GEOLOGICAL CIRCULAR 74-2

SHORELINE CHANGES ON GALVESTON ISLAND (BOLIVAR ROADS TO SAN LUIS PASS)

AN ANALYSIS OF HISTORICAL CHANGES OF THE TEXAS GULF SHORELINE

BY ROBERT A. MORTON

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ABSTRACT

Historical monitoring along Galveston Island records the type and magnitude of changes in position of the shoreline and vegetation line and provides insight into the factors affecting those changes.

Documentation of changes is aided by the compilation of shoreline and vegetation line position from topographic maps, aerial photographs, and coastal charts of various vintages. Comparison of shoreline position based on topographic charts (dated 1851-52) and aerial photographs (taken in 1930, 1956, 1965, and 1973) indicates short-term changes of accretion and erosion along Galveston Island between the south jetty at Bolivar Roads and San Luis Pass. *Erosion* produces a net loss in land, whereas *accretion* produces a net gain in land. Comparison of the vegetation line based on the aforementioned aerial photographs indicates definite short-term cycles of erosion related to storms (primarily hurricanes) and recovery during intervening years of low storm incidence.

Long-term trend or direction of shoreline changes averaged over the 135-year time period of this study indicates net accretion along East Beach from the south jetty to the seawall; maximum net accretion on East Beach was greater than 6,000 feet. The beach in front of the seawall experienced net erosion ranging from 30 to 875 feet. Most of this net erosion is attributed to reorientation of the shoreline between 1850 and 1930. Net erosion was also recorded from the end of the seawall west approximately 3.75 miles; maximum net erosion was 1,260 feet or approximately 10.3 feet per year. Minimum net erosion for this segment was 140 feet or about 1.2 feet per year. Minor net accretion was recorded along the next 4.75 miles of beach; maximum net accretion was 100 feet. Net accretion at the other points was 90 feet or less and averaged about 75 feet. Thus, rates of change along the 4.75 miles of beach are less than 1 foot per year. Net erosion, which dominated the remaining 10 miles of beach westward to San Luis Pass, ranged from 20 to 210 feet and averaged about 150 feet. Rates of change for this western segment over the 120-year time interval ranged from less than 1 foot per year to 1.7 feet per year and averaged 1.3 feet per year.

Because of limitations imposed by the technique used, rates of change are subordinate to trends or direction of change. Furthermore, values determined for long-term net changes should be used in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

Major and minor factors affecting shoreline changes include: (1) climate, (2) storm frequency and intensity, (3) local and eustatic sea-level conditions, (4) sediment budget, and (5) human activities. The major factors affecting shoreline changes along the Texas Coast, including Galveston Island, are a deficit in sediment supply and relative sea-level rise or compactional subsidence. Changes in the vegetation line are primarily related to storms.

Studies indicate that shoreline and vegetation line changes on Galveston Island are largely the result of natural processes. A basic comprehension of these physical processes and their effects is requisite to avoid or minimize physical and economic losses associated with development and use of the beach.

INTRODUCTION

The Texas Coastal Zone is experiencing changes as a result of natural processes and man's activities. What was once a relatively undeveloped expanse of beach along deltaic headlands, peninsulas, and barrier islands is presently receiving considerable attention. Competition for space exists among such activities as recreation, construction and occupation of seasonal and permanent residential housing, industrial and commercial development, and mineral and resource production.

Studies indicate that shoreline and vegetation line changes on Galveston Island and along other segments of the Texas Gulf Coast are largely the result of natural processes. A basic comprehension of these physical processes and their effects is requisite to avoid or minimize physical and economic losses associated with development and use of the coast.

The usefulness of historical monitoring is based on the documentation of past changes in shoreline and vegetation line and the prediction of future changes. Reliable prediction of future changes can only be made from determination of long-term historical trends. Therefore, the utility of the method dictates the type of data used. Topographic maps dating from 1851 provide a necessary extension to the time base, an advantage not available through the use of aerial photographs which were not generally available before 1930.

Purpose and Scope

In 1972, the Bureau of Economic Geology initiated a program in historical monitoring for the purpose of determining quantitative long-term shoreline changes. The recent acceleration in Gulf-front development necessitates adequate evaluation of shoreline characteristics, where change is occurring by erosion and by accretion, or where the shoreline is stable or in equilibrium.

The first effort in this program was an investigation of Matagorda Peninsula and the adjacent Matagorda Bay area, a cooperative study by the Bureau of Economic Geology and the Texas General Land Office. In this study, basic techniques of historical monitoring were developed; results of the Matagorda Bay project are now nearing publication (McGowen and Brewton, in press).

In 1973, the Texas Legislature appropriated funds for the Bureau of Economic Geology to conduct historical monitoring of the entire 367 miles of Texas Gulf shoreline during the 1973-1975 biennium. Results of the project will be published ultimately in the form of detailed, cartographically precise shoreline maps. Work versions of these maps will be on open file at the Bureau of Economic Geology until final publication. In advance of the final report and maps, a series of preliminary interim reports will be published. This report covering Galveston Island, Bolivar Roads to San Luis Pass (fig. 1), is the first in that series.

General Statement on Shoreline Changes

Shorelines are in a state of erosion, accretion, or equilibrium at any particular time. Erosion produces a net loss in land, accretion produces a net gain in land, and equilibrium conditions produce no net change. Shoreline changes are the response of the beach to a hierarchy of natural cyclic phenomena including (from lower order to higher order) tides, storms, sediment supply, and relative sea-level changes. Time periods for these cycles range from daily to several thousand years. Most beach segments undergo both erosion and accretion for lower order events, no matter what their long-term trends may be. Furthermore, long-term trends can be unidirectional or cyclic; that is, shoreline changes may persist in one direction, either accretion or erosion, or the shoreline may undergo periods of both erosion and accretion. Thus, the tidal plane boundary defined by the intersection of beach and mean high water is not a fixed position line (Johnson, 1971). Shoreline erosion assumes importance along the Texas Coast because of active loss of land as well as the potential damage or destruction of piers, dwellings, highways, and other structures.

Acknowledgments

Assistance in preparation of this report was provided by L. W. Epps, M. K. Pieper, M. L. McKinley, and M. Amdurer. Drafting was under the supervision of J. W. Macon. Cartographic work was performed by D. F. Scranton. Critical review was provided by W. L. Fisher, L. F. Brown, Jr., and J. H. McGowen.

Cooperation of personnel with the U. S. Army Corps of Engineers, Galveston District aided in the acquisition of materials and information. The Texas General Land Office and Texas Highway Department provided access to some of the aerial photographs. Meteorological data was provided by the National Climatic Center and the National Hurricane Center.

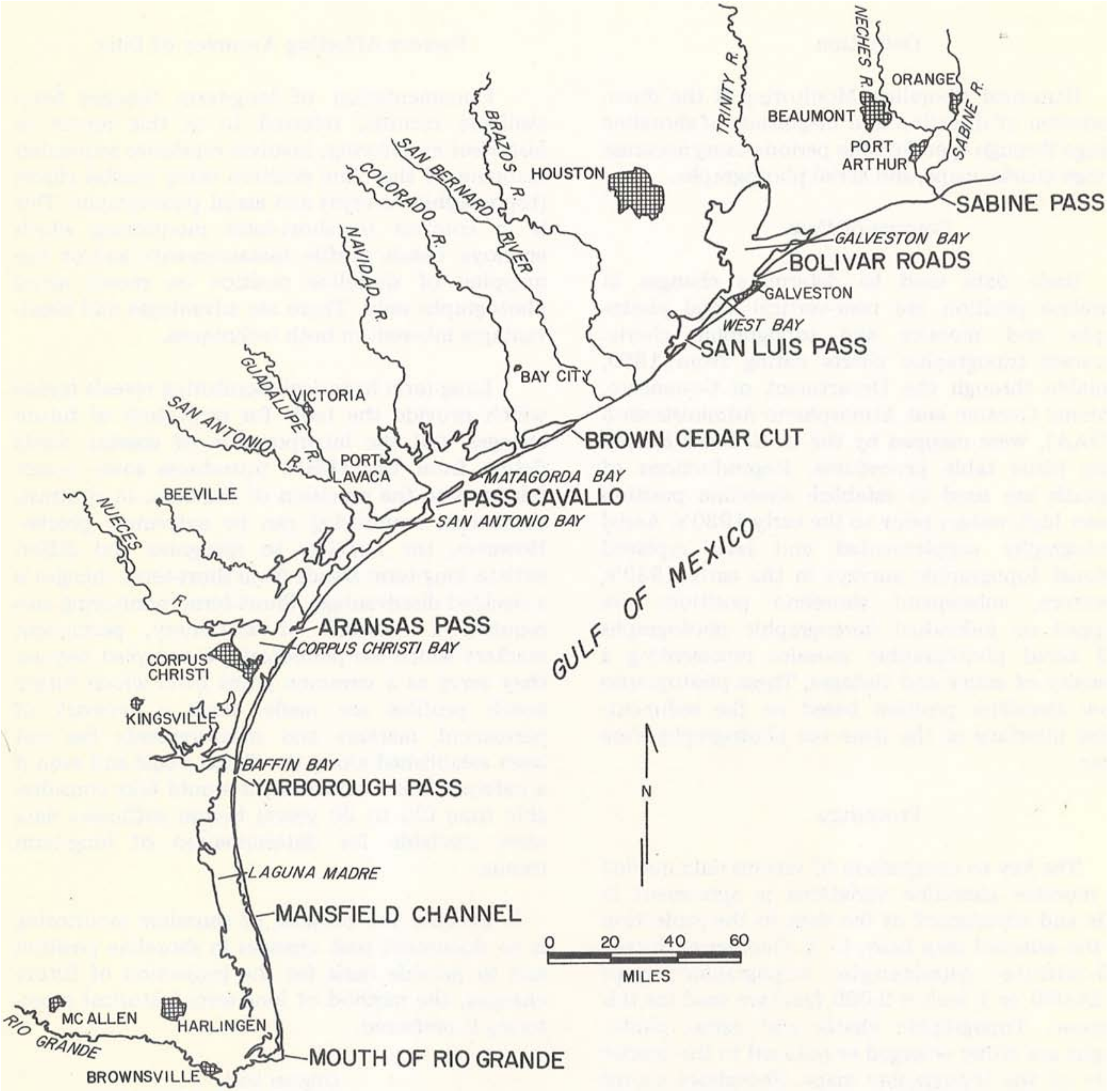

Figure 1. Index map of the Texas Gulf shoreline.

HISTORICAL SHORELINE MONITORING

GENERAL METHODS AND PROCEDURES USED BY THE BUREAU OF ECONOMIC GEOLOGY

Definition

Historical Shoreline Monitoring is the documentation of direction and magnitude of shoreline change through specific time periods using accurate vintage charts, maps, and aerial photographs.

Sources of Data

Basic data used to determine changes in shoreline position are near-vertical aerial photographs and mosaics and topographic charts. Accurate topographic charts dating from 1850, available through the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), were mapped by the U. S. Coast Survey using plane table procedures. Reproductions of originals are used to establish shoreline position (mean high water) prior to the early 1930's. Aerial photography supplemented and later replaced regional topographic surveys in the early 1930's; therefore, subsequent shoreline positions are mapped on individual stereographic photographs and aerial photographic mosaics representing a diversity of scales and vintages. These photographs show shoreline position based on the sediment-water interface at the time the photographs were taken.

Procedure

The key to comparison of various data needed to monitor shoreline variations is agreement in scale and adjustment of the data to the projection of the selected map base; U. S. Geological Survey 7.5-minute quadrangle topographic maps (1:24,000 or 1 inch = 2,000 feet) are used for this purpose. Topographic charts and aerial photographs are either enlarged or reduced to the precise scale of the topographic maps. Shorelines shown on topographic charts and sediment-water interface mapped directly on sequential aerial photographs are transferred from the topographic charts and aerial photographs onto the common base map mechanically with a reducing pantograph or optically with a Saltzman projector. Lines transferred to the common base map are compared directly and measurements are made to quantify any changes in position with time.

Factors Affecting Accuracy of Data

Documentation of long-term changes from available records, referred to in this report as *historical monitoring*, involves repetitive sequential mapping of shoreline position using coastal charts (topographic surveys) and aerial photographs. This is in contrast to short-term monitoring which employs beach profile measurements and/or the mapping of shoreline position on recent aerial photographs only. There are advantages and disadvantages inherent in both techniques.

Long-term historical monitoring reveals trends which provide the basis for projection of future changes, but the incorporation of coastal charts dating from the 1850's introduces some uncertainty as to the precision of the data. In contrast, short-term monitoring can be extremely precise. However, the inability to recognize and differentiate long-term trends from short-term changes is a decided disadvantage. Short-term monitoring also requires a network of stationary, permanent markers which are periodically reoccupied because they serve as a common point from which future beach profiles are made. Such a network of permanent markers and measurements has not been established along the Texas Coast and even if a network was established, it would take considerable time (20 to 30 years) before sufficient data were available for determination of long-term trends.

Because the purpose of shoreline monitoring is to document past changes in shoreline position and to provide basis for the projection of future changes, the method of long-term historical monitoring is preferred.

Original Data

Topographic surveys.—Some inherent error probably exists in the original topographic surveys conducted by the U. S. Coast Survey [U. S. Coast and Geodetic Survey, now called National Ocean Survey]. Shalowitz (1964, p. 81) states ". . . the degree of accuracy of the early surveys depends on many factors, among which are the purpose of the survey, the scale and date of the survey, the standards for survey work then in use, the relative importance of the area surveyed, and the ability and care which the individual surveyor brought to his task." Although it is neither possible nor practical to comment on all of these factors, much less attempt to quantify the error they represent, in general the accuracy of a particular survey is related to its date; recent surveys are more accurate than older surveys. Error can also be introduced by physical changes in material on which the original data appear. Distortions, such as scale changes from expansion and contraction of the base material, caused by reproduction and changes in atmospheric conditions, can be corrected by cartographic techniques. Location of mean high water is also subject to error. Shalowitz (1964, p. 175) states ". . . location of the high-water line on the early surveys is within a maximum error of 10 meters and may possibly be much more accurate than this."

Aerial photographs.—Error introduced by use of aerial photographs is related to variation in scale and resolution, and to optical aberrations.

Use of aerial photographs of various scales introduces variations in resolution with concomitant variations in mapping precision. The sediment-water interface can be mapped with greater precision on larger scale photographs, whereas the same boundary can be delineated with less precision on smaller scale photographs. Stated another way, the line delineating the sediment-water interface represents less horizontal distance on larger scale photographs than a line of equal width delineating the same boundary on smaller scale photographs. Aerial photographs of a scale less than that of the topographic base map used for compilation create an added problem of imprecision because the mapped line increases in width when a photograph is enlarged optically to match the scale of the base map. In contrast, the mapped line decreases in width when a photograph is reduced optically to match the scale of the base map. Furthermore, shorelines mechanically adjusted by pantograph methods to match the scale of the base map do not change in width. Fortunately, photographs with a scale equal to or larger than the topographic map base can generally be utilized.

Optical aberration causes the margins of photographs to be somewhat distorted and shorelines mapped on photographic margins may be a source of error in determining shoreline position. However, only the central portion of the photographs are used for mapping purposes, and distances between fixed points are adjusted to the 7.5-minute topographic base.

Meteorological conditions prior to and at the time of photography also have a bearing on the accuracy of the documented shoreline changes. For example, deviations from normal astronomical tides caused by barometric pressure, wind velocity and direction, and attendant wave activity may introduce errors, the significance of which depends on the magnitude of the measured change. Most photographic flights are executed during calm weather conditions, thus eliminating most of the effect of abnormal meteorological conditions.

Interpretation of Photographs

Another factor that may contribute to error in determining rates of shoreline change is the ability of the scientist to interpret correctly what he sees on the photographs. The most qualified aerial photograph mappers are those who have made the most observations on the ground. Some older aerial photographs may be of poor quality, especially along the shorelines. On a few photographs, both the beach and swash zone are bright white (albedo effect) and cannot be precisely differentiated; the shoreline is projected through these areas, and therefore, some error may be introduced. In general, these difficulties are resolved through an understanding of coastal processes and a thorough knowledge of factors that may affect the appearance of shorelines on photographs.

Use of mean high-water line on topographic charts and the sediment-water interface on aerial photographs to define the same boundary is inconsistent because normally the sediment-water interface falls somewhere between high and low tide. Horizontal displacement of the shoreline mapped using the sediment-water interface is almost always seaward of the mean high-water line. This displacement is dependent on the tide cycle, slope of the beach, and wind direction when the photograph was taken. The combination of factors on the Gulf shoreline which yield the greatest horizontal displacement of the sediment-water interface from mean high water are low tide conditions, low beach profile, and strong northerly winds. Field measurements indicate that along the Texas Gulf Coast, maximum horizontal displacement of a photographed shoreline from mean high-water level is approximately 125 feet under these same conditions. Because the displacement of the photographed shoreline is almost always seaward of mean high water, shoreline changes determined from comparison of mean high-water line and sediment-water interface will slightly *underestimate rates of erosion* or slightly overestimate rates of accretion.

Cartographic Procedure

Topographic charts.—The topographic charts are replete with a 1-minute-interval grid; transfer of the shoreline position from topographic charts to the base map is accomplished by construction of a 1-minute-interval grid on the 7.5-minute topographic base map and projection of the chart onto the base map. Routine adjustments are made across the map with the aid of the 1-minute-interval latitude and longitude cells. This is necessary because: (1) chart scale is larger than base map scale; (2) distortions (expansion and contraction) in the medium (paper or cloth) of the original survey and reproduced chart, previously discussed, require adjustment; and (3) paucity of culture along the shore provides limited horizontal control.

Aerial photographs.—Accuracy of aerial photograph mosaics is similar to topographic charts in that quality is related to vintage; more recent mosaics are more accurate. Photograph negative quality, optical resolution, and techniques of compiling controlled mosaics have improved with time; thus, more adjustments are necessary when working with older photographs.

Cartographic procedures may introduce minor errors associated with the transfer of shoreline position from aerial photographs and topographic charts to the base map. Cartographic procedures do not increase the accuracy of mapping; however, they tend to correct the photogrammetric errors inherent in the original materials such as distortions and optical aberrations.

Measurements and Calculated Rates

Actual measurements of linear distances on maps can be made to one-hundredth of an inch which corresponds to 20 feet on maps with a scale of 1 inch = 2,000 feet (1:24,000). This is more precise than the significance of the data warrants. However, problems do arise when rates of change are calculated because: (1) time intervals between photographic coverage are not equal; (2) erosion or accretion is assumed constant over the entire time period; and (3) multiple rates ($\frac{n^2 - n}{2}$, where n represents the number of mapped shorelines) can be obtained at any given point using various combinations of lines.

The beach area is dynamic and changes of varying magnitude occur continuously. Each photograph represents a sample in the continuum of shoreline changes and it follows that measurements of shoreline changes taken over short time intervals would more closely approximate the continuum of changes because the procedure would approach continuous monitoring. Thus, the problems listed above are interrelated, and solutions require the averaging of rates of change for discrete intervals. Numerical ranges and graphic displays are used to present the calculated rates of shoreline change.

Where possible, dates when individual photographs actually were taken are used to determine the time interval needed to calculate rates, rather than the general date printed on the mosaic. Particular attention is also paid to the month, as well as year of photography; this eliminates an apparent age difference of one year between photographs taken in December and January of the following year.

Justification of Method and Limitations

The methods used in long-term historical monitoring carry a degree of imprecision, and trends and rates of shoreline changes determined from these techniques have limitations. Rates of change are to some degree subordinate in accuracy to trends or direction of change; however, there is no doubt about the significance of the trends of shoreline change documented over more than 100 years. An important factor in evaluating shoreline changes is the total length of time represented by observational data. Observations over a short period of time may produce erroneous conclusions about the long-term change in coastal morphology. For example, it is well established that landward retreat of the shoreline during a storm is accompanied by sediment removal; the sediment is eroded, transported, and temporarily stored offshore. Shortly after storm passage, the normal beach processes again become operative and some of the sediment is returned to the beach. If the shoreline is monitored during this recovery period, data would indicate beach accretion; however, if the beach does not accrete to its prestorm position, then net effect of the storm is beach erosion. Therefore, long-term trends are superior to short-term observations. Establishment of long-term trends based on changes in shoreline position necessitates the use of older and less precise topographic surveys. The applicability of topographic surveys for these purposes is discussed by Shalowitz (1964, p. 79) who stated:

> "There is probably little doubt but that the earliest records of changes in our coastline that are on a large enough scale and in sufficient detail to justify their use for quantitative study are those made by the Coast Survey. These surveys were executed by competent and careful engineers and were practically all based on a geodetic network which minimized the possibility of large errors being introduced. They therefore represent the best evidence available of the condition of our coastline a hundred or more years ago, and the courts have repeatedly recognized their competency in this respect . . . ."

Because of the importance of documenting changes over a long time interval, topographic charts and aerial photographs have been used to study beach erosion in other areas. For example, Morgan and Larimore (1957), Harris and Jones (1964), El-Ashry and Wanless (1968), Bryant and McCann (1973), and Stapor (1973) have successfully used techniques similar to those employed herein. Previous articles describing determinations of beach changes from aerial photographs were reviewed by Stafford (1971) and Stafford and others (1973).

Simply stated, the method of using topographic charts and aerial photographs, though not absolutely precise, represents the best method available for investigating long-term trends in shoreline changes.

Limitations of the method require that emphasis be placed first on *trend* of shoreline changes with rates of change being secondary. Although rates of change from map measurements can be calculated to a precision well beyond the limits of accuracy of the procedure, they are most important as *relative* values; that is, do the data indicate that erosion is occurring at a few feet per year or at significantly higher rates. Because sequential shoreline positions are seldom exactly parallel, in some instances it is best to provide a range of values such as 10 to 15 feet per year. As long as users realize and understand the limitations of the method of historical monitoring, results of sequential shoreline mapping are significant and useful in coastal zone planning and development.

Sources and Nature of Supplemental Information

Sources of aerial photographs, topographic charts, and topographic base maps used for this report are identified in appendix C. Additional information was derived from miscellaneous reports published by the U. S. Army Corps of Engineers and on-the-ground measurements and observations including beach profiles, prepared as a part of this investigation.

Relative wave intensity, estimated from photographs, and the general appearance of the beach dictate whether or not tide and weather bureau records should be checked for abnormal conditions at the time of photography. Most flights are executed during calm weather conditions, thus eliminating most of this effect. On the other hand, large-scale changes are recorded immediately after the passage of a tropical storm or hurricane. For this reason, photography dates have been compared with weather bureau records to determine the nature and extent of tropical cyclones prior to the overflight. If recent storm effects were obvious on the photographs, an attempt was made to relate those effects to a particular event.

Considerable data were compiled from weather bureau records and the U. S. Department of Commerce (1972) for many of the dates of aerial photography. These data, which include wind velocity and direction and times of predicted tidal stage, were used to qualitatively estimate the effect of meteorological conditions on position of the sediment-water interface (fig. 2).

Monitoring of Vegetation Line

Changes in the vegetation line are determined from aerial photographs in the same manner as changes in shoreline position with the exception that line of continuous vegetation is mapped rather than sediment-water interface. Problems associated with interpretation of vegetation line on aerial photographs are similar to those encountered with shoreline interpretation because they involve scale and resolution of photography as well as coastal processes. In places, the vegetation "line" is actually a zone or transition, the precise position of which is subject to interpretation; in other places the boundary is sharp and distinct, requiring little interpretation. The problems of mapping vegetation line are not just restricted to geographic area but also involve time. Observations indicate that the vegetation line along a particular section of beach may be indistinct for a given date, but subsequent photography may show a well-defined boundary for the same area, or vice versa. In general, these difficulties are resolved through an understanding of coastal processes and a thorough knowledge of factors that affect appearance of the vegetation line on photographs. For example, the vegetation line tends to be ill defined following storms because sand may be deposited over the vegetation or the vegetation may be completely removed by wave action. The problem of photographic scale and optical resolution in determination of the vegetation line is opposite that associated with determination of the shoreline. Mapping vegetation line is more difficult on larger scale photographs than on smaller scale photographs, particularly in areas where the vegetation line is indistinct, because larger scale photographs provide greater resolution and much more detail. Fortunately, vegetation line is not affected by processes such as tide cycle at the time the photography was taken.

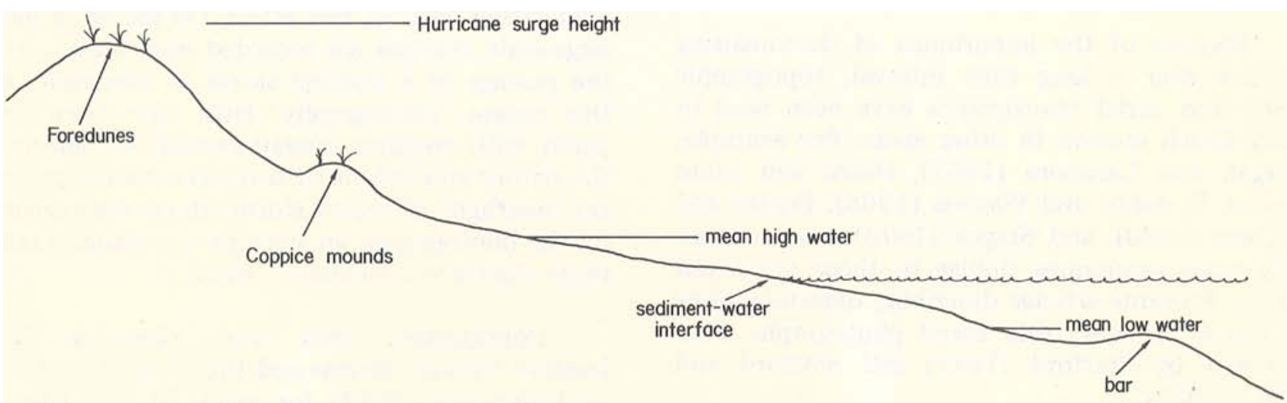

Figure 2. Generalized diagram of beach profile.

PREVIOUS WORK

Storms, shoreline changes, and protection of the east end of Galveston Island have been the subjects of numerous studies conducted by the U. S. Army Corps of Engineers dating prior to 1885 (U. S. Army Corps of Engineers, 1895, 1896-97, 1900, 1920, 1934, 1949, 1953). Conclusions and recommendations based on these studies resulted in construction of the jetties, groins, seawall, and seawall extensions that are present along the eastern end of Galveston Island. Shoreline changes from 1838 to 1934 between the south jetty and the vicinity of Fort Crockett are presented in House Document 400 (U. S. Army Corps of Engineers, 1934). However, only one report (U. S. Army Corps of Engineers, 1953) covered the West Beach area between the Galveston seawall and San Luis Pass. Comparison of shorelines for 1851 and 1934 by the U. S. Army Corps of Engineers (1953, pls. 10-11) indicates that maximum erosion of 1,000 feet at the west end of the present-day seawall decreased to equilibrium at a point 4.0 miles southwest from the seawall near Eleven Mile Road. From that point westward, the beach accreted a maximum of 250 feet for 2.7 miles near Carancahua Cove; the accretion then decreased for 3.8 miles southwestward to a point near Bird Island Cove. From that point to San Luis Pass (approximately 8 miles), the beach underwent erosion; maximum erosion of 400 feet occurred at San Luis Pass.

Herbich and Hales (1970) investigated changes in the vicinity of San Luis Pass based on comparison of a series of hydrographic charts dated from 1859 to 1969. However, the actual changes were only briefly discussed and quantitative data were not presented. Accretion and erosion at the east end of Folletts Island were attributed to seasonal changes, i.e., erosion during the winter and accretion during the summer.

A regional inventory of Texas shores was conducted by the U. S. Army Corps of Engineers (1971b); they were able to recognize qualitatively general accretion at the entrance to Galveston Harbor and erosion at San Luis Pass.

In a more recent study, Seelig and Sorensen (1973) presented tabular data regarding mean low-water shoreline changes along the Texas Coast; values calculated for the rates of shoreline change along Galveston Island were included in their report. Their technique involved the use of only two dates (early and recent); the change at any point was averaged over the time period between the two dates. Cycles of accretion and erosion were not recognized and few intermediate values were reported; thus, in certain instances, the data are misleading because of technique. Furthermore, data retrieval is difficult because points are identified by the Texas coordinate system. Rates of erosion in the area of interest determined by Seelig and Sorensen (1973, p. 17-18) range from 0 to -11 feet per year with most values falling between -1 and -3 feet per year.

Where similar data and techniques have been employed, shoreline changes along Galveston Island mapped by the U. S. Army Corps of Engineers, Seelig and Sorensen, and the Bureau of Economic Geology are compatible and in general agreement.

PRESENT BEACH CHARACTERISTICS

Texture and Composition

The beach of Galveston Island is comprised of well-sorted, fine to very fine sand (Bullard, 1942; Slingluff, 1948; Stern, 1948; U. S. Army Corps of Engineers, 1953; Bernard and others, 1959; Rogers and Adams, 1959; Hsu, 1960) composed primarily of quartz, feldspar, shell material, and heavy minerals. Shell material is commonly leached from older deposits above the water table, but where associated with more recent deposits, shell content ranges from 1.6 to 12.5 percent (U. S. Army Corps of Engineers, 1953). Shell material is comprised of whole and broken surf zone and shelf species. Analysis of heavy minerals (Bullard, 1942; Slingluff, 1948; Stern, 1948; Rogers and Adams, 1959) indicates that black opaques, hornblende, leucoxene, garnet, zircon, tourmaline, and epidote are most common with minor amounts of kyanite, staurolite, rutile, pyroxene, basaltic hornblende, and apatite also present.

Beach Profiles

West Beach of Galveston Island is characterized by a broad (approximately 200 feet wide), gently seaward sloping (about 1°30′) sand beach; daily changes in appearance reflect changing conditions such as wind direction and velocity, wave height, tidal stage, and the like. Accordingly, beach profiles are subject to change depending on beach and surf conditions that existed when measurements were recorded. In general, the most seaward extent of a beach profile is subjected to the greatest changes because in this area breakpoint bars are created, destroyed, and driven ashore. Under natural conditions, the landward portion of a beach profile is affected only by spring and storm tides or more intense events such as tropical cyclones. However, with increased use of the beach, minor alterations in beach profiles occasionally can be attributed to vehicular traffic and beach maintenance such as raking and scraping.

Beach profiles presented in figure 3 were constructed using the method described by Emery (1961). The profiles, considered typical of certain segments of west Galveston Island, represent beach conditions on October 28, 1973. The combination of northerly wind and low tide provided optimum conditions for obtaining between 200 and 350 feet of beach profile. High tide mark was identified by sand wetness and position of debris line. Beach profiles have also been surveyed by the Galveston District, U. S. Army Corps of Engineers (1968-1972). Comparison of beach profiles and beach scour patterns by Herbich (1970) suggests that beach condition (breaker bar spacing and size) may be similar over a relatively long period of time except under storm conditions. Therefore, unless beach profiles are referenced to a permanent, stationary control point on the ground, comparison of profiles at different times might be very similar, but the absolute position of the beach can be quite different. Thus, a beach profile may appear similar (except after storms) for a long period of time but the entire profile may shift seaward (accretion) or landward (erosion) during the same period.

Extant dunes are low, generally less than 5 feet in height, and discontinuous. Many areas have virtually no dunes and the absence of dune development may be attributed to storms and man. R. L. Vaughn (U. S. Army Corps of Engineers, 1920, appendix II) reported large sand dunes along Galveston Island prior to their destruction by storms in 1875 and 1900. Man's activities have also been responsible for dune destruction because dunes are commonly leveled during initial stages of construction and development. Prior to 1886 (U. S. Army Corps of Engineers, 1920), sand dunes 12 to 15 feet high (Dyer, 1916; Davis, 1952; Weems, 1957) along the island 10 to 15 miles from Galveston were removed to fill bayous and other low places.

Beach configuration is controlled primarily by wave action. Other factors determining beach characteristics are type and amount of beach material available and the geomorphology of the adjacent land (Wiegel, 1964). In general, beach slope is inversely related to grain size of beach material (Bascom, 1951). Thus, beaches composed of fine sand are generally flat. Beach width along the Texas Coast is primarily dependent on quantity of sand available. Beaches undergoing erosion due to a deficit in sediment supply are narrower than beaches where there is an adequate supply or surplus of beach material. Examples of this are evident on the Texas Coast. The beach on Galveston Island is wider than the beach west of Sabine Pass where erosion is greater; in turn, West Beach is not as wide as central Padre Island where there is an adequate supply of sand.

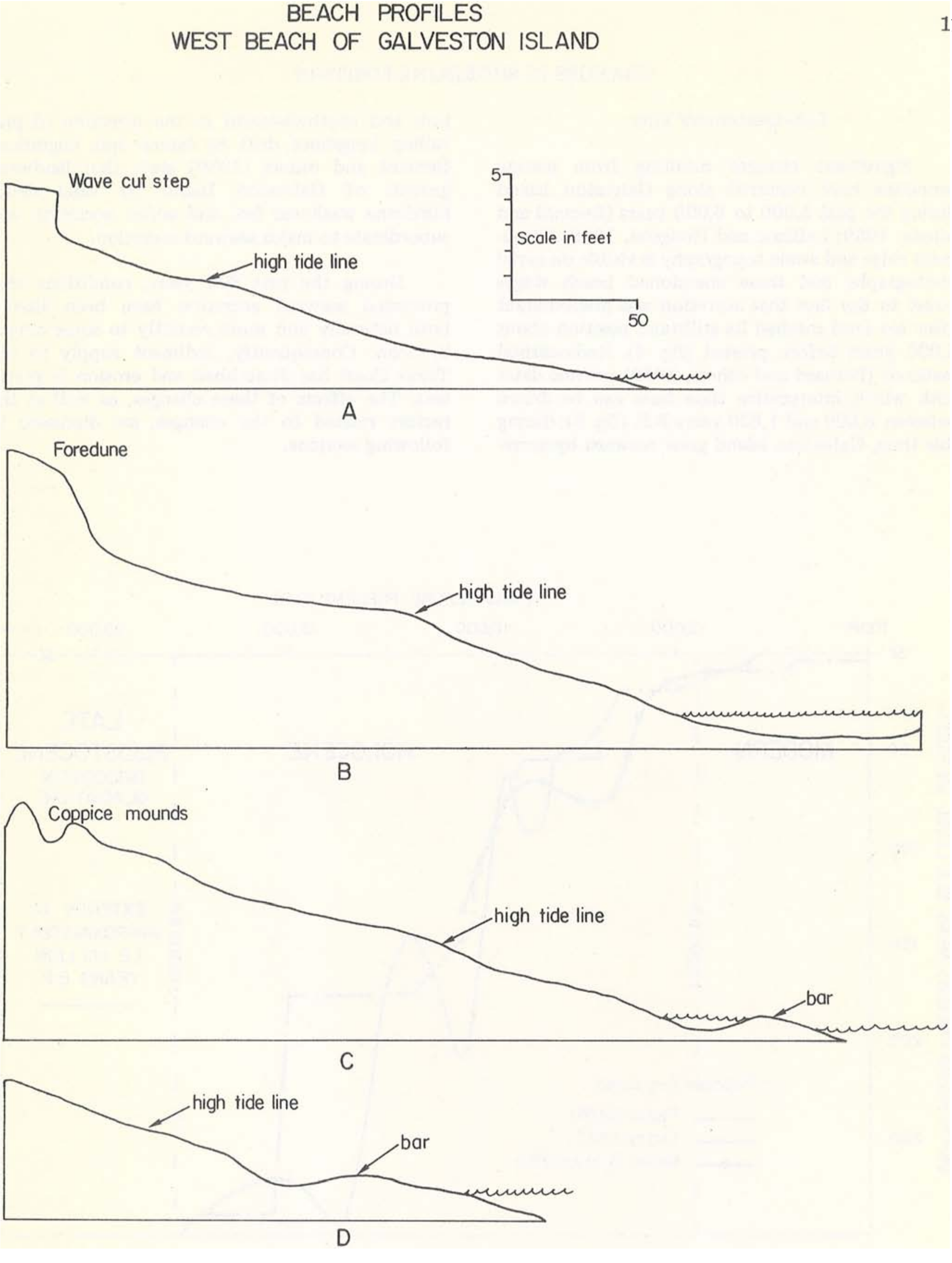

Figure 3. Beach profiles, West Beach of Galveston Island, recorded October 28, 1973. Locations plotted on figure 6.

Late Quaternary Time

Significant changes resulting from marine processes have occurred along Galveston Island during the past 5,000 to 6,000 years (Bernard and others, 1959; LeBlanc and Hodgson, 1959). Prominent ridge and swale topography is visible on aerial photographs and these abandoned beach ridges attest to the fact that accretion was predominant after sea level reached its stillstand position about 3,000 years before present (fig. 4). Radiocarbon methods (Bernard and others, 1959) provide dates with which interpretive time lines can be drawn between 6,000 and 1,600 years B.P. (fig. 5); during this time, Galveston Island grew seaward by accretion and southwestward in the direction of prevailing longshore drift by lateral spit migration. Bernard and others (1959) state that landward growth of Galveston Island by tidal delta, hurricane washover fan, and eolian accretion was subordinate to major seaward accretion.

During the past 600 years, conditions that promoted seaward accretion have been altered both naturally and more recently to some extent by man. Consequently, sediment supply to the Texas Coast has diminished and erosion is prevalent. The effects of these changes, as well as the factors related to the changes, are discussed in following sections.

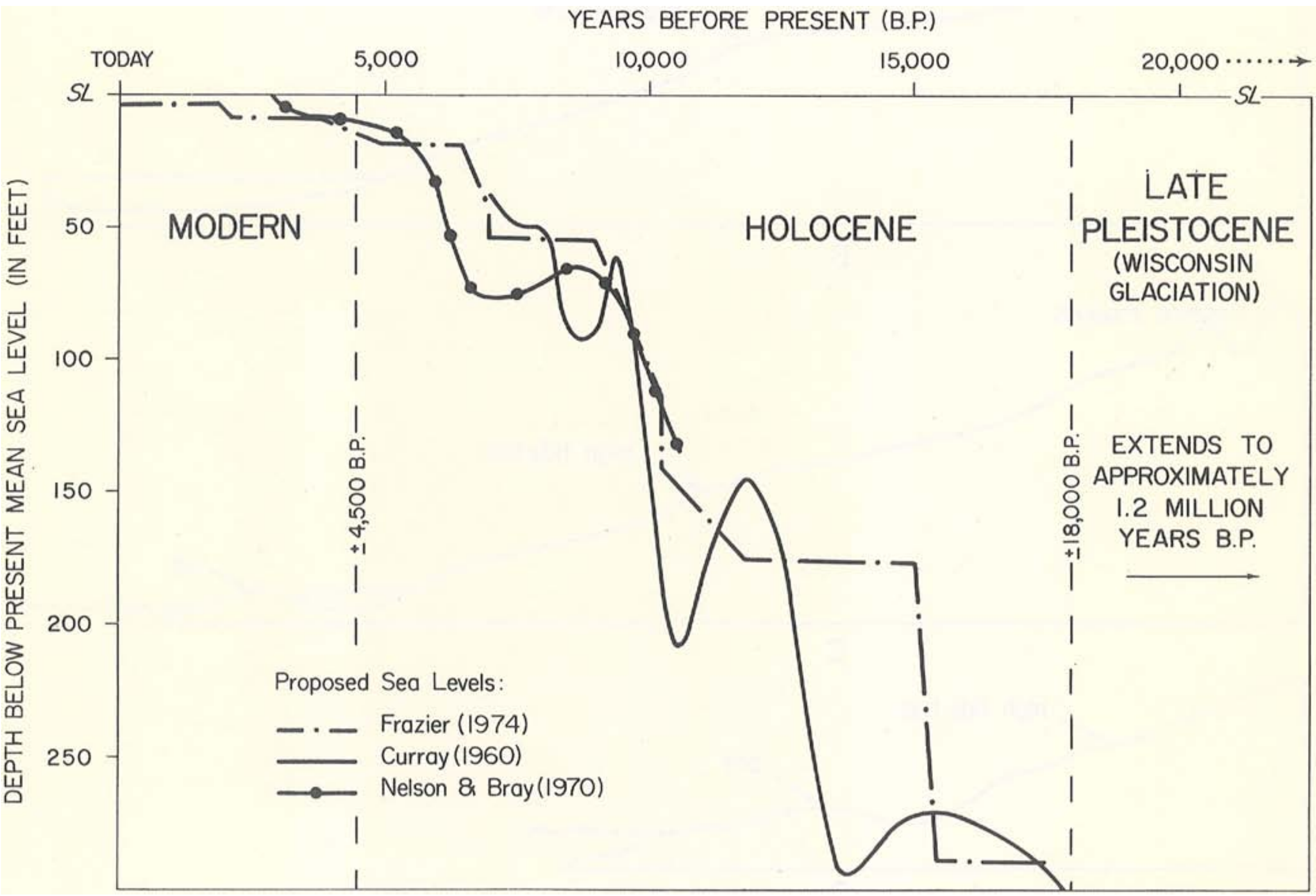

Figure 4. Proposed sea-level changes during the last 20,000 years; sketch defines use of Modern and Holocene.

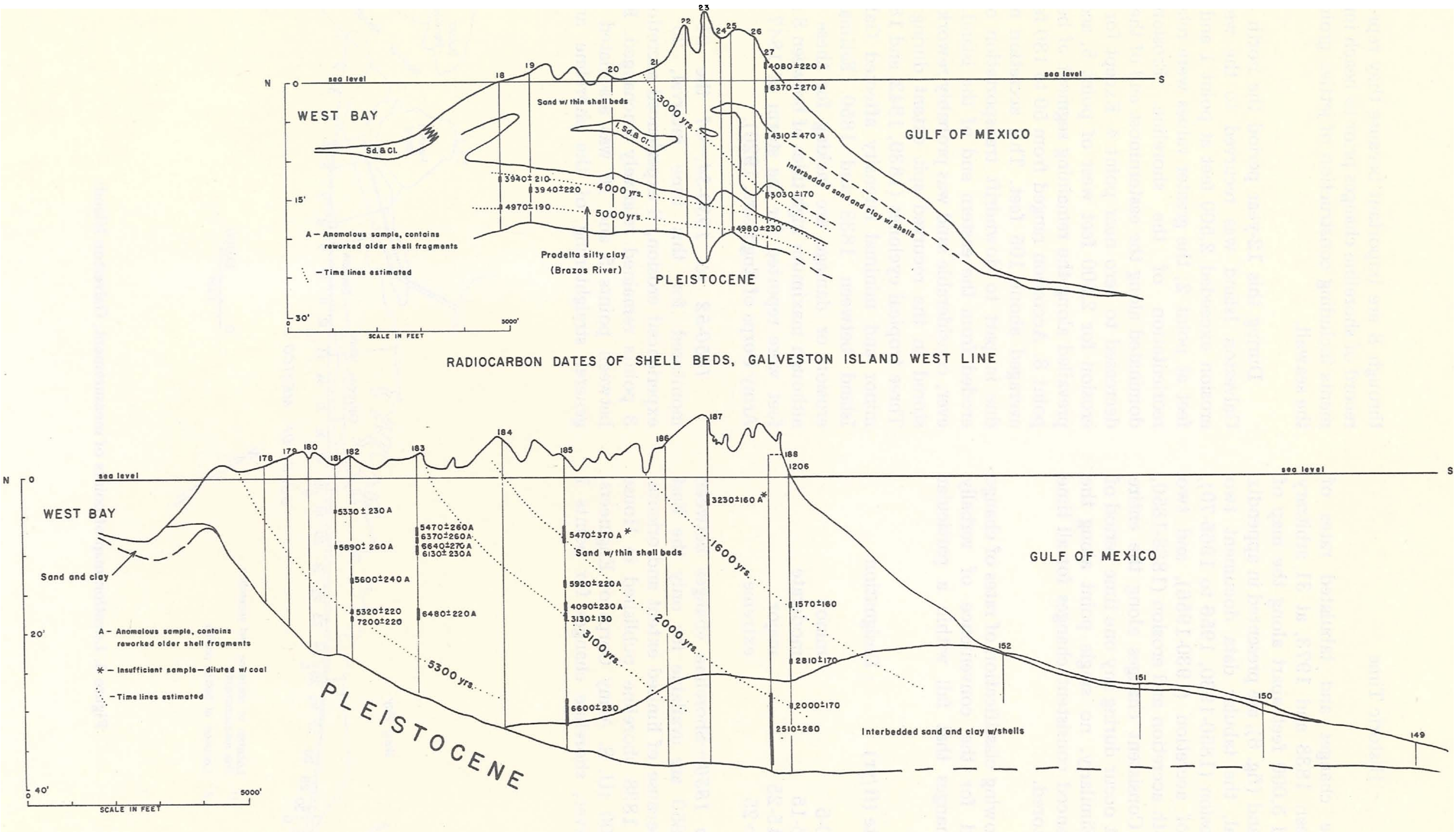

Figure 5. History of the development of Galveston Island based on radiocarbon dating. After Bernard and others (1959).

Historic Time

Shoreline changes and tabulated rates of change between 1838 and 1973, at 31 arbitrary points spaced 5,000 feet apart along the map of Galveston Island (fig. 6), are presented in appendix A. In general, the tabular data document two periods of erosion (1850-1930, 1956 to 1965-70), one period of accretion (1930-1956), and two periods of both accretion and erosion (1838-1850, 1965-1973). Consistent changes along the entire beach did not occur during any one time period of this study. Similarly, no single point along the island experienced consistent changes for all time periods monitored.

The following classification of rates of change is introduced for the convenience of verbally describing changes that fall within a particular range:

Rate (ft/yr)	Designation
0-5	minor
5-15	moderate
15-25	major
>25	extreme

1838 to 1850.—Shoreline changes between 1838 and 1850 are available for only the East Beach area because of limited extent and orientation of the 1838 shoreline published in House Document 400 (U. S. Army Corps of Engineers, 1934). However, shoreline changes for points 1 through 8 are important because they represent a record of shoreline changes prior to beach improvements including construction of jetties, groins, and the seawall.

During this 12-year period the north end of Galveston Island was recurved to the west and erosion exceeded 2,500 feet at point 1 and 1,300 feet at point 2; the greater values were related to reorientation of the shoreline. Erosion that dominated along the easternmost end of the island decreased to zero near point 4. Except for minor erosion for 2,500 feet west of point 5, accretion prevailed along the remaining segment of beach to point 8. Accretion ranged from 50 to 180 feet and averaged about 105 feet. This accretion may be due in part to downdrift transportation of sand eroded from the eastern end of the island. However, considerable sand was probably reworked and stored in the recurved spit extant during 1850. Three tropical cyclones (1839, 1842, and 1847) of minor and minimal intensity affected Galveston Island between 1838 and 1850. Estimates of erosion or damage are lacking for these storms although maximum high tides of between 8 and 10 feet were reported for the storm of 1847 (U. S. Army Corps of Engineers, 1920).

1850-52 to 1930-34.—Of the 31 points monitored for this time interval, 20 points experienced erosion, 8 experienced accretion, and 3 points remained relatively unchanged. Erosion between points 5 and 16 was associated with a general straightening of the shoreline and the

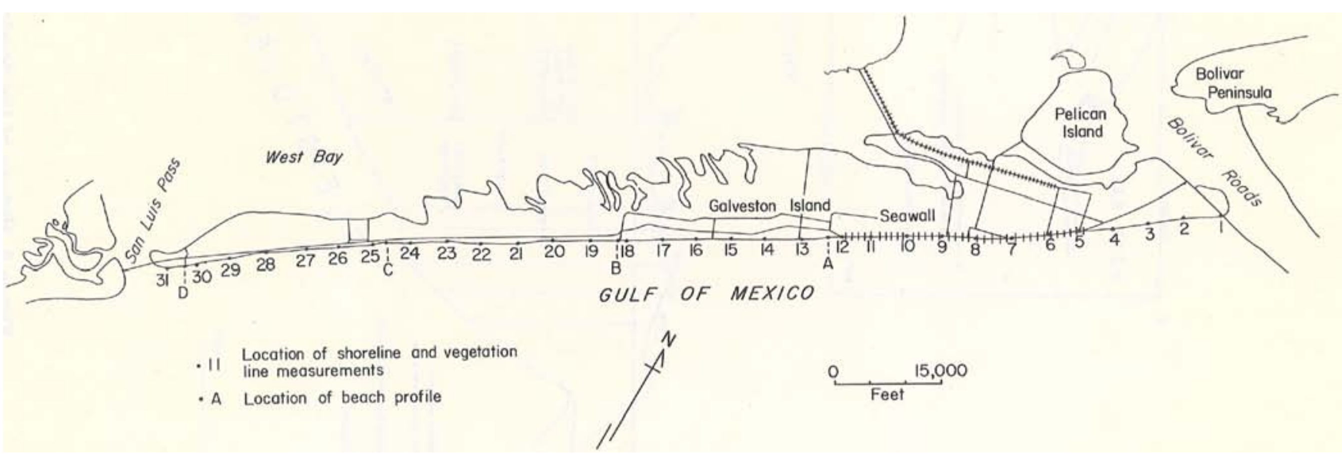

Figure 6. Location map of points of measurement, Galveston Island.

removal of a prominent bulge. Erosion was dominant west of point 22 except in the vicinity of points 26 and 28, where relatively no change occurred.

Major accretion occurred at points 1 through 3 in response to construction of the south jetty. Maximum accretion parallel to the jetty was greater than 7,000 feet; accretion at points 2 and 3 was 6,000 feet and 2,075 feet, respectively. Accretion between points 17 and 21 may have been in response to deposition by longshore currents of some of the material eroded in an updrift direction.

Flooding or storm damage on Galveston Island was caused by sixteen tropical cyclones between 1854 and 1921 (appendix B), including the severe hurricanes in 1900 and 1915. But the length of time (84 years) and the frequency of storms during the period preclude comment on changes related to a specific storm. However, extensive erosion is indicated for most of the beach fronting the city of Galveston in 1900 (U. S. Army Corps of Engineers, 1934).

Storm tides at Galveston exceeding 4.5 feet occurred at least 12 times during this period (U. S. Army Corps of Engineers, 1953). Smith (1973, p. 161-162) reported tnat Galveston suffered damage from a storm surge on September 8, 1850; unfortunately, this is not substantiated by listings of tropical cyclones that appear in other publications by Tannehill (1956), Price (1956), and Dunn and Miller (1964).

1930 to 1933-34.—Because of the lack of 1930 shoreline photography for the Lake Como quadrangle, data are incomplete along West Beach for this period, and therefore, rates of change have not been determined.

Shoreline changes for this time period between points 2 and 8 are presented in House Document 400 (U. S. Army Corps of Engineers, 1934). Apparently accretion was predominant and relatively rapid in the East Beach area; rates determined from the Corps of Engineers map range from 25 feet per year to 50 feet per year. Qualitative analysis of changes indicates that accretion occurred at points 12, 13, 23, 24, and 30. The shoreline at point 25 remained relatively unchanged. Erosion occurred between points 26 and 31 except for accretion in the vicinity of point 30.

The significance of the November 1930-January 1934 data is that the short time interval permits the evaluation of particular storm effects. Only two hurricanes during that time affected the Texas Coast near Galveston. The major storm of August 1932 that struck Freeport may account for erosion along the western end of the island; only minor damage was reported along the beach after passage of the 1933 storm (U. S. Army Corps of Engineers, 1953). Other storms in this time period made landfall along the lower part of the coast and apparently had little effect on Galveston Island.

1930 to 1956.—Between 1930 and 1956, 22 points experienced accretion, 4 experienced erosion, and 5 remained relatively unchanged. High rates of accretion occurred at points 1 through 4 as sand continued to be impounded by the south jetty. The beach in front of the seawall to point 11 also accreted between 25 feet and 150 feet except for points 9 and 10 where the shoreline remained unchanged. Details of accretion along this segment of the coast between 1938 and 1949 are presented in House Document 218 (U. S. Army Corps of Engineers, 1953). Accretion was also dominant from points 12 through 24 and 30 and 31; the shoreline remained relatively unchanged near points 14, 15, and 29. Significant erosion occurred only between points 25 and 28.

Probably the most interesting aspect of the accretion during this period is the fact that, for the total time period studied, the 1956 shoreline attained its most seaward position west of point 16 to point 23 and between points 30 and 31. No clear-cut explanation exists for this phenomenon; however, general accretion was also occurring updrift between Sabine Pass and Bolivar Roads during the same time period. Hurricane frequency was low from 1945 to 1956, but the storm of 1949 caused surge of 5.3 feet at Galveston (Harris, 1963). This was the only major storm to affect Galveston between 1949 and 1956.

1956 to 1965-70.—During this period the beach continued to accrete at points 1 and 2, but erosion of 25 feet to 250 feet occurred in front of the seawall. No significant changes occurred at points 3, 7, and 8. Erosion prevailed along the entire West Beach shoreline between 1956 and 1965, although one point (16) is considered relatively unchanged because the horizontal shift is less than 10 feet.

Hurricanes Debra (1959), Carla (1961), and Cindy (1963) were the only hurricanes of any consequence in the vicinity of Galveston Island during this period. Debra and Cindy were of minimal intensity and associated storm surges were only 2.8 feet and 4.2 feet, respectively. On the other hand, Carla, classified as an extreme storm, caused considerable damage and apparently was responsible for most of the changes in shoreline between 1956 and 1965. Maximum erosion was 610 feet at point 31; however, this is abnormally high in comparison to points far removed from the tidal inlet. Average erosion for the remaining 24 points, excluding 3, 7, 8, 16, and 31, was 120 feet.

1965 to 1973.—Points of accretion and erosion between the west end of the seawall and San Luis Pass are equally divided for the final interval (1965-1973) with 9 points each; the shoreline remained nearly stationary at points 20 and 26. Erosion continued between points 12 and 20, except near point 18, where a minor advance occurred. Moderate shoreline accretion between points 21 and 29 ranged from 40 to 80 feet and averaged about 50 feet. Erosion was most noticeable at and just west of the seawall where the beach, which was present seaward of the seawall prior to 1965, was removed and the shoreline retreated to a position landward of the seawall.

Storm frequency did not diminish during this period, but Hurricane Beulah (1967) was the only major storm to affect Galveston Island. Minor storm damage was not caused by high winds or hurricane surge but rather flooding in conjunction with the tremendous rainfall. Storm tides in the Galveston area were 3.7 to 3.8 feet (U. S. Army Corps of Engineers, 1968). Therefore, shoreline changes during this period appear to be related to factors other than storms.

Net Historic Change (1838 to 1973)

Calculations from previously determined changes provide information on the net effect of shoreline retreat and advance along Galveston Island (appendix A and figure 7). Using the earliest shoreline as a base line, the comparison is equal to the difference between the earliest and latest shorelines.

Construction of the south jetty with attendant reorientation of the shoreline and impoundment of large quantities of sand account for the tremendous net accretion on East Beach. It should be noted that net changes along the seawall are relatively low especially after seawall construction because, in general, sand was deposited on East Beach and removed from in front of the seawall which left little beach for further changes. Greater net erosion at points 9 through 16 is related to reorientation of the shoreline between 1851 and 1930. Net accretion was recorded between points 17 and 21 with a maximum net gain of 100 feet at point 17. Net accretion at the other points was 90 feet or less and averaged about 75 feet. Net erosion

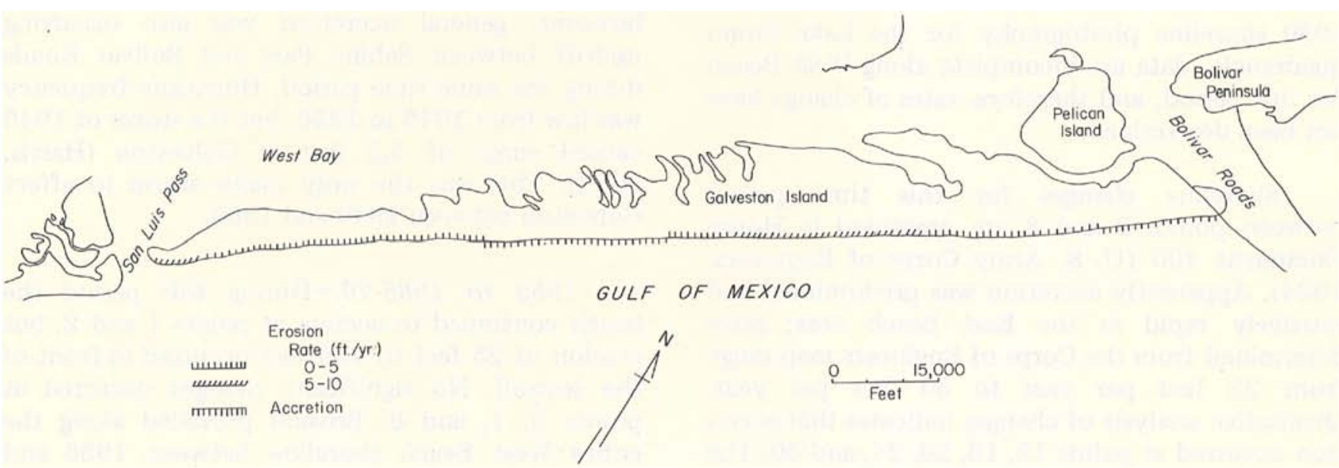

Figure 7. Net shoreline changes along Galveston Island.

from point 22 west to San Luis Pass ranged from 20 to 210 feet (excluding point 31) and averaged about 150 feet. Minor accretion was recorded for the 1965-1973 interval. Predictably, greatest short-term changes occurred in the vicinity of San Luis Pass; greatest overall changes occurred just west of the south jetty and just west of the seawall.

Rates of change were also calculated for net change between 1851-52 and 1973; the results are included in appendix A. These figures estimate long-term net effect, but the values should be used in context. The values for rates of net change are adequate for describing long-term trends; however, rates of short-term changes may be of greater magnitude than rates of long-term changes, particularly in areas where both accretion and erosion have occurred.

Net rates of shoreline change along Galveston Island are minor except for extreme and major accretion west of the south jetty (points 1-3) and moderate erosion near the west end of the seawall (points 10-14) and at San Luis Pass (point 31). Minor net accretion of less than 1 foot per year was recorded at point 4 and between points 17 and 21. Net erosion at the remaining points ranged from less than 1 foot per year to 4.5 feet per year and averaged 1.9 feet per year.

CHANGES IN POSITION OF WEST BEACH VEGETATION LINE

Documentation of changes in position of the vegetation line along Galveston Island is limited to the natural vegetation line along privately owned property fronting the Gulf of Mexico (West Beach); the remainder of Gulf-fronting property from the west end of the seawall to the south jetty on East Beach is owned by the city of Galveston.

Changes in the vegetation line (appendix A) are considered independently from shoreline changes because, in many instances, the nature of change and rate of shoreline and vegetation line recovery are quite dissimilar. Thus, the shoreline and vegetation line should not be viewed as a couplet with fixed horizontal distance; this is illustrated in figure 8. Although response of the shoreline and vegetation line to long-term changes is similar, a certain amount of independence is exhibited by the vegetation line because it reacts to a different set of processes than does the shoreline. Furthermore, documentation of changes in vegetation line for this particular study draws on considerably more data (appendix C) than does documentation of shoreline changes.

Accurate information on position of vegetation line is neither available for the middle 1800's nor for the early 1900's. Therefore, accounts of changes in vegetation line are restricted to the time period covered by aerial photographs (1930-1973).

The tabular data on line of vegetation changes present a more consistent picture than do similar data for shoreline changes; two cycles of vegetation line erosion and two cycles of recovery have been recognized.

1930 to 1938-44.—Information on vegetation line in 1930 is not available between points 14 and 21 because that part of West Beach is missing on the 1930 photographs. Nonetheless, data at 10 of the remaining 12 points monitored suggest that this was a period when the vegetation line retreated. Tropical cyclone frequency was high during the 30's and early 40's. Storm surges of 4.5, 6.0, and 4.6 feet were recorded during hurricanes in 1932, 1933, and 1934, respectively. In addition, the 1938 photographs may show the effects of a tropical storm that struck Freeport. Landfall was October 17, and the photographs were taken November 29. Hurricanes undoubtedly played an important role in determining the 1944 vegetation line. Storm surges at Galveston of 5.7 and 6.3 feet were recorded for hurricanes in 1941 and 1942. Galveston was struck by another hurricane in 1943.

1944 to 1956.—Major advances in the vegetation line at all stations between 1944 and 1956 are attributed to low storm frequency in the early 50's. During the entire 12-year period, only two storms affected Galveston. The more intense of the two, in 1949, caused a storm surge of 5.3 feet. The less intense storm occurred in 1947. Apparently the 7-year period between 1949 and 1956 was conducive to significant seaward advances in the vegetation line. Advances ranged from 130 to 750 feet and averaged about 325 feet.

1956 to 1964.—This period was characterized by vegetation line retreat, most likely the result of damage incurred from Hurricanes Carla (1961) and Cindy (1963). Comparison of 1961 vertical and oblique photographs with 1964 vertical photographs indicates that erosion of the vegetation line was primarily the result of Hurricane Carla. Hurricane Debra (1959) was of minimal intensity and only produced a storm surge of 2.8 feet. Anomalous advancement in vegetation line occurred between points 30 and 31. At other points retreat ranged from 50 to 280 feet and averaged 145 feet.

1964 to 1973.—Advancement of the vegetation line was the rule between 1964 and 1973. Except for retreat of 40 feet at point 30, the vegetation line advanced between 30 feet and 190 feet. Average advancement for the 9-year period was 90 feet. Again the low frequency of tropical cyclones appears to be the primary factor in allowing the vegetation line to advance. The only tropical cyclones active in the Galveston area during this period were Felice (1970) and Delia (1973); both storms went onshore near High Island. Hurricane Beulah was a storm of major intensity; however, storm surge at Galveston was only 3.7 feet.

Net changes in vegetation line were calculated as they were for shoreline changes. However, it should be emphasized that shifts in vegetation line are related primarily to storms, and the time period over which observations were made was not of sufficient length to establish long-term trends. Nonetheless, the general trend of change in vegetation line has been net accretion (fig. 8), except at points 12 and 14 where there has been net erosion and at points 13 and 26 where there has been no significant change.

In general, the long-term change in position of the vegetation line is similar to that of the shoreline. However, short-term changes in position of the vegetation line reflect climatic conditions and take place independent of shoreline changes. This is demonstrated in figure 8 which illustrates that the horizontal separation between shoreline and vegetation line displays short-term variations.

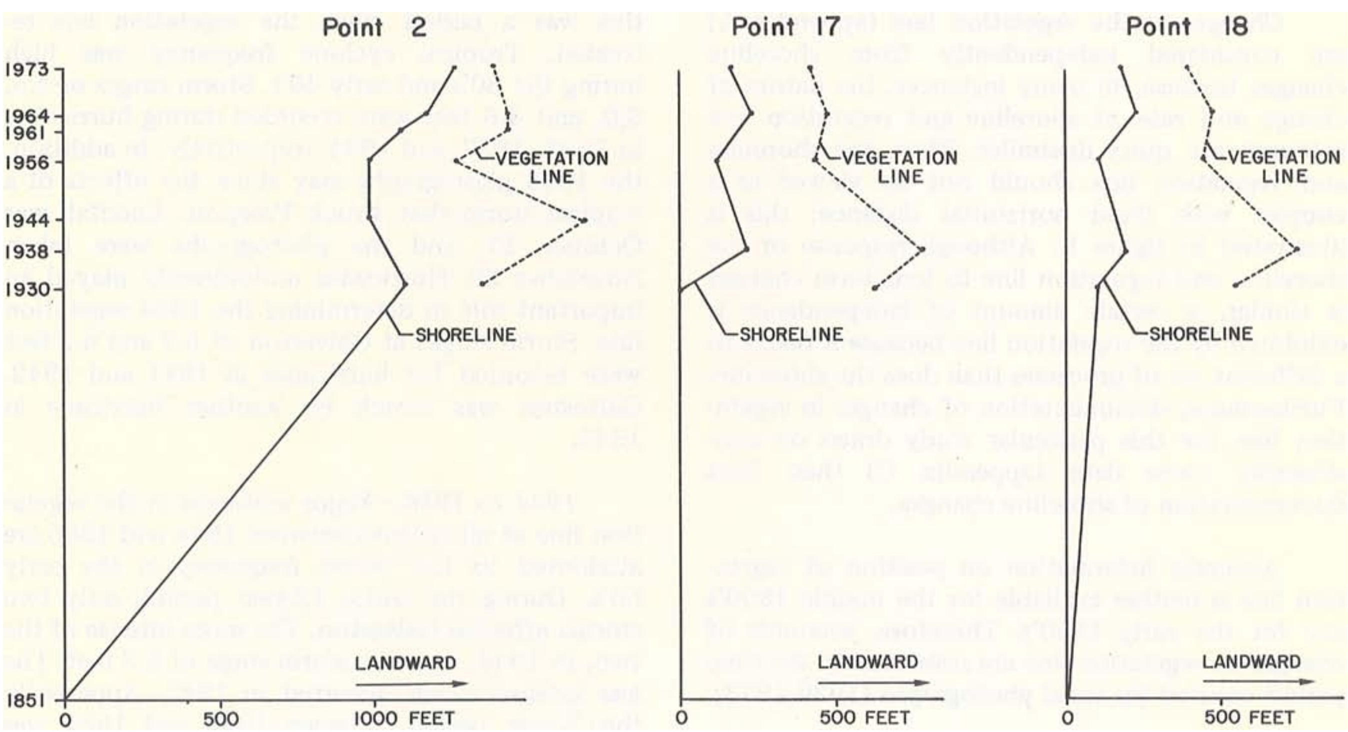

Figure 8. Relative changes in position of shoreline and vegetation line at selected locations, West Beach, Galveston Island.

FACTORS AFFECTING SHORELINE AND VEGETATION LINE CHANGES

Geologic processes and, more specifically, coastal processes are complex dynamic components of large-scale systems. Coastal processes are dependent on the intricate interaction of a large number of variables such as wind velocity, rainfall, storm frequency and intensity, tidal range, littoral currents, and the like. Therefore, it is difficult, if not impossible, to isolate specific factors causing shoreline changes. Changes in vegetation line are more easily understood. However, in order to evaluate the various factors and their interrelationship, it is necessary to discuss not only major factors but also minor factors. The basis for future prediction comes from this evaluation.

Climate

Climatic changes during the 18,000 years since the Pleistocene have been documented by various methods. In general, temperature was lower (Flint, 1957) and precipitation was greater (Schumm, 1965) at the end of the Pleistocene than at the present; the warmer and drier conditions, which now prevail, control other factors such as vegetal cover, runoff, sediment concentration, and sediment yield. Schumm (1965) stated that "... an increase in temperature and a decrease in precipitation will cause a decrease in annual runoff and an increase in the sediment concentration. Sediment yield can either increase or decrease depending on the temperature and precipitation before the change."

Changes in stream and bay conditions, as well as migration of certain plant and animal species in South Texas since the late 1800's, were attributed to a combination of overgrazing and more arid climatic conditions (Price and Gunter, 1943). A more complete discussion of the general warming trend is presented in Dunn and Miller (1964). Manley (1955) reported that postglacial temperature has increased 13°F in the Gulf region. Furthermore, Dury (1965) estimated that many rivers carried between 5 and 10 times greater discharge than present-day rivers. His remarks included reference to the Brazos and Mission Rivers of Texas. Observations based on geologic maps prepared by the Bureau of Economic Geology (Fisher and others, 1972) confirm that many rivers along the Texas Coastal Plain were larger and probably transported greater volumes of sediment during the early Holocene. This, in turn, affected sediment budget, which will be discussed in another section. Droughts are a potential though indirect factor related to minor shoreline changes via their adverse effect on vegetation. Because dunes and beach sand are stabilized by vegetation, sparse vegetation resulting from droughts offers less resistance to wave attack. Severe droughts have occurred periodically in Texas; the chronological order of severe droughts affecting Galveston Island is as follows: 1891-1893, 1896-1899, 1916-1918, 1937-1939, 1954-1956 (Lowry, 1959).

Unfortunately, changes in the position of vegetation line resulting from storms and droughts cannot be independently distinguished by sequential aerial photography. Furthermore, because of the difficulty in determining the effect of droughts, the significance of this factor cannot be evaluated.

Storm Frequency and Intensity

The frequency of tropical cyclones is dependent on cyclic fluctuations in temperature; increased frequency of hurricanes occurs during warm cycles (Dunn and Miller, 1964). Because of their high frequency of occurrence and associated devastating forces and catastrophic nature, tropical cyclones have received considerable attention in recent years. Accurate records of hurricanes affecting the Texas Gulf Coast are incomplete prior to 1887, when official data collection was initiated simultaneously with the establishment of the Corpus Christi weather station (Carr, 1967).

According to summaries based on records of the U. S. Weather Bureau (Price, 1956; Tannehill, 1956; Dunn and Miller, 1964; Cry, 1965), some 62 tropical cyclones have either struck or affected the Texas Coast during this century (1900-1973). The average of 0.8-hurricane per year obtained from these data is similar to the 0.67 per year average reported by Hayes (1967). The significance of hurricanes as geologic agents was emphasized by Hayes (1967) who concluded that most of the Texas coastline experienced the passage of at least one hurricane eye during this century. He further concluded that every point on the Texas Coast was greatly affected by approximately half of the storms classified as hurricanes.

Comparisons of the different types of some of the more recent hurricanes are available; the effects of Hurricanes Carla (1961) and Cindy (1963) on South Texas beaches were compared by Hayes (1967). Hurricanes Carla, Beulah (1967), and Celia (1970) were compared by McGowen and others (1970); individual studies of Hurricanes Carla, Beulah, and Celia were conducted by the U. S. Army Corps of Engineers (1962, 1968, 1971c).

Destructive forces and storm damage.—Carla was one of the most violent storms on record because of her extreme size and high storm surge; the entire western two-thirds of Galveston Island was inundated with still-high water elevations ranging from 10.5 to 12.1 feet above mean sea level (U. S. Army Corps of Engineers, 1962, pl. 6-2). Flooding also occurred in low-lying areas as a result of Hurricane Beulah (U. S. Army Corps of Engineers, 1968, pl. 7). However, the most intense storms to strike Galveston were the hurricanes of 1900 and 1915. Reports by the U. S. Army Corps of Engineers (1949, 1953) and Davis (1952) indicate that the 1915 storm was equal in intensity to the storm of 1900, but that damage to Galveston was less in 1915 because of construction of the seawall subsequent to the storm of 1900. Accounts of these hurricanes were recorded by Cline (1926).

High velocity winds with attendant waves of destructive force scour and transport large quantities of sand during hurricane approach and landfall. The amount of damage suffered by the beach and adjoining areas depends on a number of factors including angle of storm approach, configuration of the shoreline, shape and slope of Gulf bottom, wind velocity, forward speed of the storm, distance from the eye, stage of astronomical tide, decrease in atmospheric pressure, and longevity of the storm. Hayes (1967) reported erosion of 60 to 150 feet along the fore-island dunes on Padre Island after the passage of Hurricane Carla. Most tropical cyclones have potential for causing some damage, but as suggested by McGowen and others (1970), certain types of hurricanes exhibit high wind velocities, others have high storm surge, and still others are noted for their intense rainfall and aftermath flooding.

Hurricane surge is the most destructive element on the Texas Coast (Bodine, 1969). This is particularly true for the West Beach of Galveston Island because of low elevations and lack of high foredunes that can dissipate most of the energy transmitted by wave attack. Because of the role hurricane surge plays in flooding and destruction, the frequency of occurrence of high surge on the open coast has been estimated by Bodine (1969). Included in his report are calculations for Galveston, which suggest that surge height of 10 feet can be expected approximately four times every 100 years. Maximum hurricane surge predicted was 15 feet. These estimates were based on the most complete records of hurricane surge elevations available for the Texas Coast. Surge for specific storms was compiled by Harris (1963). Wilson (1957) estimated deep-water hurricane wave height of between 40 and 45 feet once every 20 years for Gilchrist (about 25 miles northeast of Galveston on Bolivar Peninsula). Maximum deep-water hurricane wave height predicted for the same location was 55 feet with a recurrence frequency of once every 100 years. Consequently, dissipated energy from breaking storm waves can be tremendous under certain conditions.

Changes in beach profile during and after storms.—Beach profiles adjust themselves to changing conditions in an attempt to maintain a profile of equilibrium: they experience their greatest short-term changes during and after storms. Storm surge and wave action commonly plane off preexisting topographic features and produce a featureless, uniformly seaward-sloping beach. Eroded dunes and wave-cut steps (fig. 3) are common products of the surge. The sand removed by erosion is either (1) transported and stored temporarily in an offshore bar, (2) transported in the direction of littoral currents, and/or (3) washed across the barrier island through hurricane channels. Sediment transported offshore and stored in the nearshore zone is eventually returned to the beach by bar migration under the influence of normal wave action. The processes involved in beach recovery are discussed by Hayes (1967) and McGowen and others (1970).

Foredunes are the last line of defense against wave attack, and thus, afford considerable protection against hurricane surge and washover. Dunes also represent a reserve of sediment from which the beach can recover after a storm. Sand removed from the dunes and beach, transported offshore and returned to the beach as previously described, provides the material from which coppice mounds and eventually the foredunes rebuild. Thus, dune removal eliminates sediment reserve, as well as the natural defense mechanism established for beach protection.

Whether or not the beach returns to its prestorm position depends primarily on the amount of sand available. The beach readjusts to normal prestorm conditions much more rapidly than does the vegetation line. Generally speaking, the sequence of events is as follows: (1) return of sand to beach and profile adjustment (accretion); (2) development of low sand mounds (coppice mounds) seaward of the foredunes or vegetation line; (3) merging of coppice mounds with foredunes; and (4) migration of vegetation line to prestorm position. The first step is initiated within days after passage of the storm and adjustment is usually attained within several weeks or a few months. The remaining steps require months or possibly years and, in some instances, complete recovery is never attained. This sequence is idealized for obviously if there is a post-storm net deficit of sand, the beach will not recover to its prestorm position; the same holds true for the vegetation line. Occasionally the vegetation line will recover completely, whereas the shoreline will not; these conditions essentially result in reduction in beach width.

Apparently three basic types of shift in vegetation line are related to storms, and consequently, the speed and degree of recovery is dependent on the type of damage incurred. The first and simplest change is attributed to deposition of sand and ultimate burial of the vegetation. Although this causes an apparent landward shift in the vegetation line, recovery is quick (usually within a year) as the vegetation grows through the sand and reestablishes itself. An example of this can be seen by comparison of aerial photographs taken in February 1964, and October 1965, respectively. The 1964 photographs depict post-storm conditions following Hurricane Cindy, which struck the High Island area during September 1963.

The second type of change is characterized by stripping and complete removal of the vegetation by erosion. This produces the featureless beach previously referred to; oftentimes the wave-cut cliffs and eroded dunes mark the seaward extent of the vegetation line. Considerable time is required for the vegetation line to recover because of the slow processes involved and the removal of any nucleus around which stabilization and development of dunes can occur. This process is well illustrated by comparison of 1944, 1952, and 1956 aerial photographs between points 20 and 21.

Selective and incomplete removal of vegetation gives rise to the third type of change. Frequently, long, discontinuous, linear dune ridges survive wave attack but are isolated from the post-storm vegetation line by bare sand. Recovery under these circumstances is complicated and also of long duration. However, the preserved dune ridge does provide a nucleus for dune development; at times, the bare sand is revegetated and the vegetation line is returned to its prestorm position. Comparison of 1961, 1964, 1965, 1967, 1970, 1972, and 1973 aerial photographs between points 21 and 22 confirms the slow process of revegetation.

Local and Eustatic Sea-Level Conditions

Two factors of major importance relevant to land-sea relationships along Galveston Island are (1) sea-level changes, and (2) compactional subsidence. Shepard (1960b) discussed Holocene rise in sea level along the Texas Coast based on C^{14} data. Relative sea-level changes during historical time are deduced by monitoring mean sea level as determined from tide observations and developing trends based on long-term measurements (Gutenberg, 1933, 1941; Marmer, 1949, 1951, 1954; Hicks and Shofnos, 1965; Hicks, 1968, 1972). However, this method does not distinguish between sea-level rise and land-surface subsidence. More realistically, differentiation of these processes or understanding their individual contributions, if both are operative, is an academic question; the problem is just as real no matter what the cause. A minor vertical rise in sea level relative to adjacent land in low-lying coastal areas causes a considerable horizontal displacement of the shoreline in a landward direction (Bruun, 1962).

Swanson and Thurlow (1973) attributed the relative rise in sea level at Galveston to compactional subsidence. Their conclusion was based on tide records between 1950 and 1971. However, continuous tide data are available from 1904 (Gutenberg, 1933; Marmer, 1951), and the trend has indicated rising sea level since that time (fig. 9). Interpreted rates of sea-level rise depend a great deal on the specific time interval studied; thus, short-term records can be used to demonstrate most any trends. On the other hand, long-term records provide a better indication of the overall trend and are useful for future prediction. Rates of relative sea-level rise determined by previous workers range from 0.013 to 0.020 feet per year or

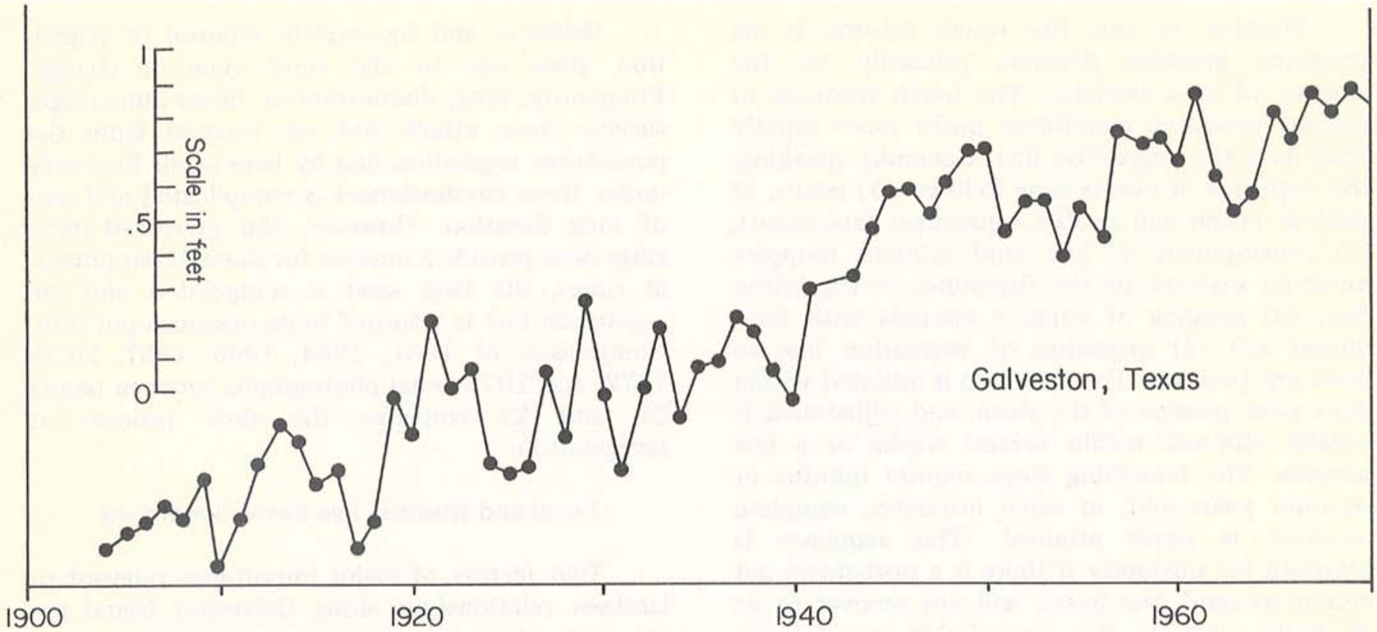

Figure 9. Relative sea-level changes based on tide gauge measurements for Galveston, Texas. Data from Gutenberg (1941), Marmer (1951), and Swanson and Thurlow (1973).

1.3 to 2.0 feet per century. It is readily apparent that rises in sea level of this order of magnitude may cause substantial changes in shoreline position.

There is increasing concern regarding land-surface subsidence in the Houston-Galveston area associated with production of oil (Pratt and Johnson, 1926) and withdrawal of ground water (Winslow and Doyel, 1954; Gabrysch, 1969). But graphs and maps depicting areas of subsidence published by Winslow and Doyel (1954) and Gabrysch (1969) indicate that Galveston Island is little affected, if at all, by subsidence attributed to subsurface withdrawal of fluids. Although Galveston does not appear to be affected significantly at the present, continued withdrawal and concomitant decline in fluid pressure could eventually affect Galveston Island as the cone of depression spreads outward from the area of principal withdrawal. Such would augment the effects of compactional subsidence and lead to future loss of land at the land-water interface.

Sediment Budget

Sediment budget refers to the amount of sediment in the coastal system and the balance among quantity of material introduced, temporarily stored, or removed from the system. Because beaches are nourished and maintained by sand-size sediment, the following discussion is limited to natural sources of sand for Galveston Island.

Johnson (1959) discussed the major sources of sand supply and causes for sand loss along coasts. His list, modified for specific conditions along the Texas Coast, includes two sources of sand: major streams and onshore movement of shelf sand by wave action. Sand losses were attributed to (1) movement offshore into deep water, (2) accretion against natural littoral barriers and man-made structures, (3) removal of sand for construction purposes, and (4) eolian processes.

The sources of sediment and processes referred to by Johnson have direct application to the area of interest. Sources of sand responsible for the incipient stages of development and growth of Galveston Island probably include both sand derived from shelf sediment and the Mississippi River. Van Andel and Poole (1960) and Shepard (1960a) suggested that sediments of the Texas Coast are largely of local origin. Shelf sand derived from the previously deposited sediment was apparently reworked and transported shoreward by wave action during the Holocene sea-level rise (fig. 4). McGowen and others (1972) also concluded that the primary source of sediment for Modern sand-rich barrier islands such as Galveston Island was local Pleistocene and early Holocene sources on the inner shelf, based on the spatial relationship of the different age deposits.

Sediment supplied by major streams is transported alongshore by littoral currents. There has been some uncertainty as to the direction of littoral drift along Galveston Island. Early reports by the U. S. Army Corps of Engineers state that drift is to the northeast based on observations along the eastern end of the island. This appears to be correct locally just west of the south jetty where a countercurrent (postulated by Stern, 1948) set up by the south jetty causes a local reversal in drift direction (fig. 10). Because of the orientation of the island, south and southwest winds also promote drift to the northeast. Under the influence of dominant southeast winds, littoral drift is from east to southwest along the upper Texas Coast (fig. 11). The only major river in an updrift direction from Galveston that supplies sediment directly to the littoral zone is the Mississippi River. Although there are indications that sediment discharge was greater during the early Holocene, Texas streams were in the process of filling their estuaries and were not contributing significant quantities of sand to the littoral currents.

Bernard and others (1959) presented data, which indicated that Galveston Island was in an accretionary state between 6,000 and 1,600 years B.P. (before present). Radiocarbon data from Gould and McFarlan (1959) suggested that shoreline accretion in the Sabine Pass area was initiated approximately 2,800 years ago. This was also the time period when the Mississippi River was debouching sediment into the Gulf of Mexico under shoal water conditions (Morgan and Larimore, 1957; Frazier, 1967). In this situation, wave action and longshore currents would be better able to transport fine sand. For the past 300 to 400 years (Morgan and Larimore, 1957), the Mississippi River has deposited its load in the deep water off the present birdfoot delta lobe, and consequently, the sand, which subsides in the water-saturated prodelta clays, is stored therein and does not become part of the littoral drift system.

Shoreline erosion at rates from 7.5 and 62.0 feet per year has been documented along the Louisiana Coast between 1812 and 1954 (Morgan and Larimore, 1957). Some of the eroded material is added to the littoral system, but this does not represent a significant contribution to the upper Texas Coast owing to the low percentage of sand in the sediment and the fact that most of this material is trapped by the jetties at Sabine Pass (Morgan and Larimore, 1957). The same holds true for the eroded sediment west of Sabine Pass, which is trapped by the jetties at the entrance to Galveston Harbor.

Sand losses listed by Johnson (1959) do not include sediment removed by deposition from tidal deltas and hurricane washovers; these are two important factors on the Texas Coast (fig. 12). Minor amounts of sand may be moved offshore in deeper water during storms and some sand is blown off the beach by eolian processes, but the high rainfall and dense vegetation preclude removal of large quantities of sand by wind. Sand removed by man-made structures and for construction purposes is discussed in the following section on human activities.

Human Activities

Shoreline changes induced by man are difficult to quantify because human activities promote alterations and imbalances in sediment budget. For example, construction of dams, erection of seawalls, groins, and jetties, training of the Mississippi River, and removal of sediment for building purposes all contribute to changes in quantity and type of beach material delivered to the Texas Coast. Even such minor activities as vehicular traffic and beach scraping can contribute to the overall changes, although they are in no way controlling factors. Erection of impermeable structures and removal of sediment have an immediate, as well as a long-term effect, whereas a lag of several to many years may be required to evaluate fully the effect of other changes such as river control and dam construction.

Construction of the jetties was initiated in 1884 and completed in 1894. A portion of the Galveston County seawall was erected between 1902 and 1904 and extended in 1918, 1926, 1927, and again in 1952. Groins were first constructed in 1885; additional groins were constructed in 1939. All of these projects serve to alter natural processes

Figure 10. Littoral drift in vicinity of Bolivar Roads and Galveston Harbor jetties.

Figure 11. Littoral drift along upper Texas Coast (Sabine Pass-Galveston Island).

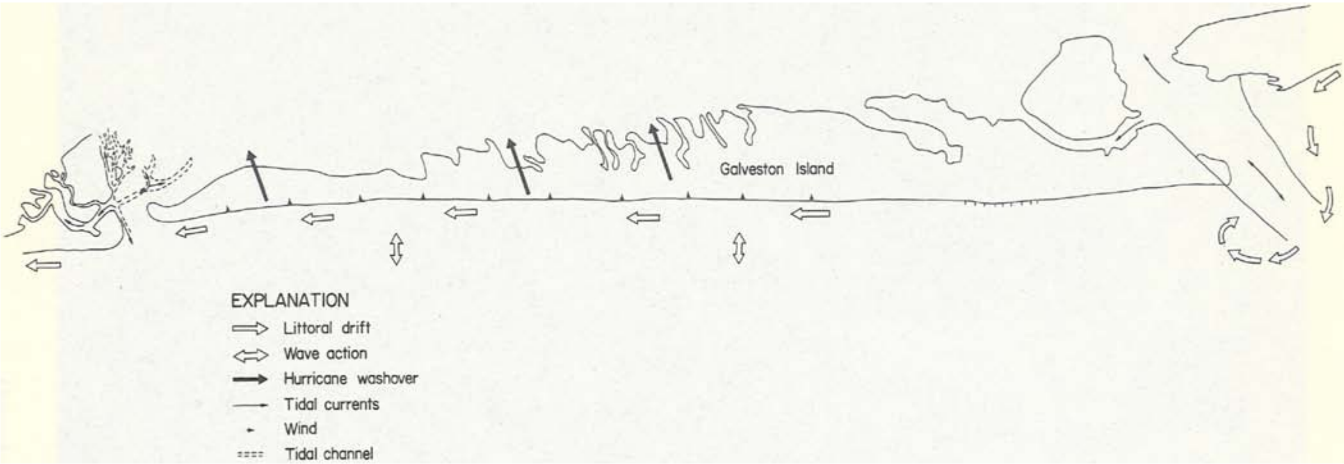

Figure 12. Generalized diagram of sediment transport directions in the vicinity of Galveston Island.

such as inlet siltation, beach erosion, and hurricane surge. Their effect on shoreline changes is subject to debate, but it is common knowledge that impermeable structures interrupt littoral drift and impoundment of sand is at the expense of the beach downdrift of the structure. Thus, it appears reasonable to expect that any sand trapped west of the south jetty is compensated for by removal of sand downdrift. Preliminary figures indicate that the area of sand accreted and stored on the west side of the south jetty is approximately equivalent to 300 feet of beach from 12th Street to San Luis Pass. Furthermore, beach erosion immediately west of the seawall end is probably aggravated by the presence of the seawall and the fact that essentially no sand beach exists in front of the seawall. The unprotected beach is the first source of sand downdrift from the area of no sand.

As previously mentioned, sand dunes were removed from West Beach for raising land elevation of Galveston. Sand was also dredged from the Gulf for the same purpose (Weems, 1957). Large, water-filled pits also attest to the fact that sand removal has been substantial, the result of which is an increased deficit in sediment supply.

The deltaic plain of the Mississippi River is characterized by both minor and major distributaries, most of which have been blocked off from the main river and thus prevented from transporting major quantities of sediment to the Gulf. Levee construction in 1868 eliminated flow through Bayou Plaquemine; discharge through Bayou Lafourche was controlled in 1904 (Gunter, 1952). But the main controls placed on the river system occurred when locks were constructed to prevent increased discharge into the Atchafalaya River, which would have eventually caused diversion of the Mississippi River because of the shorter Gulf route. The impact of these controls in modifying sediment budget is not documented, but any increase in sediment supply to the littoral system would be helpful under natural conditions. However, the presence of jetties and the proposed extension of some into deeper water would virtually guarantee the exclusion of most sand transported by littoral currents for beach nourishment.

EVALUATION OF FACTORS

Shore erosion is not only a problem along United States coasts (El-Ashry, 1971) but also a worldwide problem. Even though some local conditions may aggravate the situation, major factors affecting shoreline changes are eustatic conditions (compactional subsidence on the Texas Coast) and a deficit in sediment supply. The deficit in sand supply is related to climatic changes, human activities, and the exhaustion of the shelf supply through superjacent deposition of finer material over the shelf sand at a depth below wave scour.

Tropical cyclones are significant geologic agents and during these events, fine sand, which characterizes most of the Texas beaches, is easily set into motion. Silvester (1959) suggested that swell is a more important agent than storm waves in areas where longshore drift is interrupted and sand is not replenished offshore. For the purposes of this discussion, the individual effects of storms and swell is a moot question. Suffice it to say that water in motion is the primary agent delivering sand to or removing sand from the beach and offshore area. However, there is little doubt that storms are the primary factor related to changes in vegetation line.

PREDICTIONS OF FUTURE CHANGES

The logical conclusion drawn from factual information is that changes in position of shoreline and vegetation line will continue with landward retreat (erosion) being the long-term trend. The combined influence of interrupted and decreased sediment supply, relative sea-level rise, and tropical cyclones is insurmountable except in very local areas such as river mouths. There is no evidence that suggests a long-term reversal in any trends of the major factors. Weather modification includes seeding of hurricanes (Braham and Neil, 1958; Simpson and others, 1963), but control of intense storms is still in incipient stages of development. Furthermore, elimination of tropical storms entirely could cause a significant decrease in rainfall for the southeastern United States (Simpson, 1966).

Borings on Galveston Island (Bernard and others, 1959) indicate that sand thickness ranges from 10 to 30 feet under most of the island; thickness increases to the east. Therefore, the sand stored in the barrier island should tend to minimize erosion and keep rates relatively low.

The shoreline could be stabilized at enormous expense by a solid structure such as a seawall; however, any beach seaward of the structure would eventually be removed unless maintained artificially by sand nourishment (a costly and sometimes ineffective practice). The U. S. Army Corps of Engineers (1971a, p. 33) stated that "While seawalls may protect the upland, they do not hold or protect the beach which is the greatest asset of shorefront property." Moreover, construction of a single structure can trigger a chain reaction that requires additional structures and maintenance (Inman and Brush, 1973).

Maintenance of some beaches along the Outer Banks of North Carolina has been the responsibility of the National Park Service (Dolan and others, 1973). Recently the decision was made to cease maintenance because of mounting costs and the futility of the task (New York Times, 1973).

It seems evident that eventually nature will have its way. This should be given utmost consideration when development plans are formulated. While beach-front property may demand the highest prices, it may also carry with it the greatest risks.

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APPENDIX A

Shoreline and Vegetation Line Changes, East Beach, Galveston Island

+ accretion
- erosion

Shoreline Changes

beach segment Galveston

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
1	1835 1850	-2500	-208.3	1850 1930	+7100	+88.2	1930 1956	+1750	+67.3	1956 1970	+ 75	+ 5.4				1838 1970	+6425	+48.7
2	"	-1300	-108.3	"	+6000	+74.5	"	+1200	+46.2	"	+100	+ 7.1				"	+6000	+45.5
3	"	- 800	- 66.7	"	+2075	+25.8	"	+ 850	+32.7	"	0	0				"	+2075	+15.7
4	"	+ 50	+ 4.2	"	- 500	- 6.2	"	+ 550	+21.2	"	- 50	- 3.6				"	+ 50	+<1.0
5	"	- 30	- 2.5	"	- 575	- 7.1	"	+ 125	+ 4.8	"	- 75	- 5.4				"	- 555	- 4.2
6	"	+ 180	+ 15.0	"	- 300	- 3.7	"	+ 100	+ 3.8	1956 1965	- 75	- 8.3				1838 1965	- 95	-<1.0
7	"	+ 120	+ 10.0	"	- 175	- 2.2	"	+ 25	+ 1.0	"	0	0				"	- 30	-<1.0
8	"	+ 75	+ 6.3	"	- 125	1.6	"	+ 50	+ 1.9	"	0	0				"	0	0
9				1851 1930	- 475	- 6.0	"	0	0	"	- 25	- 1.8				1851 1965	- 500	- 4.4
10				"	- 550	- 6.9	"	0	0	"	-125	- 8.9				"	- 675	- 5.9
11				"	- 775	- 9.7	"	+ 150	+ 5.8	"	-250	-17.9				"	- 875	- 7.6
12				"	- 980	-12.4	"	+ 40	+ 1.5	"	-120	-13.3	1965 1973	-200	-25.0	1851 1973	-1260	-10.3
13				"	- 925	-11.7	"	+ 120	+ 4.6	"	-190	-21.1	"	-130	-16.3	"	-1125	- 9.2
14				1851 1933-34	- 640	- 7.7	1933-34 1956	-<10	-<1.0	"	- 50	- 5.6	"	-180	-22.5	"	- 880	- 7.2
15				"	- 350	- 4.2	"	+<10	+<1.0	"	- 50	- 5.6	"	-160	-20.0	"	- 550	- 4.5
16				"	- 100	- 1.2	"	+ 80	+ 3.5	"	-<10	-<1.0	"	-110	-13.8	"	- 140	- 1.2
17				"	+ 80	+ 1.0	"	+120	+ 5.2	"	- 70	- 7.8	"	- 30	- 3.8	"	+ 100	+<1.0
18				"	+ 120	+ 1.5	"	+ 50	+ 2.2	"	-110	-12.2	"	+ 30	+ 3.8	"	+ 90	+<1.0
19				"	+ 170	+ 2.1	"	+ 80	+ 3.5	"	-180	-20.0	"	- 30	- 3.8	"	+ 40	+<1.0
20				"	+ 120	+ 1.5	"	+ 80	+ 3.5	"	-120	-13.3	"	- 20	- 2.5	"	+ 60	+<1.0
21				"	+ 40	+<1.0	"	+130	+ 5.7	"	-130	-14.4	"	+ 40	+ 5.0	"	+ 80	+<1.0
22				"	- <10	-<1.0	"	+140	+ 6.1	"	-200	-22.2	"	+ 50	+ 6.3	"	- 20	-<1.0
23				1851 1930	- 180	- 2.3	1930 1956	+150	+ 5.8	"	-100	-11.1	"	+ 50	+ 6.3	"	- 80	-<1.0
24				1852 1930	- 170	- 2.2	"	+ 80	+ 3.1	"	-120	-13.3	"	+ 80	+10.0	1852 1973	- 130	- 1.1
25				"	- 70	-<1.0	"	- 70	- 2.7	"	-100	-11.1	"	+ 40	+ 5.0	"	- 200	- 1.6
26				"	- <10	-<1.0	"	- 90	- 3.5	"	-130	-14.4	"	+ 20	+ 2.5	"	- 210	- 1.7
27				"	- 60	-<1.0	"	- 40	- 1.5	"	-150	-16.7	"	+ 50	+ 6.3	"	- 200	- 1.6
28				"	+ <10	<1.0	"	-100	- 3.9	"	-120	-13.3	"	+ 60	+ 7.5	"	- 150	- 1.2
29				"	- 100	- 1.3	"	-<10	-<1.0	"	-120	-13.3	"	+ 50	+ 6.3	"	- 180	- 1.5
30				"	- 190	- 2.4	"	+340	+13.1	"	-190	-21.1	"	-160	-20.0	"	- 200	- 1.6
31				"	- 80	- 1.0	"	+770	+29.6	"	-610	-67.8	"	-720	-90.0	"	- 640	- 5.3
		mixed			erosion			accretion			erosion			mixed				

Shoreline and Vegetation Line Changes, West Beach, Galveston Island (continued)

+accretion
-erosion

beach segment Galveston

Point	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Time	Dist. ft	Rate ft per yr	Net Time	Net Dist.	Net Rate
							Vegetation Line Changes								
12	1930 1944	-300	-21.4	1944 1956	+380	+31.7	1956 1964	-280	-35.0	1964 1973	+ 80	+ 8.9	1930 1973	-120	- 2.8
13	"	-590	-42.1	"	+750	+62.5	"	-250	-31.3	"	+100	+11.1	"	+ 10	+<1
14				"	+130	+10.8	"	-240	30.0	"	+ 40	+ 4.4	1944 1973	- 70	- 2.4
15				"	+160	+13.3	"	-160	-20.0	"	+100	+11.1	"	+100	+ 3.4
16				"	+260	+21.7	"	-160	-20.0	"	+ 90	+10.0	"	+190	+ 6.6
17				"	+350	+29.2	"	-120	-15.0	"	+ 90	+10.0	"	+320	+11.0
18				"	+400	+33.3	"	-100	-12.5	"	+ 30	+ 3.3	"	+330	+11.4
19				"	+290	+24.2	"	-130	-16.3	"	+ 70	+ 7.8	"	+230	+ 7.9
20				"	+330	+27.5	"	- Bulkhead - 50	- 6.3	"	0	0	"	+280	+ 9.7
21				"	+380	+31.7	"	-120	-15.0	"	+ 40	+ 4.4	"	+300	+10.3
22	1930 1944	+ 30	+ 2.1	"	+350	+29.2	"	-180	-22.5	"	+130	+14.4	1930 1973	+330	+ 7.7
23	1930 1938	-<10	- 1.0	1938 1956	+390	+21.7	"	-130	-16.3	"	+190	+21.1	"	+440	+10.2
24	"	+ 50	+ 6.3	"	+380	+21.1	"	-100	-12.5	"	+130	+14.4	"	+460	+10.7
*25	"	- 50	- 6.3	"	+280	+15.6	"	-160	-20.0	"	+160	+17.8	"	+230	+ 5.3
*26	"	-250	-31.3	"	+350	+19.4	"	-180	-22.5	"	+ 60	+ 6.7	"	- 20	-<1
27	"	-140	-17.5	"	+200	+11.1	"	-130	-16.3	"	+120	+13.3	"	+ 50	+ 1.2
28	"	-150	+18.8	"	+330	+18.3	"	- 60	- 7.5	"	+ 70	+ 7.8	"	+190	+ 4.4
29	"	- 60	- 7.5	"	+350	+19.4	"	- 50	- 6.3	"	+100	+11.1	"	+340	+ 7.9
30	"	- 80	-10.0	"	+220	+12.2	"	+ 90	+11.3	"	- 40	- 4.4	"	+190	+ 4.4
31	"	- 80	-10.0	"	+280	+15.6	"	+210	+26.3	"	+ 30	+ 3.3	"	+440	+10.2
*Bulkhead area (1964-70)		erosion			recovery			erosion			recovery				

APPENDIX B

Tropical Cyclones Affecting the Texas Coast 1854-1973
(compiled from Tannehill, 1956; Dunn and Miller, 1964; and Cry, 1965).

Intensity Classification from Dunn and Miller

	Maximum Winds	Minimum Central Pressures
Minor	Less than 74	above 29.40 in.
Minimal	74 to 100	29.03 to 29.40 in.
Major	101 to 135	28.01 to 29.00 in.
Extreme	136 and higher	28.00 in. or less

Year	Area	Intensity	Year	Area	Intensity	Year	Area	Intensity
1854	Galveston southward	major	1900	Upper coast	extreme	1940	Upper coast	minimal
1857	Port Isabel	?	1901	Upper coast	minor	1940	Upper coast	minor
1866	Galveston	minimal	1902	Corpus Christi	minimal	1941	Matagorda	minimal
1867	Galveston southward	major	1908	Brownsville	?	1941	Upper coast	minimal
1868	Corpus Christi	minimal	1909	Lower coast	minor	1942	Upper coast	minimal
1871	Galveston	minor	1909	Velasco	major	1942	Matagorda Bay	major
1871	Galveston	minimal	1909	Lower coast	minimal	1943	Galveston	minimal
1872	Port Isabel	minimal	1910	Lower coast	minor	1943	Upper coast	minor
1874	Indianola	minimal	1910	Lower coast	minimal	1945	Central Padre Island	minor
1874	Lower coast	minor	1912	Lower coast	minimal	1945	Middle coast	extreme
1875	Indianola	extreme	1913	Lower coast	minor	1946	Port Arthur	minor
1876	Padre Island	?	1915	Upper coast	extreme	1947	Lower coast	minor
1877	Entire coast	minimal	1916	Lower coast	extreme	1947	Galveston	minimal
1879	Upper coast	minor	1918	Sabine Pass	minimal	1949	Freeport	major
1880	Lower coast	major	1919	Corpus Christi	extreme	1954	South of Brownsville	minor
1880	Sargent	?	1921	Entire coast	minimal	1955	Corpus Christi	minimal
1880	Brownsville	major	1921	Lower coast	minor	1957	Beaumont	minor
1881	Lower coast	minimal	1922	South Padre Island	minor	1957	Sabine Pass	minimal
1885	Entire coast	minimal	1925	Lower coast	minor	1958	Extreme southern coast	minimal
1886	Upper coast	minor	1929	Port O'Connor	minimal	1958	Corpus Christi	minimal
1886	Entire coast	extreme	1931	Lower coast	minor	1959	Galveston	minimal
1886	Lower coast	minimal	1932	Freeport	major	1960	South Padre Island	minor
1886	Upper coast	minimal	1933	Lower coast	minor	1961	Palacios	extreme
1887	Brownsville	minimal	1933	Matagorda Bay	minor	1963	High Island	minimal
1888	Upper coast	minimal	1933	Brownsville	major	1964	Sargent	minor
1888	Upper coast	minor	1933	Brownsville	minimal	1967	Mouth Rio Grande	major
1891	Entire coast	minimal	1934	Rockport	minimal	1968	Aransas Pass	minor
1895	Lower coast	minor	1934	Entire coast	minor	1970	Corpus Christi	major
1895	Lower coast	minor	1936	Port Aransas	minimal	1970	High Island	minor
1897	Upper coast	minimal	1936	Lower coast	minor	1971	Aransas Pass	minimal
1898	Upper coast	minor	1938	Upper coast	minor	1973	High Island	minor

APPENDIX C

List of Materials and Sources

List of aerial photographs used in determination of changes in vegetation line and shoreline. *Indicates vegetation line and/or shoreline was used in map preparation.

Date		Source of Photographs
Nov. 1930	*	Tobin Research Inc.
Nov. 1938	*	U. S. Dept. Agriculture
Sept. 1942		U. S. Army Corps Engineers
April 1944	*	(in Slingluff, 1948; Stern, 1948)
March 1952		U. S. Dept. Agriculture
Aug. 1956	*	Tobin Research Inc.
Sept. 1961		U. S. Army Corps Engineers
Feb. 1964	*	Texas Highway Department
Oct. 1965	*	Natl. Oceanic and Atmospheric Admin.
July 1967		U. S. Army Corps Engineers
April 1970		Texas Highway Department
Aug. 1972		Texas Highway Department
Dec. 1973	*	Texas Forest Service

List of Maps Used in Determination of Shoreline Changes

Date	Description	Source of Maps
Jan.-May 1851	topographic map 328	Natl. Oceanic and Atmospheric Admin.
Feb.-April 1852	topographic map 324	Natl. Oceanic and Atmospheric Admin.
1933-1934	from Plates 10 and 11	U. S. Army Corps Engrs. (1953)

List of 7.5-minute quadrangle topographic maps used in construction of base map. Source of these maps is the U. S. Geological Survey.

Galveston, Texas
Virginia Point, Texas
Lake Como, Texas
Sea Isle, Texas
San Luis Pass, Texas