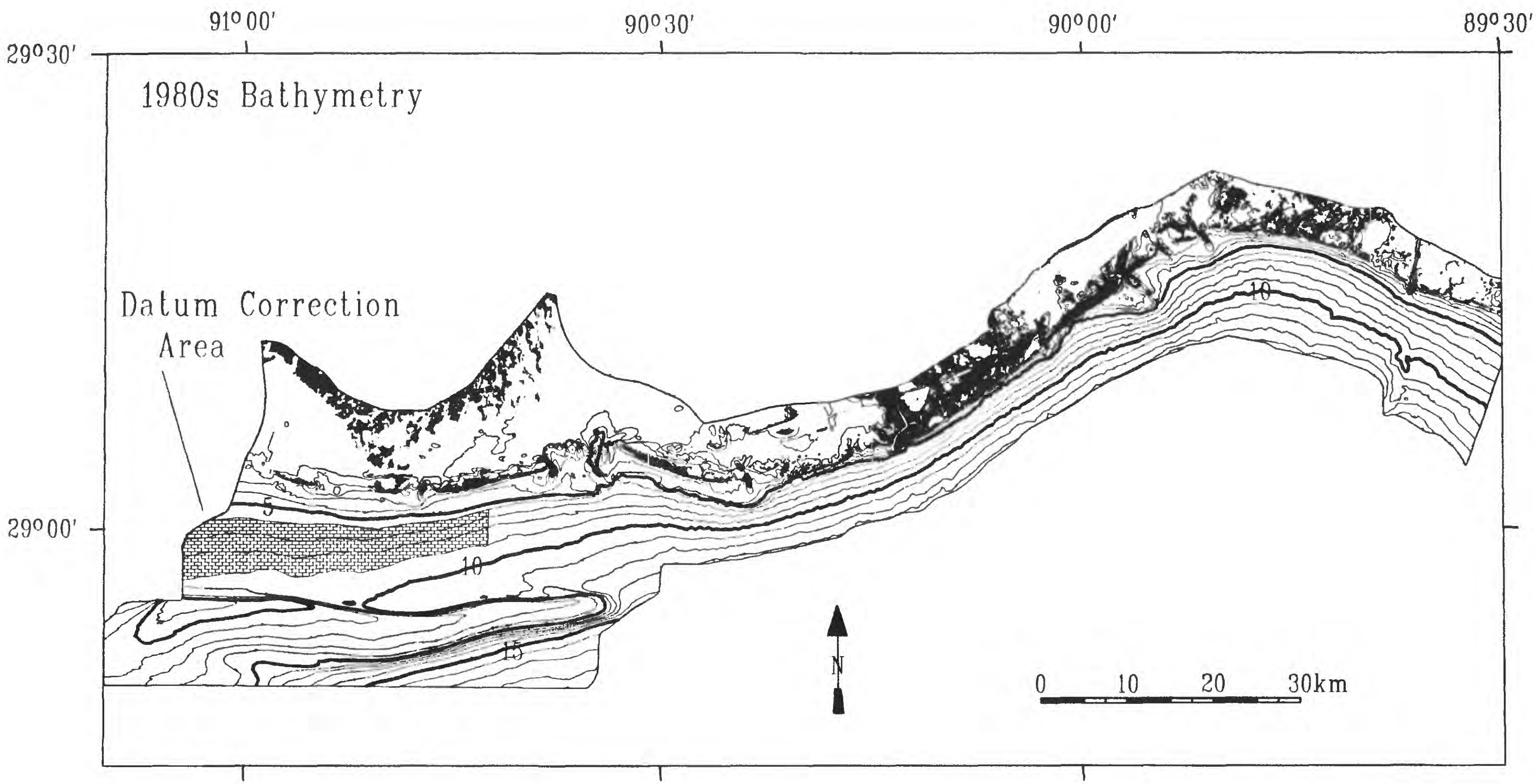


Figure 15- 1980s bathymetry showing the relationship between the larger study area and the region for the datum correction.