IDENTIFICATION OF SHORELINE EROSION FEATURES AND 60 YEAR PROJECTION OF THE GULF SHORELINE POSITION, GALVESTON AND BRAZORIA COUNTIES, TEXAS

Prepared for the Texas General Land Office

GLO Contract 96-204 R

by

Robert A. Morton and Edward S. Angle

Assisted by Erika M. Boghici

Bureau of Economic Geology

The University of Texas at Austin

Noel Tyler, Director

December 1996

CONTENTS

Figure Captions

Tables

ABSTRACT

Changes in shoreline position along the southeastern Texas Gulf coast between 1974 and 1996 were documented by conducting a kinematic real-time differential global positioning system (GPS) field survey in 1996 and comparing that shoreline with other shorelines archived in a geographic information system. Results of the investigation show that (1) beach morphology, shoreline movement, and the regional geologic framework are closely interrelated, (2) Gulf beaches are generally retreating, and (3) the rates of retreat have accelerated locally.

Gulf beaches between High Island and Rollover Pass have been retreating for centuries and they continue to retreat. On Bolivar Peninsula, beaches between Rollover Pass and Caplen are retreating rapidly, whereas those farther southwest are either slowly retreating or are relatively stable; at the southern end of the Peninsula, beaches are stable or advancing from the sand supplied by updrift erosion.

The shoreline on East Beach of Galveston Island undergoes minor fluctuations, but the beach position is relatively stable. West Beach of Galveston Island continues to retreat, but rates of retreat vary depending on location. The beach segment between the Indian Beach and Sea Isle subdivisions has the lowest long-term average retreat rate, whereas retreat rates generally increase to the northeast toward the seawall and to the southwest toward San Luis Pass. These three segments with different beach morphologies and retreat rates were also identified in prior studies. Beaches from San Luis Pass to the mouth of the Brazos River also are generally retreating and rates of retreat near Surfside, Quintana, and Bryan Beach are influenced by the jetties at Freeport Harbor and the diversion of the mouth of the Brazos River.

The long-term average annual erosion rate of beaches in Galveston and Brazoria Counties was determined using the database of digital shoreline positions and a framework of shore-normal transects spaced 150 ft apart along the shore. The linear regression statistical function of the Shoreline Shape and Projection Program (SSAPP) was used to calculate the average annual erosion rate and to estimate the position of the shoreline erosion feature in 60 years. The possible long-term effects of engineering projects such as shoreline protection structures and beach nourishment projects also were analyzed to assist in evaluating the validity of the projected shoreline position.

The field surveys and statistical analyses demonstrated that the high water line mapped on aerial photographs undergoes large seasonal fluctuations and therefore is a less reliable indicator of shoreline position than the vegetation line, berm crest, or backbeach erosional scarp. The study also showed that GPS field surveys are a rapid,

relatively low cost method of acquiring accurate shoreline positions and they have many advantages compared to aerial photographs.

INTRODUCTION

State and Federal agencies with coastal management responsibilities currently rely on average rates of shoreline movement and projected future shoreline positions for regulatory purposes. As a result of this dependency on scientific data, regional studies of shoreline movement are now regarded as important sources of information for formulating coastal management policies and long-range planning. These coastal investigations that at one time were considered merely academic exercises now serve as a primary technical basis for decisions made by coastal planners and managers of natural resources located near the shore.

The use of oceanic shorelines to establish legal boundaries and construction setback lines or to delineate flood hazard zones creates a high mapping standard that can only be achieved with highly accurate analyses of historical changes in shoreline position. The keys to improved accuracy and reliability of predicting future shoreline positions are (1) understanding the conditions that control beach morphology, (2) documenting short-term variability in shoreline position at representative sites, and (3) reducing the errors that are inherent in mapping and analyzing changes in shoreline positions (Morton, 1991).

Increased public demand for quantitative shoreline data and predictions of future shoreline positions that are both reliable and current have altered the ways coastal scientists collect and analyze shoreline data. Field monitoring of beaches for twenty years or mapping shorelines on sets of aerial photographs to distinguish long-term shoreline movement from short-term fluctuations is no longer an option in some regions because decisions to develop valuable coastal property are being made rapidly. Now coastal scientists must utilize rapid, highly accurate methods that minimize the errors of mapping and processing data.

The Bureau of Economic Geology has met the challenge of accurately mapping shoreline movement by improving the methods of data collection and analysis. The most common shoreline proxy derived from aerial photographs is the high water line separating the wet beach from the dry beach. However, more than two decades of beach surveys and field observations have demonstrated clearly that the high water line mapped on aerial photographs is dynamic and therefore is a less reliable indicator of shoreline position than the berm crest, base of the dune, vegetation line, or other beach feature that is either unaffected or only nominally altered by short-term changes in water levels. Furthermore, development of relatively low-cost, accurate Global Positioning Systems (GPS) now permit direct correlation between mapped shorelines and field observations of the mapped features instead of relying on interpretations from aerial photographs (Morton et al., 1993).

A principal objective of this study was to document recent Gulf shoreline movement along the southeastern Texas coast in Galveston and Brazoria Counties between High Island and the mouth of the Brazos River (fig. 1). This objective was accomplished by comparing shoreline positions that were mapped from aerial photographs taken in 1974, 1982, and 1990, and from GPS field surveys and observations conducted in 1996. Secondary objectives were (1) to document the variability in shoreline erosion features along the coast, and (2) to relate beach morphology and shoreline movement to the regional geologic framework.

SHORELINE MONITORING FEATURES

Shoreline movement is typically documented by identifying and monitoring the positions of beach features that are leading indicators of beach movement. This means that the monitored feature should respond to changes in environmental conditions but it should not be so sensitive to fluctuations in local conditions that it gives spurious results if monitored in the field or on aerial photographs. Typical morphological features on the Gulf beaches of Galveston and Brazoria Counties are the berm crest, erosional scarp, vegetation line, and crest of the washover terrace (fig. 2).

In the absence of a more reliable morphological feature, the high water line or wet-beach/dry-beach line may be used as the shoreline proxy. Shoreline positions may also be defined by hard structures or other artificial features that largely constrain the inland extent of high water. Shoreline monitoring features used in this study are the same as shoreline erosion features (SER) defined by the Federal Emergency Management Agency (FEMA).

Berm Crest

The berm crest (fig. 2a) is the morphological feature that separates the steeper forebeach from the gentler sloping backbeach. It is a depositional feature when constructed by runup of normal waves (generally summer conditions) and a destructional feature when eroded by waves at abnormally high water levels (generally winter conditions). The berm crest may be entirely eroded by high storm waves, transforming the beach into a broad, featureless surface that slopes seaward uniformly.

On some beaches there are two berm crests; a high crest and a low crest (fig. 2a). Multiple berm crests are constructed by erosion of the backbeach and subsequent deposition on the forebeach by onshore migration of a sand bar and runup by low waves. Eventually the low berm will increase its height and merge with the high berm or the cycles of erosion and partial recovery will be repeated. Where there are multiple berm crests, the highest, most landward crest is used as the shoreline monitoring feature because it is more stable and responds to events of lower frequency than the lower berm crest. Laterally along the beach, the berm crest may become steeper and change to a mid-beach erosional scarp (fig. 2c) or it may flatten, become indistinct, and grade into a concave beach profile without a berm crest (fig. 2e).

Erosional Scarp

Erosional scarps are destructional features that are located in the mid-beach or form an abrupt break in slope at the landward limit of the backbeach (fig. 2c). Backbeach scarps normally represent the long-term beach morphology and they typically coincide with the vegetation line (fig. 2c). In contrast, mid-beach scarps are ephemeral features that are excavated during a rapid rise in water level when waves approach the shore at a high angle and generate strong alongshore currents, or a mid-beach scarp may be constructed when the forebeach gradient is extremely steep such as after a beach nourishment project. Backbeach scarps typically grade into low dunes or washover terraces (fig. 2b), whereas mid-beach scarps generally pass laterally into high berm crests (fig. 2a).

Vegetation Line

On beaches and in wetlands, the vegetation line (fig. 2a, 2c, 2d, 2e) is a biological indicator of the limits of regular flooding by high water and therefore it represents a nearly ideal indicator of shoreline movement. Because the vegetation line is controlled by backbeach flooding, elevations of the vegetation line are consistently about 5 to 6 ft above sea level along sand beaches of the southeastern Texas coast (fig. 3). Plants that colonize the dunes and backbeaches can tolerate salt spray but they cannot survive if their roots are submerged for prolonged periods. The vegetation line can be a more reliable indicator of long-term shoreline movement than the high water line because it is not affected by short-term variations in water level.

Two factors prevent the vegetation line from being an ideal mapping boundary. First, the vegetation line is a biological feature. It responds to terrestrial environmental conditions that are different from those oceanic conditions controlling beach morphology and position. For long periods (decades) the vegetation line will naturally reflect beach movement, but the vegetation line on sandy beaches can move independent of and in directions opposite to those of the beach for short periods (Morton, 1974; 1975; Paine and Morton, 1989). Second, the vegetation line is not always a distinct, easily identifiable feature. On many stable or accreting sand beaches, there are two vegetation boundaries that can be mapped; a line of dense vegetation that spreads continuously inland, and a line of sparse vegetation adjacent to the bare backbeach (Morton, 1974; 1975). The line of dense vegetation marks the most stable position beyond which the beach typically is unaffected by most storm surges. The zone of sparse vegetation consists of low mounds or dunes that have accumulated since the last major storm but have not coalesced to form a more continuous ridge of vegetated dunes.

The vegetation line is also subject to either deliberate or unintentional manipulation and artificial stabilization. In general, position of the vegetation line in Galveston and Brazoria Counties is at least partly controlled by property owners or beach scraping activities (Morton et al., 1995b). Property owners erect sand fences, plant dune grasses, and engage in other activities that tend to encourage the accumulation of sand and seaward advancement of the vegetation line. Rubble-cored sand mounds have been constructed in some areas of Bolivar Peninsula and Galveston Island to serve as wave protection and to dispose of debris created by Hurricane Alicia in 1983.

Artificial dunes have also been created by the counties in conjunction with beach raking and scraping. Beach cleaning inadvertently mixes some sand with the beach debris. To keep the sand on the beach, piles of sand and trash are pushed into the backbeach where they become vegetated and act as low dunes. Along some beach segments, the piles of sand and debris form a zone as much as 115 ft wide, which represents an artificial advancement of the vegetation line. Because manipulation of the vegetation line is prevalent along the southeastern Texas beaches, an ordinal ranking was developed to classify the extent of backbeach modification on the basis of field observations (Table 1).

In wetlands, such as salt-water marshes, the vegetation line is typically lower in elevation and seaward of the high water line because the wetland plants require frequent flooding to survive. Despite this discrepancy between the shoreline and the high water line, the marsh vegetation line is a good indicator of shoreline movement. Between High Island and the Brazos River, the marsh vegetation line forms the shore only for a short segment of Bolivar Flats, just north of the north jetty at Bolivar Roads (fig. 1).

Crest of Washover Terrace

Washover terraces (fig. 2b) are deposited where beaches are highly erosional and adjacent ground elevations are lower than the highest storm surges. The terraces are composed of sand with high concentrations of shell and rock fragments (Morton, 1975). The crest of the washover terrace forms the highest beach elevation and is the best indicator of shoreline movement for these types of beaches. Terrace crests can pass laterally into backbeach erosional scarps (higher elevations) or marshes (lower elevations). During storm washover, beach sand and shell are transferred onshore burying adjacent marsh or upland vegetation and concealing the vegetation line until vegetation either grows through the washover deposit or new vegetation colonizes the washover surface.

A broad washover terrace composed of sand and shell was deposited on the southwestern end of Galveston Island by Hurricane Alicia in 1983. Since then, the terrace has been modified by beach retreat, consequently the erosional scarp was used as the shoreline erosion feature for this beach segment instead of the crest of the washover terrace. Washover terraces that have been active recently are not common beach features in Galveston and Brazoria Counties.

High Water Line

Some eroding sandy beaches exhibit a concave upward profile that lacks a distinct berm crest (fig. 2e). On these beaches the vegetation line and the high water line are two potential indicators of shoreline movement.

The high water line is also commonly used on aerial photographs as the shoreline proxy because it is easily identified (Stafford, 1971; Morton, 1979, 1991; Dolan and Hayden, 1983; Leatherman, 1983). The high water line observed in the field and on aerial photographs has been described as closely approximating the position of mean high water (McBeth, 1956; Shalowitz, 1964; Stafford, 1971). However, field surveys clearly show that the position of the high water line is a function of beach morphology, water level, and wave characteristics immediately preceding the field observation. Furthermore, the wet-beach/dry-beach boundary seldom coincides with the berm crest (even when one is present) or with the mean high water line, which is a surveyed boundary. Most of the time the high water line is seaward of the berm crest but it can also be landward of the berm crest when slowly rising water floods the backbeach (spring tides) without completely eroding the berm.

The high water line was mapped on the aerial photographs taken in 1974, 1982, and 1990. It was not mapped during the 1996 field surveys because morphological features identified in the field are more reliable indicators of long-term beach movement.

Coastal Structures

On some Galveston and Brazoria County beaches, especially developed beaches, the most prominent shoreline features are coastal structures erected parallel to the shore (fig. 2f). Such structures include bulkheads, seawalls, and revetments that are designed to protect the adjacent upland property from flooding by high water and erosion by storm waves. Coastal structures have variable lengths parallel to the beach. Some structures are extremely long, such as the 10 mile-long Galveston seawall, whereas others may extend only the width of a single lot (75 to 100 ft). Because coastal structures are products of human intervention, they have discrete lateral limits and can be adjacent to any other type of shoreline or shoreline feature.

Coastal structures such as seawalls and bulkheads do not always indicate that the beach is eroding and they are commonly constructed on stable or accreting beaches to prevent storms from damaging upland property. In these situations, the coastal structure is landward of the shoreline feature that should be used for monitoring beach movement. On retreating beaches, coastal structures form the shore and coincide with the landward limit of annual flooding by high water. Where beaches are highly erosional, coastal structures may fail physically and the shore will continue to retreat, thus establishing a new shoreline feature or another coastal structure position for monitoring.

BEACH MORPHOLOGY

Proper selection of a shoreline monitoring feature that tracks long-term shoreline movement partly depends on understanding the factors that control beach morphology at different time scales. Shoreline stability is ultimately controlled by the regional geologic framework, which includes the bedrock or late Quaternary deposits and coastal processes. Where tidal range and wave climate are essentially constant, such as along the southeastern Texas coast, alongshore variations in beach morphology (fig. 3) are related to the interaction of several factors including beach composition, substrate composition, direction and volume of sediment transport, beach stability, adjacent elevations, and strength of the highest storm waves. Beach morphology is an integrated response to these variables, which themselves are interactive and not totally independent. For example, beach morphology is closely linked to pairs of physical variables such as (1) beach and substrate composition, (2) volume of sediment transport and beach stability, and (3) adjacent elevations and storm wave heights.

Beach and Substrate Composition

The relationship between beach morphology and sediment textures is well known. Gravel beaches are generally steep and devoid of dunes, whereas fine sand beaches typically have low slopes and well-developed dunes. Beach morphology is also related to underlying sediments because they are a source of some beach material and they can control beach shape if the substrates are either immobile (bedrock or cemented sediments) or resistant to wave and current erosion (stiff mud).

The Gulf shore between High Island and the mouth of the Brazos River can be divided into three morpho-compositional sections that are related to the regional coastal depositional systems (Fisher et al., 1973). The eastern section, which extends from High Island to Rollover Pass, consists of a headland that is composed of late Pleistocene fluvial-deltaic deposits (McGowen et al., 1977). These mud-rich deposits are the source of abundant rock fragments, caliche nodules, and estuarine shells (*Rangia* and *Crassostrea*) that constitute the gravel concentrated on the beach northeast of High Island (fig. 1). Beaches that coincide with the Pleistocene headland (fig. 3b) are narrow, relatively steep, and covered by shell pads that migrate along the beach depending on wave heights and sediment transport directions. Forebeaches are steep and high berm crests are well defined where thick shell pads are present.

A transitional morpho-compositional section between the Pleistocene headland and barrier island (Bolivar Peninsula) is located between Rollover Pass and Caplen (fig. 1). This segment of Bolivar Peninsula is narrow and overlies Holocene muddy estuarine deposits that contain oyster shells that constitute the gravel component commonly found on the beach.

The western morpho-compositional section is the broad, sand-rich barriers (Bolivar Peninsula, Galveston Island, Follets Island) that extend from Caplen to Freeport (fig. 1). Within this section, Gulf beaches are sandy and moderately wide, and the undeveloped backbeaches grade into low, densely vegetated dunes (fig. 3f) or an erosional scarp (fig. 3e). Beach morphologies from Freeport to the Brazos River (new Brazos delta) are similar in that Gulf beaches are sandy, and the undeveloped backbeaches grade into low, densely vegetated dunes (fig. 3f) or an erosional scarp (fig. 3e). However beaches tend to be relatively narrow southwest of Freeport.

Sediment Supply and Beach Stability

There is a direct correlation between volume of sediment transported along a coastal compartment and stability of the adjacent beaches. Where sediment supply is abundant relative to wave energy, the beaches advance; conversely, where sediment supply is low, the beaches typically retreat. Sediment supply is also related to transport directions. Sand eroded at one site is transported by longshore currents and deposited at another downdrift or offshore site.

The Gulf shore between High Island and the mouth of the Brazos River corresponds to three coastal compartments. The jetties at Bolivar Roads and at Freeport (fig. 1) form the boundaries of the middle compartment. No rivers empty into the first two compartments, and the only sediment available for beach construction is either sand and shell eroded from substrates exposed on the shoreface or suspended sediment transported around the jetties and deposited in the wave shadow zone immediately west of the jetties. Although the flow of longshore currents throughout the year is bidirectional, net flow is to the southwest under the influence of east and southeast winds.

Where sediment supply is negligible or low, such as near High Island and on Bolivar Peninsula east of Caplen, the narrow steep beaches are generally retreating. Conversely, where sediment supply is moderate or high, such as on Bolivar Peninsula west of Caplen, on East Beach and central Galveston Island, and on Follets Island, relatively flat sand beaches are slowly retreating or advancing.

Adjacent Elevations and Storm-Wave Heights

The relationship between wave heights in the Gulf of Mexico and elevations of adjacent land largely determines if erosion or deposition occurs during high water events. Where waves are higher than the adjacent land, the land is inundated, overwashed, and possibly buried by washover deposits. Conversely, where storm waves are lower than the adjacent land, the backbeach-dune area is eroded by high water and scarps typically form in the dunes or barrier flat.

Between High Island and Caplen (fig. 1), storm waves regularly flood the adjacent land and deposit washover terraces of sand and shell. Frequent upland flooding coupled with long-term erosion have destroyed Highway 87 northeast of High Island. Thickest washover deposits are preserved near Caplen where sediments deposited by Hurricanes Carla (1961) and Alicia (1983) are about 4 ft thick. Age of the thickest washover deposit (Carla) is inferred by examining post-storm aerial photographs and by the presence of concrete slabs and a TV antenna at the base of the deposit (fig. 4). Storm waves currently do not exceed the land elevation, therefore the washover deposits are exposed in a high erosional scarp. Southwest of Caplen where the beach is sandy and wide, storm waves seldom overtop the dunes, which are about 10 ft high.

Dunes on East Beach of Galveston Island are also high enough to prevent washover by most storm waves except where the dunes have been removed at the parks and for beach parking. The lack of well-developed dunes on West Beach of Galveston Island makes it vulnerable to overwash as shown by the extensive flooding and washover deposition associated with Hurricane Alicia (Morton and Paine, 1985). Only the dunes northeast of Sea Isle are high enough to prevent inundation by most hurricanes. Dunes on Follets Island, Quintana Beach, and Bryan Beach are generally narrow and low, and adjacent land elevations are incapable of preventing overwash by even moderate storms.

MAPPED SHORELINE POSITIONS

Various field and laboratory methods are available for delineating shoreline positions and analyzing shoreline movement. These generic methods and their limitations were recently reviewed by Morton (1996).

Field Surveys

Classification and Distribution of Shoreline Features

Before the field survey was conducted, an ordinal ranking of shoreline features was prepared based on the variability in shoreline types (figs. 2 and 5) observed along the southeastern Texas coast (Morton, 1974, 1975; Morton and Pieper, 1975; Morton and White, 1995). The ordinal ranking emphasizes stable beach features that are sensitive to long-term movement in beach position but are not appreciably altered by human activities. The ranking, which follows, provided the basis for selecting a shoreline proxy that was practical, repeatable, and relatively stable: (1) berm crest, (2) crest of washover terrace, (3) base of erosional escarpment, (4) vegetation line, (5) high water line, (6) artificial shore.

From High Island to Rollover Pass (fig. 1), either the upper berm crest or the trough between the high and low berms was surveyed as the shoreline feature. Southwest of Rollover Pass, an erosional scarp forms the shore except where the shoreline is locally altered by hard structures such as concrete and rock revetments. The protective structures typically are only one or two lots wide, but they protrude so far toward the water that they frequently block lateral movement along the beach. Maximum elevation of the erosional scarp (8 ft) is near Caplen (fig. 2).

Southwest of Caplen, scarp elevation is lower and the scarp passes into a wide sand and shelly sand beach with low dunes and a berm crest that forms the shore. This beach morphology characterizes the Gulf shore to the southwestern end of Bolivar Peninsula where the normal berm crest passes into broad sand flats that are a depositional continuation of the beach. A high berm crest and the vegetation line were surveyed as the shoreline feature from the northeastern boundary of the Bolivar Flats Bird Refuge to the marsh shore at the Bolivar Roads jetty.

The high berm crest also was surveyed as the shoreline feature on East Beach of Galveston Island between the south jetty and the rock groin at 10th Street. The 1996 shoreline was not surveyed where the shore is formed by the Galveston seawall (transects 5-12, fig. 1).

On West Beach, a prominent erosional scarp forms the shore between the southwestern end of the seawall and Galveston Island State Park. At the State Park, the beach widens and the upper berm crest is the shoreline feature that was mapped to near the Bay Harbor subdivision (fig. 1). There beach morphology changes and an erosional scarp forms the shore. The scarp is continuous to just northeast of San Luis Pass where it is locally buried by a recent accumulation of sand. At San Luis Pass the beach merges into a broad sand flat that has low, sparsely vegetated dunes. Along this short beach segment, both the vegetation line and the berm crest were mapped as shoreline features.

The high berm crest was the mapped shoreline feature in Brazoria County with the following exceptions. On the northeastern end of Follets Island, several houses and associated bulkheads form the shore and southwest of the bulkheads an erosional scarp forms the shore. For the remainder of Follets Island, at Surfside, along Quintana Beach, and along the east flank of the Brazos delta, the berm crest forms the shore.

Global Positioning System

The 1996 shoreline feature between High Island and the mouth of the Brazos River was surveyed using a dual antenna real-time kinematic differential GPS system (Trimble Pathfinder and Omnistar DGPS) mounted on a four-wheel drive all terrain vehicle (fig. 6). The DGPS equipment provided positions that are probably accurate to within 3 to 6 ft compared to shoreline positions derived from aerial photographs, which are only accurate to about 25 ft (Morton, 1991). During kinematic beach surveys, horizontal positions (UTM WGS-84) were collected at a 1 sec sampling rate, which translates to an average spacing of approximately 15 ft at high speed and 10 ft at low speed. Static positions were recorded for 5 minutes at the beginning and at the end of each beach segment (data file). Beach segments were limited in length by natural features, such as large drainage channels, or physical barriers, such as cables or revetments across the beach, that prevented continuous lateral movement. Within a beach segment, way points were recorded to mark the positions of prominent (reference) features (drainage channels, houses on the beach) or the locations where the surveyed shoreline feature changed from one type to another. Most of the way points were photographed and field notes were recorded for future reference.

The raw GPS data were converted to State Plane, South-central Zone, NAD 27 datum, survey feet. Several files were collected in a non-differential mode when the Omnistar receiver was unable to provide corrected positions. These files were corrected in post-processing using differential corrections from the Texas Department of Transportation HARN station in Houston, Tx. The converted files of shoreline segments were merged, creating a single, continuous coverage for the 1996 shoreline.

Beach Profiles

Beach profiles from High Island to Bolivar Roads have been surveyed intermittently since 1974, whereas profiles on West Beach of Galveston Island and the northeastern end of Follets Island have been surveyed continuously since 1983 (Morton et al., 1994, 1995a). Most of the original profile markers east of High Island have been destroyed by erosion and several of those west of Caplen have been destroyed by beach-front construction. Markers have been reestablished at those sites where monitoring has been continuous.

Alongshore variability in beach morphology is illustrated by representative profiles at selected sites from each of the morpho-compositional sections (fig. 3). The shapes of the profiles, particularly the width and steepness of the backbeach, are indicators of long-term beach stability.

Most of the beach profiles on West Beach document shoreline retreat. Profiles exhibiting the most retreat are just east of San Luis Pass near transect 29 and just southwest of the seawall near transect 14. Profiles exhibiting the least retreat are at Galveston Island State Park near transect 19, and at Jamaica Beach near transect 21. Beach profiles on West Beach showing shoreline advancement are east of Sea Isle near transect 24 and at San Luis Pass near transect 31.

The temporal variability in beach morphology at a particular site and the evolution of beach shape from one type to another is documented by comparing sequential profiles surveyed over a period of several years. The morphological evolution of beach profiles reflects changes in beach shape that are primarily responses to changes in sand supply (figs. 7 and 8). On Follets Island, alongshore transport of sand and subsequent beach deposition during a 10-year period produced a change in beach shape from an erosional scarp to a wide sandy beach with low dunes (fig. 7). Conversely, erosion of sand on Galveston Island just downdrift of the seawall during an 8-year period transformed a wide sandy beach with low dunes into a steep, narrow concave beach with no dunes and an erosional scarp (fig. 8). The composite beach profiles illustrate how beach morphologies rapidly evolve depending on a surplus or deficit in the sediment budget.

Geographic Information System (GIS)

The dynamics of Gulf beaches in southeastern Texas were analyzed using standard mapping techniques. Historical monitoring procedures included identifying and mapping selected shoreline features on topographic maps or low-altitude vertical aerial photographs (Morton, 1974; 1975; Morton and Pieper, 1975). The mapped shorelines spanning the period from 1850 to 1990 were optically transferred to topographic bases having common map scales and the shorelines and shore-normal transects constructed for data reduction were then digitized, manipulated, and stored in a geographic information system (ARC-INFO). Magnitudes and rates of coastal change were quantified at each of the transects, which are equally spaced along the coast (fig. 1).

Recent shoreline movement between Sabine Pass and the Brazos River was documented by comparing shoreline positions in June 1974 and either February 1996 (Sabine to Bolivar) or May 1996 (Galveston to Brazos River). The 1974 shoreline was already in the BEG ARC-INFO GIS, whereas the 1996 shoreline was derived from a real-time kinematic differential GPS survey that was later incorporated into the ARC-INFO shoreline coverage. Distances between the 1974 and 1996 shorelines were measured at each transect, rates of change were calculated for the 21.7 or 21.9 year period, and a table was generated summarizing the trends (- retreat, + advance), magnitudes of shoreline movement, and average rates of retreat or advance (Table 2).

ANALYSIS OF NET SHORELINE MOVEMENT 1974-1996

Shoreline Features

Beaches and bluffs are dynamic coastal features that are constantly changing shape and position in response to waves and water levels of the adjacent water body. Therefore, accurate depiction of shoreline movement relies on the accuracy of each shoreline position and consistency among shorelines incorporated into the shoreline change analysis. Consistency involves using the same shoreline feature and mapping criteria for each time period, whereas reliability refers to how accurately the shoreline feature represents long-term shoreline movement.

Ever since the concept of monitoring the shoreline from aerial photographs was first proposed, there has been an ongoing debate regarding the most appropriate proxy for shoreline position along coasts where beach morphologies are diverse. The wet beach/dry beach boundary, which is also referred to as the high water line, is widely accepted as the reference feature for mapping shorelines (Stafford, 1971; Morton, 1979, 1991; Dolan and Hayden, 1983; Leatherman, 1983) despite the fact that the high water line is also an unstable feature that moves frequently throughout the year. For most shores, the stability of shoreline features increases landward and the frequency of movement of a shoreline feature increases seaward. Consequently the vegetation line, crest of washover terrace, erosional scarp, or bluff toe are more stable than the berm crest, and the berm crest is more stable than the high water line. However, defining the shoreline as the erosional scarp, vegetation line, or crest of the washover terrace instead of the high water line or berm crest may result in a landward shift of the mapped shoreline feature and an apparent change in the rate of movement for the period that includes the redefined shoreline. The magnitude of the discrepancy and apparent shift in shoreline position attributed to redefinition is the ground distance between the newly defined and previously defined features.

In the Gulf coast region, aerial photographic missions are commonly flown in the winter after a cold front passes the coast because then the atmosphere is clear and there are no clouds to block the view of the camera. Preceding passage of a cold front is also the time when low barometric pressure and strong onshore winds typically cause abnormally high water and flooding of the backbeach. Under these conditions the high water line depicted on aerial photographs corresponds to the vegetation line, erosional scarp, or other backbeach feature regardless of whether the forebeach morphology is characterized by a convex profile with a berm crest or a concave profile without a berm crest. Beach observations during the past 25 years clearly demonstrate that (1) the high water line responds to high frequency events and therefore does not have any particular physical significance regarding long-term shoreline movement and (2) the lateral mobility of the high water line results in noisy data sets and may be responsible for apparent cycles of shoreline advance and retreat that are only a function of sequential differences in water levels and not actual changes in beach sediment volume.

Spatial Analysis

Shoreline movement from High Island to the mouth of the Brazos River between 1974 and 1996 (Table 2) describes an alongshore pattern similar to the one established by previous analyses (Morton, 1974, 1975; Morton and Pieper, 1975). Shoreline recession was recorded at 62 of the 80 transects, indicating that about 78 % of the shore was retreating, whereas only about 22 % of the shore was stable or advancing. The summary data (Table 2) help identify different shoreline segments based on the most recent trend of shoreline movement, either segments where the shoreline is receding or segments where the shoreline is stable or advancing.

<u>High Island to Bolivar Roads</u> - The entire Gulf shoreline retreated from transects 36 through 58. Recession rates were relatively low near and southwest of High Island (transects 37-42) where the berm crest is the mapped shoreline feature. This moderately wide sand beach with artificial dunes is partly nourished by sand eroded from beaches to the northeast. The anomalous low retreat rate at transect 42 (Table 2) is a result of sand trapped by pilings at a nearby fishing pier that acts as a permeable groin.

Near Rollover Pass (transects 43-46), rates of shoreline recession averaged about 5 ft/yr. This segment of the Gulf shore is characterized by a relatively steep narrow sand beach and washover terrace without dunes, or a low (< 5 ft) erosional scarp. The high berm crest or erosional scarp is the shoreline feature mapped for this segment (fig. 5).

Recession rates are moderate (4-6 ft/yr) along Bolivar Peninsula southwest of Caplen (Table 2, transects 47-58). There the beach is sandy, relatively wide, and low vegetated dunes occupy the backbeach. Because the beach is relatively wide, the berm crest is the shoreline feature mapped for this segment (fig. 5).

From transect 59 to the north jetty at Bolivar Roads, the Gulf shoreline is advancing (fig. 9) in response to the sand supplied by updrift erosion and alongshore transport. The berm crest is the shoreline feature mapped for this segment, which is characterized by a wide sand beach and low vegetated dunes. Rates of shoreline advancement systematically increase to the southwest from a few feet per year to more than 17 ft/yr (Table 2). Rapid deposition near the north jetty caused continued expansion of a broad sand flat (Bolivar Flats), which is a designated sanctuary for nesting and migrating birds.

<u>Galveston Island</u> - Almost the entire Gulf shore of Galveston Island experienced net retreat between 1974 and 1996 (Table 2, fig. 9). Exceptions to this general statement were beaches at the extreme northeastern and southwestern ends of the island, where the shoreline advanced, and along the Galveston seawall where a beach nourishment project in 1995 stabilized the shore between 10th Street and 61st Street. Average annual rates of shoreline retreat were lowest on East Beach and highest on West Beach between the seawall and Galveston Island State Park (transect 19, fig. 1). Retreat rates were moderate for the remainder of West Beach to San Luis Pass.

East Beach (transects 1-4) is characterized by a wide sand beach with a well defined berm crest that is frequently modified by beach scraping to remove trash and debris that floats in from the Gulf. Sand trapped by the counter current between the seawall and the jetties has kept the beach relatively stable since the mid 50s (Appendix B). This explains the net shoreline advance at transects 1 and 2 and the generally low average annual retreat rates of less than 3 ft/yr at transects 3 and 4 (Table 2).

On West Beach, average annual rates of shoreline retreat were 10 to 14 ft/yr from the end of the seawall to Galveston Island State Park (Table 2, fig. 9). The beach, which is narrow and steep at the seawall, gradually widens to the southwest. Except for a few rubble revetments and bulkheads in the Spanish Grant and Bermuda Beach subdivisions, the shoreline erosion feature for this beach segment is the erosional scarp that is generally well exposed. Recent beach scraping and placement of sand mounds in the backbeach obscures the scarp in some places. Despite the beach maintenance activities, the scarp persists throughout this reach and an indicator of frequent backbeach flooding and scour by waves. From Galveston Island State Park (transect 19) to Bay Harbor (transect 27), the undeveloped beach is wider, the dunes are 5 to 12 ft high, and the shoreline erosion feature is the berm crest. For this beach segment, average annual retreat rates are 5 to 8 ft/yr (Table 2). Southwest of Bay Harbor (transects 28-30) the beach progressively narrows and steepens, and the shoreline erosion feature is an erosional scarp. Average annual retreat rates for this segment of narrow beach range from 7 to 16 ft/yr (Table 2). Near San Luis Pass (transect 31), the erosional scarp grades southwestward into low, sparsely vegetated dunes and the beach widens into a broad sand flat. For this beach segment the shoreline advanced seaward nearly 500 ft between 1974 and 1996. The sand flat is part of the tidal inlet system at San Luis Pass that gains and loses sand volume as the channel and adjacent shoals shift position. Marginal sand flats of tidal inlets are notoriously unstable; consequently shoreline movement on the flats is rapid and typically covers large distances.

San Luis Pass to the Brazos River - An analysis of shoreline movement from San Luis Pass to the Brazos River between 1974 and 1996 (Table 2) reveals some trends that are similar and some trends that are different from those established by prior surveys (Morton and Pieper, 1975). Shoreline movement along the northeastern half of Follets Island was characterized by alternating zones of net retreat and net advance (Table 2). Greatest net changes occurred on the northeastern end of the island (transect 1) where the beach retreated about 890 ft at an average annual rate of about 40 ft/yr. Near transect 1, along the southern margin of San Luis Pass, the shore rapidly changes from a wide sand beach with berm crest to a narrow beach with erosional scarp that abuts several bulkheads at the Treasure Island subdivision. These bulkheads became the shoreline feature after Hurricane Alicia removed the broad sand flat that previously formed the shore. The beach is relatively narrow and an erosional scarp is present just southwest of the bulkheads indicating recent beach retreat, possibly related to the bulkheads interfering with the littoral system. Some of the beach and shoreface sand eroded near transect 1 during Hurricane Alicia, has been deposited near transect 3 (fig. 8), which explains the relatively rapid advance of the shore at that location. This recent accumulation of beach sand also has been documented with beach profiles since 1983 (Morton et al., 1995a).

From central Follets Island to Surfside (transects 8-15), the beach is moderately wide and the berm crest is the shoreline erosion feature (fig. 5). Along this beach segment, the shoreline advanced slightly or was relatively stable between 1974 and 1996 (Table 2, fig. 9) despite lowering of the beach 1 to 1.5 ft and inland transport of sand by Hurricane Gilbert in 1988. Slight net advancement of the beach at transect 15 (Table 2) is related to dredged material placed on the beach in conjunction with relocation of the jetties and widening the ship channel at the entrance to Freeport Harbor. This undesigned beach replenishment project was conducted by the Corps of Engineers in October, 1991.

The beach at Quintana southwest of the Freeport jetty is narrow and the beach locally widens at the mouth of the Brazos River. Essentially all of the shore on Quintana Beach and Bryan Beach (transects 16-21) experienced net retreat except at the mouth of the Brazos River (transect 22) where net advance was recorded (Table 2, fig. 9). Greatest retreat occurred at transects 19-21 where the Bryan Beach side of the Brazos delta has been reworked by oceans waves and currents. Along this beach segment, a well defined erosional scarp reflects the trend in shoreline movement except near the mouth of the river were the scarp merges with low vegetated dunes that are adjacent to a broad sand flat characterized by sand ridges and swales containing water. This beach topography in 1996 indicates relatively recent accumulation of sand at the river mouth where the beach was formerly retreating. Sand was deposited at the river mouth after several major floods on the Brazos River built a broad mouth bar that was later reworked and welded to the former shore.

Temporal Analysis

Recent accelerations and decelerations in shoreline movement and changes in the trend of net advancement or retreat can be evaluated by comparing shoreline changes at each transect during the last two twenty-year periods. Twenty-year monitoring periods are considered to be long enough so that the long-term trend is accurately reflected in the changes in shoreline position. Comparing shoreline trends and rates of change from 1955-56 to 1974 (Morton, 1974; Morton 1975; Morton and Pieper, 1975) and from 1974 to 1996 (Tables 2-4) reveals the following conditions that are illustrated in Appendices A, B, and C.

High Island to Bolivar Roads - Addition of a 1990 shoreline position helps delineate shoreline movement for the remaining transects from High Island to Bolivar Roads (fig. 1, Appendix A). Shoreline movement at transects 32-35 was similar to trends at nearby transects to the northeast. The shore was generally stable or retreating slowly from 1956 to 1982 and then retreat accelerated from 1990 to 1996. Shoreline movement was cyclical at transects 36 to 58. The shoreline retreated between 1956 and 1974, advanced from 1974 to 1990, and then retreated between 1990 and 1996. The overall trend since the 1950s has been net retreat. At transects 59 and 60, shoreline movement was also cyclical with recent retreat; however, the overall trend since the 1950s has been net advance. At transects 61 and 62, the most recent trend of shoreline stability between 1990 and 1996 suggests a reduction in the rate of advancement that had been recorded previously (Appendix A).

Galveston Island - Since 1956, the beach at transects 1 and 2 generally has either remained stable of advanced slightly (Appendix B). Although some sand continues to accumulate south of the south jetty, rates of advancement greatly declined after the beach reached an equilibrium position in the mid 1950s. The beach at transect 3 also has been relatively stable, despite short-term cycles of shoreline advance and retreat. Shoreline movement also has been cyclical at transect 4, but the overall trend has been net retreat (Appendix B).

On West Beach, shoreline movement since 1956 has been variable, but net retreat has been the predominant trend at transects 13-18, 22-25, and 28-30. Net shoreline retreat has also been the predominant trend at transects 19-21 and 26-27 even though the most recent change in shoreline position was minor advancement (Appendix B). This apparent reversal in trend may be an artifact of using the berm crest modified by beach scraping as the erosion feature rather than the vegetation line.

At San Luis Pass (transect 31), actual trends of shoreline movement reversed following Hurricane Alicia in 1983 (Appendix B). The shore, which had been rapidly retreating, began advancing as the shoal and tidal flat on the eastern side of San Luis Pass began to accumulate sand (Morton et al., 1995a).

<u>San Luis Pass to the Brazos River</u> - The beach between San Luis Pass and the Brazos river has undergone net retreat at all transects since 1956; however, there have been more recent changes in shoreline movement that are significant. Between 1956 and 1996, the major trends of shoreline movement reversed at transects 1 and 2 (Appendix C). Retreating beaches advanced between 1956 and 1974 and then later began retreating again. These large-scale trend reversals involving hundreds of feet of shoreline movement are attributed to dynamics of tidal inlets and the large volumes of beach and shoreface sediment that get redistributed periodically by storms. The trend of shoreline movement also reversed at transect 3, but the beach is still advancing slightly and has not retreated since 1974.

Anomalous shoreline advance between 1982 and 1991 was followed by either retreat or stability at transects 4 through 22 (Appendix C). Since 1982, short-term net advance was recorded at transects 4, 8-17, and 22, whereas short-term net retreat was recorded at transects 5-7 and 18-21. On Follets Island and at Surfside (transects 4-15), the trend toward greater shoreline stability began about 1974 (Appendix C). Short-term reversing cycles of advance and retreat are difficult to interpret and essentially impossible to predict with available data and available quantitative methods of analysis. If the short-term variability in shoreline position is minor (less than 100 ft) then the oscillations tend to indicate either stable or slowly changing long-term conditions.

60 YEAR PROJECTION OF THE SHORELINE EROSION FEATURE

Shoreline Shape and Projection Program (SSAPP)

SSAPP Functions

The 60 year projected position of the Gulf shoreline erosion feature in Galveston and Brazoria Counties was determined using a Bureau of Economic Geology computer routine referred to as the Shoreline Shape and Projection Program (SSAPP). This program is a modular algorithm of FORTRAN statements that uses a series of subroutines to compute average annual rates-of-change (AAER) and to project future shoreline positions on the basis of the calculated rates-of-change and a user specified period of projection, in this application the specified period was 60 years. The program accepts shoreline data as digital geographic positions through a GIS such as ARC-INFO or as an ASCII file in which shoreline positions are defined as distances from a baseline at particular locations (transects) along the shore. Coordinates of shoreline positions are converted from stateplane (ARCINFO) to universal transverse Mecator to run in SSAPP and then reconverted to stateplane for storage and manipulation in ARCINFO.

The primary program module of SSAPP determines the type of input data, reads the data, prompts the user for the desired calculations, and directs execution of the program (Gibeaut, in preparation). As discussed by Morton (1974), immediate post-storm shoreline positions are deliberately excluded from the data set of shoreline positions to avoid excessive noise in the shoreline history plots and mathematical analyses.

Although SSAPP is capable of determining rates of shoreline movement on the basis of at least five quantitative analytical methods (end point, jack knife, average or rates, linear regression, Fenster et al., 1993), average annual rates of change used in this report were determined using the linear regression method in accordance with FEMA recommendations and preferred practices. Average annual rates of change calculated by SSAPP at 150 ft (50 m) intervals were left unaltered; that is they were not smoothed or rounded using some arbitrary alongshore spatial averaging technique. The State of Texas has not adopted any rules regarding calculation of average annual erosion rates or moving averages, therefore using the unaltered data to project the 60 year shoreline position does not conflict with any coastal management policy in Texas.

Discussion of Input Data

To facilitate the SSAPP analysis, the Gulf shoreline in Galveston and Brazoria Counties was divided into four segments, which are separated by physical barriers. Segment 1 extends from High Island to the north jetty at Bolivar Roads, segment 2 includes all of Galveston Island from the south jetty at Bolivar Roads to San Luis Pass, segment 3 includes Follets Island from San Luis Pass to the jetty at Freeport Harbor, and segment 4 stretches from the jetty at Freeport Harbor to the mouth of the Brazos River. Each of these beach segments has experienced recent periods of accelerated or decelerated shoreline movement or even reversals in trend. These changes in patterns of deposition and erosion are a result of large-scale changes in sediment supply related to human activities (Morton, 1974, 1975; Morton and Pieper, 1975) or storms (Morton et al., 1995a). Examination of individual shoreline history plots (Appendices A, B, C) shows that simple linear regression of all shoreline positions will not honor the major turning points when historical trends or rates of shoreline movement changed. Therefore, the unsupervised results of linear regression may be erroneous if the input data contain shoreline positions that are no longer consistent with the most recent trends and rates of change.

To improve the accuracy of shoreline positions predicted by SSAPP, the shoreline history plots were consulted to determine the longest period of shoreline movement that is consistent in trend and suitable for long-term (60 yr) projection of future shoreline position. The time period selected for linear regression analysis was applied to the entire beach segment by removing the 1800s shoreline or both the 1800s and 1930s shorelines from the input data. For each beach segment, the historical period of analysis used to project the future shoreline position is as follows: segment 1 (1882-1996), segment 2 (1955-1996), segment 3 (1930-1996), and segment 4 (1955-1996).

SSAPP provides accurate results where the sequential shoreline positions are parallel to the arbitrary baseline internally constructed by SSAPP. However, where successive shorelines are highly divergent, such as on the margins of tidal inlets, at artificial channels, and at river mouths, SSAPP gives spurious results because it is unable to construct a baseline that will satisfy the requirement of mutual orthogonal intersections among the baseline, shorelines, and transects. To overcome this program limitation at selected sites (Bolivar Roads, San Luis Pass, mouth of the Brazos River), shoreline history plots were consulted to define the longest, most recent, and most representative period of empirical data that would eliminate the oldest divergent shoreline(s). Historical analyses of anomalous shoreline movement, especially those that are related to engineering projects, show that shorelines typically adjust to altered conditions in a few decades and then the subsequent changes are much slower. The accuracy of SSAPP is improved by (1) eliminating the oldest period of shoreline movement when the shorelines are typically divergent and (2) concentrating on the most recent periods, which are more likely to be representative of future shoreline movement.

Construction of the Projected Shoreline Position

The 60-year projected position of the Gulf shoreline in Galveston and Brazoria Counties (fig. 10) represents a compilation of three controlling conditions. Most of the projected shoreline is the SSAPP calculated position, which is generated by multiplying the average annual erosion rate by 60 and adding that distance to the 1996 shoreline erosion feature. However, where the long-term trend of shoreline movement is accretion, such as at the southwestern end of Bolivar Peninsula (fig. 9), the 60-year projected shoreline position is the same as the 1996 shoreline position. Defaulting to the 1996 shoreline position in areas of accretion conforms with the standard procedures established by FEMA for the project. The third condition that controls the projected shoreline is the large-scale cyclical fluctuation in shoreline position at the margins of San Luis Pass. On southwestern Galveston Island and northeastern Follets Island, the SSAPP generated shoreline position was truncated at the transect where projections are erratic because shoreline curvature and divergence are significant.

Sources of Error and Estimated Magnitudes

The potential sources of error that influence the final projected position of the shoreline erosion feature include (1) errors in the original mapping and registry of shoreline positions, (2) errors introduced while digitizing the shoreline positions, (3) inaccuracies in the recorded 1996 GPS shoreline position, (4) transformation errors in the digital data in ARC-INFO, and (5) errors associated with merging the projected shoreline position with scanned aerial photographs that are georeferenced using externally generated ARC-INFO layers.

Typical sources of error attributed to the scales and inaccuracies in the original materials (T sheets, aerial photographs), tracing the wet beach-dry beach boundary, and compiling the shoreline positions on a base map were discussed by Anders and Byrnes (1991) and Crowell et al. (1991). For the shorelines in Galveston and Brazoria Counties, the cumulative non-systematic errors of mapping are estimated to be about 25 ft (Morton, 1974; 1975). Digitizing inaccuracies introduced as a result of equipment limitations and operator error are estimated to be about 30 ft, which is comparable to those estimated by Crowell et al. (1991). The potential digitizing errors in the Galveston and Brazoria County data set were estimated by comparing distances between shoreline positions measured directly from the topographic maps (Morton, 1974, 1975; Morton and Pieper, 1975) with distances measured in ARC-INFO at the same transects.

The GPS recorded field positions of the shoreline are probably within 6 ft of their actual position. This error estimate is made on the basis of equipment specifications established by the manufacturer and independent field tests at known geographic locations. Even with some positioning error, the 1996 GPS shoreline position is more accurate than shoreline positions mapped from aerial photographs. The 60 year shoreline position projected by SSAPP is sensitive to the 1996 shoreline. Consequently, minor changes in shoreline orientation or position caused by beach obstructions (dune walkovers, barriers at beach access roads, protruding bulkheads or riprap structures) were magnified in the projected 2056 shoreline. Spikes in the projected shoreline position that are artifacts of minor irregularities in the 1996 shoreline were deleted to produce a smooth, more realistic projected shoreline.

Alongshore offsets in the SSAPP generated shoreline occur where one of the shoreline data sets is incomplete. For example, on Bolivar Peninsula between major transects 43 and 46, the 1882 shoreline is absent on the old maps and the average annual erosion rate calculation is limited to the period from 1930 to 1996. The slightly lower average rate of retreat calculated for this period causes the predicted shoreline to be offset seaward as much as 500 ft. These anomalies were left unedited in the 60 year projected shoreline position because any attempt to substitute a reconstructed shoreline in the data set before the SSAPP analysis would introduce a quantitative error that could not be estimated. Within that same beach segment, offsets in the projected shoreline centered on Rollover Pass (between transects 45 and 46) are real. They reflect lower average rates of retreat along the margins of the channel caused by the groin effect of the sheet piling.

GPS coordinates were recorded in the field at eight prominent road intersections along the coastal highway of Galveston Island. These GPS coordinates were then compared to those determined from the georeferenced aerial photographs of the same area to estimate the amount and direction of geographic displacement introduced by warping the images. The differences in coordinates ranged from 19 to 131 ft and averaged 64 ft. Most of the GPS points plotted south of the image, indicating that the scanned images are shifted landward relative to the GPS coordinates.

Excluded Areas

The 1996 field surveys and analysis of shoreline movement in Galveston and Brazoria Counties encompass the entire Gulf shoreline from High Island to the mouth of the Brazos River with the following exceptions. Detailed analysis of shoreline movement was not conducted for long beach segments that (1) exhibit long-term shoreline stability or advancement that is expected to continue for at least the next 60 years, (2) are generally inaccessible to the public, or (3) are seaward of the Galveston seawall.

Long beach segments that are in public ownership or are otherwise protected from development include Bolivar Flats bird sanctuary on Bolivar Peninsula, Galveston Island State Park on Galveston Island, and Bryan Beach State Park, which is just east of the mouth of the Brazos River. Gulf shoreline segments that are undeveloped and not easily accessible to the public include the west flank of the Brazos delta between the Brazos River and the San Bernard River, and the shoreline segment in southwestern Brazoria County between the San Bernard River and Cedar Lakes. These two beach segments are low, flood-prone strips of land between the Gulf shore and the Gulf Intracoastal Waterway that have no houses or other buildings. Beach segments that have been stable or accreting for at least the past 60 years and are expected to be stable or accreting for the next 60 years include the southwestern end of Bolivar Peninsula and the west flank of the Brazos delta between the Brazos and San Bernard Rivers (Morton, 1975; Morton and Pieper, 1975).

The Galveston seawall extends from the south jetty at Bolivar Roads to its end at West Beach. The reasons a 1996 GPS shoreline survey was not conducted along the seawall are: (1) the groins break up the beach into a series of individual compartments, each with slightly different responses to wave energy and currents, (2) the high rock groins represent physical barriers that are difficult to traverse in a vehicle, (3) the seawall beach from 10th street to 61st street was artificially nourished in the spring of 1995 and comparison of the 1996 shoreline with pre-nourishment shorelines would appear as recent beach advancement, and (4) the shoreline was near the wall before it was nourished, (5) because the wall is so massive and nearly indestructible, future shoreline positions will not be farther landward than the wall.

Influence of Human Activities on Shoreline Movement

The stability of some segments of the Gulf shoreline in Galveston and Brazoria Counties has been altered by coastal projects (fig. 11) that changed the volume of sediment supplied to the coast and the rate of relative sea-level rise (Morton, 1974; 1975; Morton and Pieper, 1975). Some beach segments have been altered so profoundly and/or for so long that the long-term trend and average annual rate of shoreline movement has already adjusted to the altered conditions. Other engineering projects have been so minor that they will have no long-term effect on rates of shoreline movement. Whether or not a coastal engineering project should be considered in the calculation of long-term average annual erosion rates was determined on the basis of engineering design, construction materials, sources of funding, maintenance schedules, and project performance during the most recent major storm events.

Coastal Structures

Hard structures used along the Gulf shore in Galveston and Brazoria Counties to protect adjacent property from flooding and erosion can be classified on the basis of their ability to withstand major storms and to provide adequate protection from coastal hazards for at least 60 years. The most common class consists of small structures such as low bulkheads constructed of wood, aluminum, or concrete, and low rip-rap revetments constructed of concrete and rock. These structures vary in length because they may protect only a single lot or a group of buildings within a subdivision. Small shoreline protection structures are present at Gilcrest, near Rollover Pass, on the West Beach of Galveston Island, on Follets Island, and at Surfside (fig. 11). The composition and design of the small structures do not permit them to survive a major storm as demonstrated by the damage or destruction they incurred during Hurricane Alicia (Morton and Paine, 1985). Most of the small structures in Galveston and Brazoria counties are in the backbeach and currently do not interfere with longshore transport of sand. As a result of these conditions, the small structures do not influence the 1996 shoreline position but they can influence the erosion feature from which future shoreline positions might be projected. Along some segments where the beach is eroding, the structures project seaward of the vegetation line, erosional scarp, or other shoreline erosion feature. The small structures were not considered in calculating the long-term average annual erosion rate for the following reasons: the structures were constructed by individual property owners, the property owners do not have a dedicated fund for maintenance or replacement of the structures, and the structures have failed or have been heavily damaged during the past 20 years.

Three shoreline altering projects in Galveston and Brazoria Counties meet the criteria for consideration in calculating the long-term average annual rate of shoreline movement.

They are: (1) the Galveston seawall, (2) the jetties at Bolivar Roads, and (3) the jetties at Freeport Harbor. Each of these features is a massive coastal structure that was designed and built by the Federal government (U.S. Army Corps of Engineers), each has been maintained for decades, and each has withstood the strongest hurricanes since they were built. The Galveston seawall is considered to be the ultimate landward limit of the Gulf shoreline in 60 years if the beach is not renourished periodically. The enormous size of the seawall alone (17 ft high and 3 to 10 ft thick) suggests that it would survive any storm of record and remain at least 60 years from now even if it was not maintained. Furthermore, the necessity of the seawall to protect the City of Galveston ensures that it will be maintained in the future. For these reasons, the seawall, where it is present, marks the 60 year projected position of the Gulf shoreline. After the Galveston seawall was constructed, retreat rates on West Beach accelerated immediately downdrift of the wall (Morton, 1988). The beach profile has adjusted to the increased erosion (fig. 9) and the higher rates of beach retreat are now considered to be the normal rates that would be expected to continue in the future.

The shoreline on both sides of Bolivar Roads advanced rapidly after the jetties were constructed (Morton, 1974; 1975). The sand that supplied the rapid advancement came from reworking the ebb tidal delta and from trapping littoral drift (Morton, 1977). The beach continues to advance on southwestern Bolivar Peninsula, whereas East Beach on Galveston Island is relatively stable (Appendix A and B). The jetties have been in place so long that the long-term trends of shoreline movement have equilibrated to the altered conditions.

Shoreline movement on both sides of the Freeport Jetties has been complicated by dramatic changes in sediment supply (Morton and Pieper, 1975). Both shorelines advanced after the jetties were constructed, but they began retreating in 1929 (Appendix C) after the mouth of the Brazos River was diverted 6 mi to the southwest where it currently empties into the Gulf of Mexico. Beaches adjacent to the jetties at Surfside and Quintana continue to retreat as the shoreline attempts to reach its pre-jetty position. Enough time has elapsed since the Brazos River was diverted that the current average annual erosion rates of beach segments near the jetties are expected to continue in the future.

Rollover Pass (fig. 1) is another man-made feature in Galveston County that has substantially altered the response of the Gulf shoreline to waves and currents. After this artificial channel was constructed in 1955, rates of beach retreat increased near the inlet, especially on the downdrift (southwest)beach toward Caplen. Slightly higher rates of retreat for this beach segment compared to those to the northeast are partly attributable to the groin effect of the channel stabilizing structures and attendant sand losses from the littoral system through the pass. Some sand migrating along the beach is transported through Rollover Pass into East Bay where it is deposited as a flood-tidal delta. The fish pass at Rollover has been open long enough that the shoreline has adjusted to the decreased sand supply. Rapid beach retreat southwest of Rollover is partly related to impoundment of beach sediment by riprap structures that have been removed recently. Therefore, future rates of retreat should not be higher than the long-term average rates since the pass was opened.

River Diversion

The recent history of engineering modifications at the mouth of the Brazos River and attendant changes in shoreline position were summarized by Morton and Pieper (1975). As described in the preceding section, the shoreline advanced on both sides of the jetties after they were constructed, but the same shorelines began retreating immediately after the river mouth was diverted to its present position. Initial retreat rates were rapid because sediment supply from the fluvial source was eliminated. Later, the rates of retreat diminished and now are relatively low (Appendix C, transect 16). The relatively low rates of extant shoreline retreat indicate that quasi-equilibrium conditions have been reestablished and that rates of shoreline movement since 1955 are adequate for projecting future shoreline positions.

Beach Nourishment

Beach nourishment in Galveston and Brazoria Counties (fig. 11) has involved both undesigned and designed projects. Undesigned projects involve the placement of dredged or excavated material on the beach without the benefit of engineering specifications to establish key project criteria such as the width and slope of the reconstructed beach and the estimated life of the project. Designed projects, on the other hand, involve engineering plans, a maintenance schedule, an adequate economical supply of sand, contingency plans for emergency replenishment, and minimal post-project monitoring requirements.

Undesigned beach nourishment has been conducted within the study area at Rollover Pass and at Surfside. In 1957, 6,000 yds^3 of sand was placed on the beach southwest of Rollover Pass, but the material quickly eroded (U.S. Army Corps of Engineers, 1959). Because the volume of sand was so small and the beach rapidly adjusted to its pre-nourishment shape, the renourishment at Rollover does not effect the long-term average annual erosion rate. At Surfside, the beach is slightly wider after dredged material was placed on the beach in 1991 in conjunction with widening and deepening the ship channel and harbor entrance to Freeport. It is not likely that this material will have a significant effect on future beach stability and it is not considered in calculating the long-term average annual erosion rate of the beach. A small undesigned beach nourishment project along the Galveston seawall is not germane to the calculation of average annual erosion rates because the project was short lived (Giardino et al., 1987) and the seawall represents the 60 year projected shoreline position.

The only designed nourishment of a Gulf beach in Galveston or Brazoria Counties was conducted in 1995 along the Galveston seawall between 10th St and 61st St. Although this project may meet the criteria necessary for projection of future shoreline positions, it is not considered in calculating the long-term average annual erosion rate because the seawall, where it is present, marks the 60 year projected position of the Gulf shoreline.

Projected Shoreline Position and Economic Reality

The Texas coast is just now experiencing some of the political pressures from economic development that have persisted for many decades along other coasts in the US. Greater awareness of erosion hazards and demands by property owners for action at the State and local levels of government are being manifested in a variety of forms including proposed changes in legislation, lawsuits against the State, and local shoreline protection projects. Considering the current emphasis on property rights, it is clear that the 60 year projected shoreline position will not be obtained in those developed areas where the economic investment and existing infrastructure will preclude responses such as abandonment or retreat, and the shoreline will be stabilized in a position not far from its 1996 location. The most likely method of stabilizing the shore will be beach nourishment. This opinion is based on the fact that the State is not allowing the construction of hard structures on the beach to protect private property, and several concrete revetments on Bolivar Peninsula have been removed recently by the State (December, 1996). Furthermore, legislation drafted for the 1997 session of the State Legislature proposes the establishment of a statewide beach nourishment program.

CONCLUSIONS

Alongshore variations in beach morphology of the southeastern Texas coast are controlled by beach composition, substrate composition, sand transport volume, adjacent elevations, and storm wave height. Decadal variations in beach morphology at a site are related to changes in sand transport; consequently beach morphology and beach composition are also strongly correlated with rates of beach movement and the regional geologic framework.

Shoreline features used to depict shoreline position in Galveston and Brazoria Counties are the vegetation line, berm crest, erosional scarp, and crest of washover terrace. These shoreline proxies have predictable morphologies, occupy predictable positions on the beach, and spatial changes in their positions reflect long-term stability of the beach. Four linked beach morphologies and shoreline stability pairs are recognized within the study area. They are wide backbeach with distinct berm crest (stable or advancing sand beach), concave beach or scour trough (slowly retreating sand beach), erosional scarp (moderately to rapidly retreating sand beach), and crest of washover terrace (rapidly retreating sandy shell beach over mud).

Although the high water line (wet beach/dry beach line) has been widely used in prior studies as the shoreline proxy, it is not recommended for future analyses of shoreline movement. This change in shoreline mapping strategy is justified because the high water line occupies a wide range of seasonal positions related to fluctuations in water level, it does not conform to a particular geomorphic feature on the beach, and it is less diagnostic of long-term shoreline movement than the other shoreline features.

Between High Island and the Brazos River, regional patterns of shoreline advancement and retreat generally were similar during the past twenty years as they were during previous monitoring periods. Most of the developed beach segments continue to retreat. There were, however, some local differences in the trend of shoreline movement or the rates of movement. For example, shoreline retreat was more noticeable between Rollover Pass and Caplen on Bolivar Peninsula. Some beach segments of Follets Island either advanced or retreated more slowly after 1983 when strong alongshore currents during Hurricane Alicia transported sand from San Luis Pass to the southwest, where it has nourished beaches northeast of Freeport. Also, the beach is slightly wider at Surfside after dredged material was placed on the beach as part of widening and deepening the ship channel and harbor entrance to Freeport.

Projected shoreline positions calculated by SSAPP are consistent with the most recent trends and rates of retreat within each beach segment. The use of linear regression analysis of empirical data to predict shoreline positions 60 years from now assumes that the physical conditions that caused shoreline retreat in the past will not change in the future. This assumption may be valid for some undeveloped segments of the shore, but it is not likely that the shoreline position will reach its projected position in densely developed areas where economic investments are substantial and where efforts to stabilize the beach have already begun.

ACKNOWLEDGMENTS

This work was supported by the Texas General Land Office Coastal Division and the U.S. Geological Survey Coastal Geology Program. We gratefully acknowledge the cooperation of the Oil Spill Division of the Texas General Land Office for providing the all terrain vehicles used to conduct the 1996 GPS shoreline surveys.

REFERENCES

Anders, F. J., and Byrnes, M. R., 1991, Accuracy of shoreline change rates as determined from maps and aerial photographs: Shore and Beach, v. 59, p. 17-26.

Crowell, M., Leatherman, S. P., and Buckley, M. K., 1991, Historical shoreline change; Error analysis and mapping accuracy: Journal of Coastal Research, v. 7, p. 839-852.

Dolan, R. and Hayden, B., 1983, Patterns and prediction of shoreline change, *in* Komar, P. D., ed., Handbook of coastal processes and erosion. CRC Press, Inc., Boca Raton, FL, p. 123-149.

Fenster, M. S., Dolan, R., and Elder, J. F., 1993, A new method for predicting shoreline positions from historical data: Journal of Coastal Research, v. 9, p. 147-171.

Fisher, W. L., Brown, L. F., McGowen, J. H., and Groat, C. G., 1973, Environmental geologic atlas of the Texas coastal zone, Beaumont-Port Arthur area. University of Texas, Bureau of Economic Geology, Austin, TX, 93 p.

Giardino, J. R., Bednarz, R. S., and Bryant, J. T., 1987, Nourishment of San Luis Beach, Galveston Texas: An assessment of the impact: Coastal Sediments '87, Am. Soc. Civil Engineers, v. 2, p. 1145-1157.

Gibeaut, J. C., in preparation, Predicting shorelines based on past shoreline change: effect of rate-of-change calculation method and baseline selection: Journal of Coastal Research.

Leatherman, S., 1983, Shoreline mapping: a comparison of techniques. Shore and Beach, 51: 28-33.

McBeth, F. H., 1956, A method of shoreline delineation: Photogrammetric Engineering, v. 22, p. 400-405.

McGowen, J. H., Garner, L. E., and Wilkinson, B. H., 1977, The Gulf shoreline of Texas: Processes, characteristics and factors in use: University of Texas at Austin, Bureau of Economic Geology, Geological Circular 77-3, 27 p.

Morton, R. A., 1974, Shoreline changes on Galveston Island: University of Texas at Austin, Bureau of Economic Geology, Geological Circular 74-2, 34 p.

Morton, R. A., 1975, Shoreline changes between Sabine Pass and Bolivar Roads: University of Texas at Austin, Bureau of Economic Geology, Geological Circular 75-6, 43 p.

Morton R. A., 1977, Nearshore changes at jettied inlets, Texas Coast: Coastal Sediments '77, Am. Soc. Civil Engineers, p. 267–286.

Morton, R. A., 1979, Temporal and spatial variations in shoreline changes, Texas Coast. Journal of Sedimentary Petrology, v. 49, p. 1101-1111.

Morton, R. A., 1988, Interactions of storms, seawalls, and beaches of the Texas Coast, *in* Kraus, N. C., and Pilkey, O. H., The effects of seawalls on the beach: Journal of Coastal Research, Spec. Issue 4, p. 113-134.

Morton, R. A., 1991, Accurate shoreline mapping: past, present, and future: American Society of Civil Engineers, Coastal Sediments '91, v. 1, p. 997-1010.

Morton, R. A., 1996, Geoindicators of coastline and wetland changes, *in* Berger, A. R., and Iams, W. J., eds., Geoindicators: Assessing rapid environmental changes in earth systems: A. A. Balkema, Rotterdam, p. 207-230.

Morton, R. A., and Paine, J. G., 1985, Beach and vegetation-line changes at Galveston Island, Texas: erosion, deposition, and recovery from Hurricane Alicia: The University of Texas at Austin, Bureau of Economic Geology, Geological Circular 85-5, 39 p.

Morton, R. A., and Pieper, M. J., 1975, Shoreline changes in the vicinity of the Brazos River delta: University of Texas at Austin, Bureau of Economic Geology, Geological Circular 75-4, 47 p.

Morton, R. A., and White, W. A., 1995, Shoreline types of the upper Texas Coast: Sabine-Galveston-Freeport-Sargent Areas: University of Texas at Austin, Bureau of Economic Geology, contract report prepared for the Texas Natural Resources Inventory Program, Interagency Contract IAC 94-0198, 40 p.

Morton, R. A., Leach, M. P., Paine, J. G., and Cardoza, M. A., 1993, Monitoring beach changes using GPS surveying techniques: Journal of Coastal Research, v. 9, p. 702-720.

Morton, R. A., W. A. White, J. C. Gibeaut, R. Gutierrez, and J. G. Paine, 1994, East Texas and Western Louisiana Coastal Erosion Study Annual Report, Year 3: University of Texas at Austin, Bureau of Economic Geology, contract report prepared for the U.S. Department of Interior, Geological Survey Contract No. 14-08-0001-A0912, variously paginated.

Morton, R. A., Gibeaut, J. C., and Paine, J. G., 1995a, Meso-scale transfer of sand during and after storms: implications for prediction of shoreline movement: Marine Geology, v. 126, p. 161-179.

Morton, R. A., W. A. White, J. C. Gibeaut, R. Gutierrez, and J. G. Paine, 1995b, East Texas and Western Louisiana Coastal Erosion Study Annual Report, Year 4: University of Texas at Austin, Bureau of Economic Geology, contract report prepared for the U.S. Department of Interior, Geological Survey Contract No. 14-08-0001-A0912, variously paginated.

Paine, J. G., and Morton, R. A., 1989, Shoreline and vegetation-line movement, Texas Gulf Coast, 1974-1982. University of Texas at Austin, Bureau of Economic Geology, Geological Circular 89-1, 50 p.

Shalowitz, A. L., 1964, Shore and sea boundaries: U.S. Department of Commerce Publ. 10-1, v. 2, 749 p.

Stafford, D. B., 1971, An aerial photographic technique for beach erosion surveys in North Carolina. Technical Memorandum 36, Coastal Engineering Research Center, 115 p.

U.S. Army Corps of Engineers, 1959, Gulf shore of Bolivar Peninsula in the vicinity of Rollover Fish Pass, Texas: House Doc. 286, 86th Congress, 2d Session, 30 p.

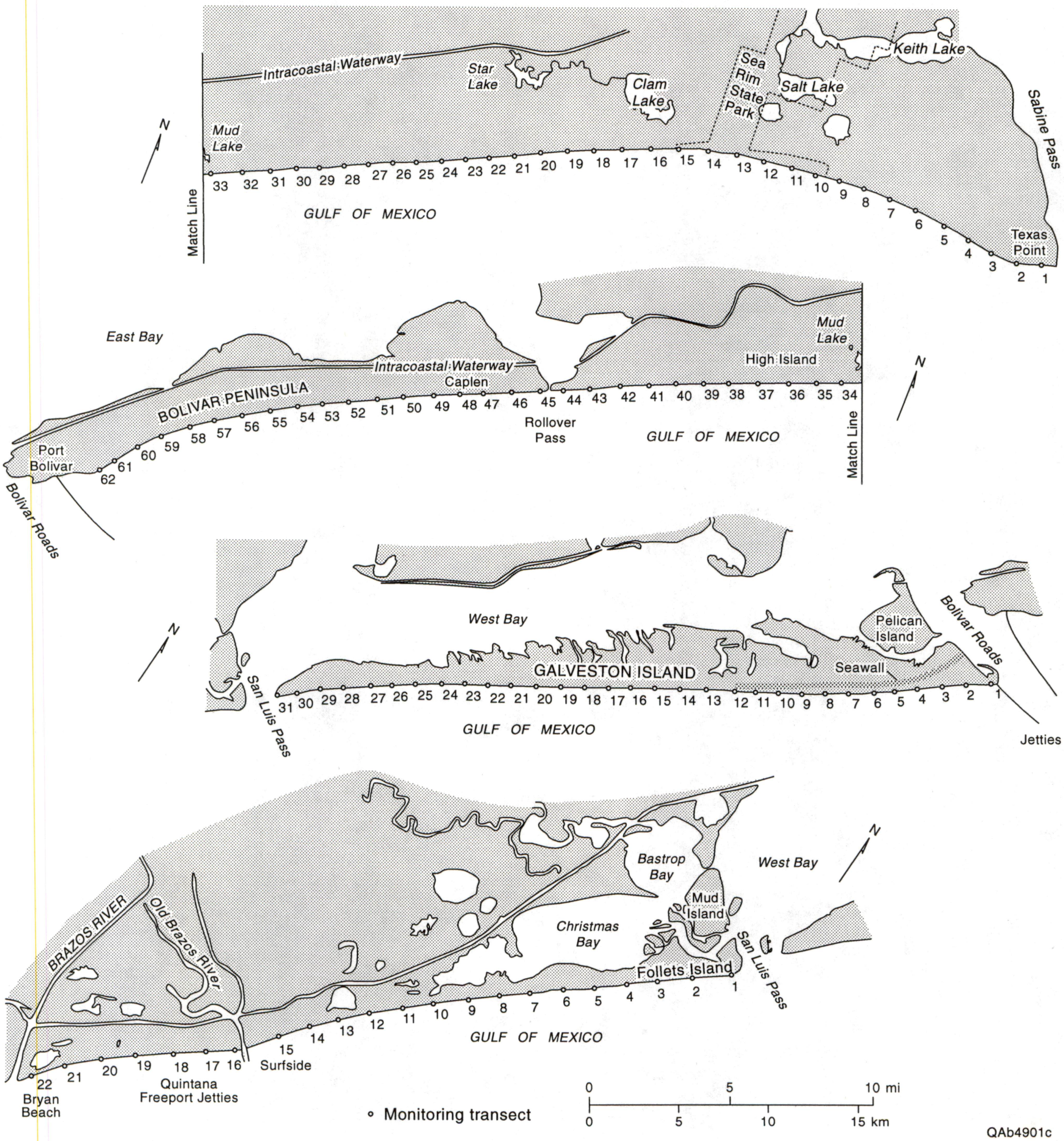


Figure 1. Geographic localities and locations of shore-normal transects used to analyze recent movement of the Gulf shore between Sabine Pass and the Brazos River.

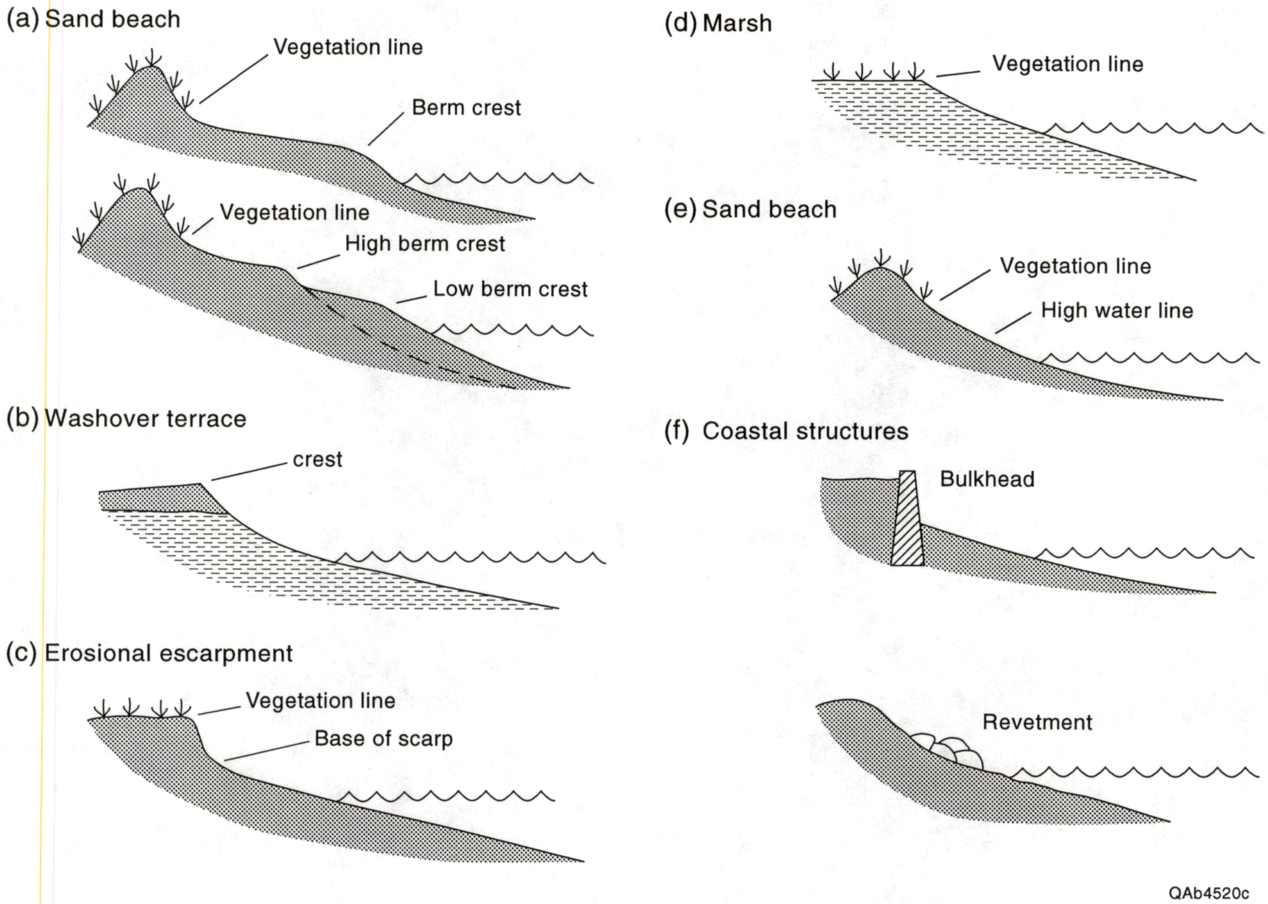


Figure 2. Generalized beach profiles illustrating typical beach morphologies and associated shoreline features observed in the study area. The profiles represent (a) sand beach with single and multiple berm crests, (b) sandy washover terrace overlying mud beach, (c) erosional scarp, (d) marsh vegetation line, (e) concave erosional sand beach without berm crest, and (f) common small-scale coastal structures.

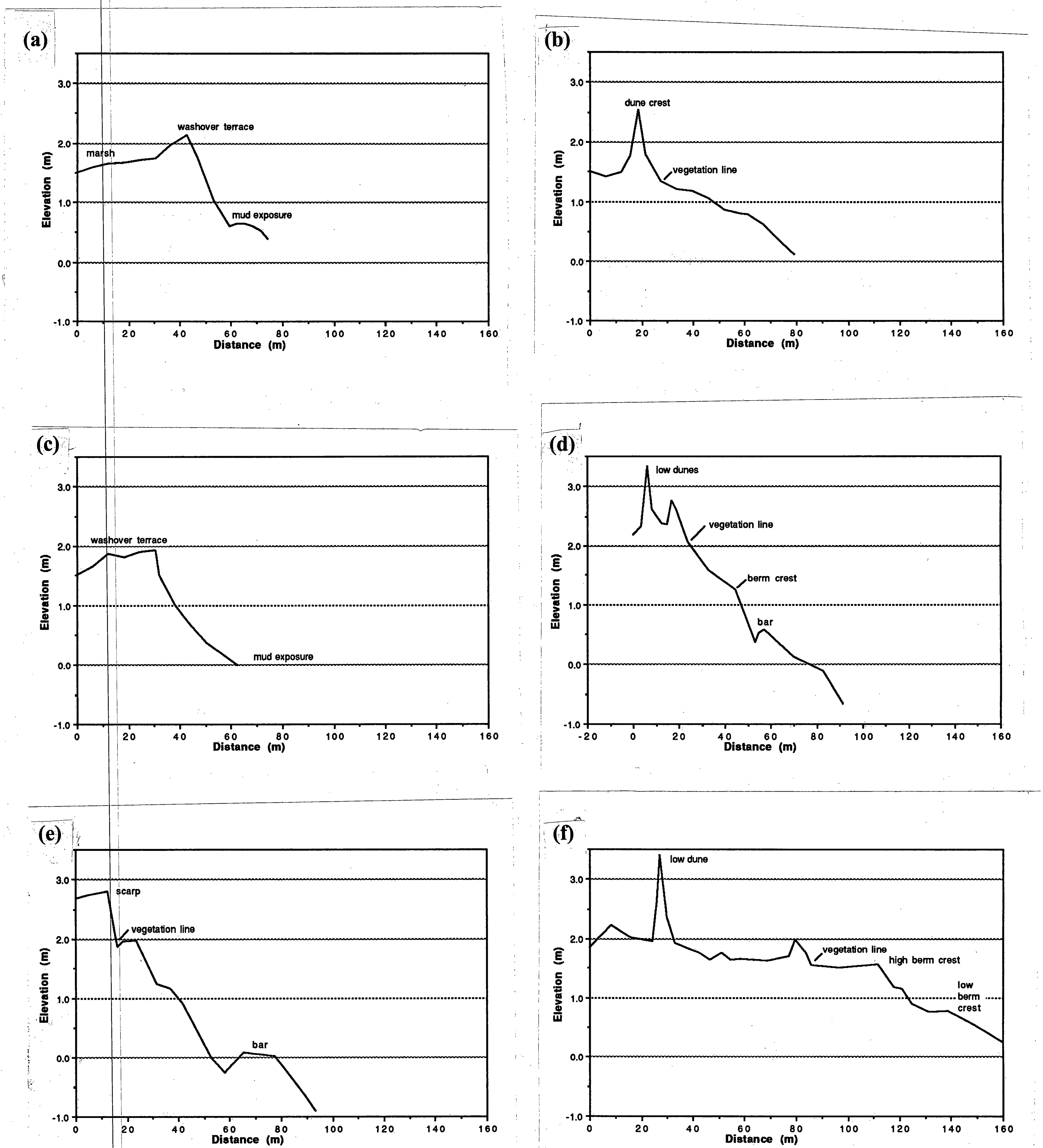


Figure 3. Surveyed profiles selected from the four morpho-compositional beach sections representing (a) washover terrace and marsh (mud) substrate west of Sabine Pass, (b) sand beach with low dunes near Sea Rim State Park, (c) washover terrace with mud substrate along Highway 87 east of High Island, (d) narrow sand beach with artificial dunes west of High Island, (e) steep sand beach and erosional scarp west of Rollover Pass, and (f) wide sand beach with low dunes on the southwestern end of Bolivar Peninsula.

Figure 4. Washover sand and shell deposited by Hurricanes Carla (1961), and exposed by erosion of a scarp. Large concrete slab is at the base of the washover deposit. Location is near transect 47 between Caplen and Rollover Pass (fig. 1).

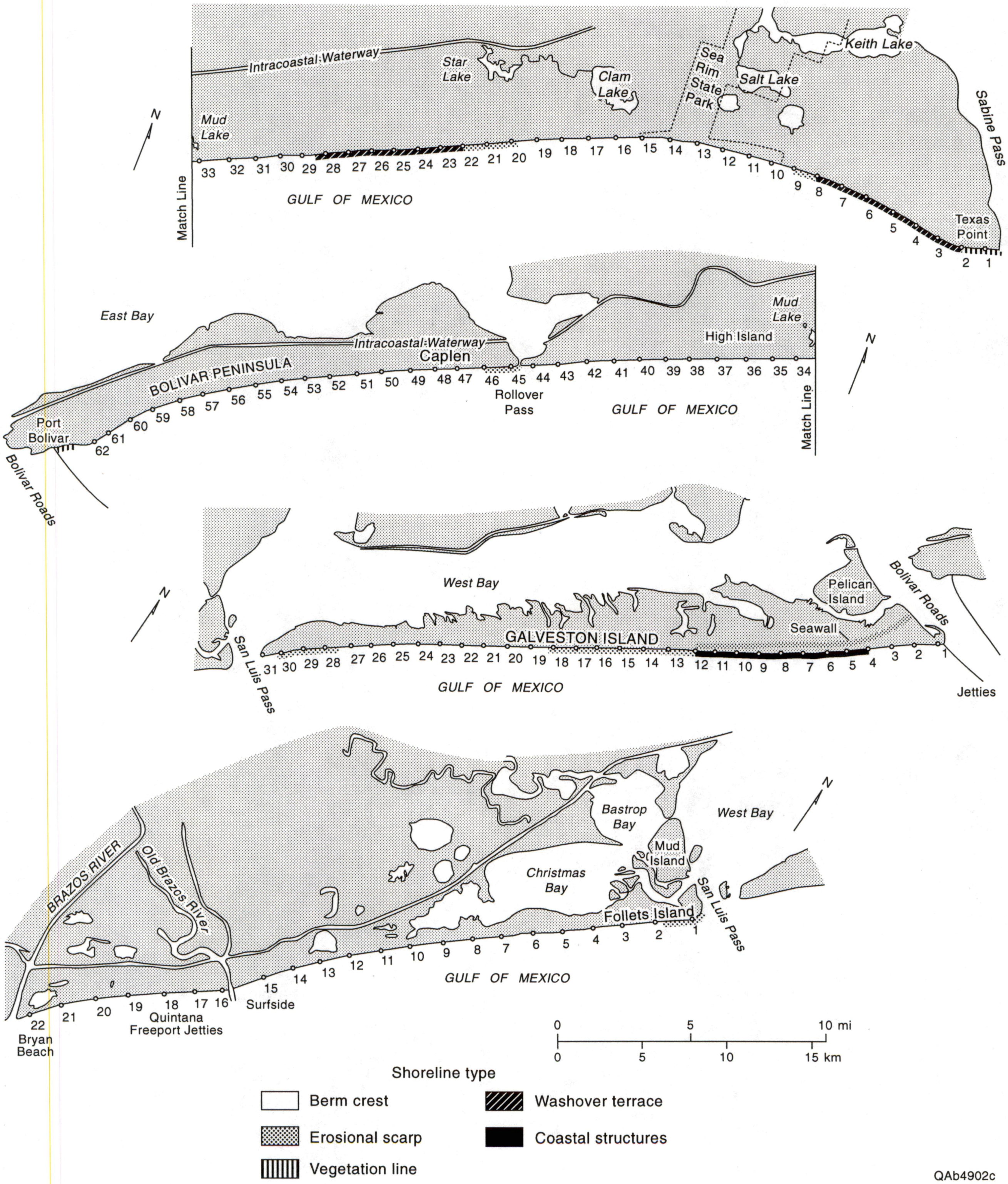


Figure 5. Distribution of shoreline types between Sabine Pass and the Brazos River.

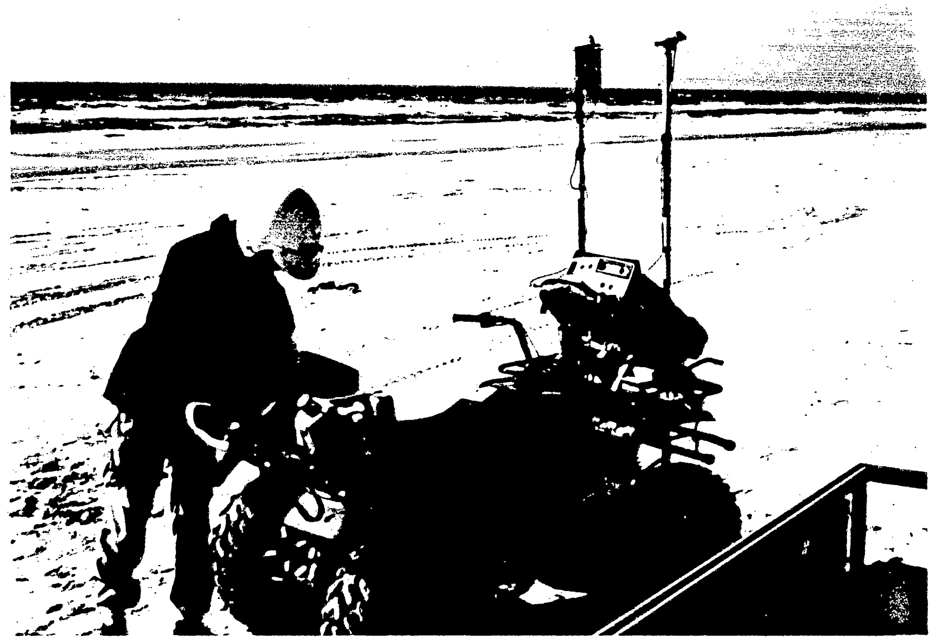


Figure 6. Real-time differential GPS equipment mounted on a four-wheel drive all terrain vehicle.

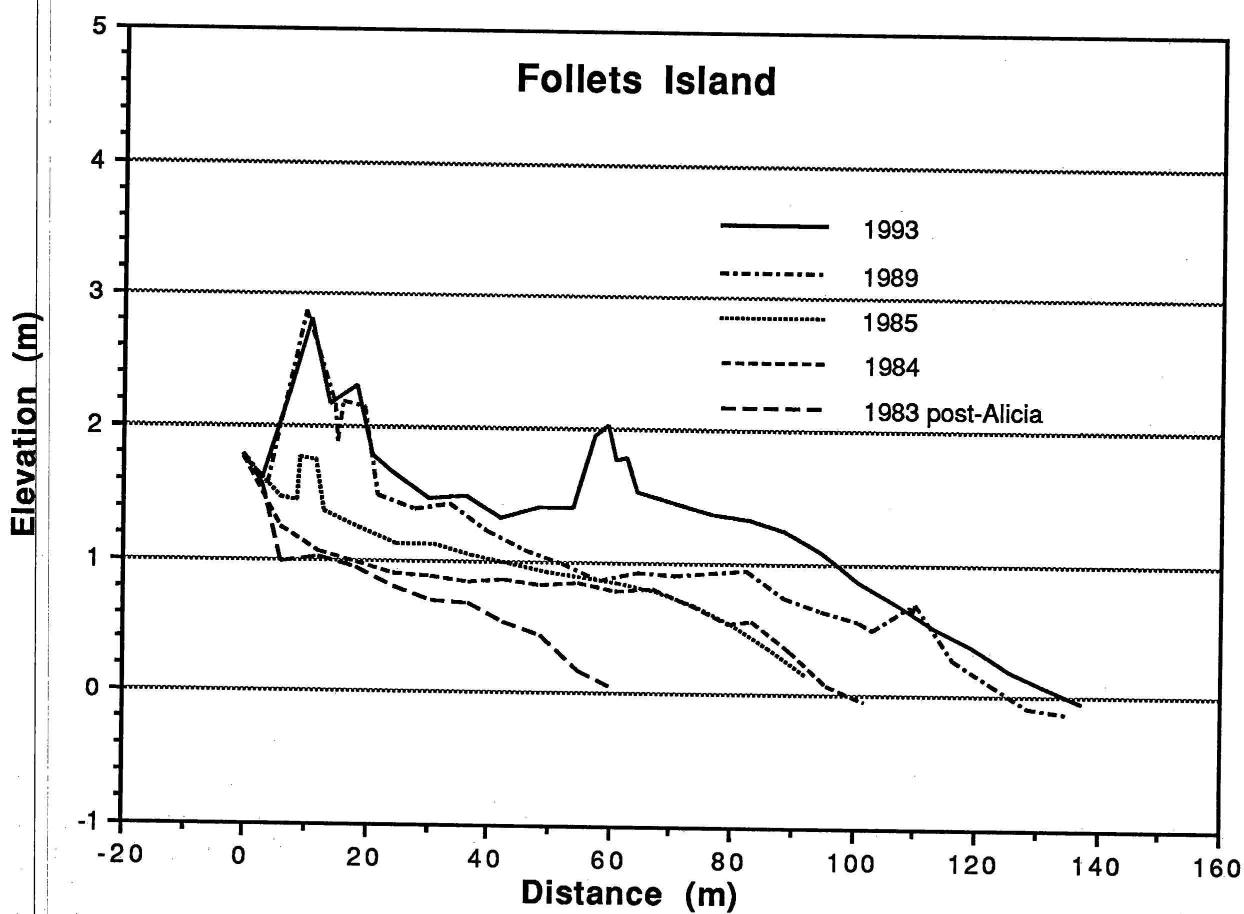


Figure 7. Ten-year evolution of an advancing beach profile, Follets Island near transect 3.

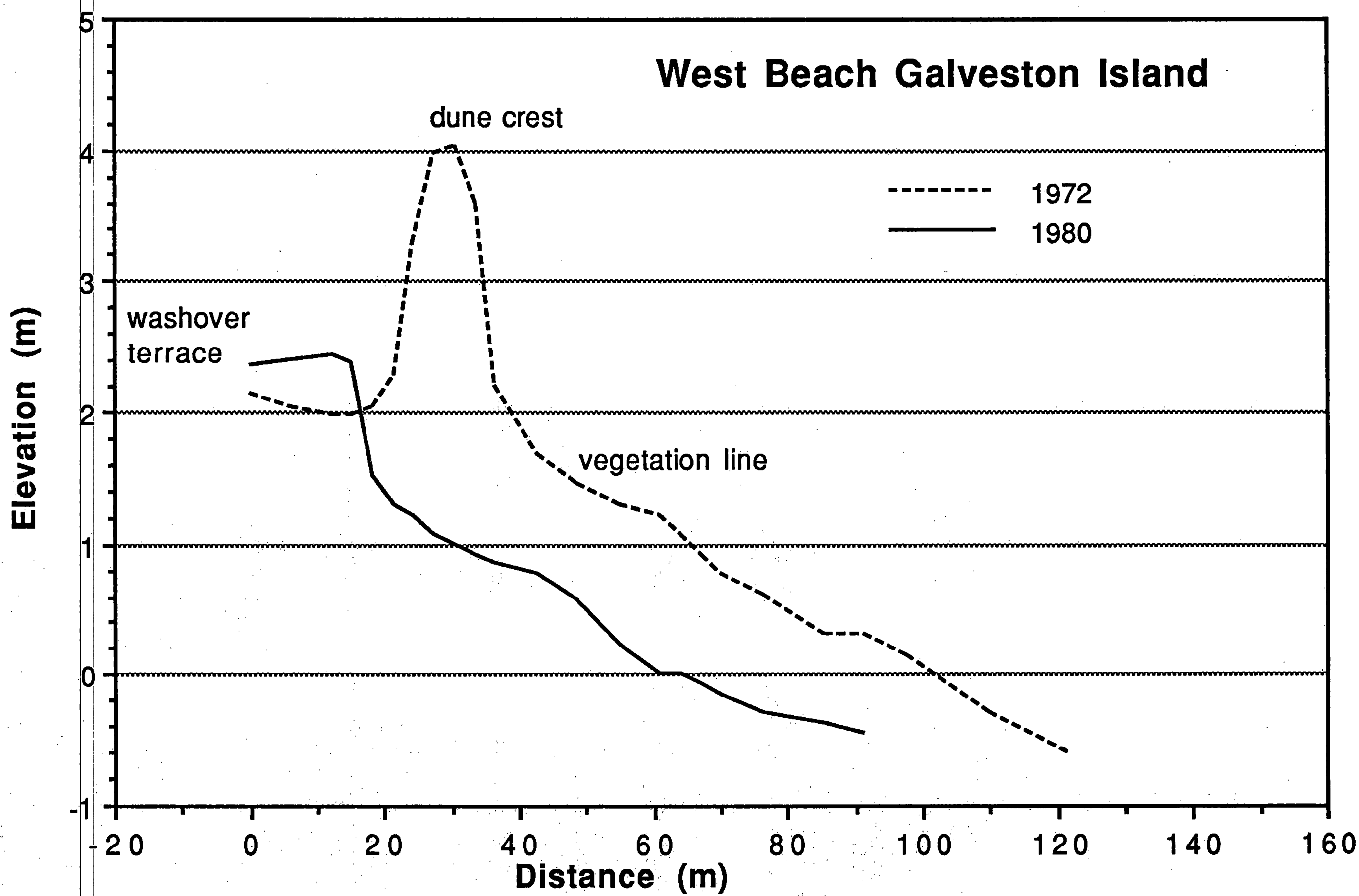


Figure 8. Eight-year evolution of a retreating beach profile, Galveston Island near transect 13.

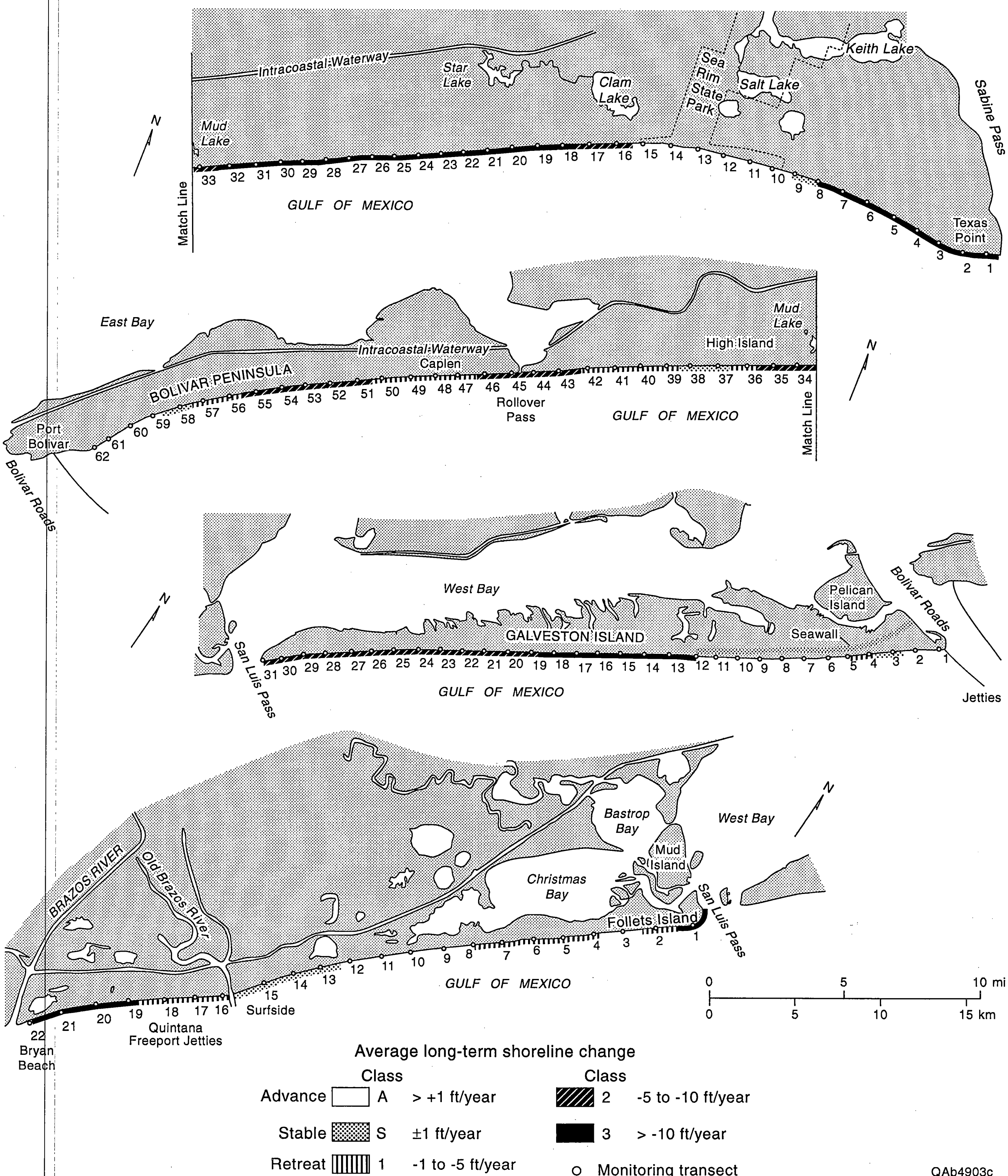


Figure 9. Summary diagram illustrating recent (1974-1996) shoreline movement between Sabine Pass and the Brazos River.

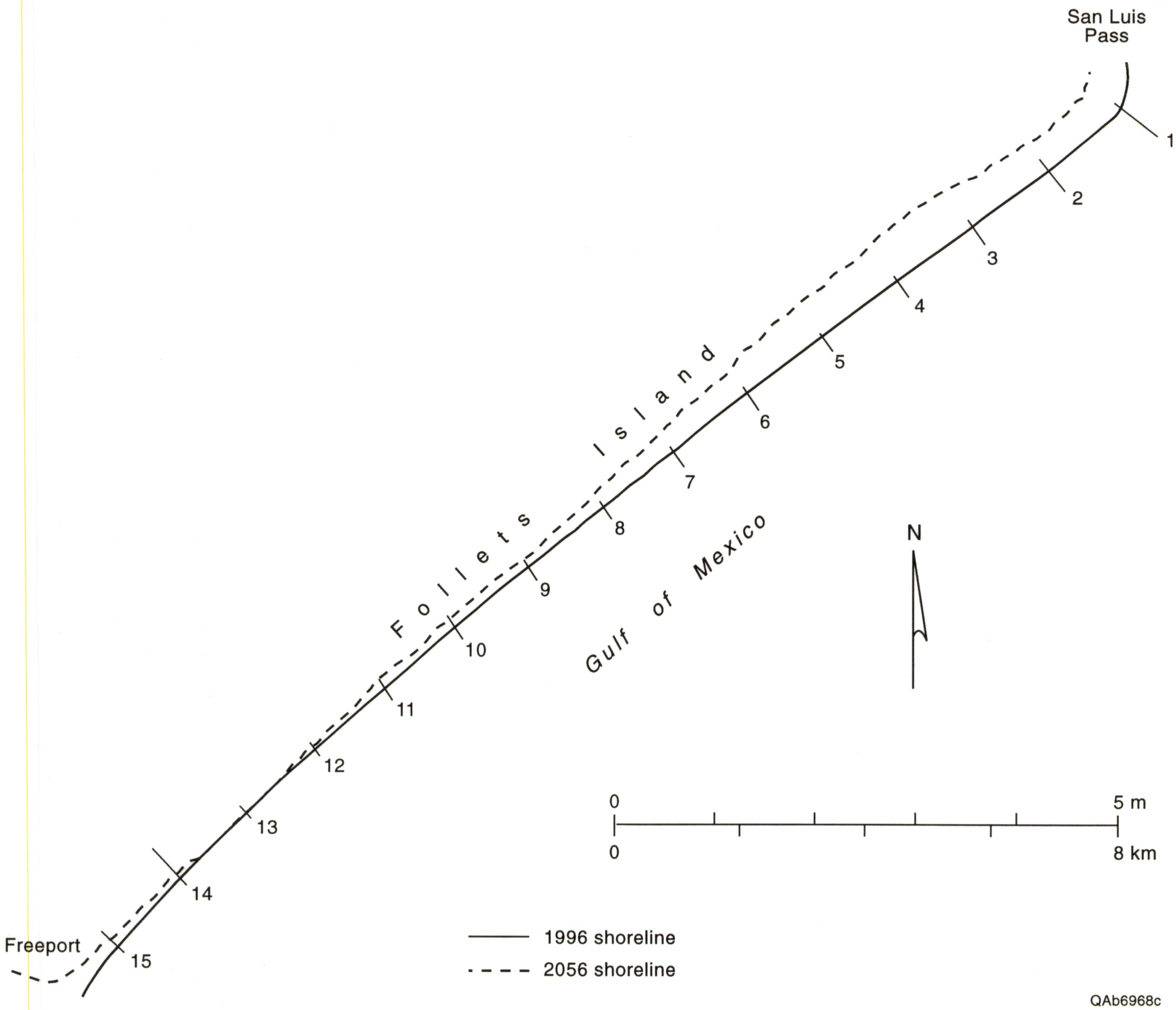


Figure 10. Example of beach segment for Follets Island showing the 1996 shoreline position and 60 year projected shoreline position generated by SSAPP.

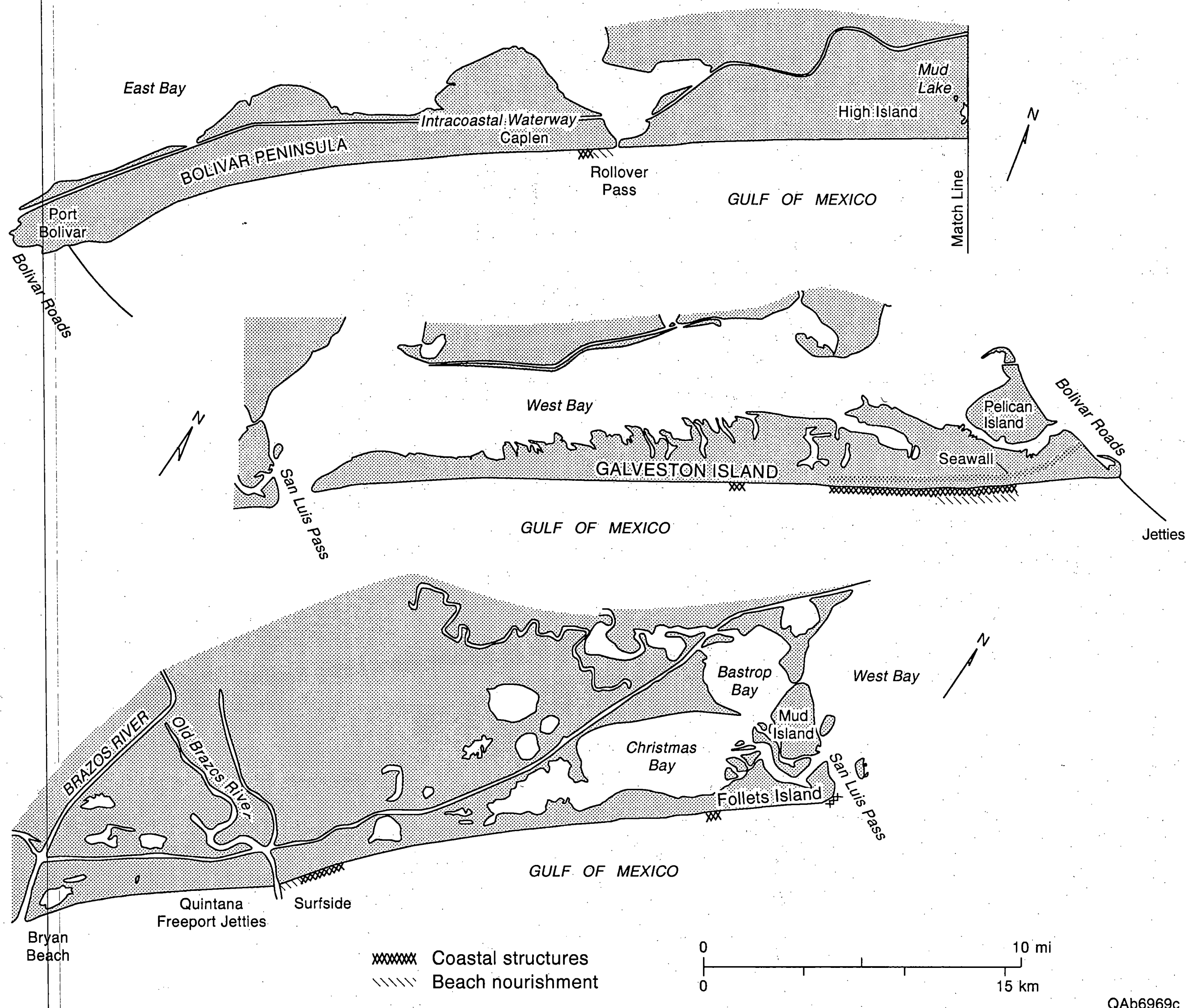


Figure 11. Locations of coastal structures and beach nourishment activities in Galveston and Brazoria Counties.

Table 1. Index of human impact on dunes and beach vegetation of the southeastern Texas coast.

Index	Description
0	No visible impact of beach scraping or evidence of backbeach dumping. Dune morphologies and plant communities are natural. Essentially no modification of beach and dune profile.
1	Low, small-volume mounds of sand containing some minor beach trash such as *Sargassum*. Trash represents less than 20% of mound volume. Altered zone is narrow relative to the entire beach width.
2	Low, small-volume mounds of sand and some minor beach trash such as *Sargassum* and small pieces of wood. Trash represents less than 33% of mound volume. Altered zone is narrow relative to the entire beach width.
3	Moderately large mounds of sand at least 3 ft high. Mounds composed of approximately 33% trash including moderately large pieces of wood or other debris. Several rows (2-3) of modified dunes or sand mounds. Altered zone is moderately wide relative to the entire beach width.
4	Moderately large mounds of sand greater than 3 ft high. Mounds composed of more than 33% trash. Multiple rows of modified dunes or sand mounds forming moderately wide zone relative to the entire beach width. Modified area may include bypass zone(s) representing former backbeach road(s).
5	Large mounds of sand up to 6 ft high. Mounds composed of as much as 50% trash containing large logs, cut wood, tires, appliances, and concrete or other rubble. Multiple rows of modified dunes or sand mounds forming wide zone relative to the entire beach width. Modified area may include bypass zone(s) representing former backbeach road(s).

Table 2. Net shoreline changes between High Island and the mouth of the Brazos River, 1974-1996. Locations of transects shown on fig. 1. Plus sign indicates shoreline advance, minus sign indicates shoreline retreat.

Bolivar Peninsula

Transect	Net Change (ft)	Average Rate (ft/yr)
36	-83	-3.8
37	-18	-0.8
38	-5	-0.2
39	-39	-1.8
40	-42	-1.9
41	-28	-1.3
42	-8	-0.4
43	-110	-5.1
44	-99	-4.6
45	-122	-5.6
46	-138	-6.3
47	-90	-4.2
48	-109	-5.0
49	-105	-4.8
50	-50	-2.3
51	-131	-6.0
52	-77	-3.5
53	-140	-6.5
54	-167	-7.7
55	-108	-5.0
56	-57	-2.6
57	-116	-5.4
58	-16	-0.7
59	28	1.3
60	49	2.2
61	142	6.5
62	379	17.5

Galveston Island

Transect	Net Change (ft)	Average Rate (ft/yr)
1	+353	+16.1
2	+116	+5.3
3	-12	-0.6
4	-52	-2.4
13	-313	-14.3
14	-303	-13.8
15	-260	-11.9
16	-286	-13.1
17	-273	-12.5
18	-225	-10.3
19	-159	-7.2
20	-171	-7.8
21	-178	-8.0
22	-149	-6.7
23	-137	-6.1
24	-152	-6.8
25	-105	-4.7
26	-112	-4.9
27	-138	-5.9
28	-154	-6.9
29	-217	-9.7
30	-346	-15.8
31	+501	+22.9

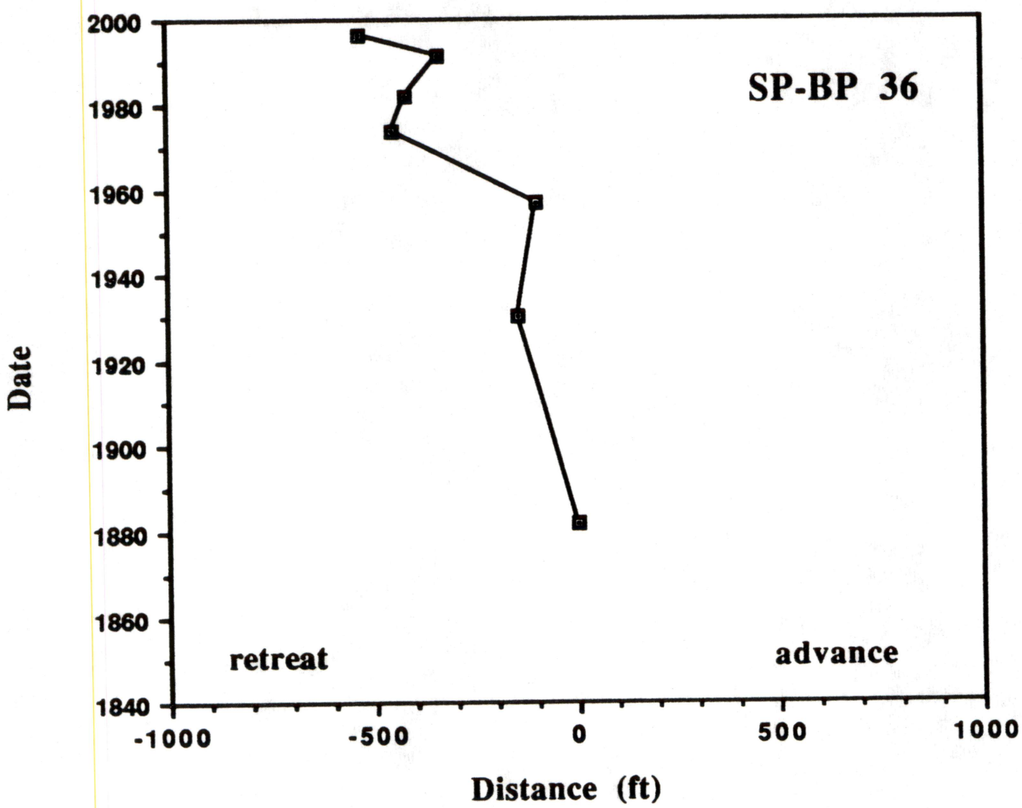
Follets Island and the Brazos Delta

Transect	Net Change (ft)	Average Rate (ft/yr)	Transect	Net Change (ft)	Average Rate (ft/yr)
1	-892	-40.7	12	+79	+3.8
2	-66	-3.0	13	+16	+0.9
3	+292	+13.3	14	+4	+0.4
4	+69	+3.1	15	+27	+1.5
5	-39	-1.8	16	-27	-1.2
6	-56	-2.6	17	-25	-1.0
7	-34	-1.6	18	-112	-5.0
8	+57	+2.6	19	-302	-13.6
9	+86	+3.9	20	-289	-13.0
10	+81	+3.7	21	-243	-10.9
11	+30	+1.4	22	+78	+3.8

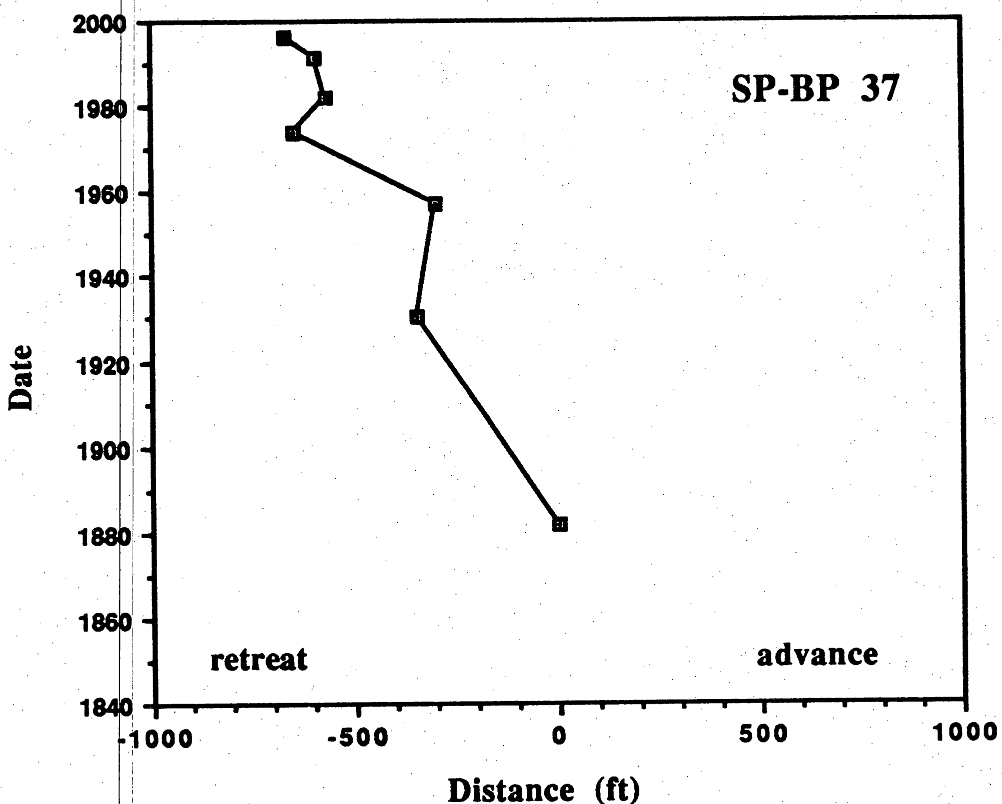
APPENDIX A

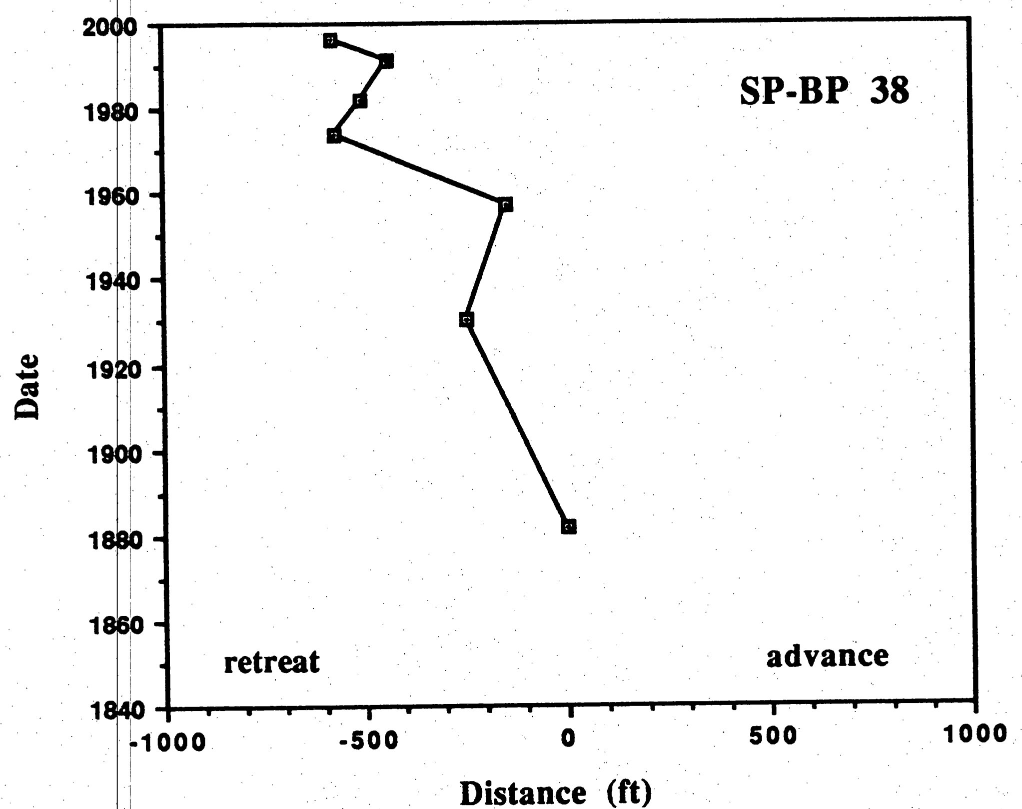
SHORELINE HISTORY PLOTS

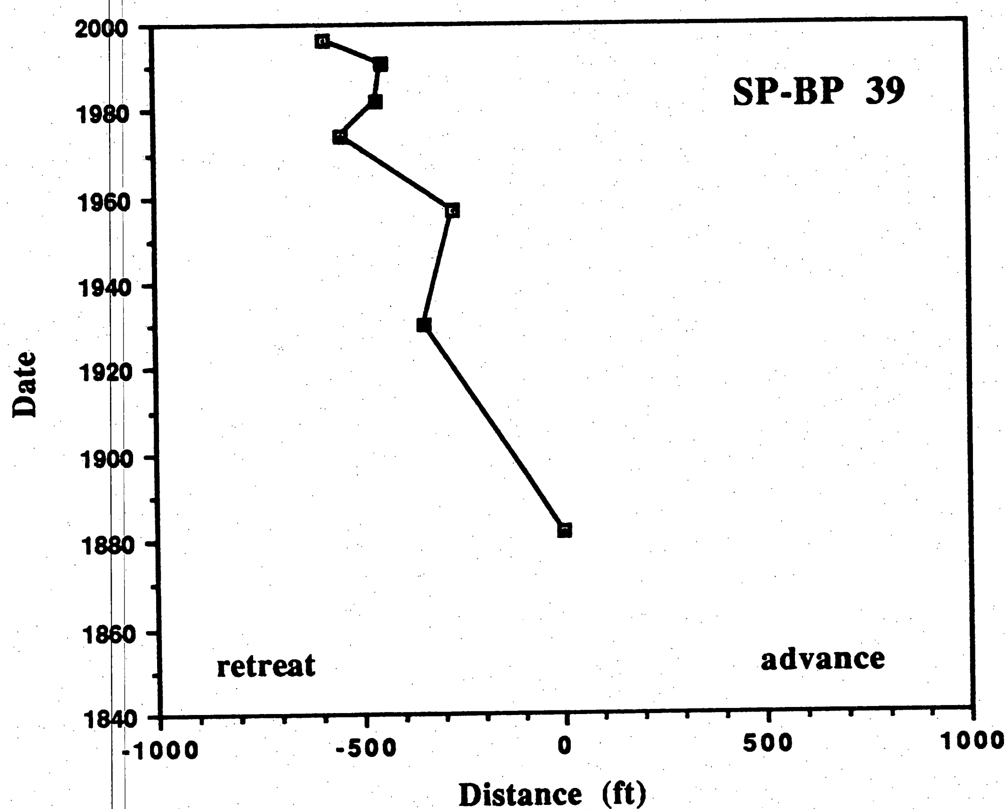
HIGH ISLAND TO BOLIVAR ROADS



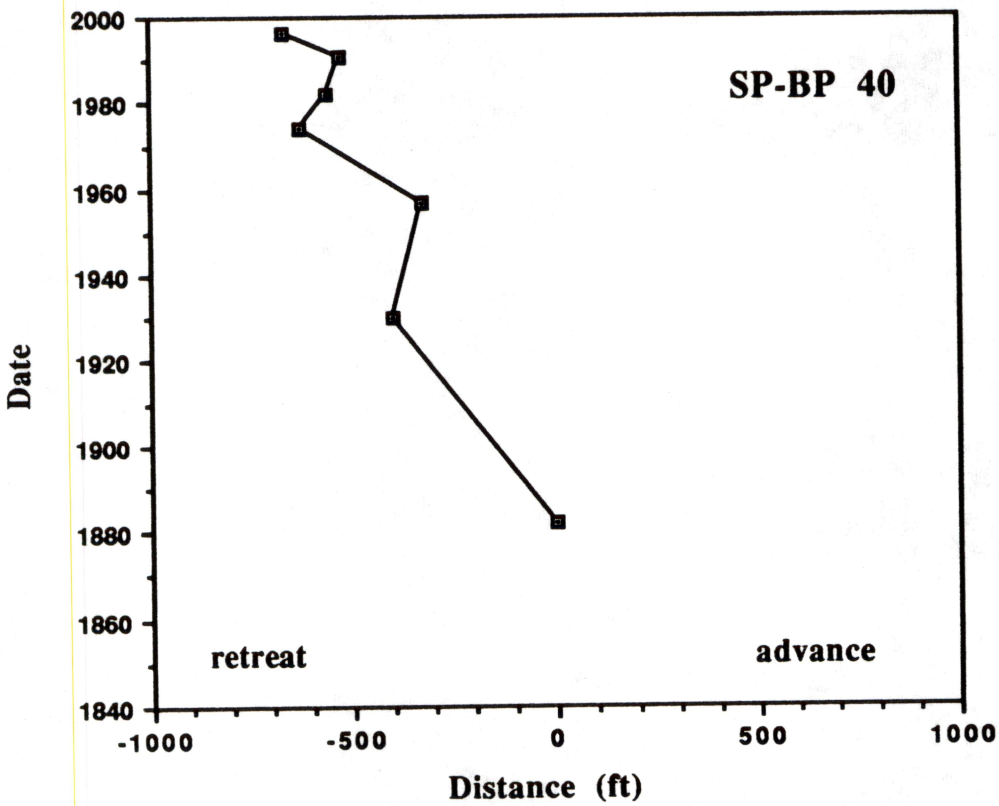
SP-BP 36
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

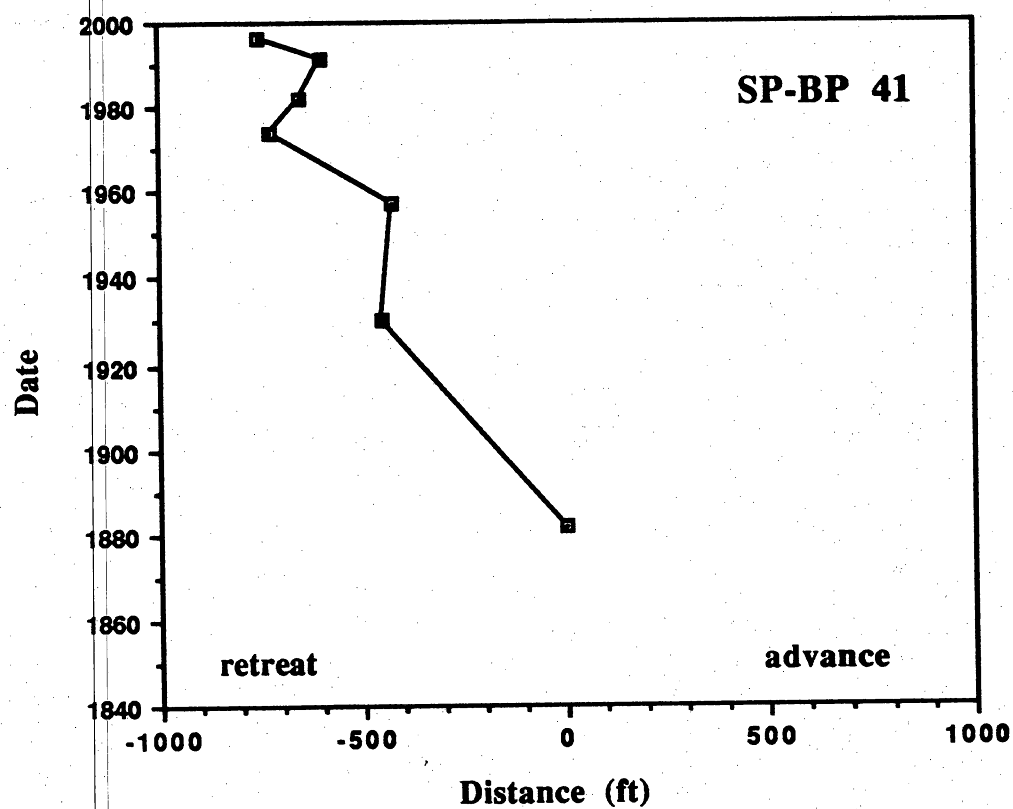

SP-BP 37
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000


SP-BP 38
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

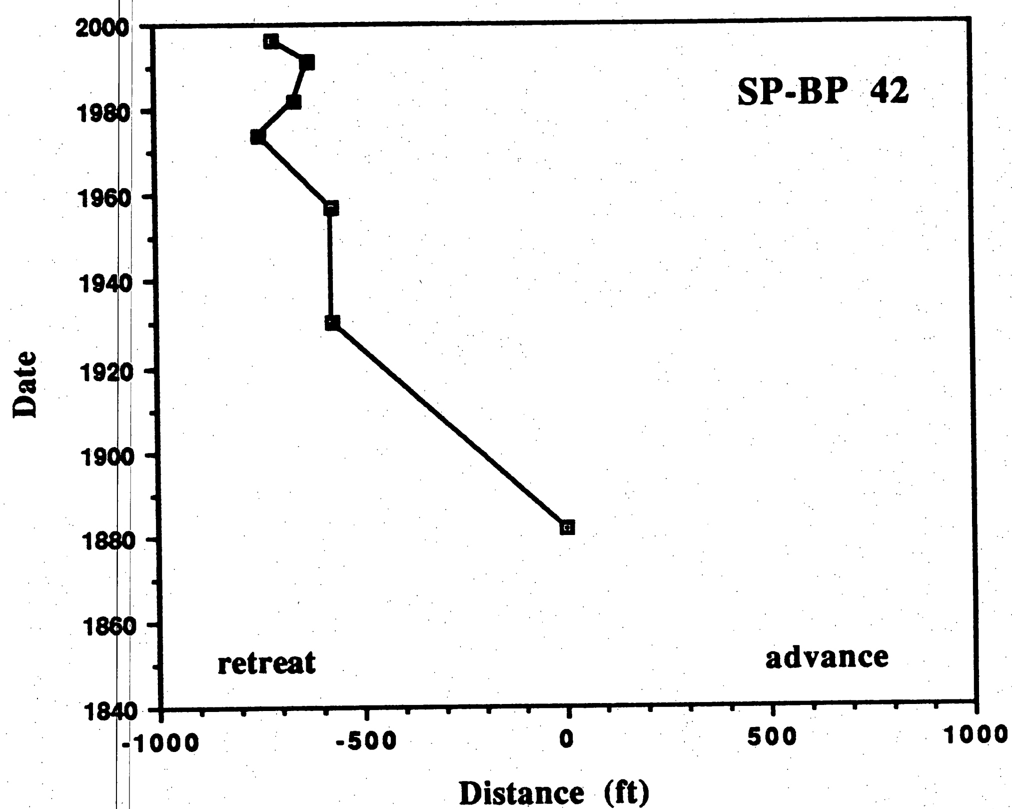


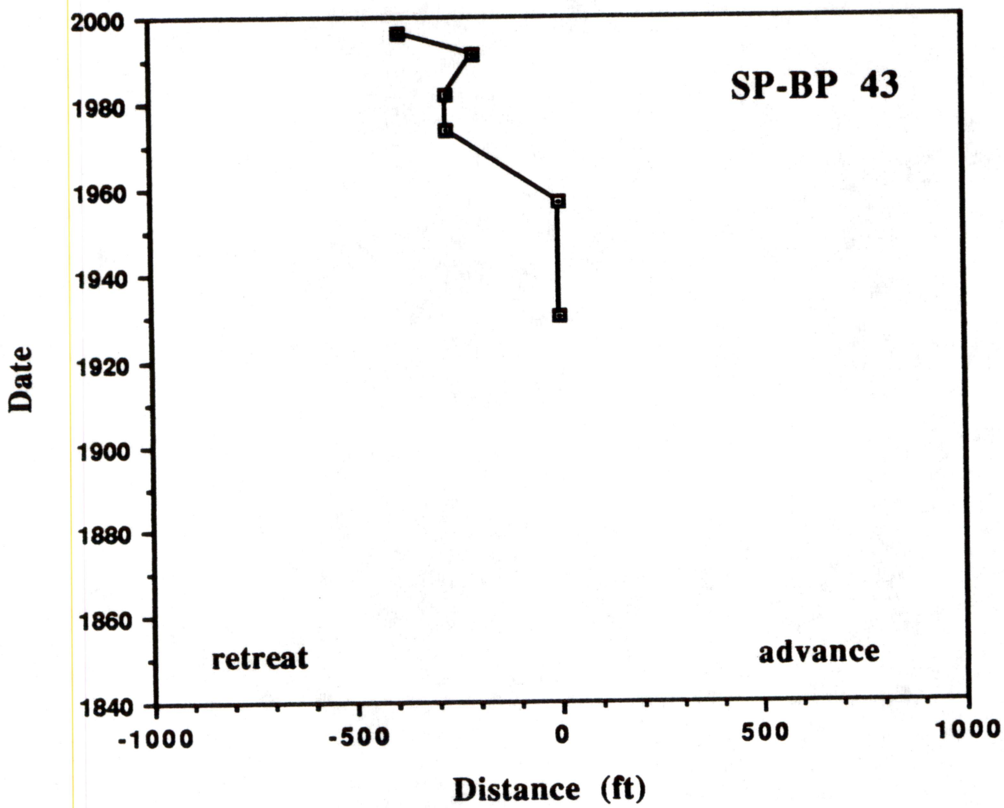
SP-BP 39
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

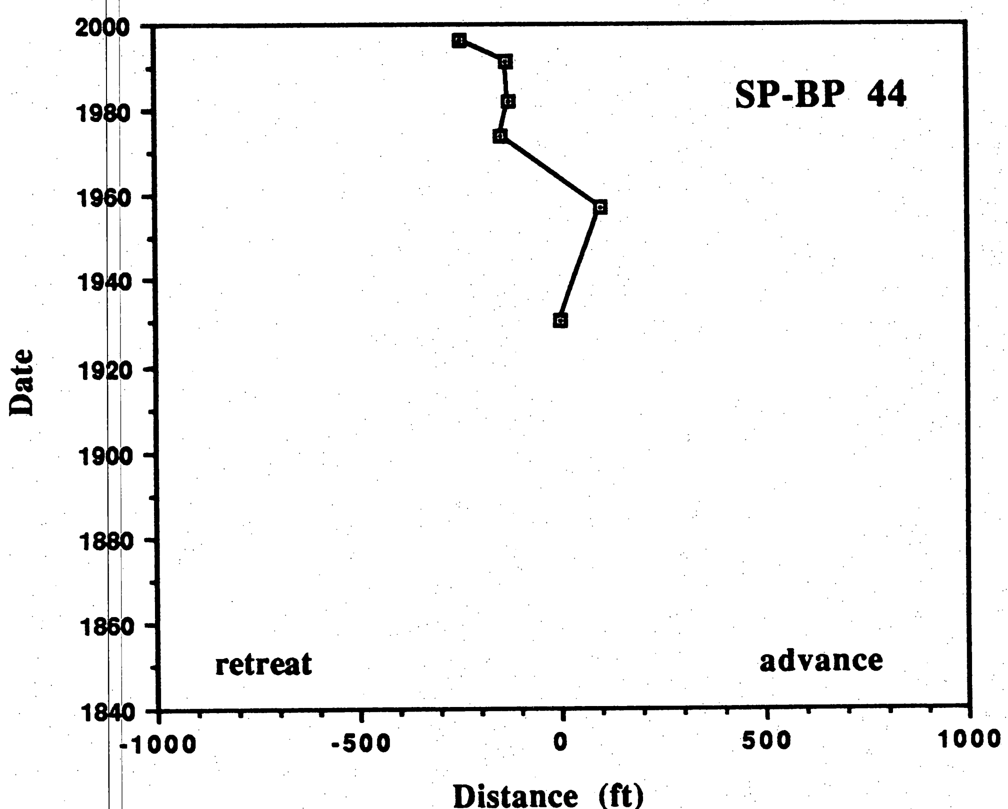

SP-BP 40
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



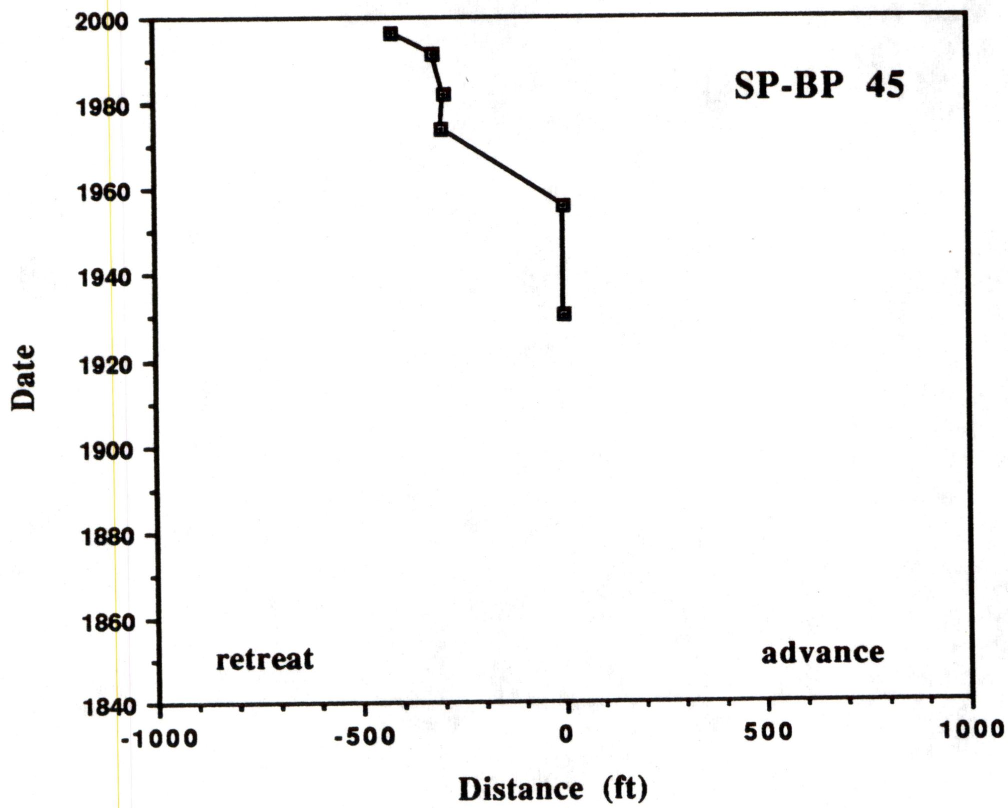
SP-BP 41
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

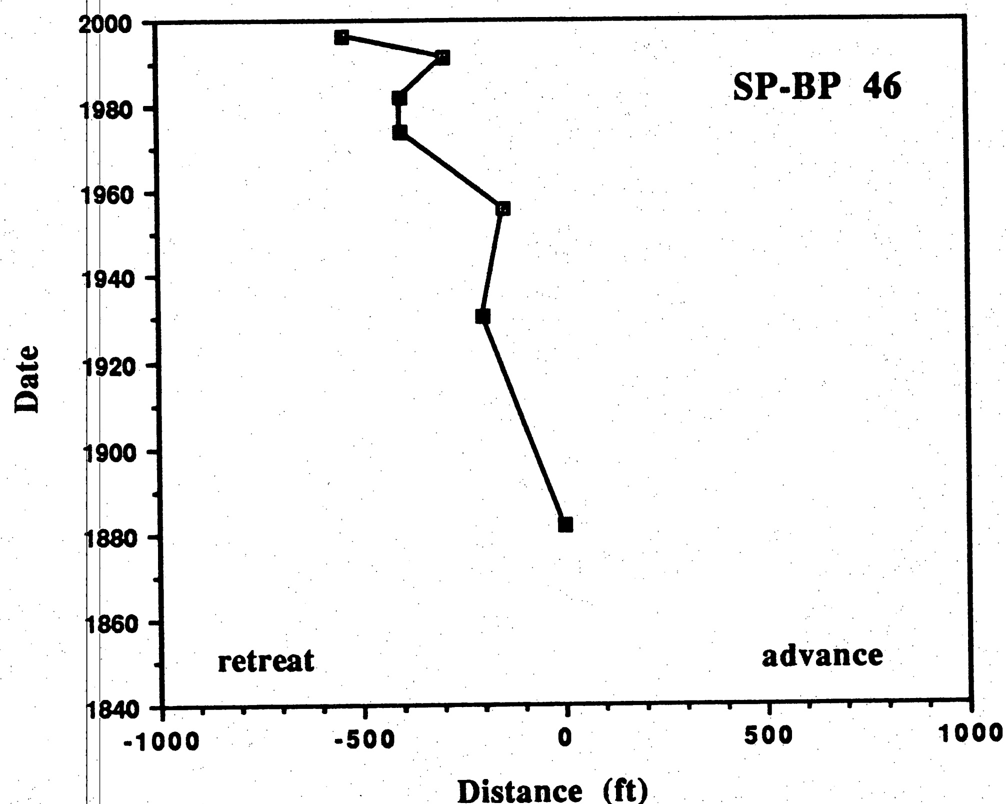

SP-BP 42
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

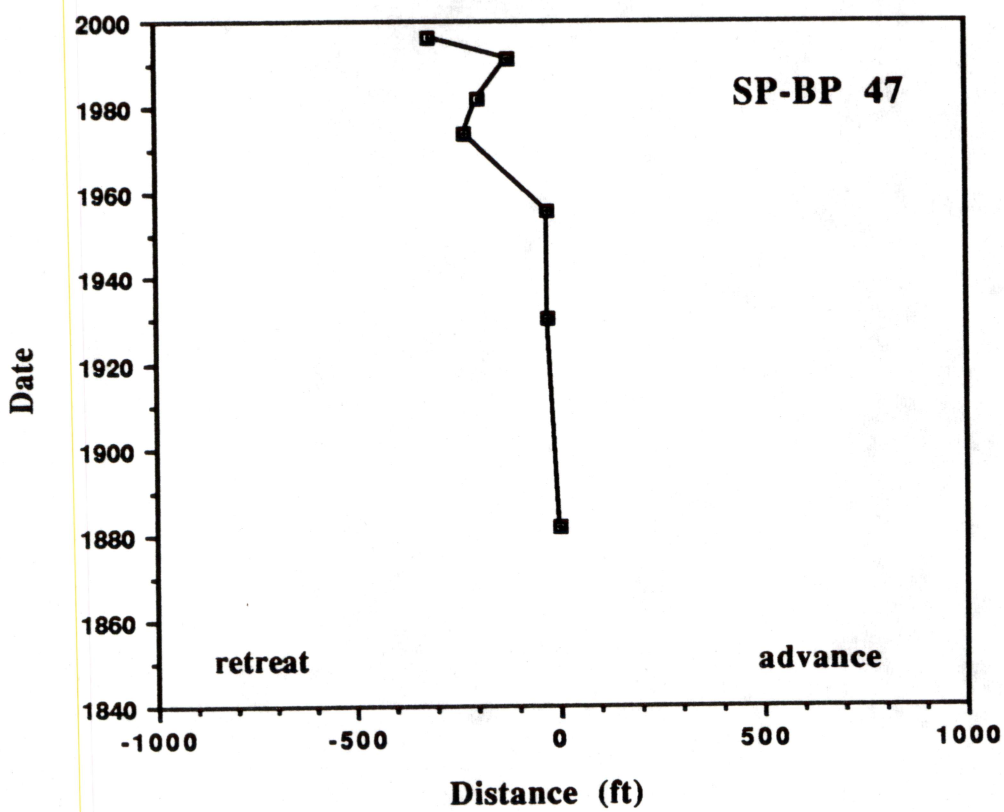

SP-BP 43
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

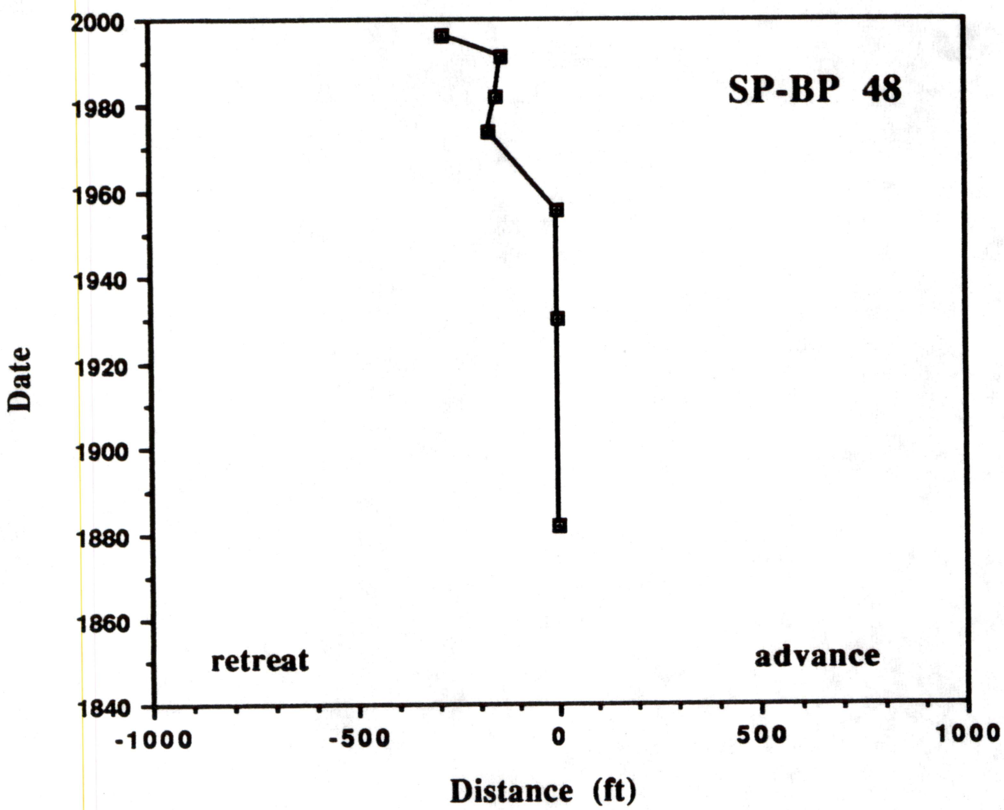


SP-BP 44
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

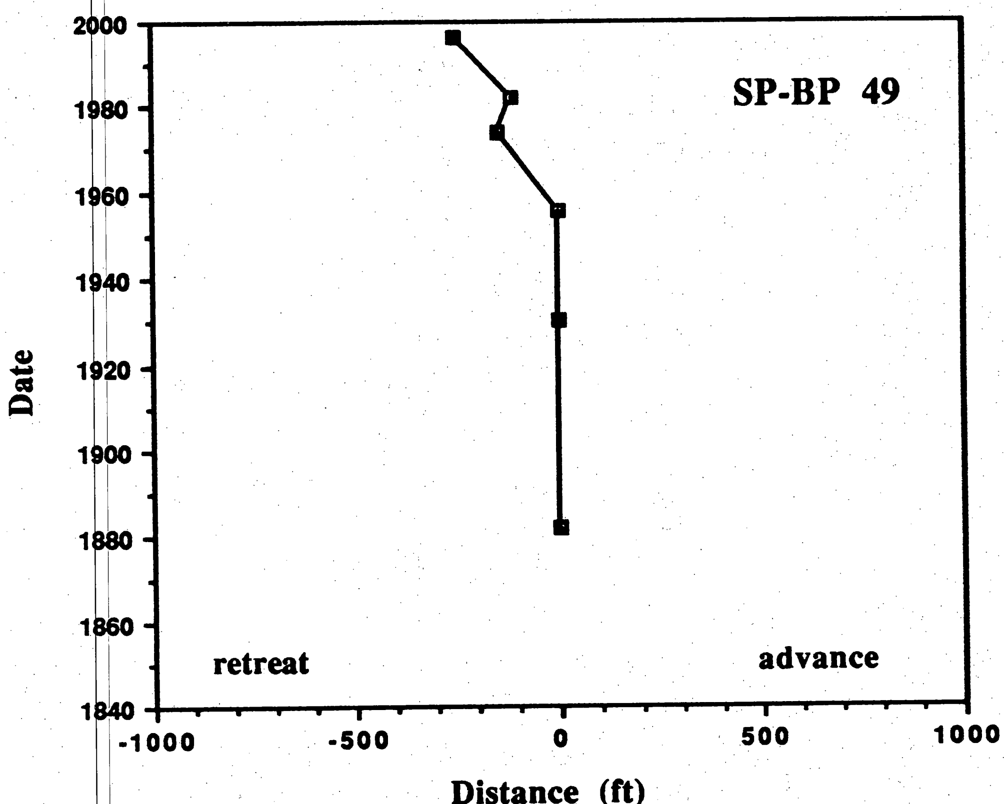

SP-BP 45
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

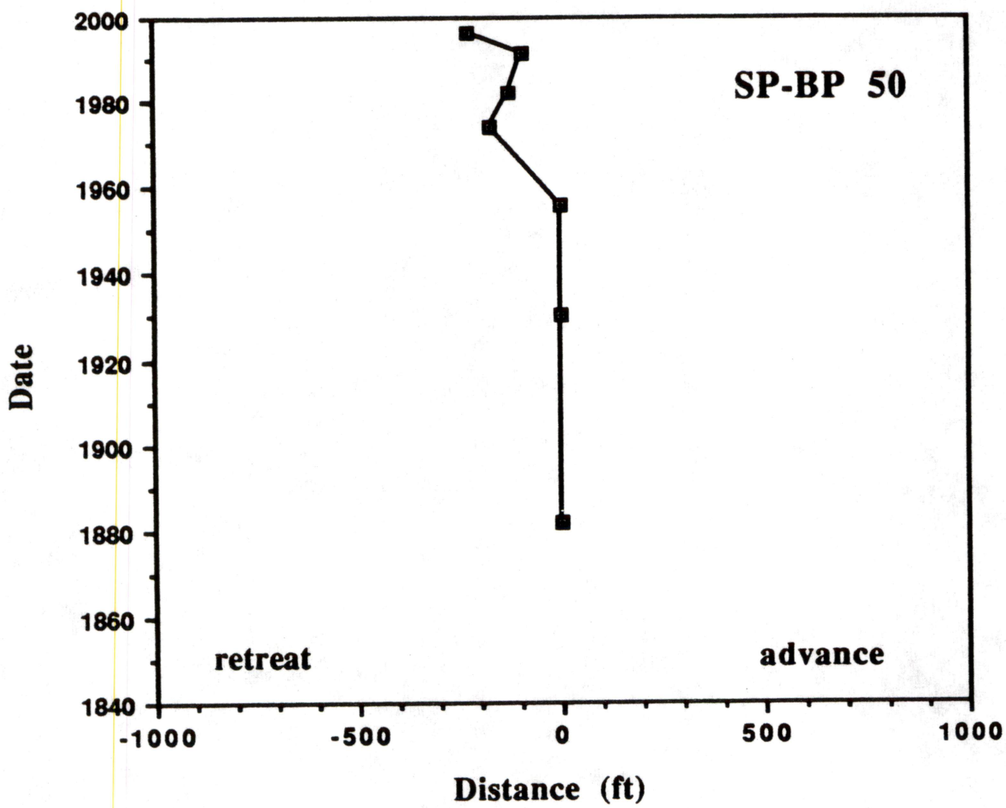

SP-BP 46
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000
retreat
advance
Distance (ft)

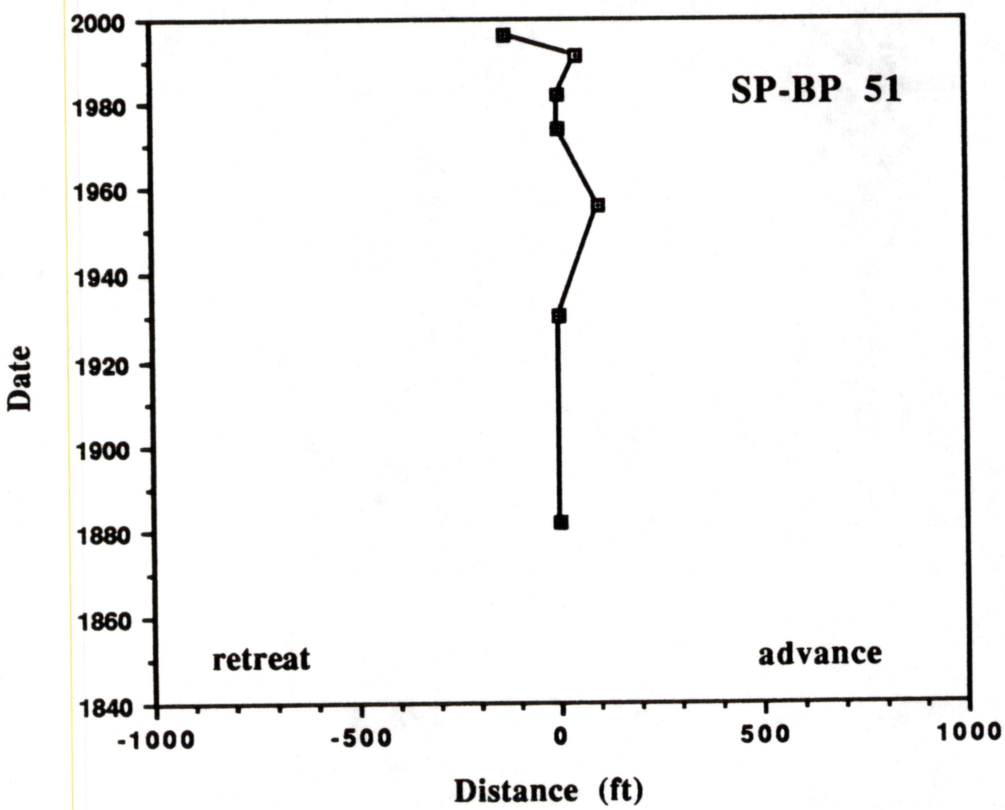

SP-BP 47
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

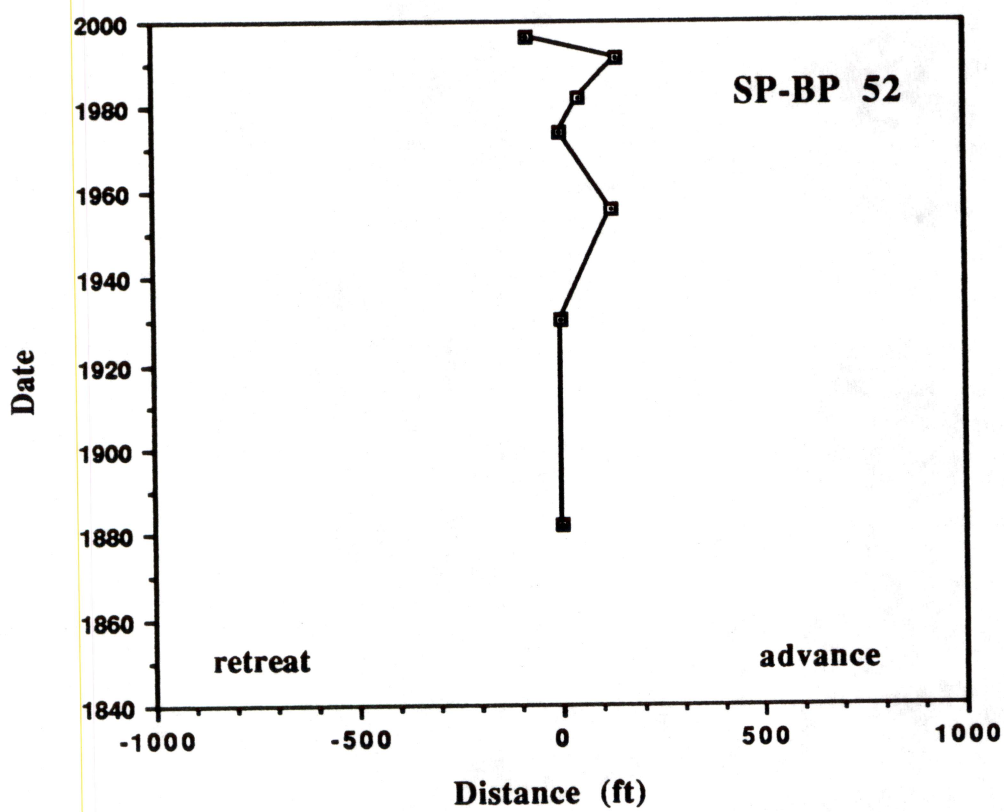


SP-BP 48
retreat
advance
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000
Distance (ft)

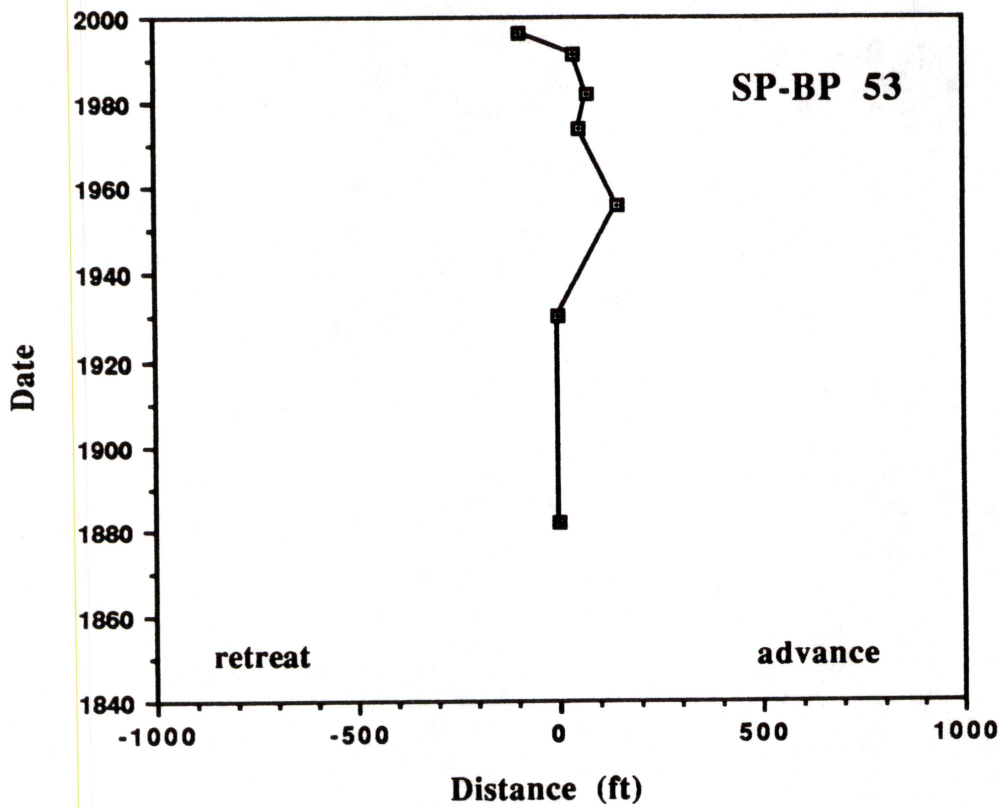

SP-BP 49
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


SP-BP 50
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

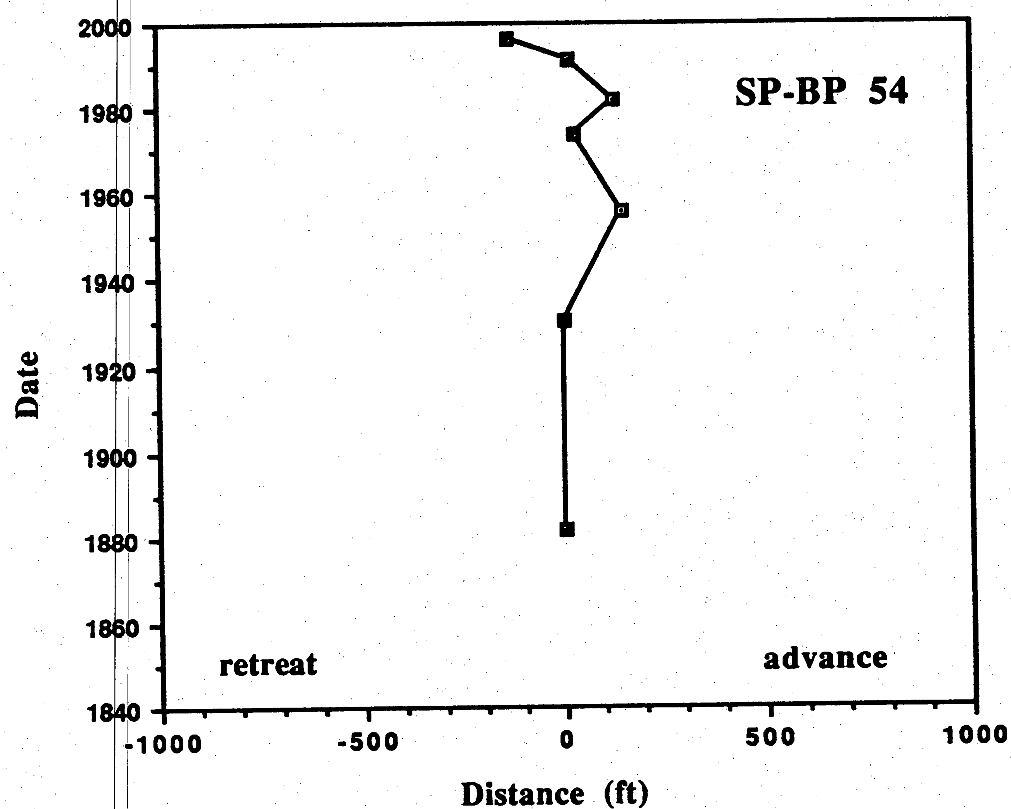

SP-BP 51
retreat
advance
Date
Distance (ft)
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

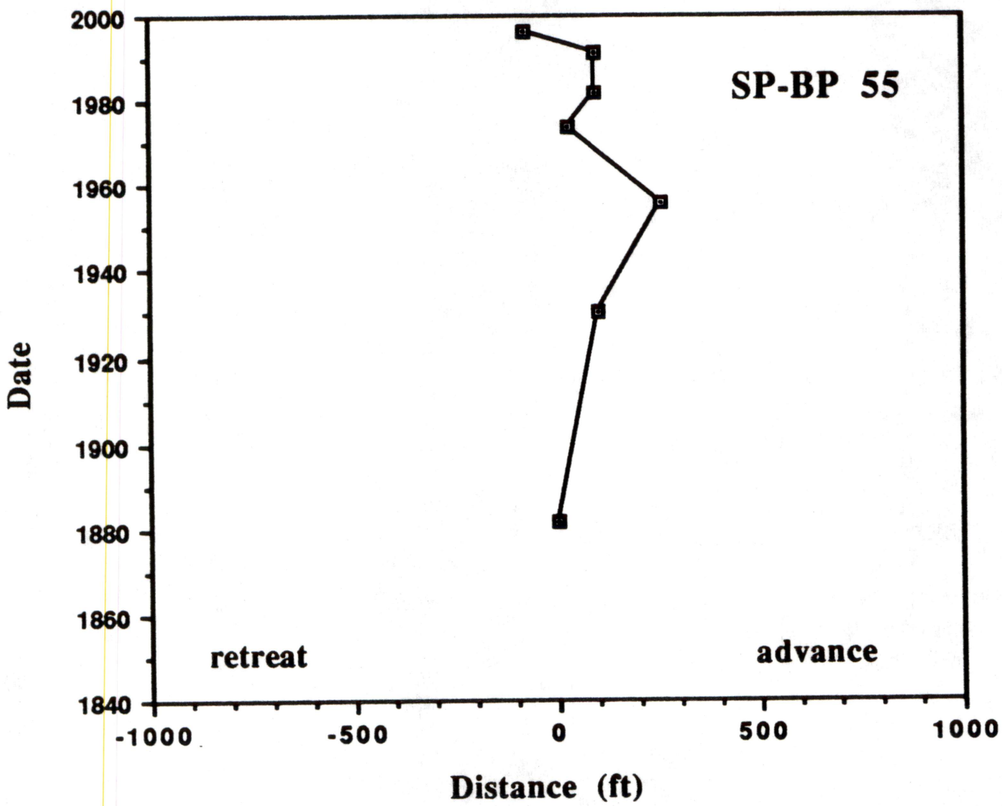


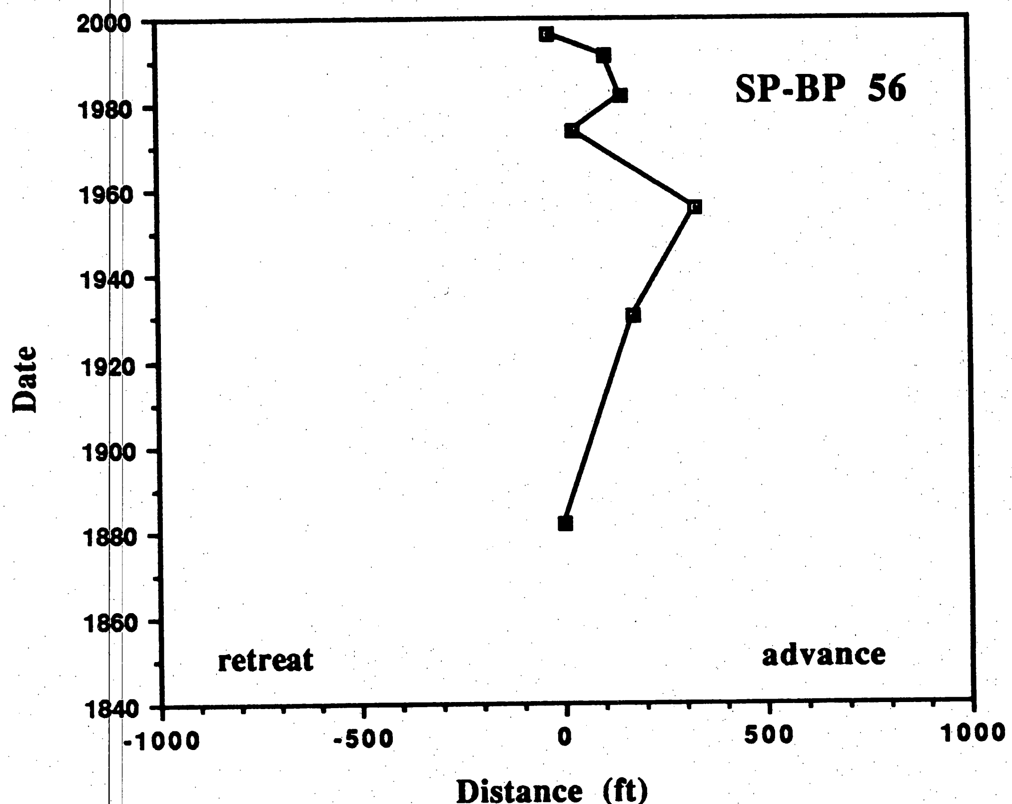
SP-BP 52
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000
Distance (ft)
retreat
advance



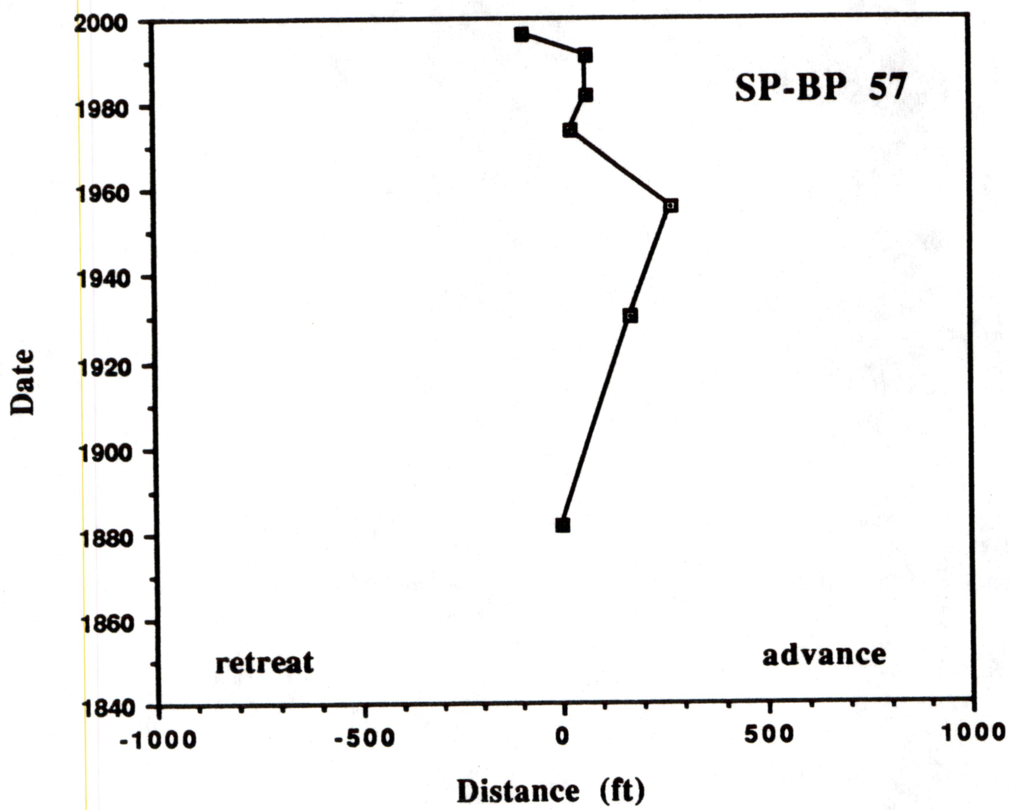
SP-BP 53
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

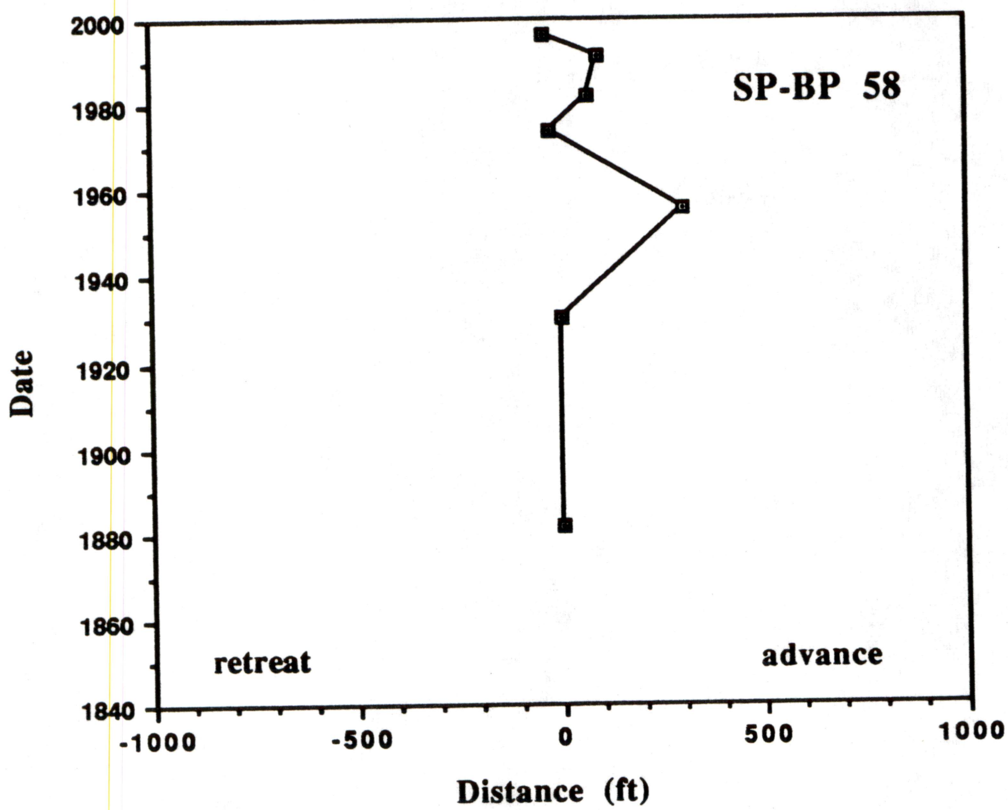

SP-BP 54
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

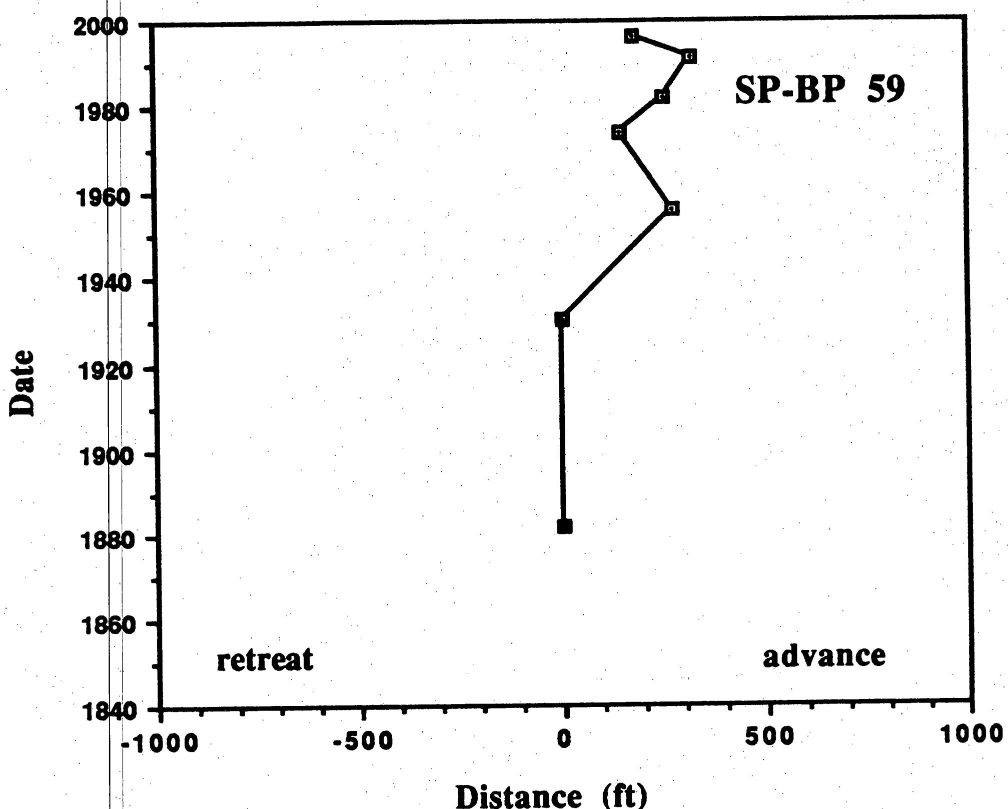

SP-BP 55
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



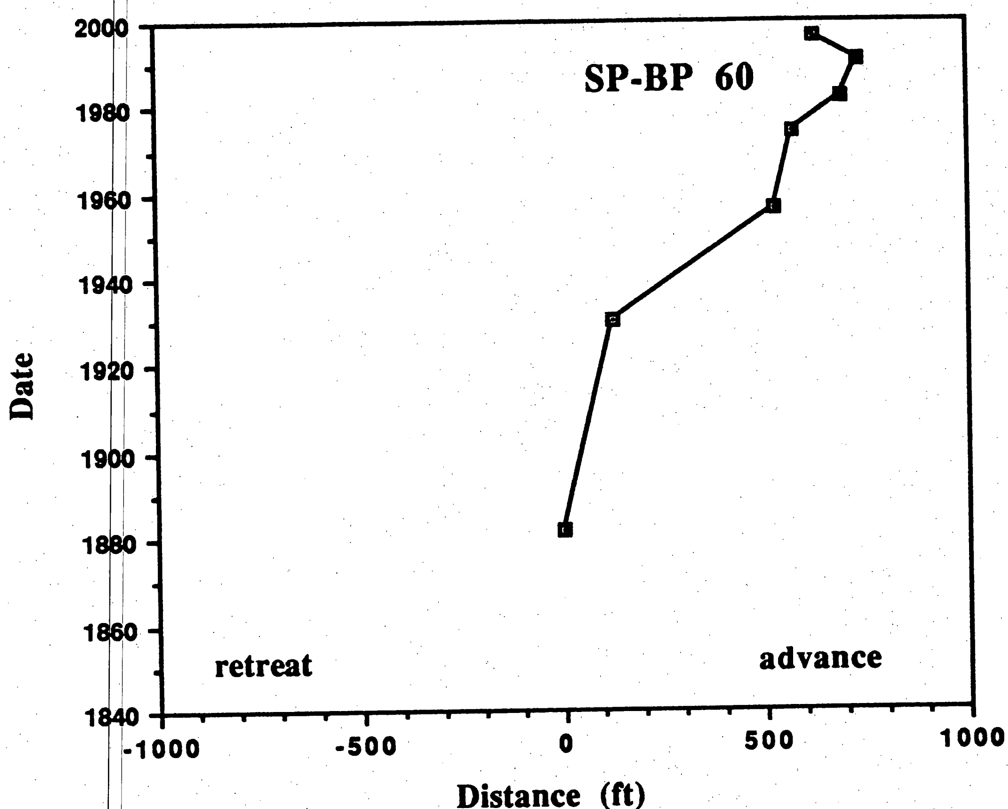
SP-BP 56
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


SP-BP 57
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

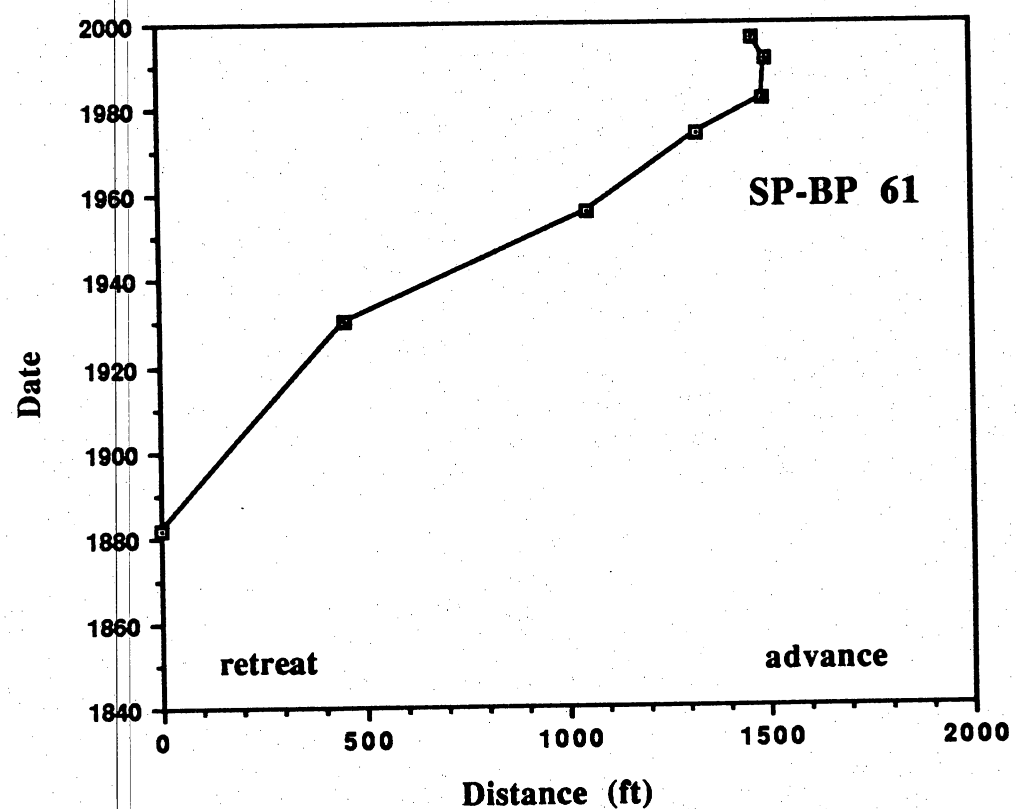

SP-BP 58
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

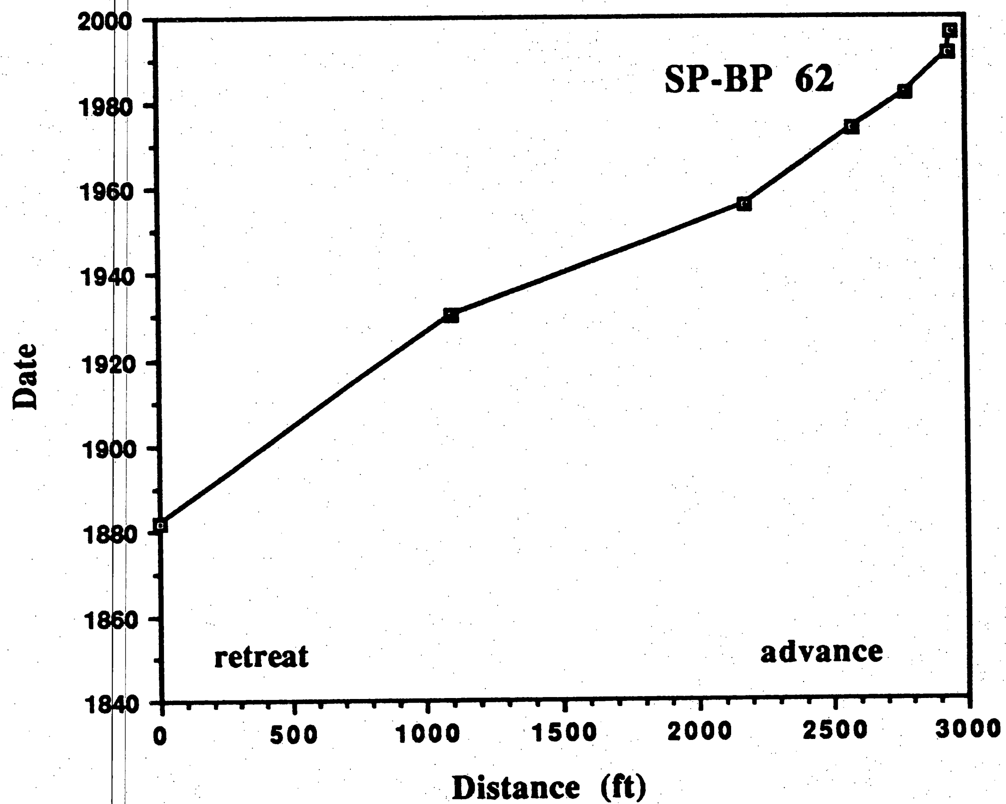


SP-BP 59
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



SP-BP 60
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


SP-BP 61
retreat
advance
Date
Distance (ft)
2000
1980
1960
1940
1920
1900
1880
1860
1840
0
500
1000
1500
2000

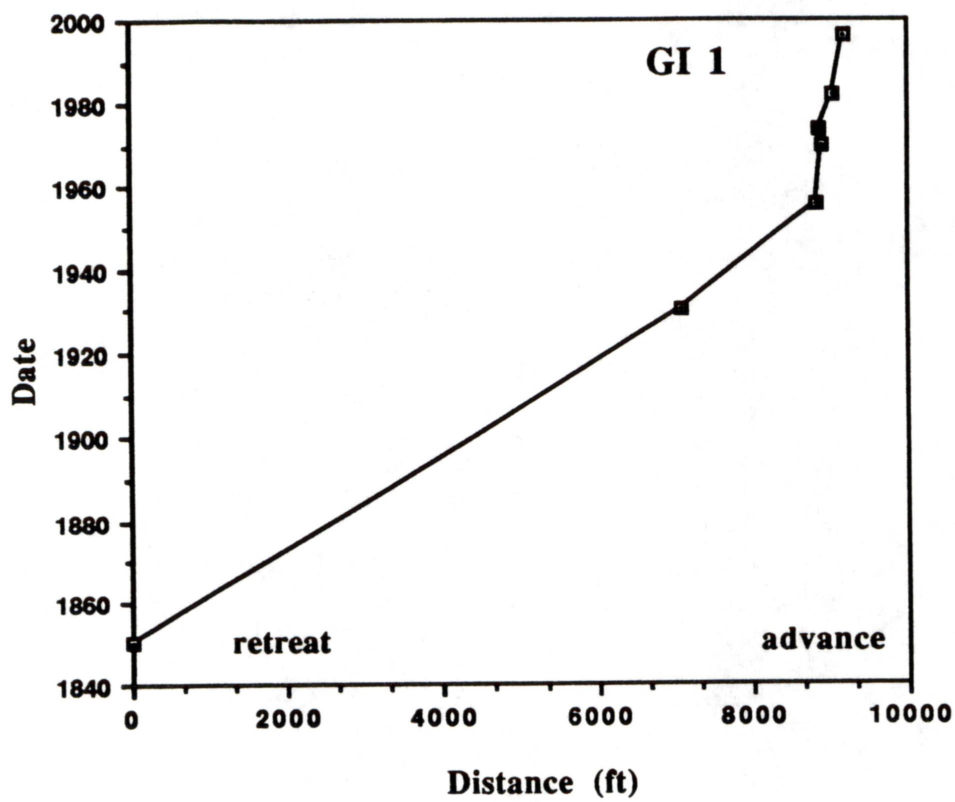


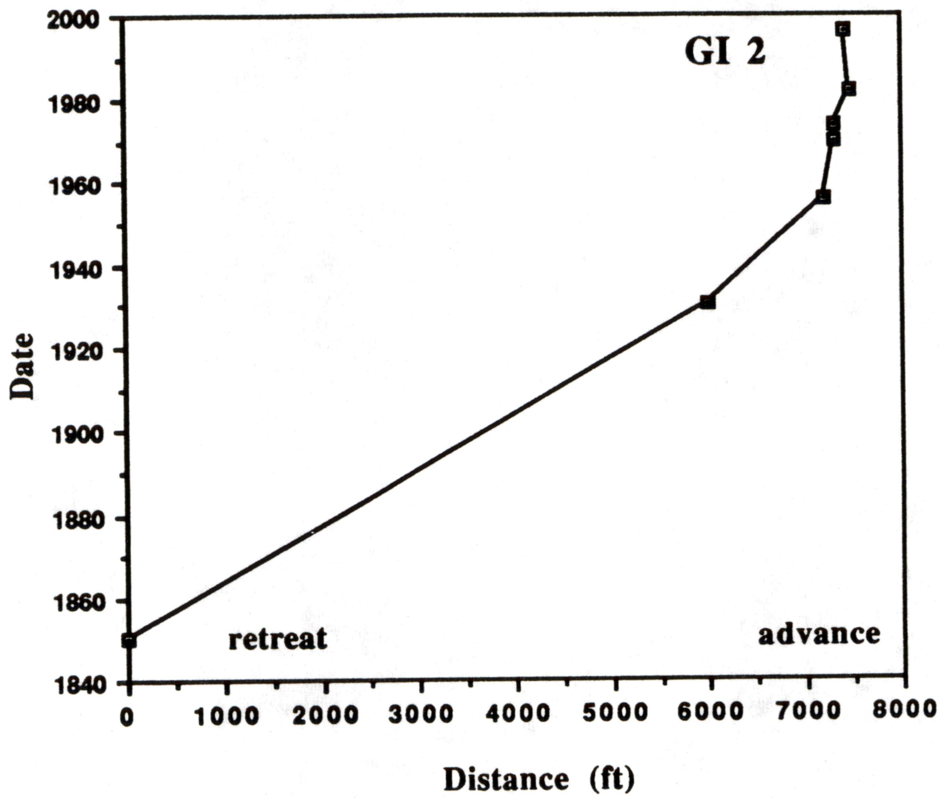
SP-BP 62
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
0
500
1000
1500
2000
2500
3000
Distance (ft)

APPENDIX B

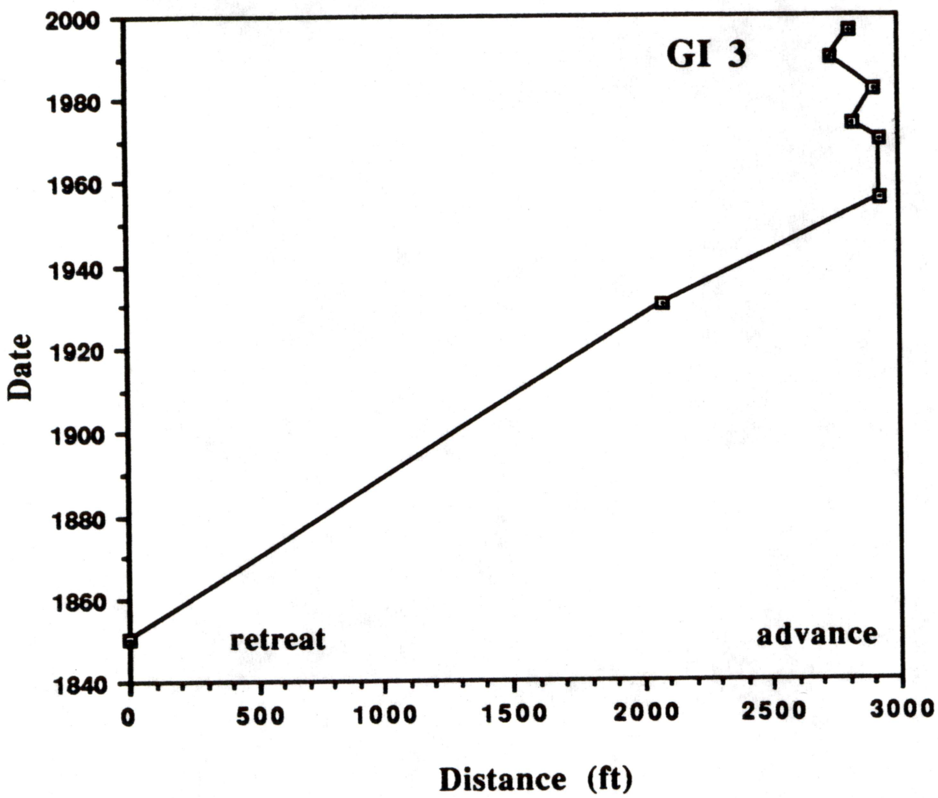
SHORELINE HISTORY PLOTS

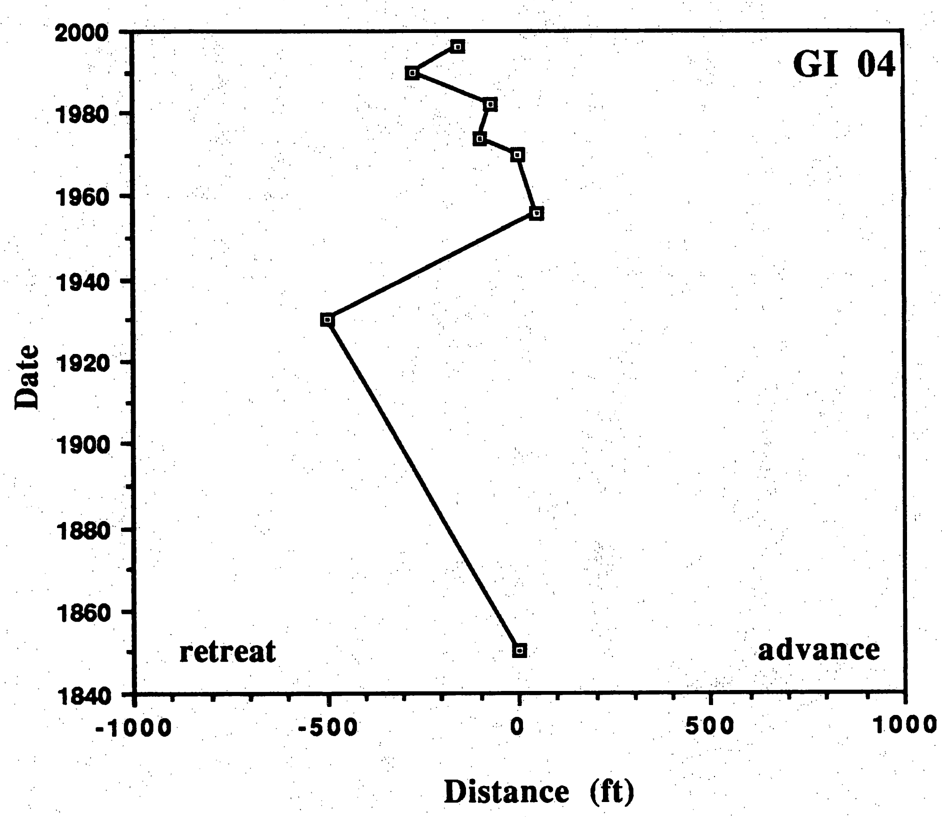
BOLIVAR ROADS TO SAN LUIS PASS
(GALVESTON ISLAND)


GI 1
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
0
2000
4000
6000
8000
10000
Distance (ft)

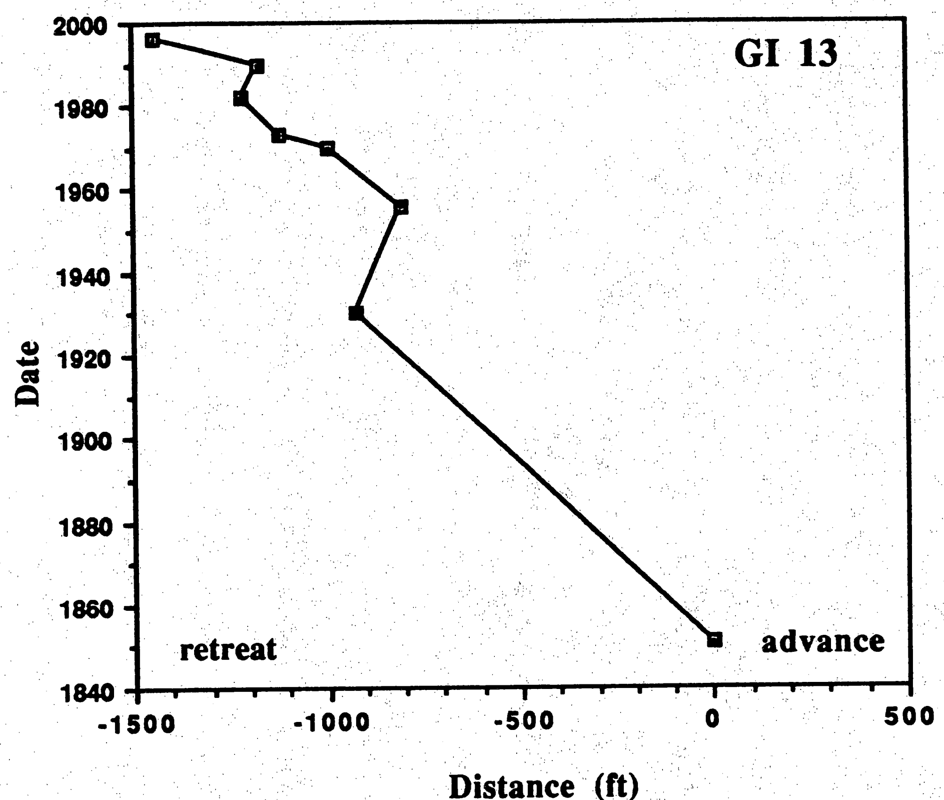


GI 2
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)

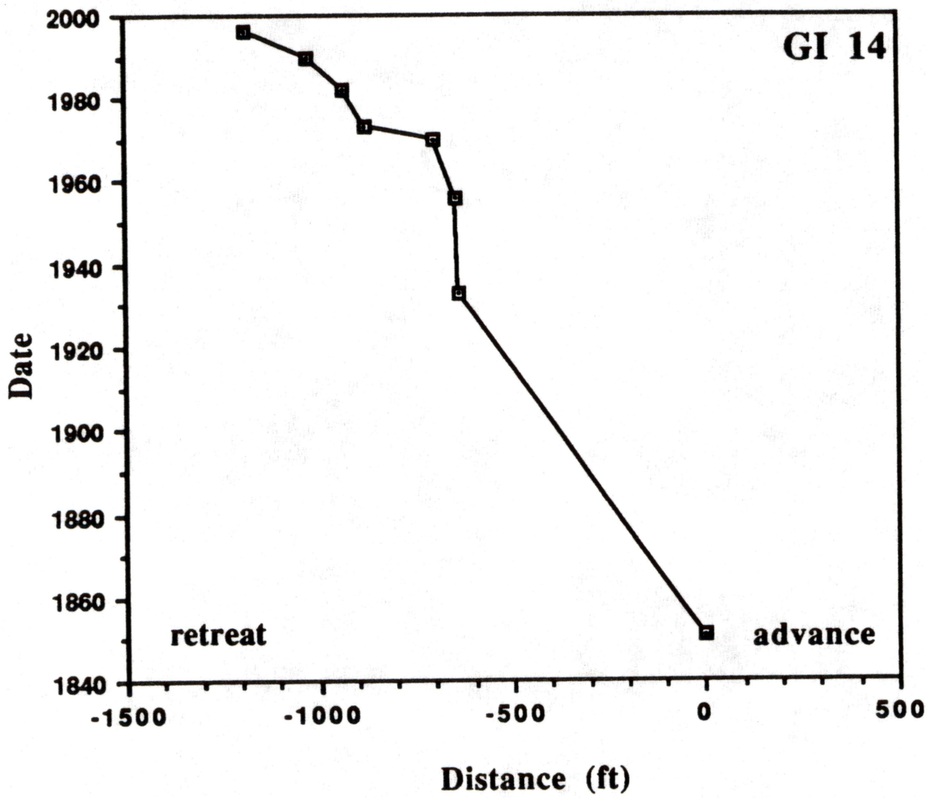

GI 3
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
0
500
1000
1500
2000
2500
3000
Distance (ft)



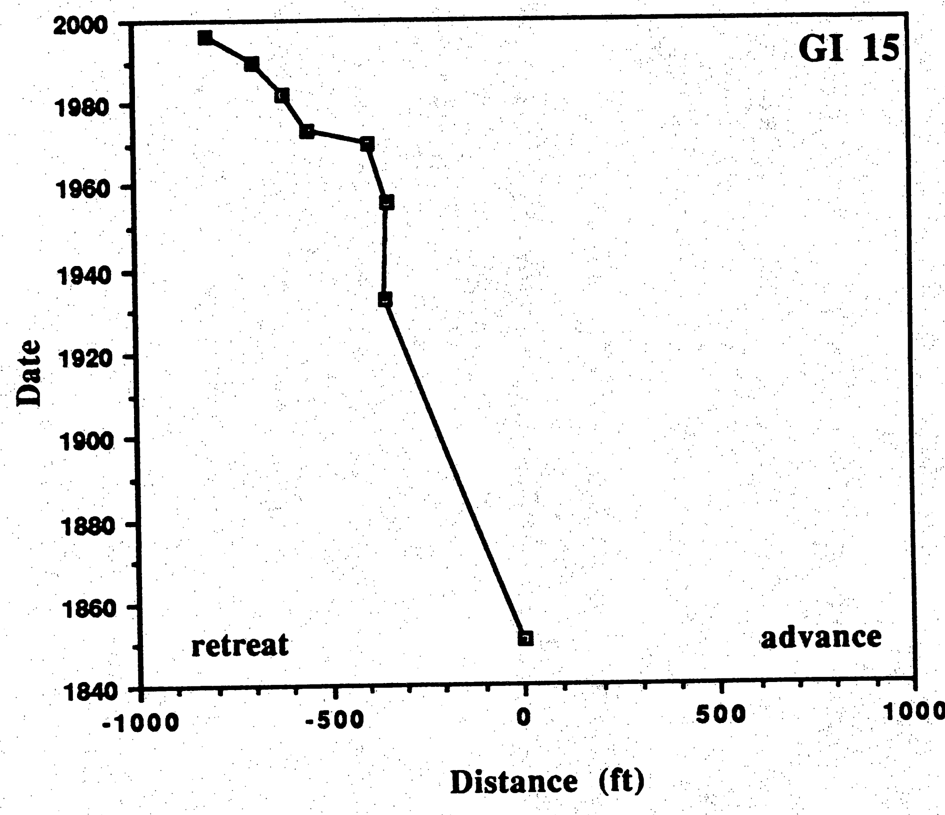
GI 04
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



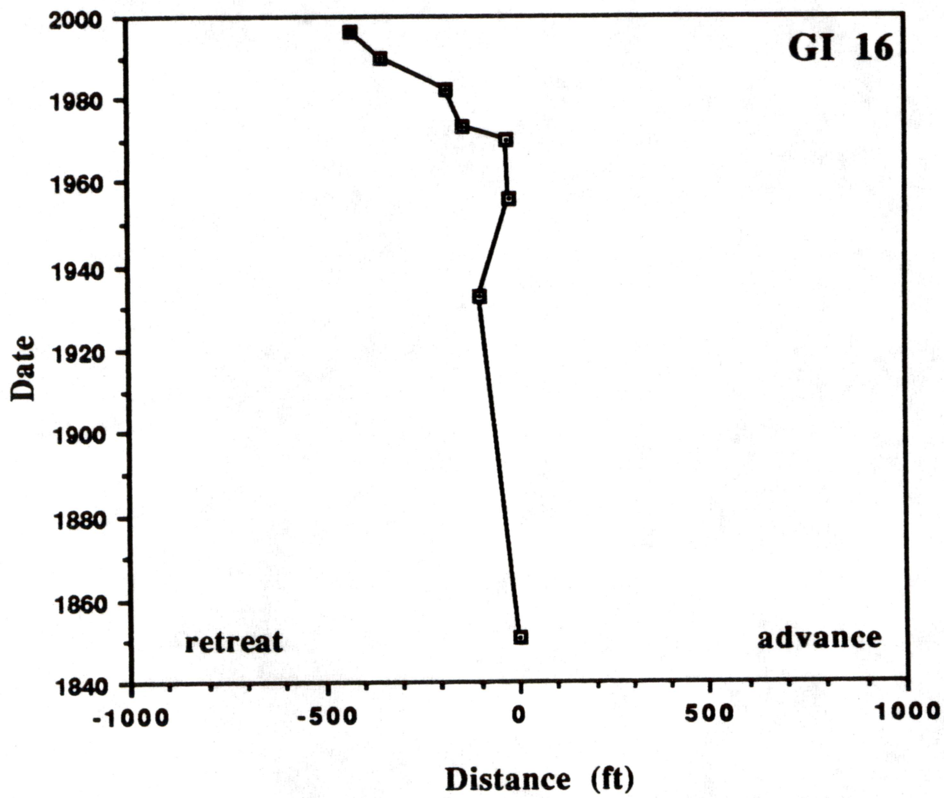
GI 13
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1500
-1000
-500
0
500

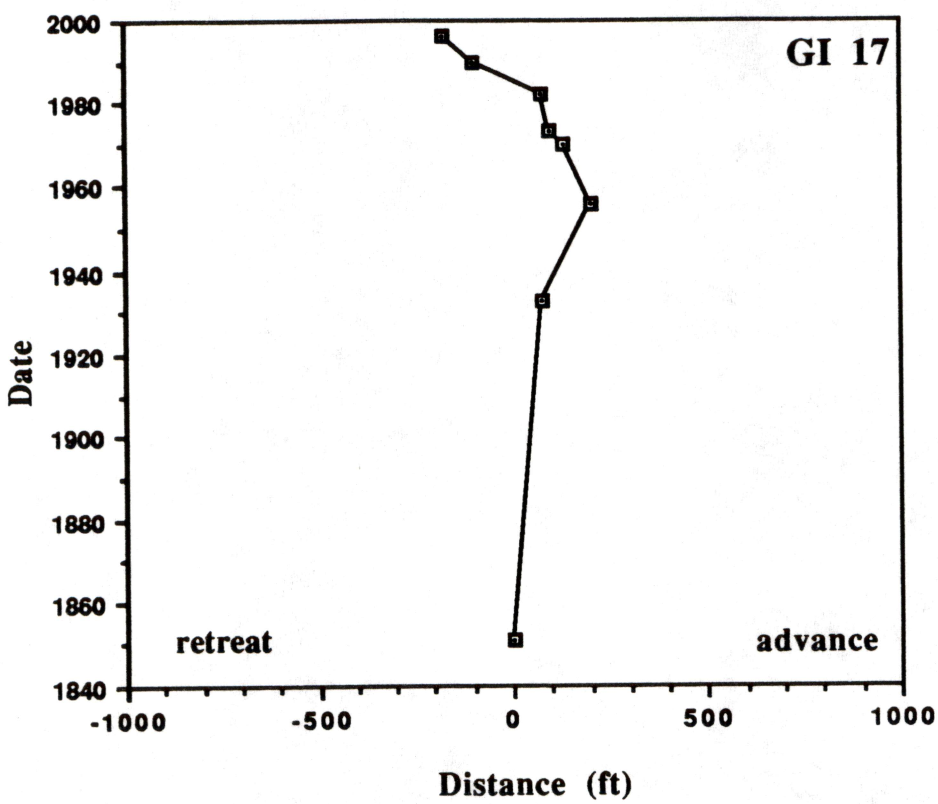


GI 14
retreat
advance
Date
Distance (ft)
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1500
-1000
-500
0
500

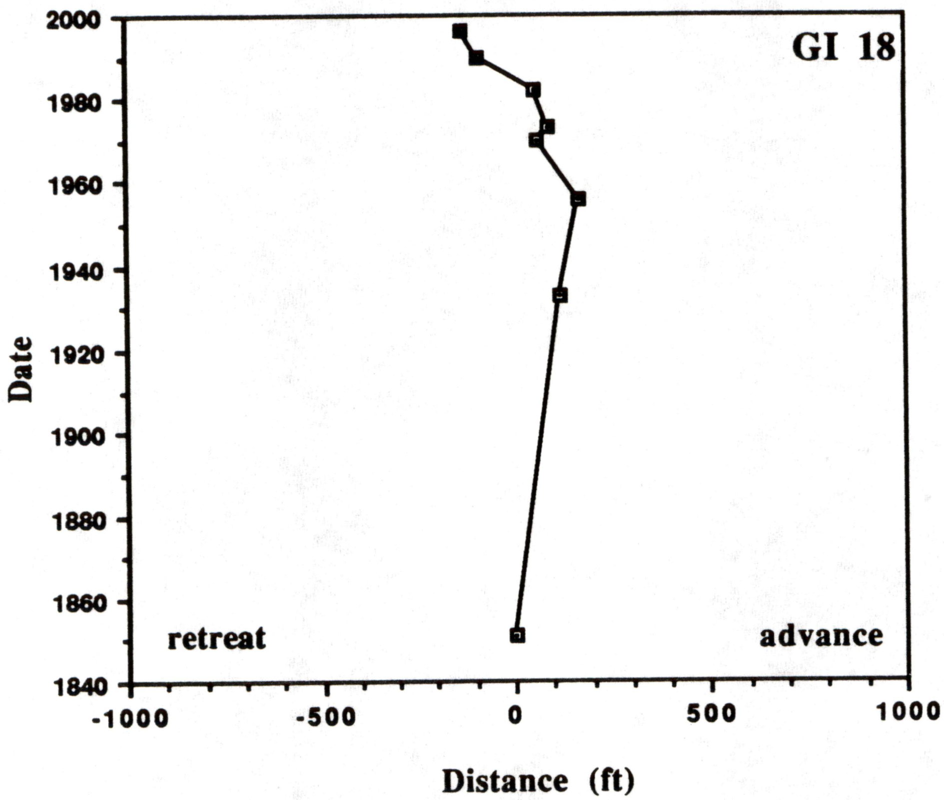


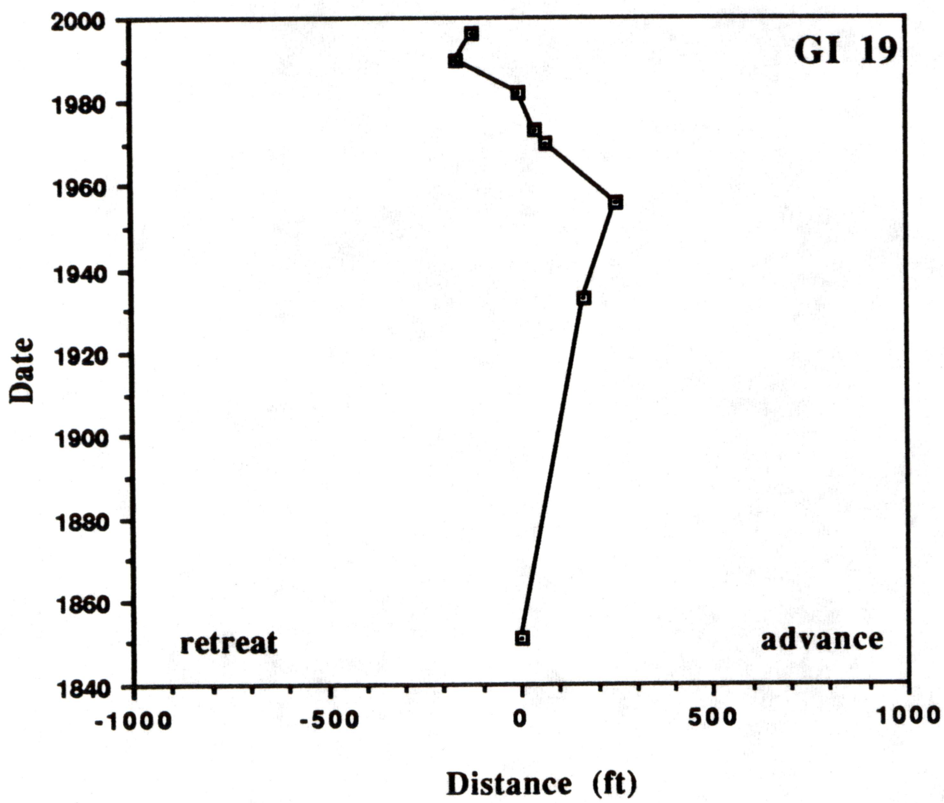
GI 15
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

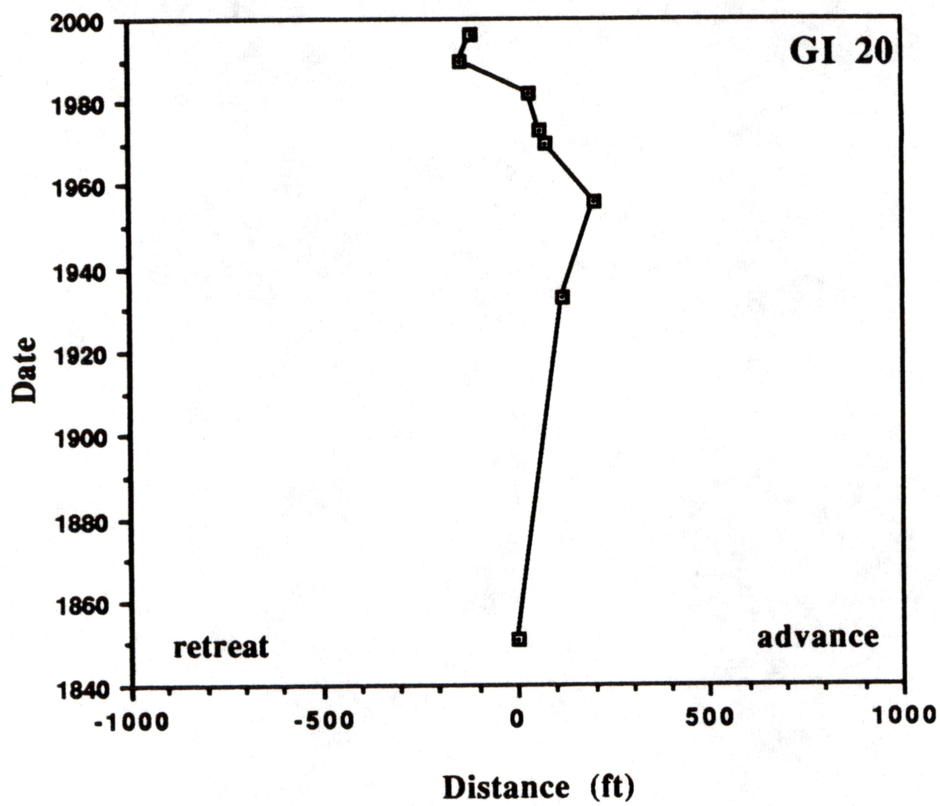

GI 16
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

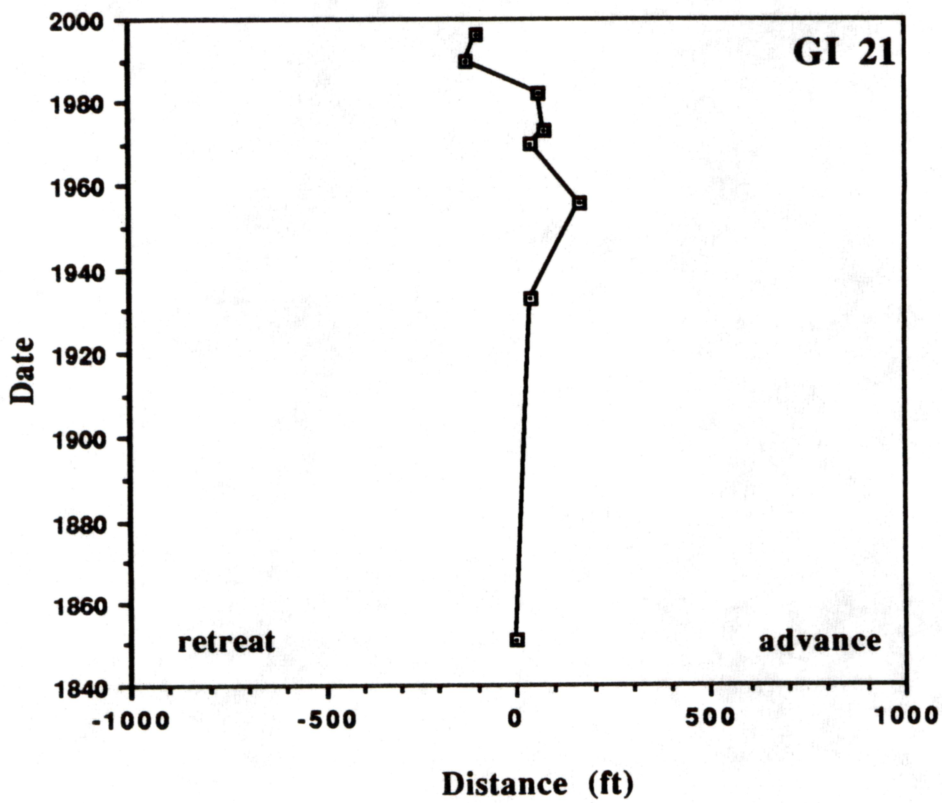


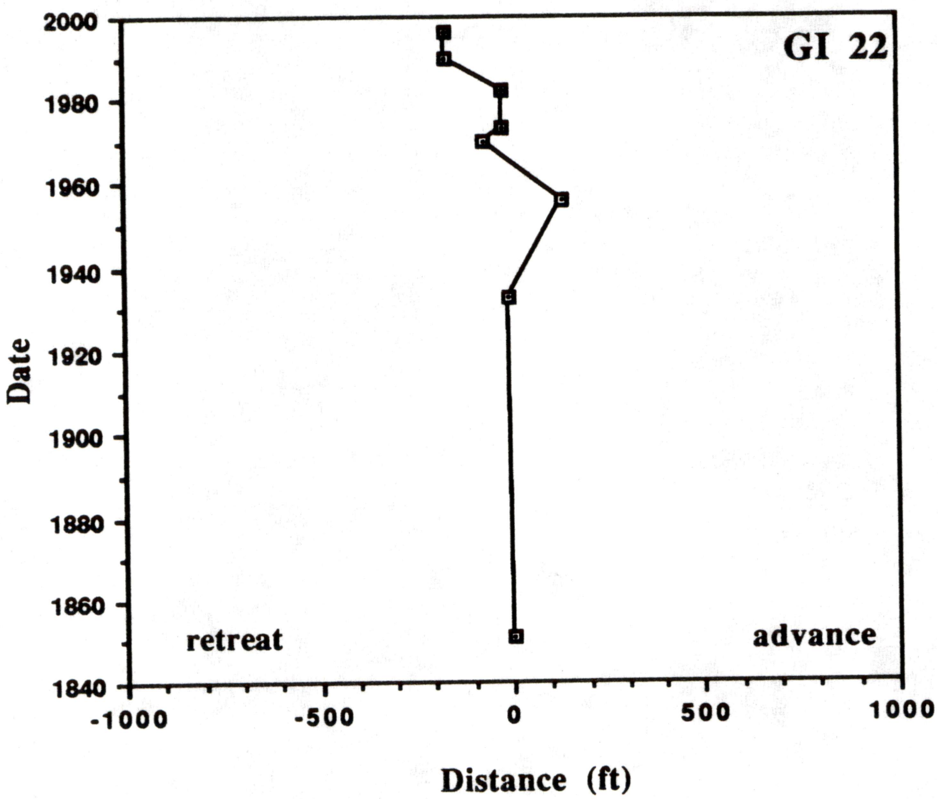
GI 17
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

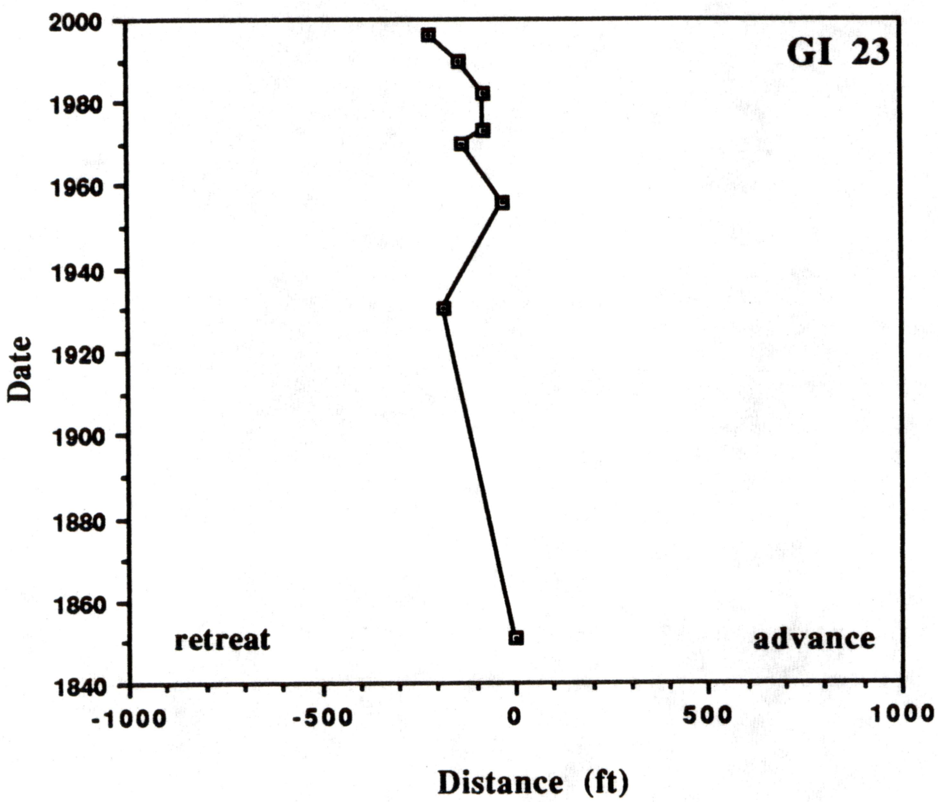

GI 18
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

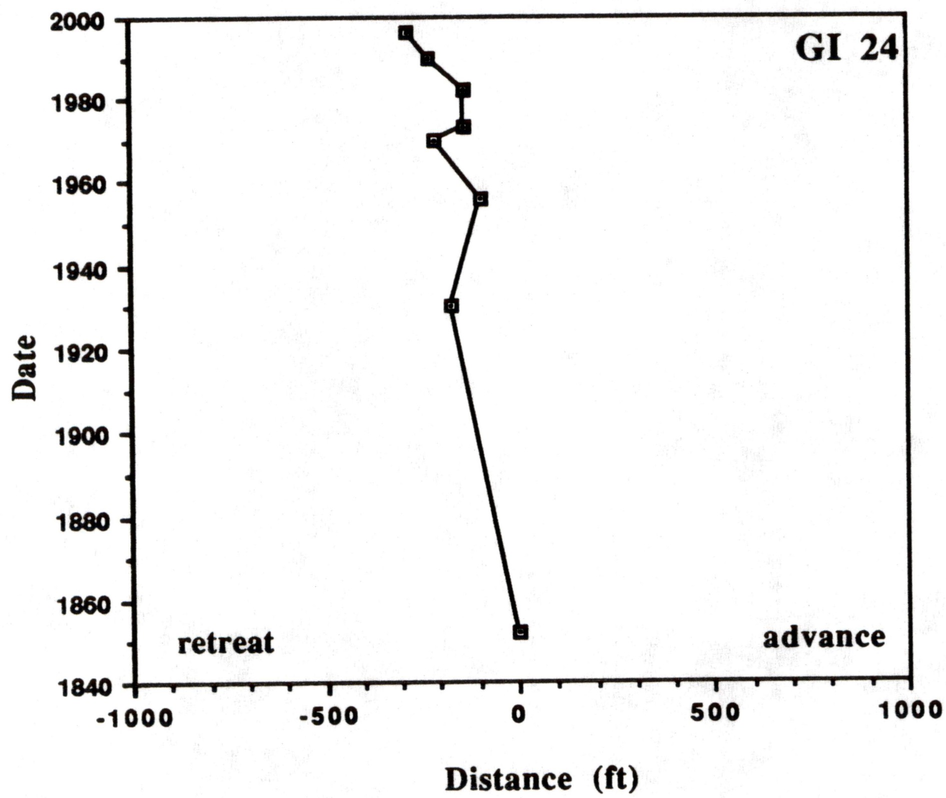

GI 19
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

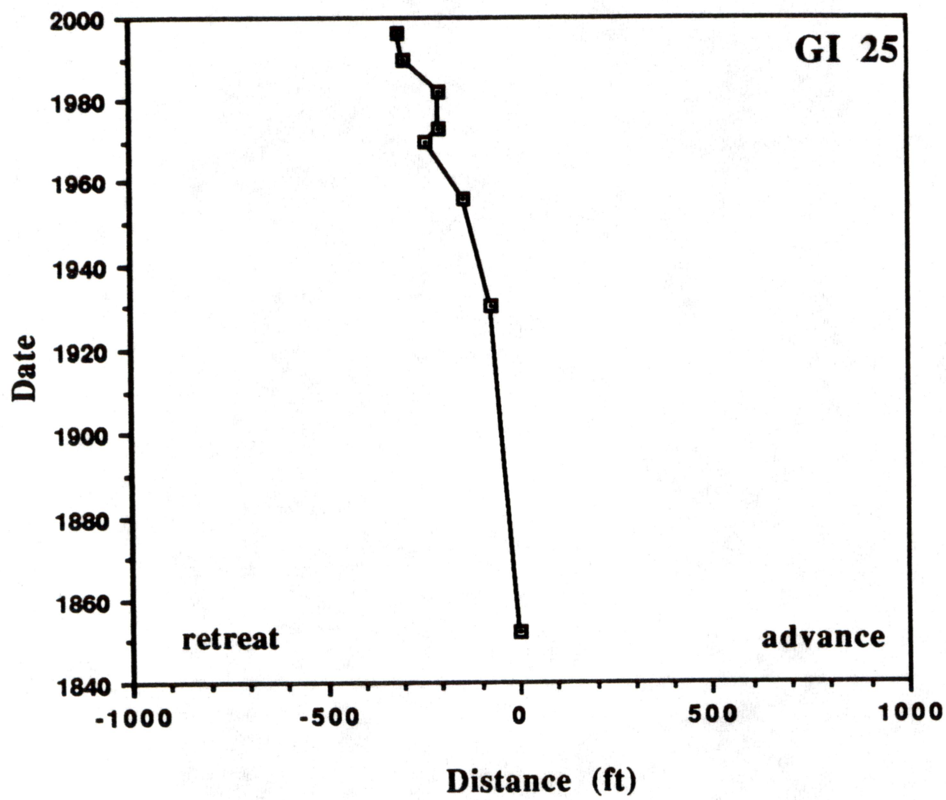

GI 20
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000


GI 21
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

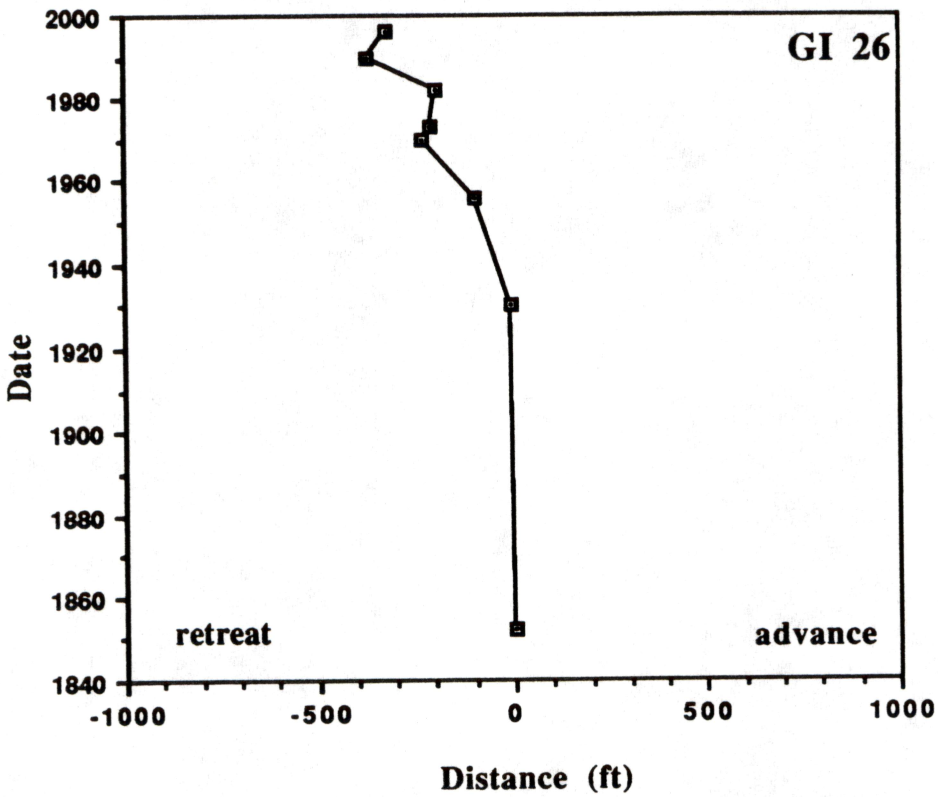

GI 22
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


GI 23
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

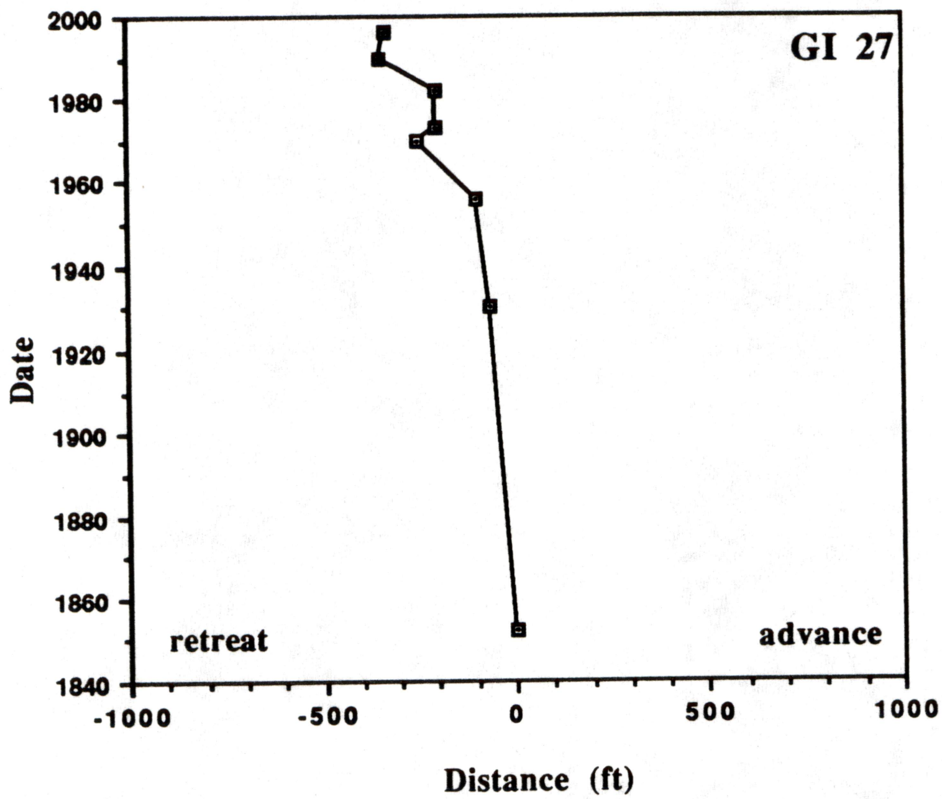

GI 24
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

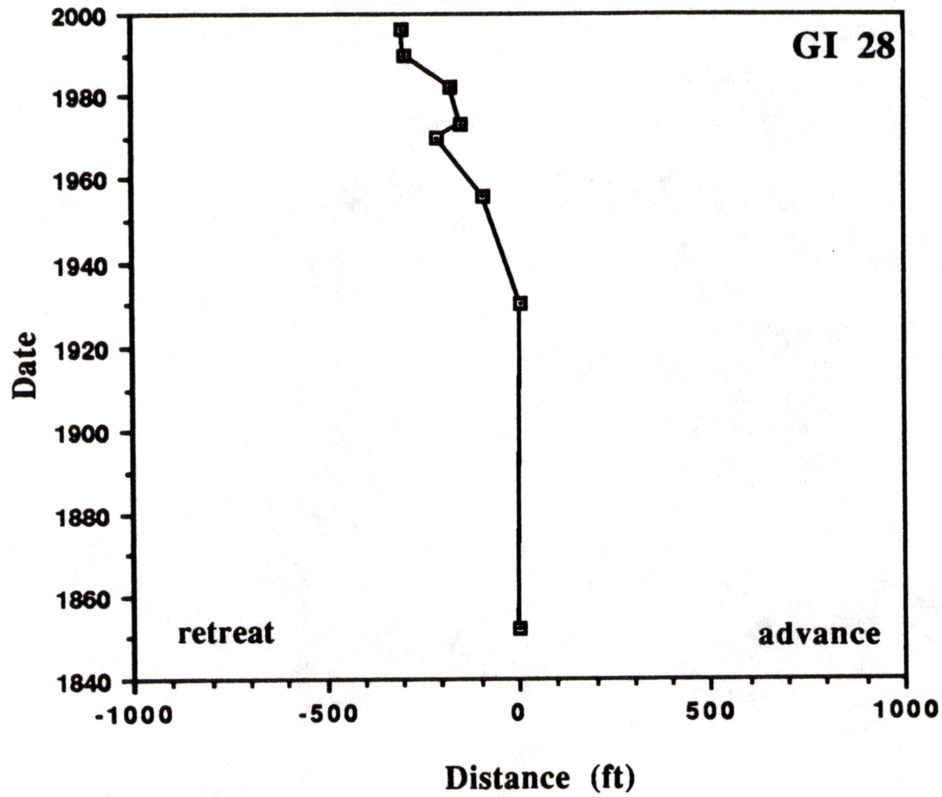


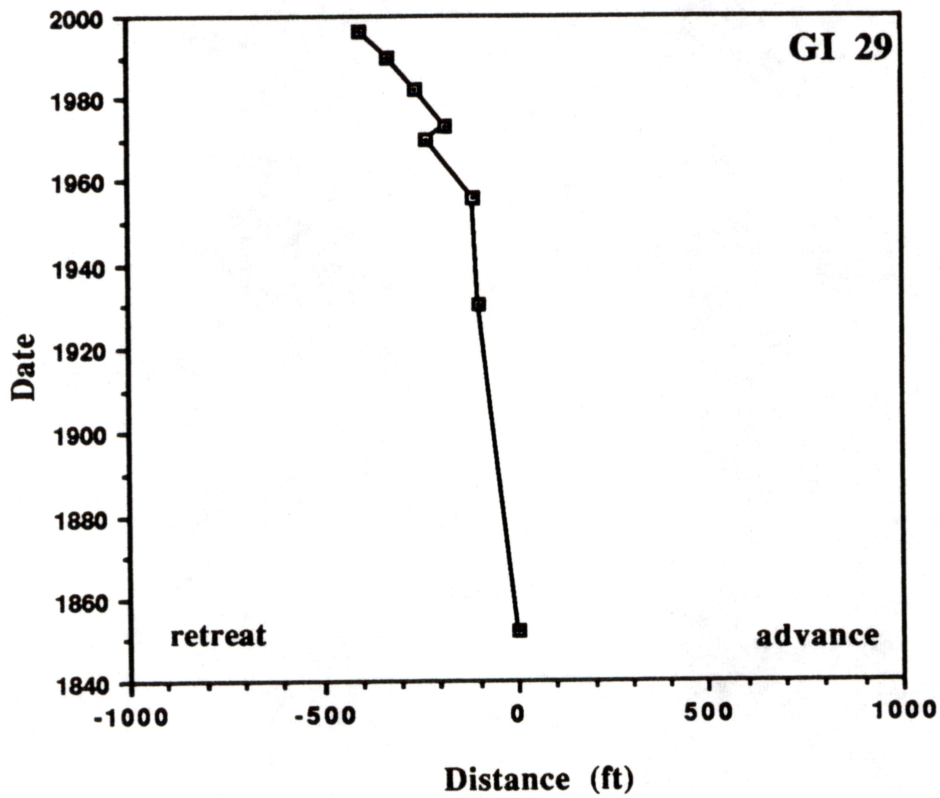
GI 25
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



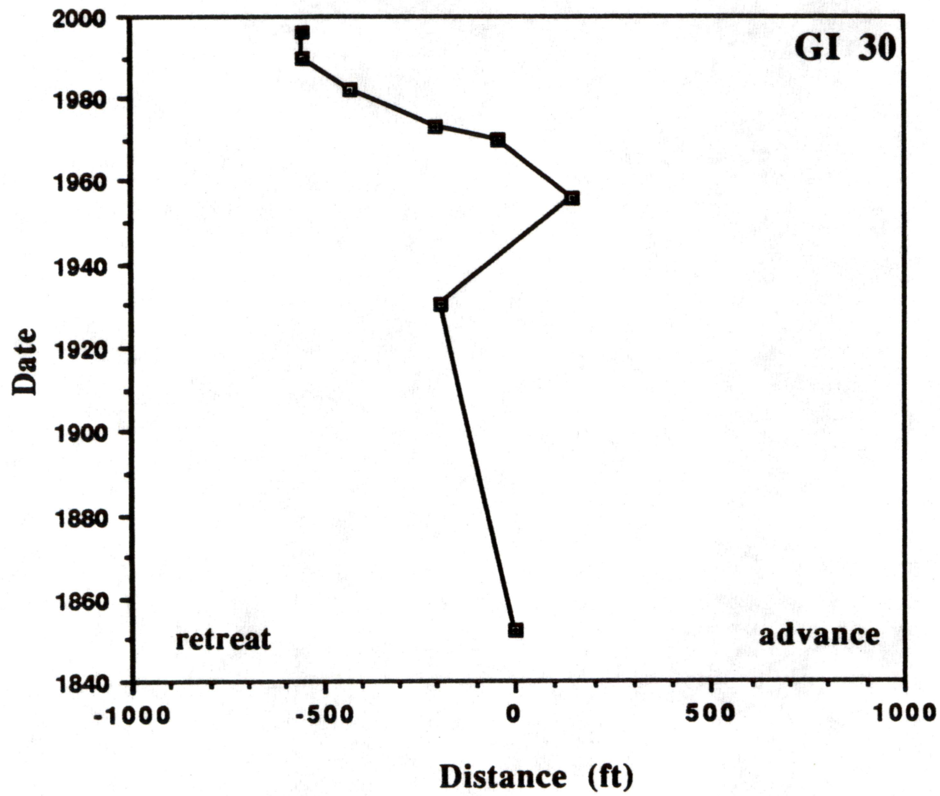
GI 26
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

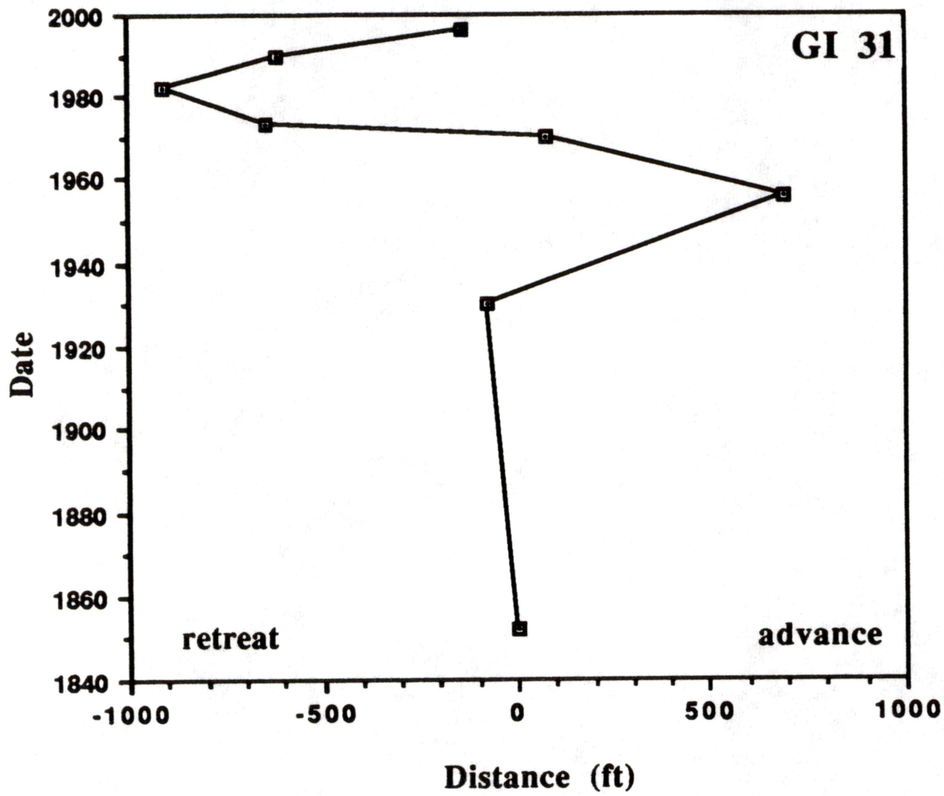

GI 27
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


GI 28
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



GI 29
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


GI 30
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

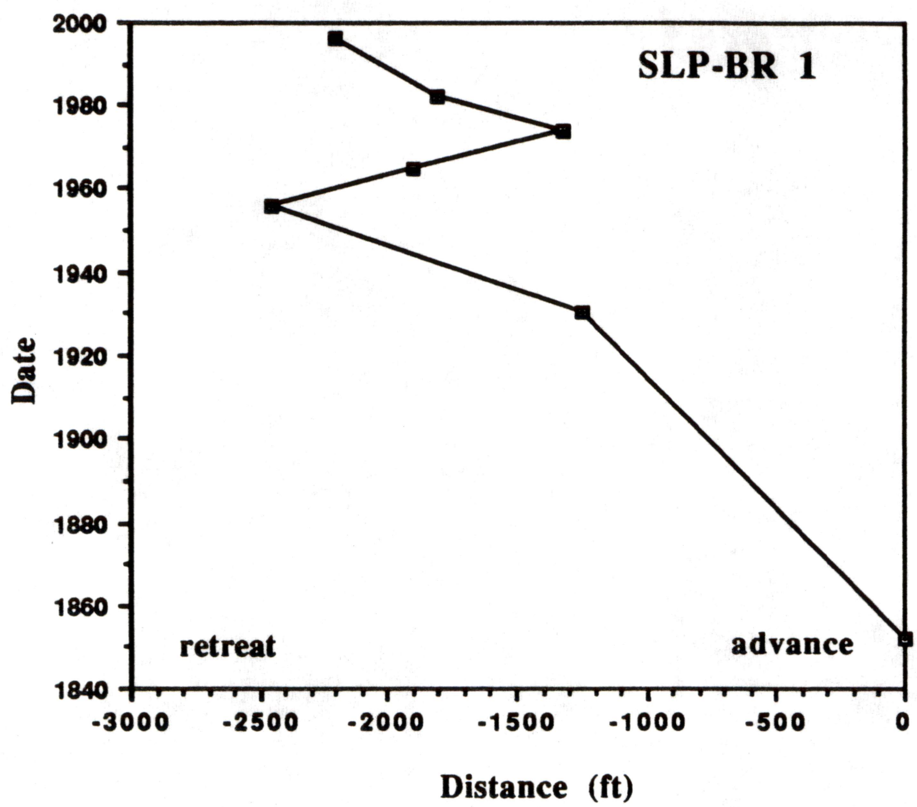


GI 31
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

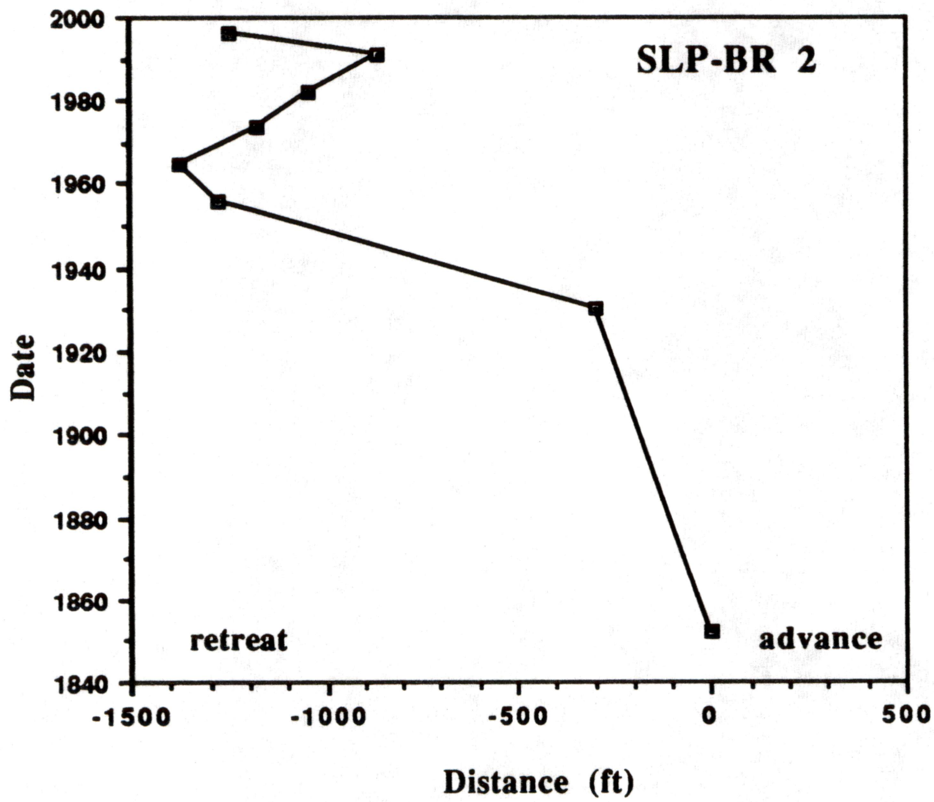
APPENDIX C

SHORELINE HISTORY PLOTS

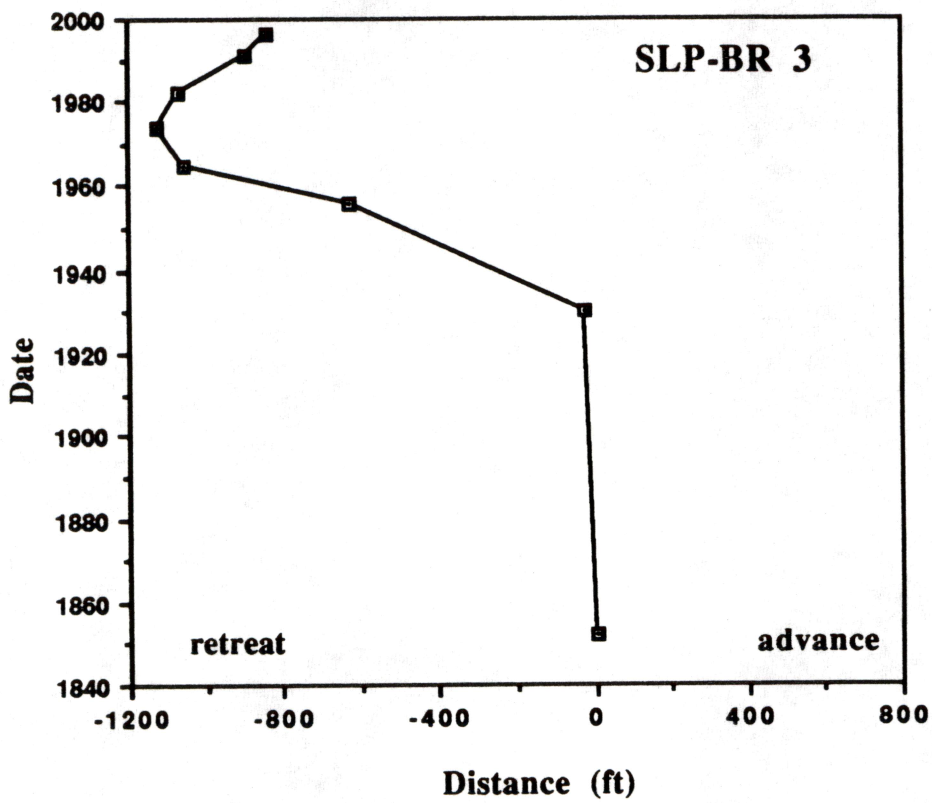
SAN LUIS PASS TO THE BRAZOS RIVER



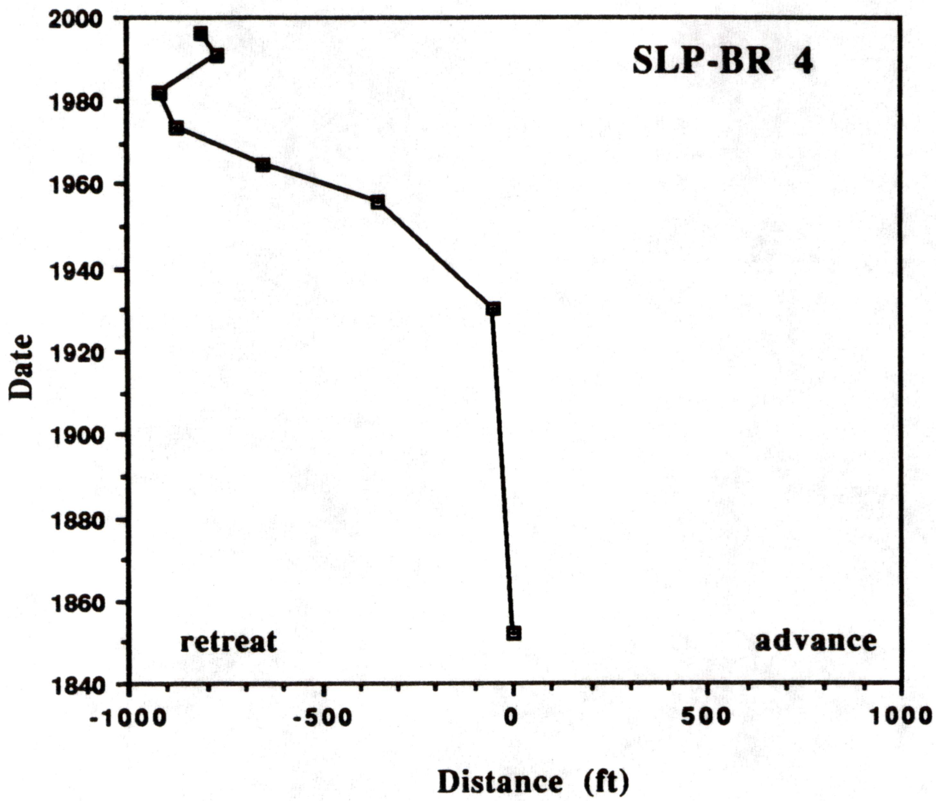
SLP-BR 1
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-3000
-2500
-2000
-1500
-1000
-500
0
Distance (ft)



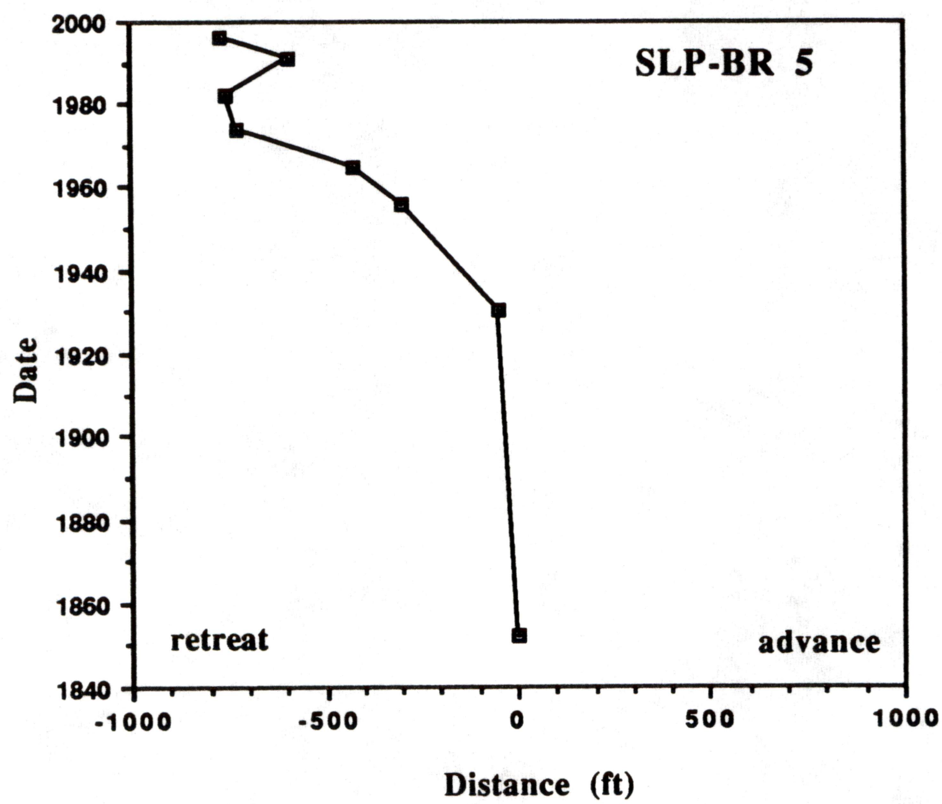
SLP-BR 2
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1500
-1000
-500
0
500
Distance (ft)



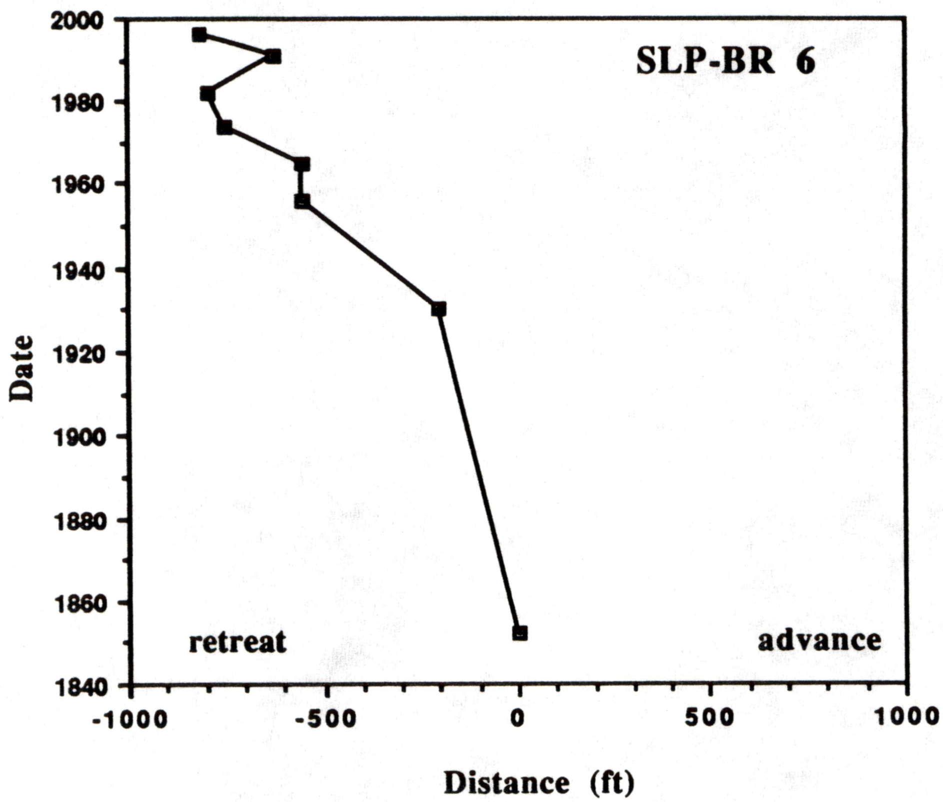
SLP-BR 3
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1200
-800
-400
0
400
800
Distance (ft)



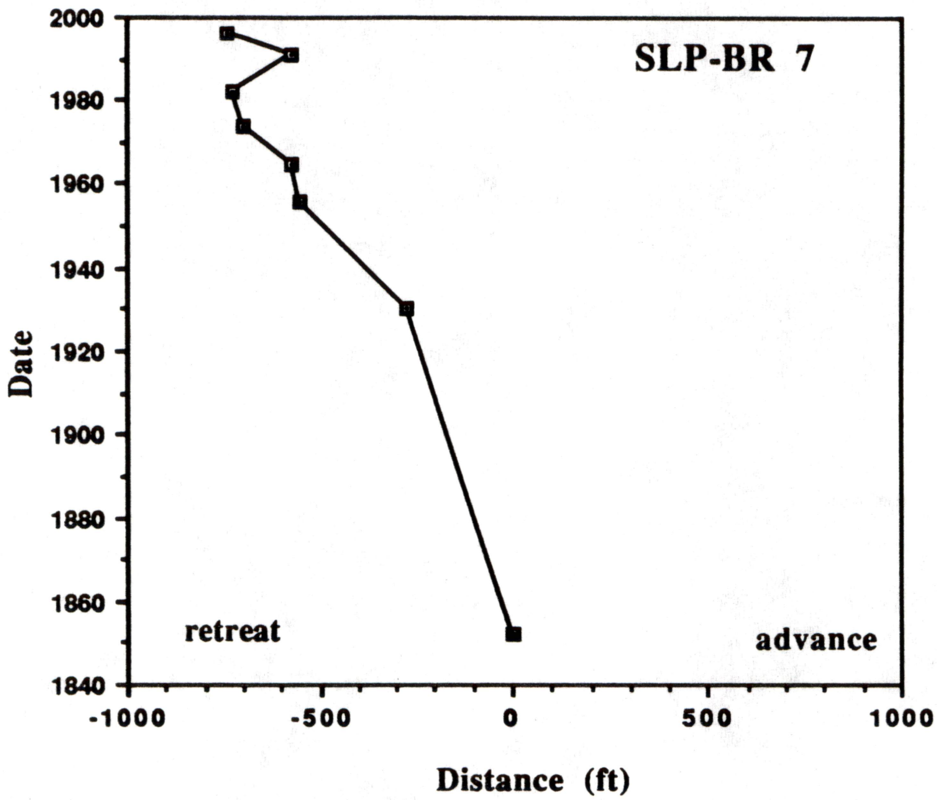
SLP-BR 4
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



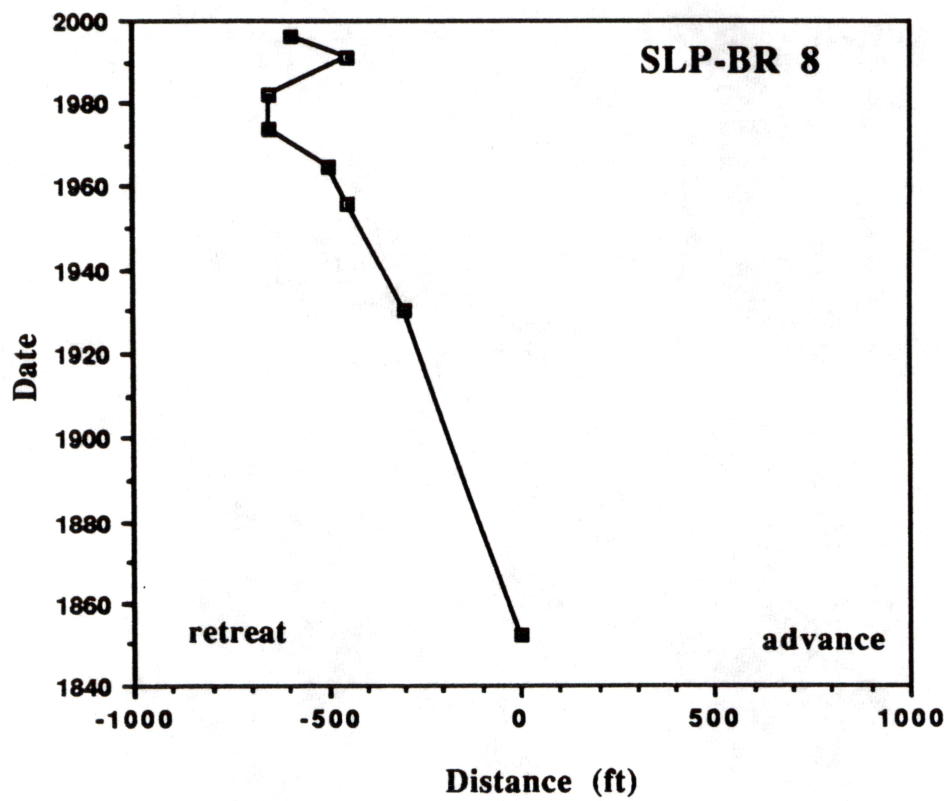
SLP-BR 5
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



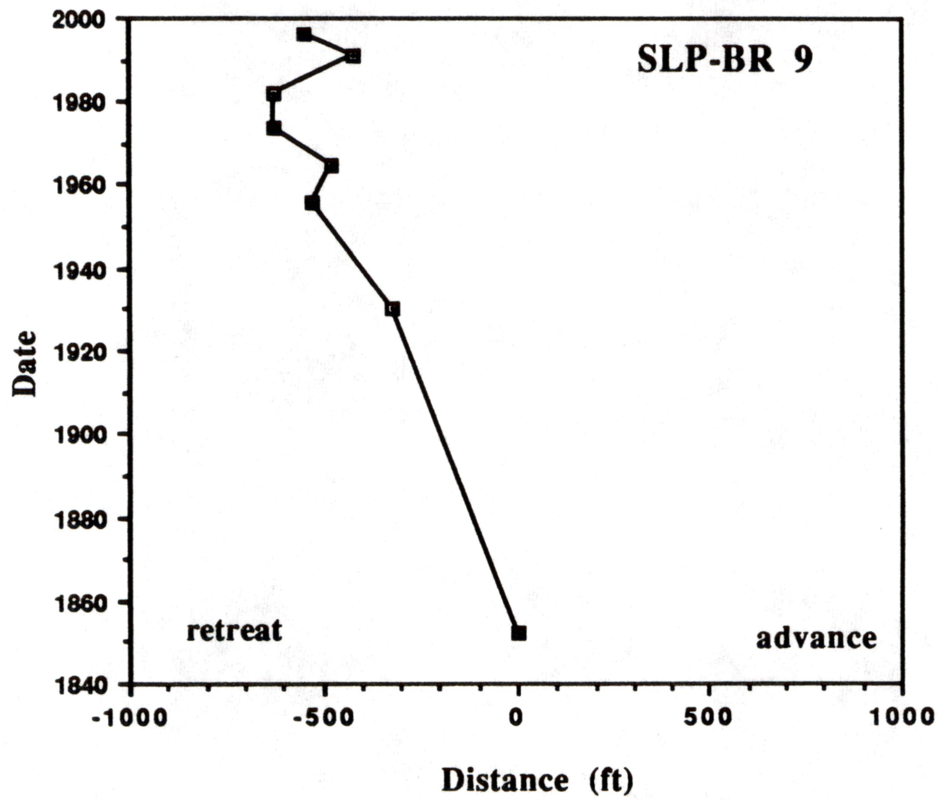
SLP-BR 6
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
-1000
-500
0
500
1000
Distance (ft)



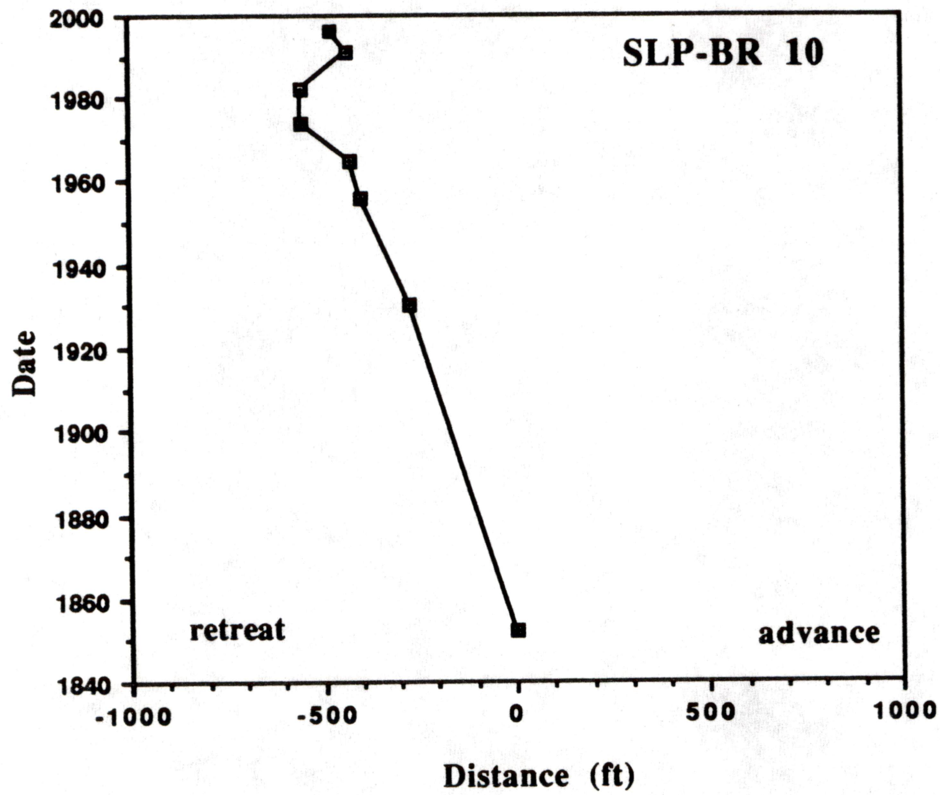
SLP-BR 7
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

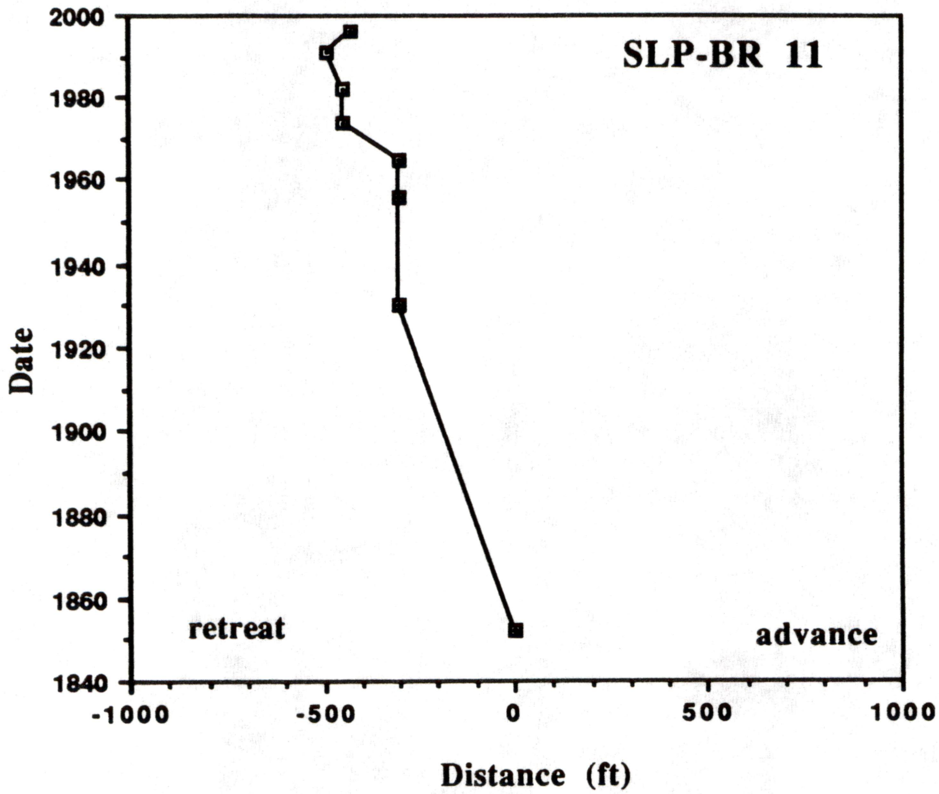


SLP-BR 8
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

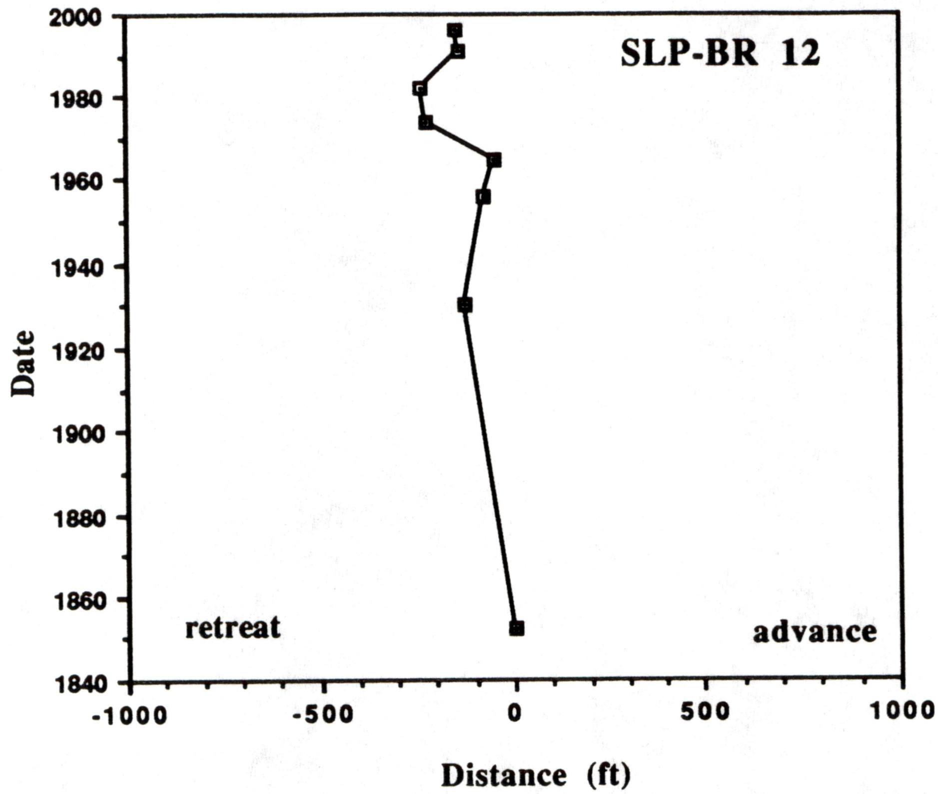


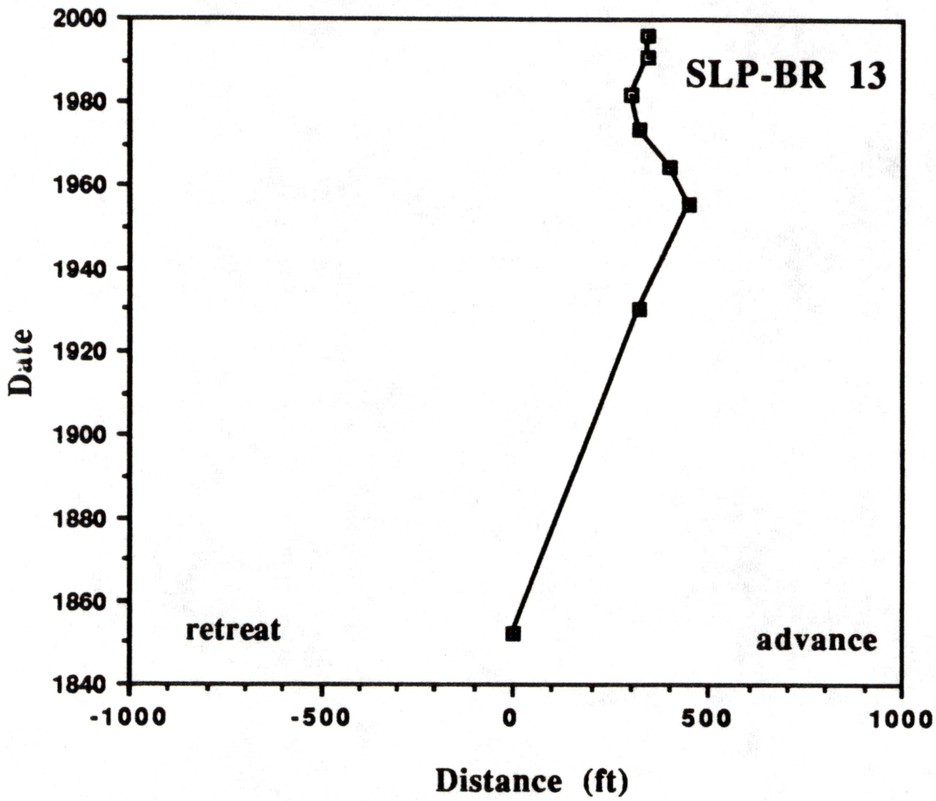
SLP-BR 9
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)


SLP-BR 10
retreat
advance
Date
Distance (ft)
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

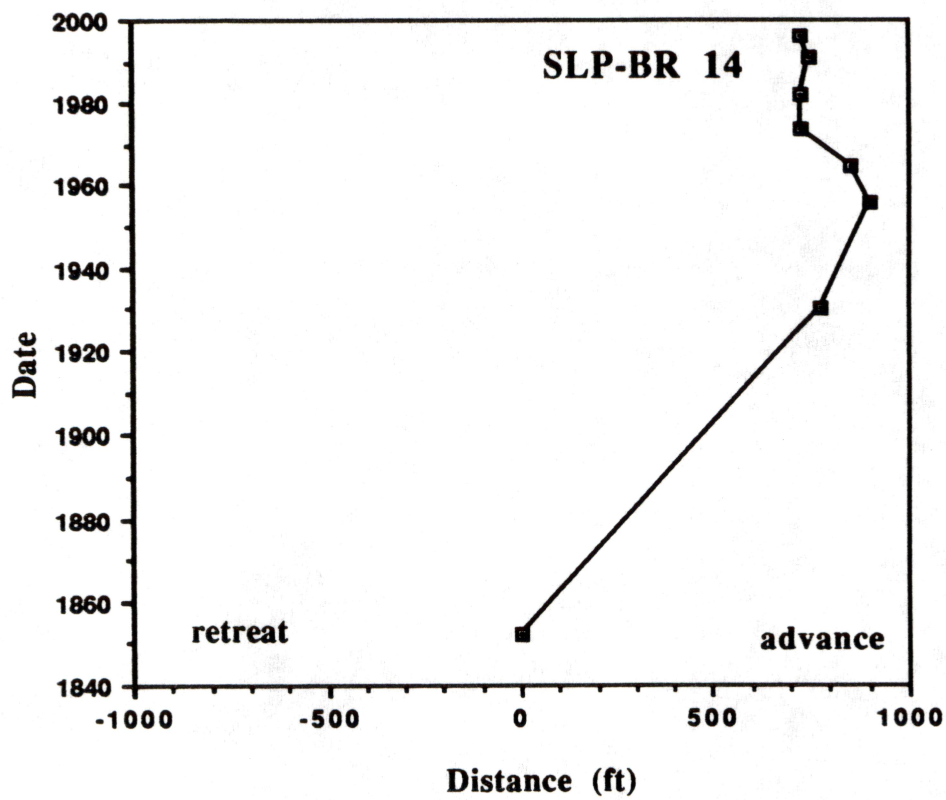


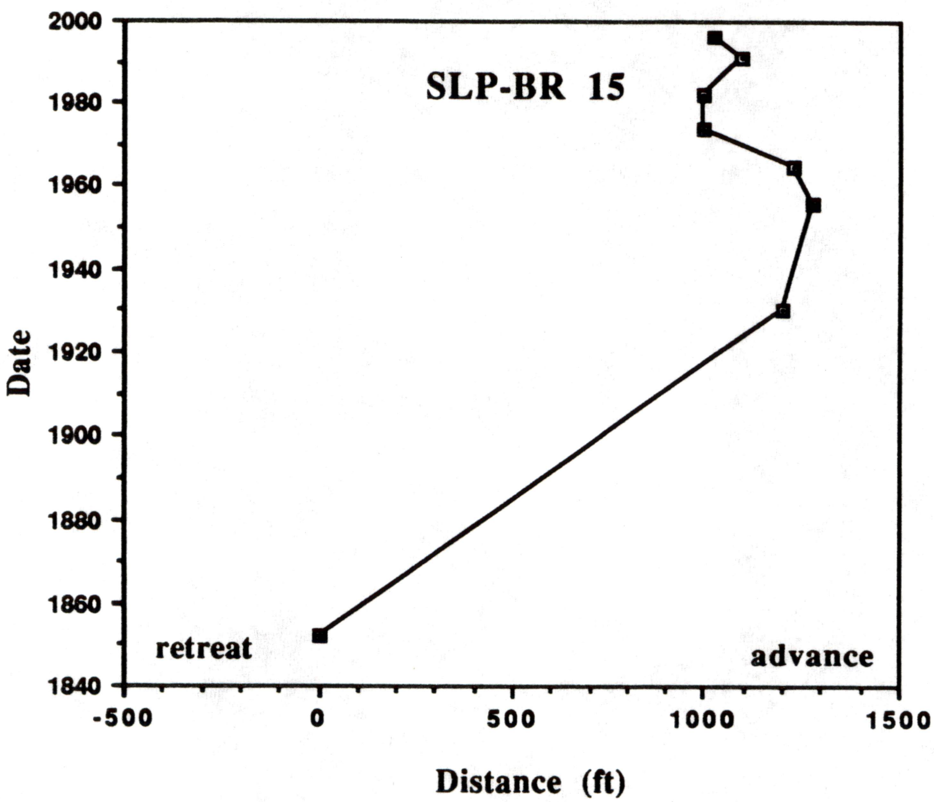
SLP-BR 11
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000

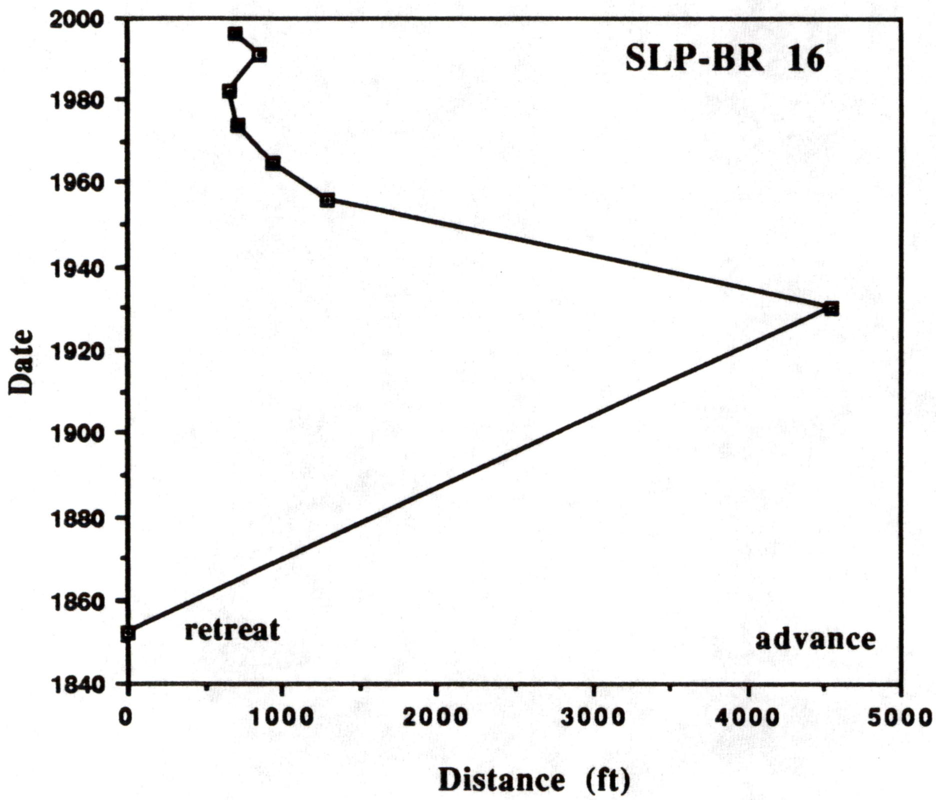

SLP-BR 12
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

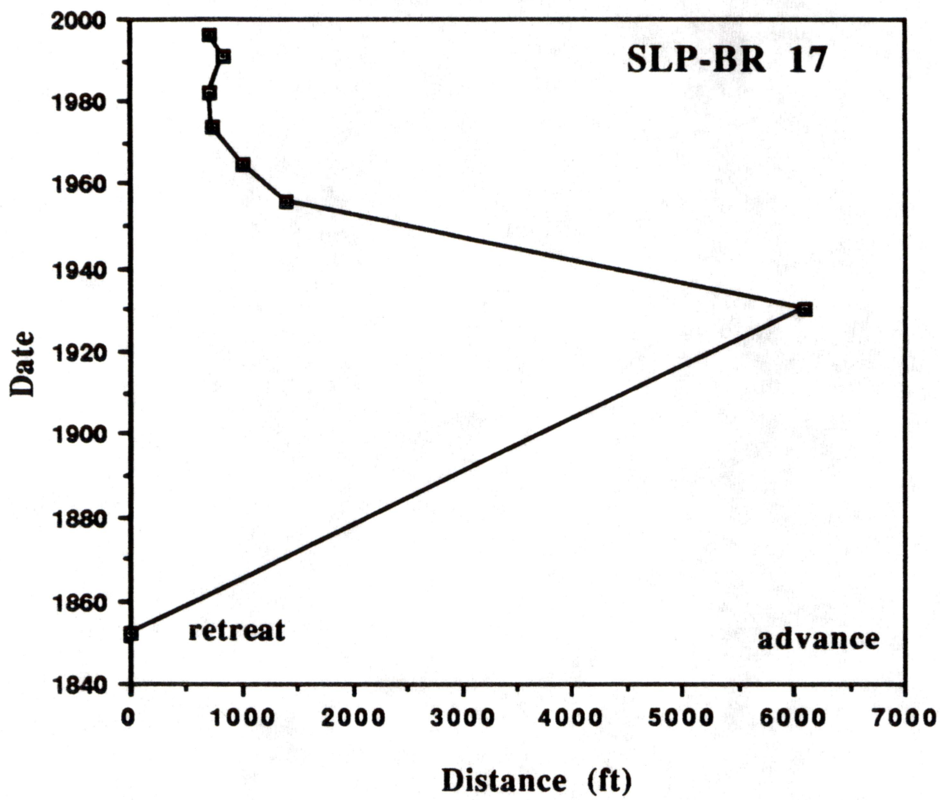


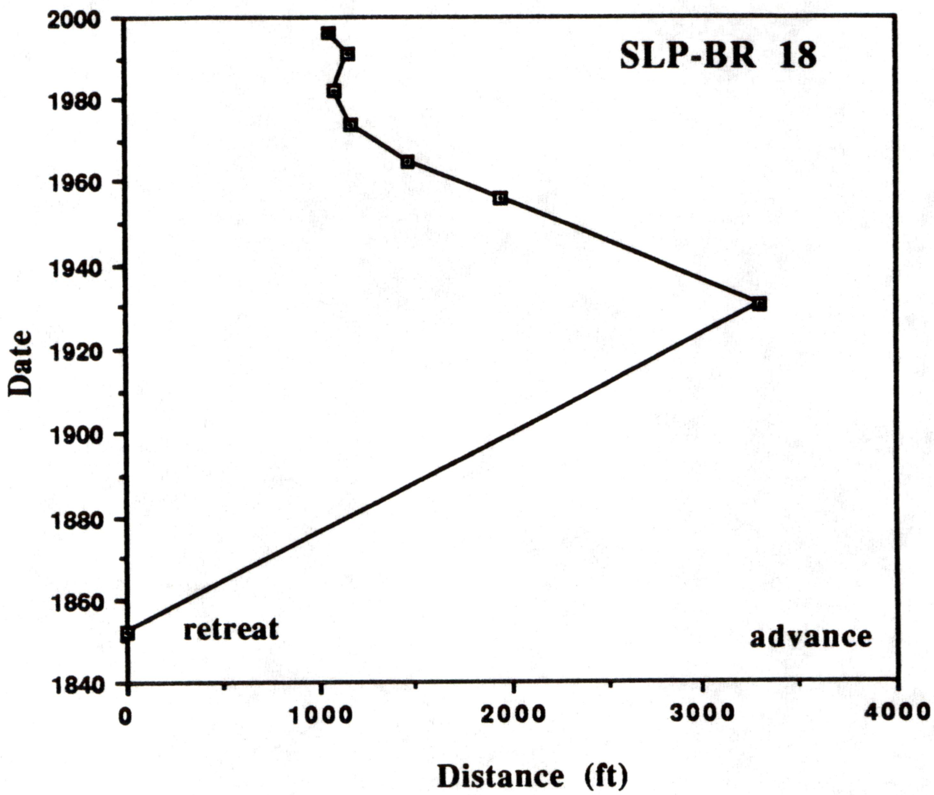
SLP-BR 13
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-1000
-500
0
500
1000


SLP-BR 14
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
-500
0
500
1000
Distance (ft)

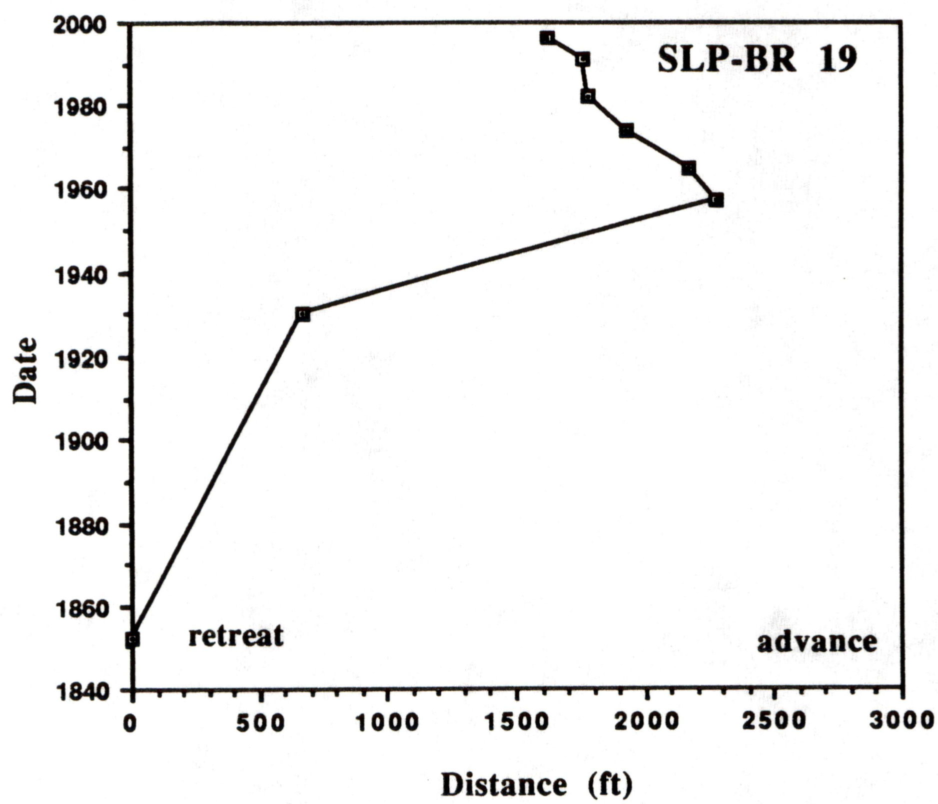

SLP-BR 15
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
-500
0
500
1000
1500


SLP-BR 16
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
0
1000
2000
3000
4000
5000

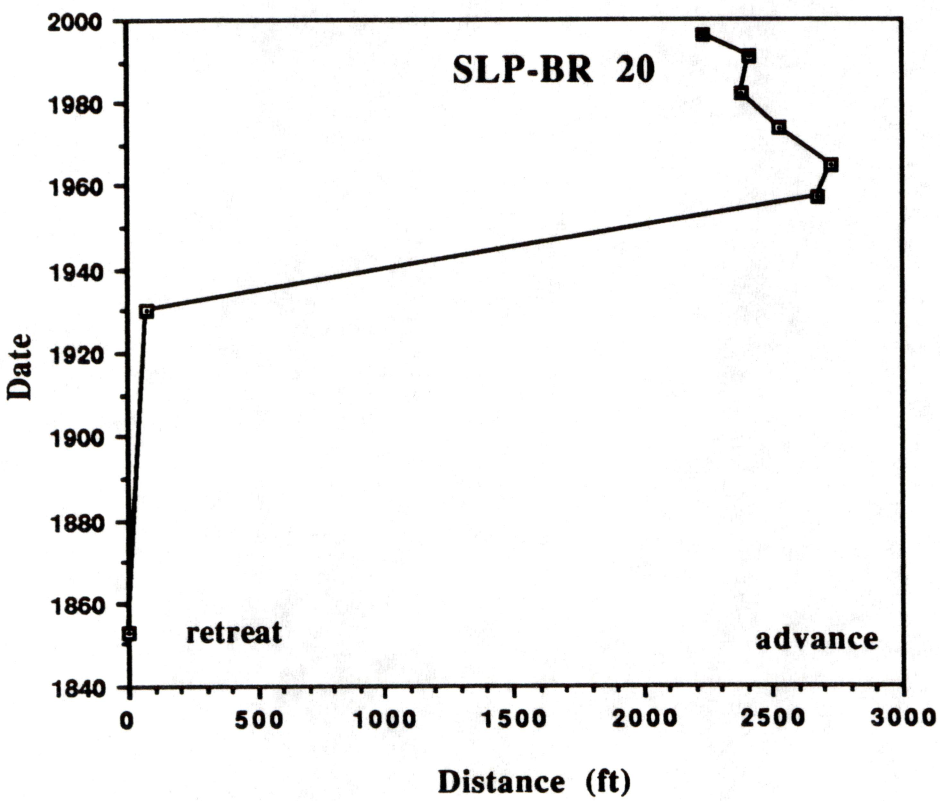

SLP-BR 17
2000
1980
1960
1940
1920
1900
1880
1860
1840
Date
retreat
advance
0
1000
2000
3000
4000
5000
6000
7000
Distance (ft)

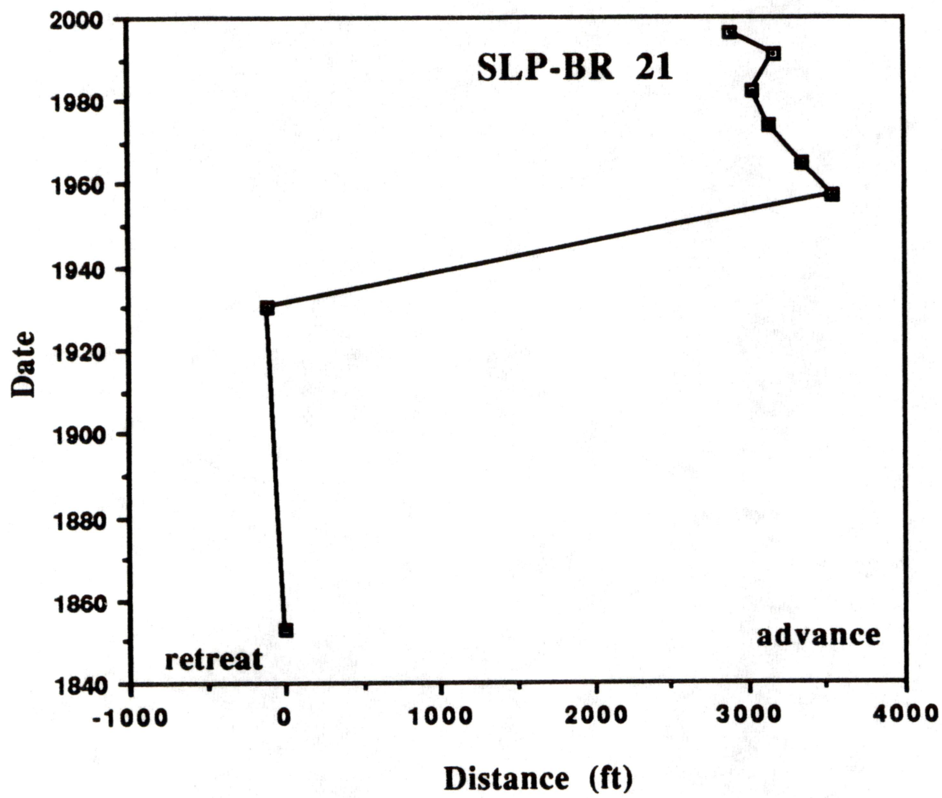


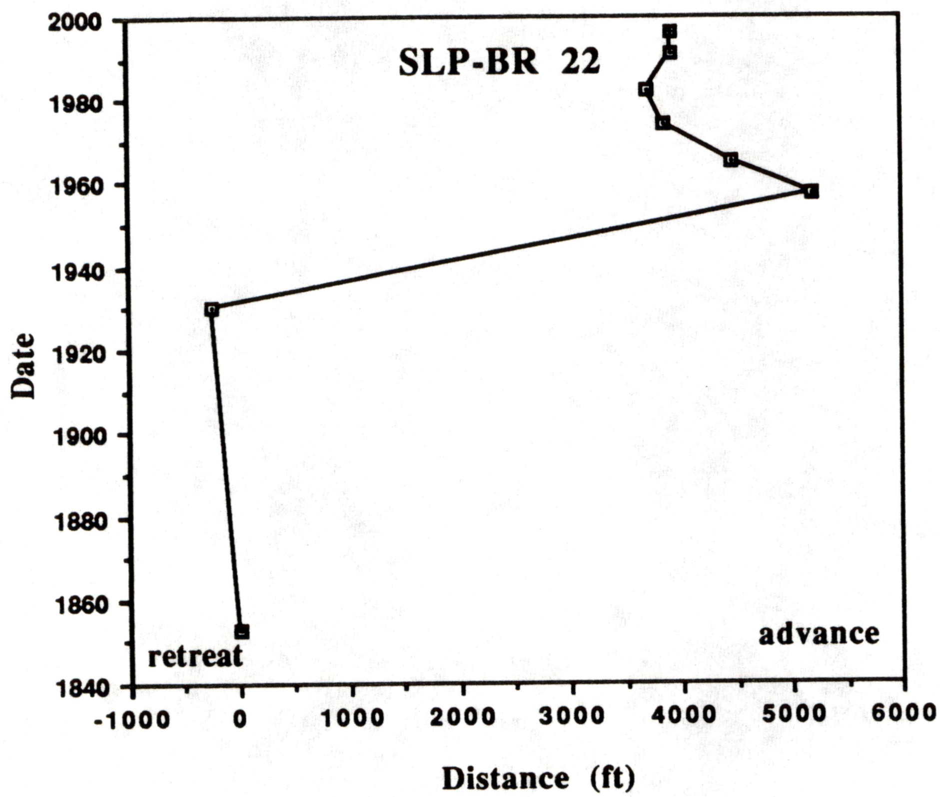
SLP-BR 18
Date
Distance (ft)
retreat
advance
2000
1980
1960
1940
1920
1900
1880
1860
1840
0
1000
2000
3000
4000



SLP-BR 19
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
0
500
1000
1500
2000
2500
3000
Distance (ft)


SLP-BR 20
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
0
500
1000
1500
2000
2500
3000
Distance (ft)


SLP-BR 21
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
0
1000
2000
3000
4000
Distance (ft)



SLP-BR 22
Date
2000
1980
1960
1940
1920
1900
1880
1860
1840
retreat
advance
-1000
0
1000
2000
3000
4000
5000
6000
Distance (ft)