ABSTRACT

Title of Thesis: HISTORICAL SHORELINE CHANGES IN RESPONSE TO ENVIRONMENTAL CONDITIONS IN WEST DELAWARE BAY

Name of Degree Candidate: Gregory Thomas French

Degree and Year: Master of Arts, 1990

Thesis directed by: Stephen P. Leatherman, Associate Professor, Department of Geography

This study quantified historical changes in the coastline of the west shore of Delaware Bay. Shoreline changes were measured through the compilation of historical maps and photographs utilizing the Metric Mapping technique. These changes were correlated with various environmental conditions and with human influences.

The results portray a 135 year pattern of overall erosion, with long-term rates averaging -4.5 ft/yr, which is considerably greater than the U.S. Atlantic coast average. Coastal engineering (e.g., groins, jetties and beach nourishment) were locally effective in reducing erosion rates and in some cases promoting limited accretion. Perhaps more importantly, there were few associated negative effects alongshore suggesting that various forms of coastal engineering can be effective in a low-energy environment, even when done in a somewhat unorganized fashion.

A correlation was found between erosion rates and underlying Pleistocene morphology. Where pre-Holocene

sediments were exposed in the nearshore, erosion rates were lower. However, erosion rates were substantially higher along marshy shorelines.

This erosion is not continuous either spatially or temporally, but instead is largely storm-driven. Periods of relative quiescence corresponded with lowered rates of average annual shoreline recession. With the exception of the northernmost marshy areas, severe erosion occurs along all shorelines, regardless of morphology, in response to major coastal storms.

HISTORICAL SHORELINE CHANGES IN RESPONSE TO ENVIRONMENTAL CONDITIONS IN WEST DELAWARE BAY

by

Gregory T. French

Thesis submitted to the Faculty of the Graduate School of the University of Maryland in partial fulfillment of the requirements for the degree of

Master of Arts

1990

Advisory Committee:

Dr. Stephen Leatherman (Thesis Director)
Dr. Robert Nicholls (Second Reader)
Dr. Michael Kearney (Third Reader)
Dr. Paul A. Groves (Director of Graduate Studies)

DEDICATION

To my mother

Helen H. French

Without whose support this study

would simply never have happened.

ACKNOWLEDGMENTS

I especially thank my graduate advisor, Dr. Stephen P. Leatherman, for his guidance, inspiration, patient editing, and willingness to provide the resources to conduct my research. I thank Dr. Robert Nicholls for his advice, support and continued interest in my progress. I also thank the remaining members of my committee, Dr. Michael Kearney and Dr. Paul Groves for their valued input and advice.

The Delaware Department of Natural Resources and Environmental Control was very cooperative in providing essential research materials. I would like to thank Mr. Robert Henry and Mr. Tony Pratt for their assistance and advice.

I want to thank the Geological Society of America, whose support helped fund this research. I also want to thank my colleagues, Ms. Karen Clemens, Ms. Lynda Downs and Ms. Rachel Donham for their discussion, criticism, moral support and friendship during this study. I especially wish to thank Mr. Mark Crowell and Captain Frank Galgano (USA) for their detailed instruction in the methodology of the Metric Mapping technique. Finally, I wish to express my deepest thanks to Ms. Debra Ryan for her infinite patience, encouragement, moral support, and invaluable graphics assistance throughout the process of conducting this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPH PLATES

INTRODUCTION

Background to Research

Delaware Bay is one of the two largest estuaries along the Atlantic Coast of North America. Since the Delaware Bay estuary is by definition a drowned river valley, its formation has necessarily entailed continued coastal inundation and erosion since the last period of glaciation.

Throughout most of the period of the Bay's natural development, this continual reshaping of the shoreline has presented no human problem. Indeed, rates of post-glacial sea-level rise (and consequential coastal inundation) had dropped significantly some 6,000 years ago (National Research Council, 1987), long before the rise of even the most ancient of the world's great civilizations, let alone those of North America. While sea levels have since continued to rise, albeit at decelerated rates, and general coastal recession has continued, early human occupation of the Bay shore is rarely threatened by these changes. This was due in part to the generally low population density and to the fact that little of the historic development of North America was truly rigid in nature. As the Bay waters would begin to encroach on a homestead or township, it was a relatively simple matter to merely move their tents or rebuild the log cabins further inland.

Today, the reshaping of Delaware Bay's shoreline continues. What has changed are the patterns of human occupation compounded by the as yet unclear effects of the industrial revolution on global climate.

The U.S. Census has estimated the 1990 population of the United States to be 249 million. Of that population, over 110 million, or nearly one-half, live within the coastal zone (U.S. Department of Commerce, 1990), and more than one half (53%) live within 50 miles of some coastline (National Research Council, 1990). This figure is expected to increase to 127 million by the year 2010, only 20 years from now. This urbanization is occurring in spite of the fact that nearly 90% of all sandy beaches in the United States are experiencing some degree of erosion (Leatherman, 1988).

This general scenario of increasing population pressures, driven by the powerful human desire to live near the shore, is resulting in an ever-expanding pattern of rigid coastal development wherever the shore can be easily accessed. It is, therefore, reasonable to expect this same pattern of continued development along the western shore of Delaware Bay.

The western shore of Delaware Bay, south of New Castle, has only been lightly developed to date. The majority of those areas which are presently occupied, such as Slaughter Beach and Kitts Hummock, could best be described as small coastal villages (Kraft and Caulk, 1972). Only Lewes could be considered "developed" in the contemporary sense of the word as might be applied to such coastal cities as Rehoboth or Bethany Beach. These un-, or under-developed areas are, however, facing the potential for accelerated near-term expansion of both commercial and residential growth as population pressures induce more and more people to move to the largely unoccupied Bay coast. The very act of this human occupation of the coastal environment has, in itself, the potential to drastically alter the natural morphological processes of that area.

At the same time great concern is being expressed over the possible industrial effects of global warming. It is widely believed that sea levels are presently rising eustatically about six inches per century (National Research Council, 1987). This change presents a potential hazard to coastal development, especially when combined with isostatic subsidence. However, it is believed by some researchers that, due to human influences on global climate, the rate of sea-level rise may double or even triple in the next century (National Research Council, 1987). Clearly, this human move toward the sea as the sea moves toward the land presents a recipe for disaster. The resultant problems can well be expected to be of major human and economic proportions unless appropriate steps are made to anticipate and deal with the consequences. Decisions in Delaware affecting potentially thousands of individuals and hundreds of millions of dollars must be made as the encroaching marine transgression continues its inexorable inland march. In order to optimize any human interaction with such a dynamic environment, those decisions must be based on a sound understanding of the relevant geomorphic processes and responses.

Recent developments in coastal research have resulted in an ever-expanding body of knowledge regarding the causes of shoreline changes through time. This by no means suggests that what is occurring at any given shoreline is automatically understood. Widely applied rules, such as erosion necessarily following sea-level rise (Bruun, 1962), do not always apply for all areas. The generally accepted idea that marshes erode more slowly than sandy shorelines (Phillips, 1986; Rosen, 1977) can also be questioned. Attempting to apply generalized coastal management practices to large segments of shoreline (National Research Council, 1990) ignores what may be widely varying conditions and responses. In addition, implementing management practices based on such conditions measured over only the past 10 or 20 years can be equally misleading (Leatherman 1989a, in press; Galgano, 1989).

Each segment of shore is the result of a unique agglomeration of wind, wave, tide, storm, sea level, and geologic characteristics, in addition to the as yet poorly understood effects of human influences. Each segment of shore must, therefore, be individually considered in light of its own unique conditions. This evaluation must begin with a quantitative understanding of exactly what is changing and by how much. Coastal changes are not usually smoothly occurring processes; they more often happen in a sudden, step-wise, fashion (Galgano, 1989; Davis, 1985; Bascom, 1980). An average rate of erosion of one foot per year might hardly be noticed by local residents, let alone considered by large development speculators or state regulatory agencies. Yet, a 50-year storm which abruptly erodes 50 feet of real estate would certainly garner some attention. This is further complicated by the natural seasonal variations in the position of the shoreline between summer and winter (Leatherman, 1989a).

This situation, where an inadequate understanding of the varying specific rates of change is combined with a great potential for future development, describes much of the western shore of Delaware Bay today. There is plentiful anecdotal information regarding severe erosion taking place in the north-western areas, as well as areas of obvious accretion occurring along some of southeastern shores

(Friedlander, 1977). There have been some attempts at presenting these rates of change (Weil, 1977; Kraft and Caulk, 1972; U.S. Army Corps of Engineers, 1966), but many of the techniques employed in those earlier attempts were often flawed by numerous sources of error making them highly unreliable (Crowell, et. al., 1990; Anders and Byrne, 1990; Leatherman, 1983b; Clow and Leatherman, 1984).

This leaves many unanswered questions regarding the past, present and future shoreline responses along the western shore of Delaware Bay. This, in turn, results in great ambiguity about the future direction of human occupation and use of this dynamically changing coast.

Research Objectives

The purpose of this study was three-fold. The overall objective was to investigate the shore behavior along the morphologically gradational coastal environment of the western Delaware Bay shore and how human activities may have altered the natural patterns. Specific objectives of the research were:

1) to establish quantitatively the historic rates of erosion for the area under study.

2) to correlate the factors of sediment type and sources, wind and wave climate regime, and storm occurrence and magnitude with historic shoreline response in the form of rates of erosion and general shoreline configuration; and

3) to identify and attempt to explain the historic effects of human modifications to the shore zone.

To accomplish these objectives, the historical shoreline changes occurring along the western shore of Delaware Bay were mapped and quantitatively analyzed. These data were then correlated with existing environmental (i.e., wave, wind, current, storm, and sea-level change) and geological data (antecedent Pleistocene topography and sediment sources and types), and human engineering structures (i.e., groins, jetties, and beach nourishment).

THE STUDY AREA

Geographic Location

Approximately 35 miles of Delaware's southernmost estuarine shoreline was examined for this study. The study area begins west of Cape Henlopen and extends northwestward to the Simons River in the Bombay Hook National Wildlife Refuge (Figure 1).

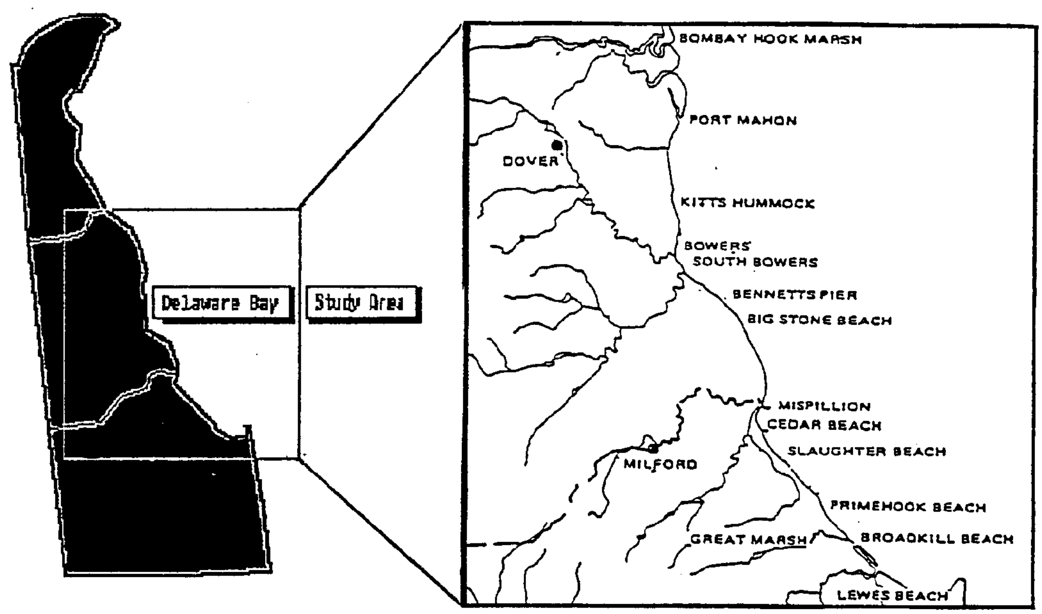


Figure 1. Location map depicting the study area.

The west Delaware Bay coastal zone is mostly flat, low-lying land with some low undulating topography generally less than 20 feet in elevation, typical of the central Atlantic coastal plain. The general orientation of the shoreline is north-northwest by south-southeast, with the principal exception of Cape Henlopen, which turns north. The northernmost portion of the study area, the Bombay Hook National Wildlife Refuge, is composed exclusively of salt marshes which extend westward from the Bay waterline, up to several miles inland. South of Port Mahon, however, intermittent narrow beaches with low dunes (<3 feet) are present.

The lower Bay coast consists primarily of narrow, sandy overwash barriers with beaches ranging between 10 and 50 feet wide at high tide. The beaches are backed by a line of dunes ranging from 50 to 300 feet wide and 5 to 15 feet high, and are usually covered with grasses and woody plants such as Baccharis halimifolia and Iva frutescens (Drew, 1981). Further landward, separating the barrier dunes from the highlands, salt marshes predominate, ranging in width from one-half to 2 miles. The marshes are typically populated by such saltwater tolerant vegetation as Spartina alterniflora, Spartina patens, Distichlis spicata, and Phragmites communis (Drew, 1981).

Geologic Setting

Subsurface Geology

Delaware Bay is the drowned river valley of the southern extent of the Delaware River overlying the Atlantic coastal plain. The Atlantic coastal plain is, in turn, part of the larger geological structure known as the Atlantic coastal plain - continental shelf geosyncline (Kraft, et al., 1976).

The coastal plain is a large clastic sedimentary wedge extending and thickening southeastward from the fall line near Trenton where the crystalline Piedmont rocks outcrop (King, 1977; Kraft, et al., 1976). The emerged portion of the wedge exhibits a general southeastward slope of approximately one foot per mile and is composed primarily of Cretaceous and Tertiary aged deposits overlain by a relatively thin layer of Pleistocene sands and gravels (up to 150 feet thick) (Jordan, 1964; Maurmeyer, 1978). Along the Atlantic shore of Delaware, the overall thickness of the wedge exceeds 8,000 feet (Kraft, et al., 1976).

Holocene Morphology

The western coast of Delaware Bay is presently that of a marine transgressive salt marsh-barrier island complex (Kraft, et al., 1975). Prior to 12,000 years ago, the area which now incorporates the western

Delaware Bay coast consisted of numerous valleys and interfluves in Pleistocene-aged sands and gravels of varying sizes, dipping gently toward the northwest. The orientation of these hills and valleys was in a general southwest-northeast direction -- perpendicular to today's Bay shore (Drew, 1981).

During the time period since the last glaciation (the Holocene Epoch), the early Pleistocene valleys first became infilled with marsh and lagoonal muds, then were inundated, and both the infilled valley areas and the Pleistocene necks eroded with progressively rising water levels. The result of the differential composition was (and is) a wide variation in texture, compactability, and consequent erodability between the infilled areas and the Pleistocene headlands (Kraft, et al., 1981; Drew, 1981).

Sediment Sources

The present configuration of the Delaware Bay coastline represents the antecedent geology as modified by a dynamic balance between sources and sinks of sedimentary materials. When the local rate of removal of material exceeds supply, then overall recession takes place. When the reverse is the case the shoreline accretes. If the two are approximately equal, then the shore can be said to be in a stable state of dynamic equilibrium. While the Bay shore is generally erosional, there are areas of relative stability and, in fact, some limited accretion. This clearly suggests a supply of appropriate sandy materials.

This sandy sediment has been found to come from several sources. The most significant source is likely to be from the series of Pleistocene sand and gravel headlands or necks (Figures 2 and 3) which separate ancient valleys (Maurmeyer, 1978). Although these headlands occasionally crop out on or near the shore, such as at Bowers Beach, they constitute even more numerous subaqueous erosional projections which contribute significantly to the longshore supply of sandy material (Maurmeyer, 1978). The necks decline in frequency northward.

The second most significant sediment source is probably littoral drift. This, of course, represents redistribution rather than new material contributed to the overall system. More recently, human intervention, in the form of groins, jetties and artificial beach nourishment, has impacted this processes (Strom, 1972).

A third source which historically has contributed sediment to the southern portion of the Bay was material from the open-ocean coast. The Atlantic coast of Delaware has been eroding at an average of 2.7 ft/yr for at least the last 150 years (Galgano, 1989). From about Bethany Beach the net longshore transport is

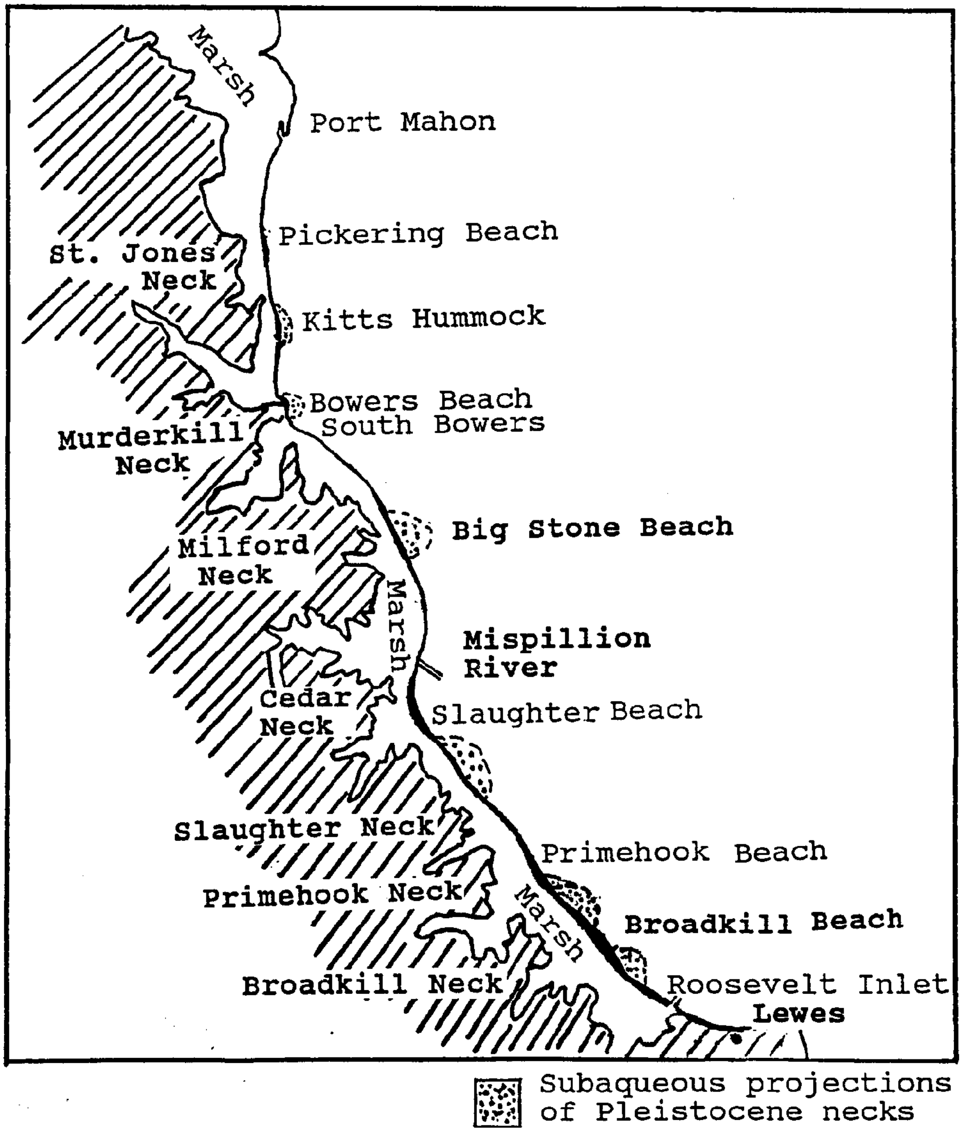


Figure 2. Major Pleistocene necks along the west Delaware Bay shore and their probable subaqueous projections offshore (after Maurmeyer, 1978).

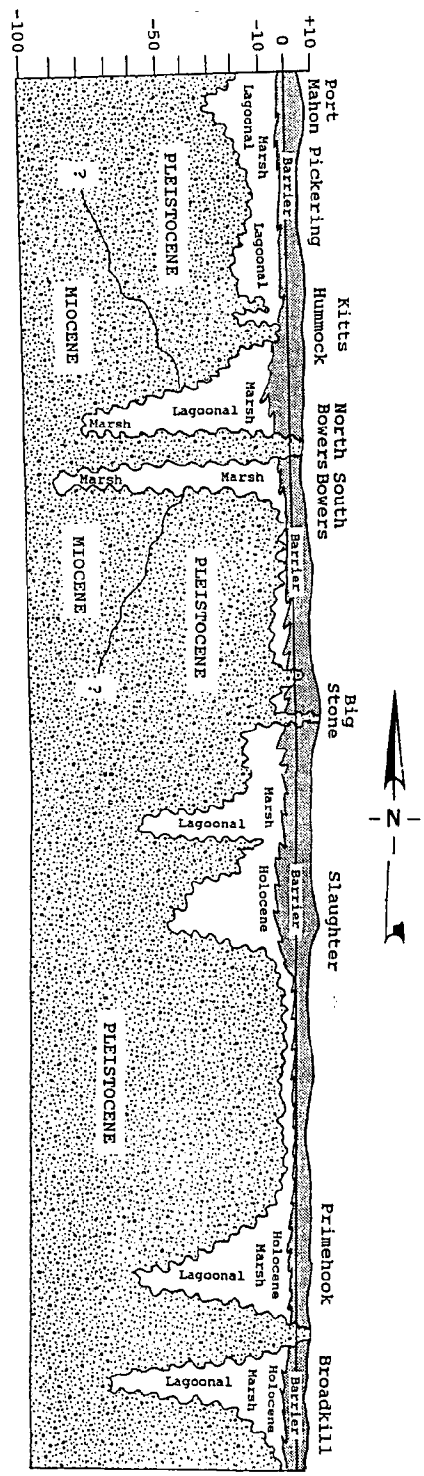


Figure 3. Coast-parallel geological cross section of west Delaware Bay (Kraft, et al., 1981). Note the Pleistocene surface declines in elevation towards the north.

northward toward Cape Henlopen. This has resulted in over 4,000 feet of northward growth of the Cape since 1845 (Figure 4). Much of this sandy material was believed to have once been transported around Cape Henlopen by the longshore currents, supplying sand as far north as Primehook Beach (Kraft and John, 1976). The continued growth of the Cape has progressively reduced the amount of sediment reaching the lower Bay over the last 150 years. In addition, during the last century, construction of two breakwaters near the Cape have further changed the overall sediment transport patterns by essentially cutting off much of this sand source (Kraft and Caulk, 1973).

A fourth possible source of beach sediments are the numerous large elongated offshore linear sand shoals in the Bay, oriented parallel to the tidal channels, which have been formed by the scouring of the channels by tidal currents (Drew, 1981). However, no pattern of significant onshore movement of the shoals has been observed, even though individual shoals are believed to have migrated as much as 3 miles to the northwest over the last century, and so probably constitute only a minor source of sediment (Weil, 1977). Alternatively, these shoals may represent sinks of beach sand eroding from the Delaware Bay beaches. In addition to these sources, the historic data show that there have been several old inlets which have

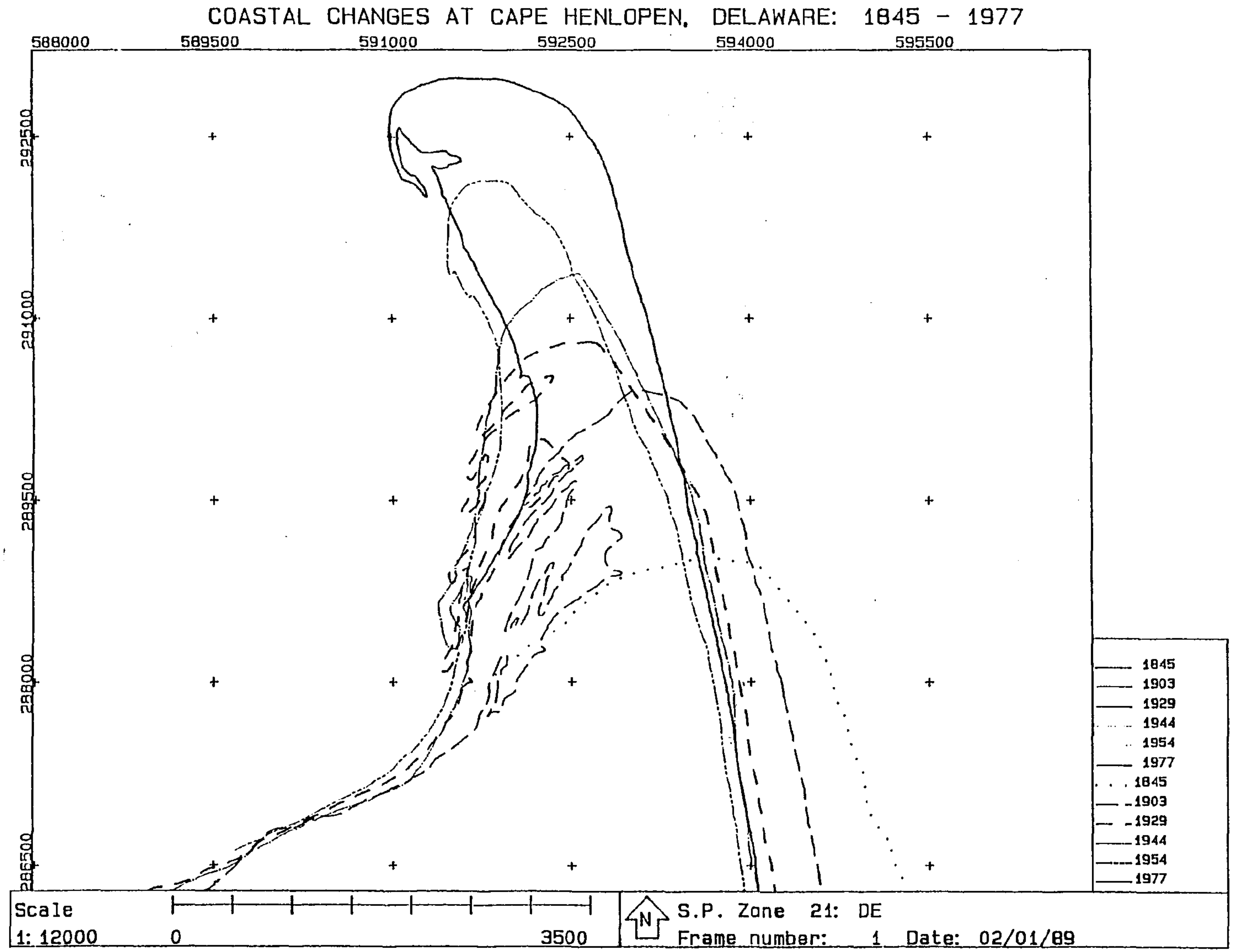


Figure 4. Shoreline change map illustrating the accretion of the Cape Henlopen spit system between 1845 and 1977 (Galgano, 1989).

since closed, leaving behind crescentic relict ebb tidal shoals composed of sand and some gravel in the nearshore (Maurmeyer, 1978). Much of this material was then driven onshore en masse by wave action, welding to the beach. This probably occurred at Broadkill River Inlet, which closed sometime between 1943 and 1954 (map 8, Appendix 1). This, however, is a short-term, localized process and probably has little effect on shoreline position in the long term.

The final possible source of sedimentary material is from fluvial sources. Although the drainage system supplies over 500,000 cubic yards of material annually to the Bay (USACOE, 1966), much of the material is fine grained since the sediments must flow along very low gradients through broad tidal marshes. It is, therefore, unlikely that much of the sands and gravels derived from inland Pleistocene deposits reach the Bay shoreline.

Beach face sediment samples were available for 13 areas along west Delaware Bay coast. Table 1 is a listing of the sediment source locations and sizes. When several beach face samples were available for a given location, they were averaged. The table shows that beach sediments were consistently medium to coarse sand, with occasional very coarse sand. The smallest material is found at Bombay Hook in the north of the study area. However, there was no apparent relation-

Bombay Hook:	1)	0.325
	2)	0.358
	3)	0.334
	(mm) MEAN:	0.339
Pickering Beach:	1)	0.707
	2)	0.758
	3)	0.660
	4)	0.871
	5)	0.547
	6)	0.801
	MEAN:	0.724
Kitts Hummock:	1)	0.550
Bowers Beach:	1)	0.586
Bennetts Pier:	1)	0.551
	2)	0.432
	3)	0.611
	4)	0.497
	5)	0.996
	6)	0.566
	7)	0.483
	MEAN:	0.587
Big Stone Beach:	1)	1.741
	2)	0.655
	MEAN:	1.117
Cedar Beach:	1)	0.382
(Mispillion R.)	2)	0.319
	3)	1.424
	MEAN:	0.708
Slaughter Beach:	1)	1.125
Fowler Beach:	1)	1.347
	2)	0.493
	3)	0.379
	MEAN:	0.739
Primehook Beach:	1)	0.758
	2)	0.493
	MEAN:	0.809
Broadkill Beach:	1)	0.865
	2)	0.210
	3)	0.933
	MEAN:	0.669
Lewes Beach:	1)	0.896
Breakwater:	1)	0.467
	2)	0.660
	3)	0.807
	MEAN:	0.645

Table 1. Sediment sizes of beach face material at 13 locations along the study area (mm) (Maurmeyer, 1978).

ship between sediment size and distance up-Bay which suggests that similar sources of sand-sized material occur throughout the area. These sources are likely the eroding Pleistocene necks (Maurmeyer, 1978).

Environmental Characteristics

Winds

Winds are of particular interest in examining shoreline changes since wind-generated wave activity is the primary forcing function behind shore erosion (Bascom, 1980; Dean, 1987). Local wave characteristics are affected by such factors as wind speed, duration, and available fetch. It is the wind blowing over Delaware Bay which creates the most significant continuous wave activity, which in turn translates into varying degrees of coastal change.

Direction and strength of these winds varies seasonally, although the prevailing (most frequently occurring) direction is from the northwest (offshore). The dominant (highest velocity) winds, however, are from the northeast (U.S. Army Corps of Engineers, 1977). Annual and seasonal wind speed and direction roses (Figure 5) show that winter winds (as represented by the January rose) are generally from the northwest. In the spring (as represented by the April rose), northwest winds still prevail; however, the frequency from the south, southeast, and northeast increases. During the summer (the July rose), wind directions from the southwest prevail. Fall winds (October rose) tend to be the most evenly distributed from all directions.

Fetch, the distance of open water across which the

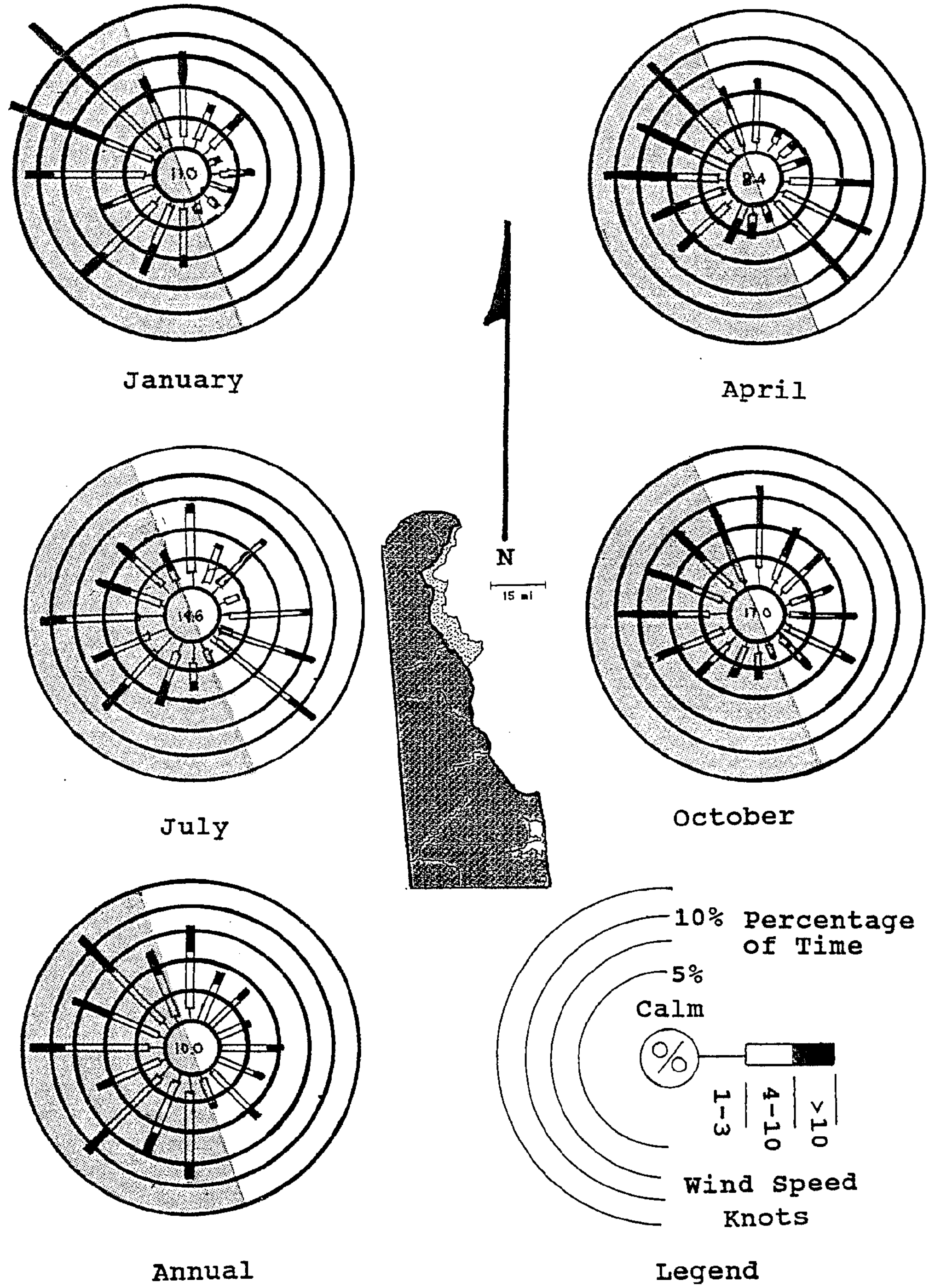


Figure 5. Wind roses showing seasonal (as represented by January, April, July, and October) and annual wind speeds and directions at Dover Air Force Base, Delaware (after Maurer and Wang, 1973). Shaded areas indicate offshore wind directions.

wind blows, is another important factor in wave generation. In general, as fetch increases, larger waves are generated. Since Delaware Bay is generally conical in shape, narrowing to the northwest, cross-bay fetch decreases in that direction and increases southeastward toward the wider central section (see Figure 10). Therefore, the central and southern shorelines of the western Bay coast are subject to the greatest wave energy from northeast winds. The lower Bay shorelines, which are oriented along a more southwest-northeast trend (e.g., the Cape), are the most susceptible to the less frequent northwest winds since the fetch is effectively the length of the entire Bay.

Waves

Waves, whether generated by prevailing winds or by storm events at sea, are undeniably the most significant erosive factor operating along the coast. Direction and intensity (i.e., height and period) of the waves determine the amount of energy expended on a given segment of shoreline. Average seasonal and annual wave heights and directions within Delaware Bay correlate closely with comparable wind data (Figure 6).

In general, wind waves in the Bay are low, with an average height less than 2 feet for almost 80% of the time. Only about 2% of the time do wind-generated

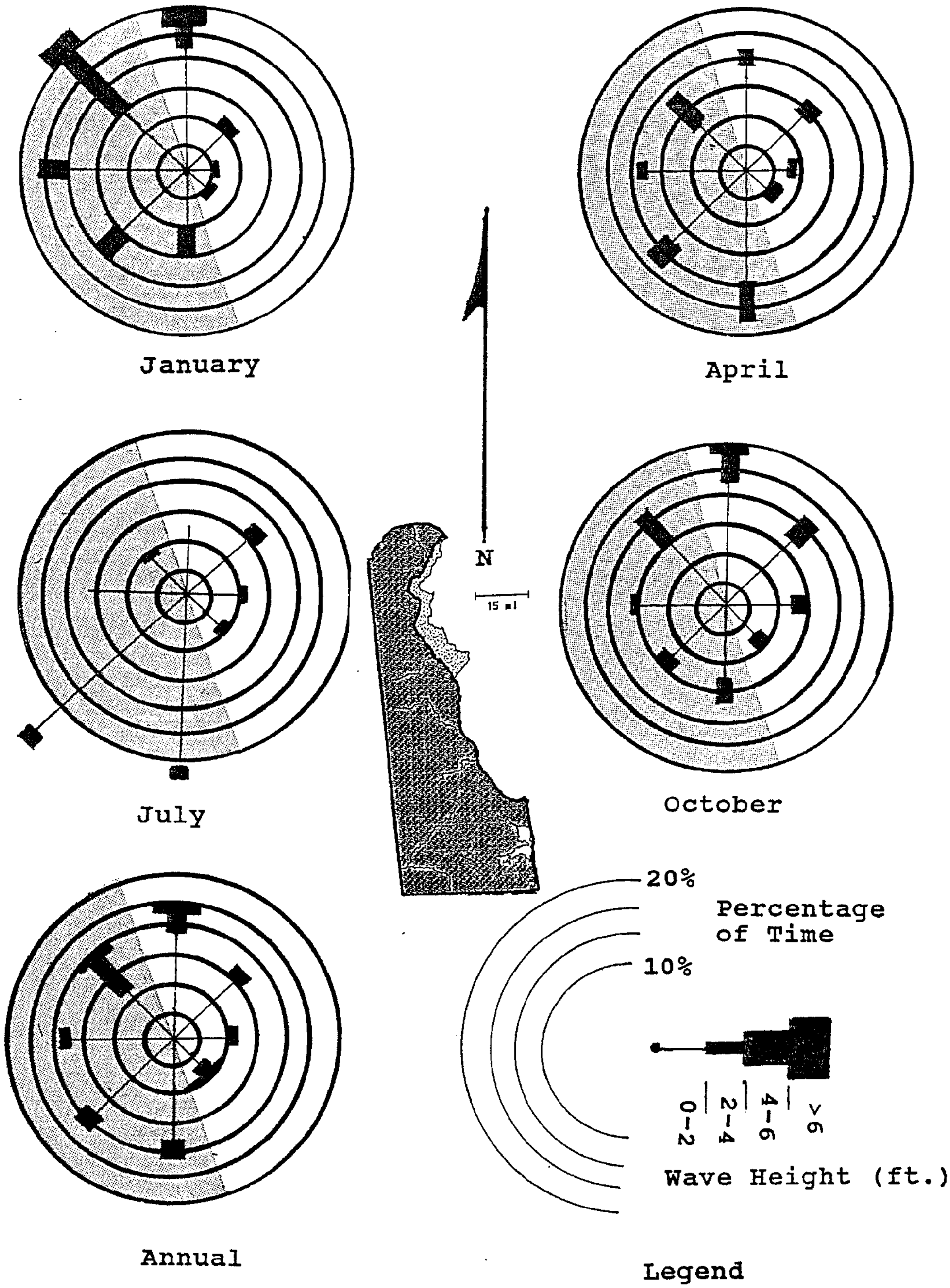


Figure 6. Significant wave directions and heights in Delaware Bay (compiled by Maurmeyer, 1978, from data presented by Maurer and Wang, 1973). Shaded areas indicate offshore directions.

waves exceed six feet (Maurer and Wang, 1973). The majority of the largest waves occur in the winter, where the January rose shows a substantial percentage of the waves exceeding the two-foot average. Most of these waves are, however, largely offshore and therefore not important along most of the western shore. The most important wave directions are from the north and northeast and are usually associated with northeasters. As would be expected, summer waves are the lowest in height with only a very small percentage exceeding the annual average.

Wave directions in Delaware Bay also show seasonal patterns. The overall annual incident direction is from the northwest through southwest (i.e., offshore). From April through the summer the direction is from the southwest. In the fall, the predominant directions are from the northerly quadrants. Maurmeyer (1978) derived a wave energy distribution graph for Delaware Bay (Figure 7), which shows a pattern similar to that derived for wave direction. The annual distribution is skewed toward the northwest by the strong winter waves from that direction.

Ocean swell waves are important in the southern portions of the Bay. The entrance to the Bay is relatively wide, allowing the passage of significant wave energy. Incoming waves, refracting around Cape Henlopen, affect longshore transport patterns in the lower Bay and supply some sediments to the lower Bay (Maurmeyer, 1978). This influence diminishes northward up the Bay (Demarest, 1978).

Boat wakes have been observed to have some impact on the shoreline, particularly in the northern reaches of the Bay (R. Henry and T. Pratt, personal communications, 1990). However, their contribution could not be quantified.

Tides

The Delaware Bay estuary experiences a semi-diurnal tidal pattern with two high and two low tides within a 24-hour 50-minute period. At Cape Henlopen, the mean tidal range is 4.1 feet, with an average spring tide extreme of 4.9 feet. Tidal ranges tend to increase up-Bay, reaching a mean of 5.5 feet and spring tide extreme of 6.4 feet at the Leipsic River Entrance station (U.S. Department of Commerce, 1977). Figures 8 and 9 illustrate the mean and spring tidal ranges along the length of the study area and several significant tidal heights at Breakwater Harbor, respectively.

Longshore Transport

Directions of longshore sediment transport were inferred from several lines of evidence, including

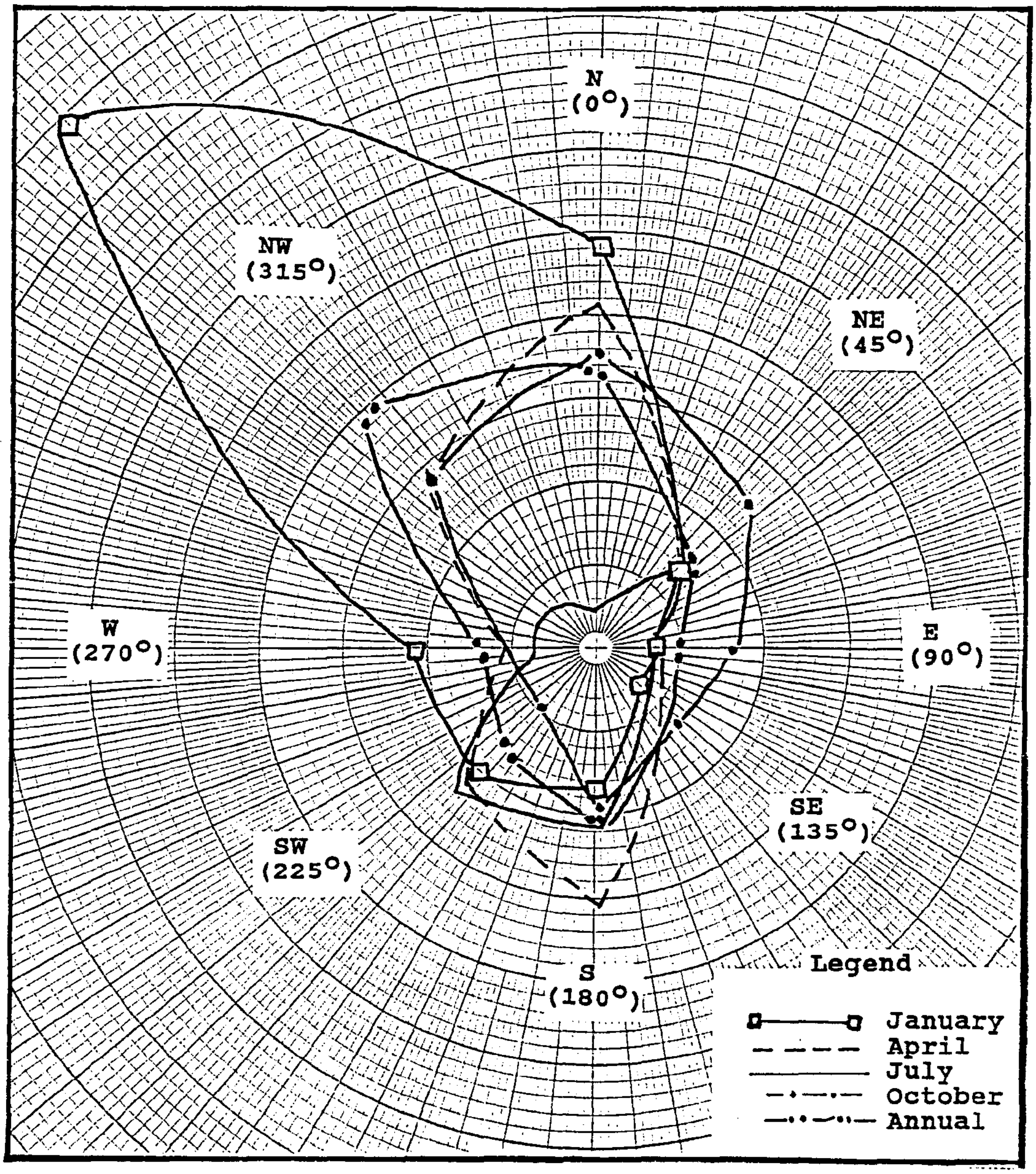


Figure 7. Annual and seasonal (January, April, July, October) wave energy distribution in the Delaware Bay (compiled by Maurmeyer, 1978).

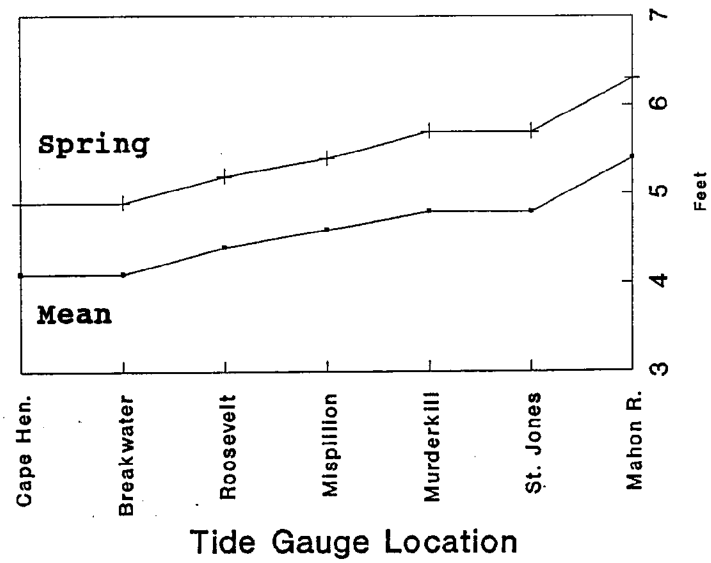


Figure 8. Mean and Spring Tidal Ranges, West Delaware Bay (U.S. Department of Commerce, 1977).

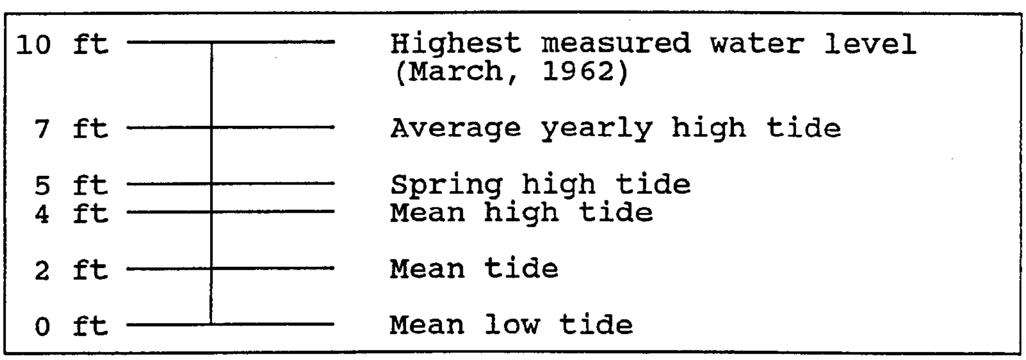


Figure 9. Significant tide heights at Breakwater Harbor (U.S. Department of Commerce, 1977).

patterns of accumulation of sand at shore-normal obstructions (e.g., jetties and groins), inlet and river mouth migrations, and spit orientations and growth. In addition, Maurmeyer (1978) conducted a series of field measurements of longshore current velocities along the western Delaware Bay between July 1976 and September 1977 (Table 2; Figure 10). Longshore current directions observed by Maurmeyer (1978) correlate fairly closely with the wind and wave data, with southerly currents occurring approximately 74% of the time, and northerly currents occurring approximately 26% of the time. However, the evidence of littoral drift observed in this study suggests a north vs. south distribution closer to 50%, although drift direction for the more northern reaches was poorly defined and showed signs of frequent reversals.

Transport directions south of Mispillion River Inlet appear to be well established and consistent throughout the study period. Buildup of material on the north side of Roosevelt Inlet (map 5, Appendix 1) indicates a net southwesterly drift direction. This is supported by the accretionary pattern at a shipwreck approximately 2,000 feet to the northwest.

Near the Bay mouth, longshore transport is influenced primarily by swell waves from the Atlantic Ocean refracting around Cape Henlopen (Maurmeyer, 1978). Because of the proximity of Lewes and Breakwater Harbor

Date	Location	Current Speed (Ft/sec)	Direction
8 July 1976	Bennetts Pier	0.98	south
13 July 1976	Broadkill Beach	0.33	south
13 July 1976	Fowler Beach	0.43	south
14 July 1976	South Bowers	0.29	south
28 Sept 1976	Pickering Beach	0.75	south
29 Sept 1976	Kitts Hummock	0.78	north
5 Oct 1976	Slaughter Beach	0.49	south
5 Oct 1976	Primehook Beach	0.62	south
5 Oct 1976	Big Stone Beach	0.85	south
5 Oct 1976	Bennetts Pier	0.66	south
5 Oct 1976	South Bowers	0.43	south
12 Oct 1976	South Bowers	0.39	north
17 Dec 1976	Fowler Beach	0.33	south
20 Dec 1976	Lewes Beach	0.10	northwest
10 Jan 1977	South Bowers	0.33	south
21 Mar 1977	Lewes Beach	0.20	northwest
21 Mar 1977	Plum Island	0.30	northwest
21 Mar 1977	Broadkill Beach	0.46	northwest
29 Mar 1977	Bennetts Pier	0.16	north
17 May 1977	Big Stone Beach	0.39	south
8 June 1977	Pickering Beach	0.26	south
29 June 1977	Fowler Beach	0.26	south
13 July 1977	Woodland Beach	0.33	south
14 July 1977	Kitts Hummock	0.82	north
25 July 1977	Conch Bar	1.31	south
28 Sept 1977	Kitts Hummock	0.46	south
28 Sept 1977	Fowler Beach	0.52	south
28 Sept 1977	Bennetts Pier	0.79	south

Table 2. Longshore current directions and velocities along the western shore of Delaware Bay (after Maurmeyer, 1978).

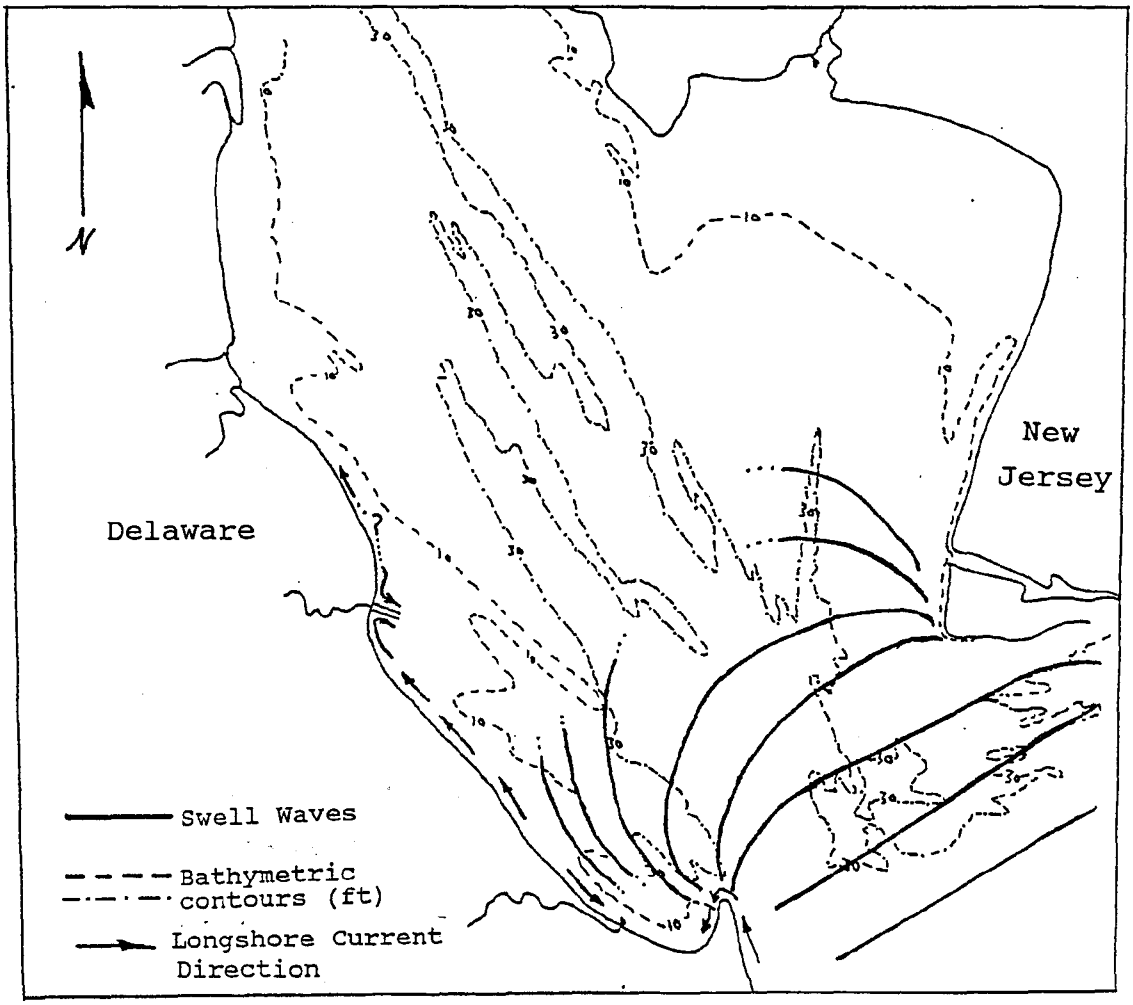


Figure 10. Schematic diagram of nearshore bathymetry, swell waves, and general directions of longshore currents along west Delaware Bay (bathymetry after Wiel, 1977).

to the Cape, tidal currents are also of particular importance. Flood tides tend to move material into the area of Lewes, while ebb tides tend to winnow fines and redistribute them onto outer shoals (Kraft and Caulk, 1972). Swell wave refraction around the Cape's tip and the breakwaters results in a more-or-less continual flow of material into the Lewes area (Kraft and Caulk, 1972). This, combined with the cyclic tidal currents, tends to form counterclockwise gyres, resulting in a southeast-moving littoral drift to just south of Broadkill Beach (Demarest, 1978). This general pattern around the Cape is diagramed in Figure 11.

Approximately two miles northwest of the Roosevelt Inlet, in the area of Broadkill Beach, the littoral drift has clearly reversed direction and is now from the southeast. This was inferred from the pattern of accretion on the south side of the town groins, the historic pattern of closure of Broadkill Inlet subsequent to 1884 (maps 10 and 11, Appendix 1; Figure 26), and an ephemeral spit 4,000 feet south of the town (map 9, Appendix 1). This indicates that a node point or reversal in littoral drift exists in the region between Roosevelt Inlet and Broadkill Beach (Strom, 1972; USACOE, 1966). From this nodal point eastward, the drift pattern is toward the southeast (Figure 10), and the change in drift direction occurs within a relatively narrow area. Therefore, a discrete free

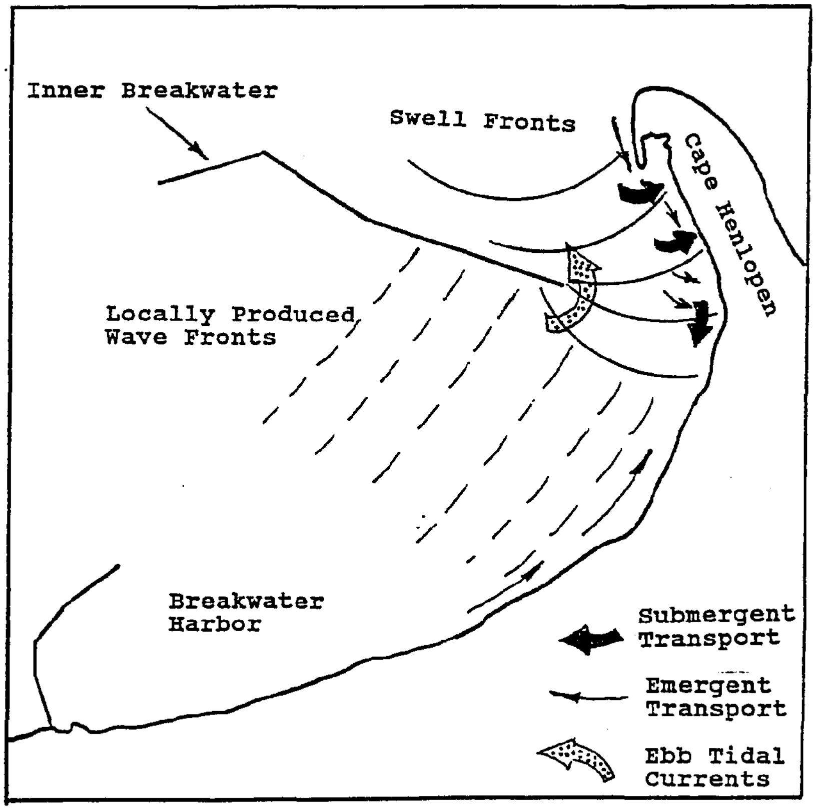


Figure 11. Refraction patterns around Cape Henlopen and the breakwaters (modified from Demarest, 1978).

littoral drift cell between the node and the Cape can be inferred (Tanner, 1973; Carter, 1988). This node point apparently formed in the early part of the 18th Century, before breakwater construction. Prior to this time, large quantities of sediments rounding what is now Cape Henlopen were transported as far north as Primehook Beach (Kraft and Caulk, 1976). Breakwater construction, combined with the continued northward accretion of the Cape, cut off this supply resulting in drift reversal with the southeastward-flowing littoral drift being caused by the counterclockwise gyres generated by the breakwaters and the Cape (Kraft and Caulk, 1972; Figure 11).

Northwest of the node, the direction of longshore transport continues in a northward direction up to the Mispillion River Inlet. This is evidenced by updrift (southeast side) sedimentation at the groin field at Slaughter Beach (maps 21 and 22, Appendix 1) and build-up of material on the south side of the Mispillion River Inlet (map 25, Appendix 1).

North of the Mispillion River Inlet, the drift patterns are not nearly so consistent as those south of the inlet. Ocean swell has little effect on the shoreline here, and littoral drift patterns are determined by local winds over the available fetch. Simultaneous buildup on the north side of Mispillion River Inlet would indicate that this is a convergence point of two drift cells (Figure 10).

Drift direction, however, appears to have again reversed direction approximately three miles north of Big Stone Beach as evidenced by spit development and migration of the relict channel (comparison of 1842 and 1882 shorelines on map 37; Appendix 1). Yet, only 4,000 feet farther northwest (map 38, Appendix 1), an elongated spit in 1977 strongly indicates a southerly flow. In addition, the shoreline changes which occurred at Bowers Beach seem to indicate a southerly migration of the St. Jones River mouth (map 36, Appendix 1). Therefore, this suggests that frequent drift reversals are the norm north of the Mispillion River.

Storms

There are two basic types of storms which can have significant effects on the Delaware Bay shoreline: tropical storms (hurricanes) and extratropical storms (northeasters). These meteorological phenomena alter coastal configuration primarily through the coupling of elevated water levels (storm surge) and high wind-driven waves (Leatherman, 1988). Tropical storms, or hurricanes with sustained wind speeds in excess of 74 mph, can result in the highest shore erosion in the shortest period of time, although the frequency of such events is low. The last hurricane to have a significant impact on the Delaware coast was Donna in September 1960, with peak winds of 110 mph. While there was extensive flooding and damage, damage could have been much worse if the peak winds had occurred at high tide (Friedlander, 1977).

On the other hand, statistically more frequent northeasters with their usually lower wind speeds and storm surges can and have wreaked havoc along the Delaware coasts. Although these storms are rarely of hurricane force, the damage which they cause can equal or even exceed that of hurricanes due to their longer duration. The vicious March 1962 northeaster which lasted for five consecutive high tides caused extensive damage along the Bay shore (Friedlander, 1977), exceeding that of Hurricane Donna in 1960.

These extratropical storms develop as low pressure areas and move slowly offshore into the Atlantic Ocean with counterclockwise winds blowing onshore from the northeast for extended periods; hence the term "northeaster." Most of the study area is very exposed to northeasters. The average storm duration for all storms recorded at Breakwater Harbor (Lewes) from 1952 through 1973 was approximately 40 hours (Friedlander, 1977). Northeasters are, therefore, probably more important than hurricanes in shaping the Delaware Bay coastline due to their higher frequency, longer duration, and orientation of wave approach relative to the western shore.

Storm events cannot reliably be predicted. However, in a statistical sense, they can be expected based on a frequency/magnitude relationship. The U.S. Army Corps of Engineers (1966) analyzed tide gauge records at Atlantic City, New Jersey, from 1937 through 1963 and calculated the return period of storm tide levels (Figure 12). Although their data reflect an open coast environment, proximity to Delaware Bay sug-

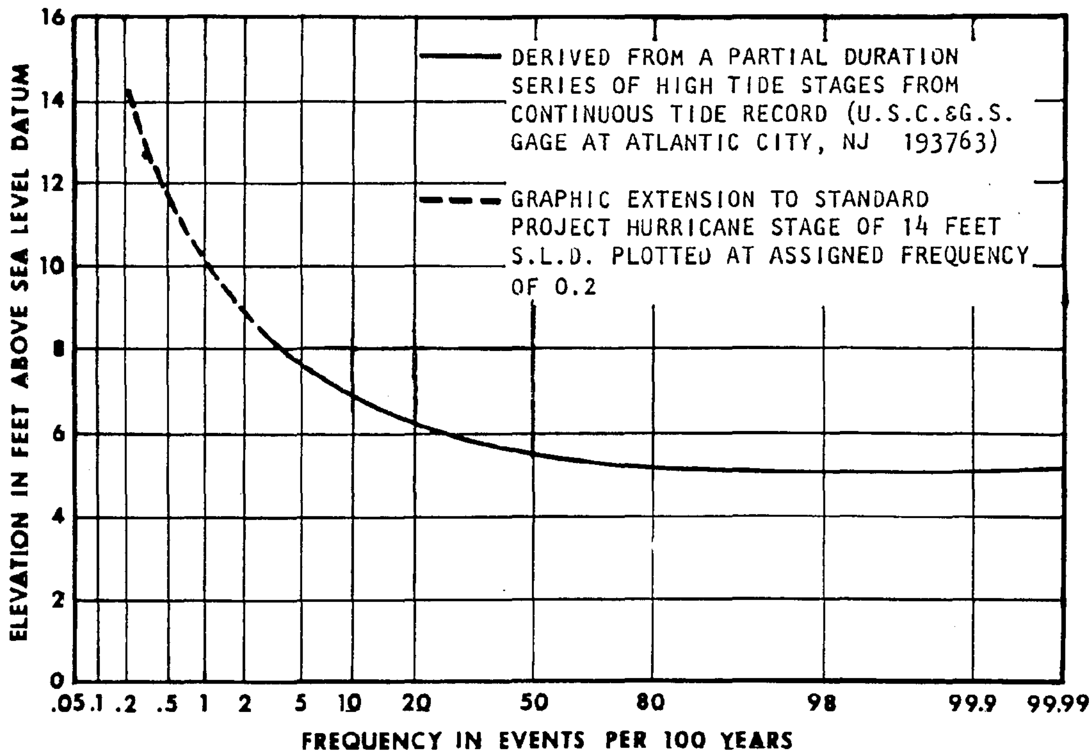


Figure 12. Recurrence intervals of various storm surge elevations (USACOE, 1966).

gests that the frequency curve relationship is similar within the Bay.

Storms striking Delaware's Atlantic and Bay coastlines between 1923 and 1977 are presented in Table 3. In this general classification, minor damage is intended to represent localized flooding with little or no structural damage along with some limited but measurable loss of beach material. Moderate damage is defined as local to general flooding, limited localized structural damage, and measurable loss of beach

Year	Date	Storm Type	Reported Level of Coastal Damage
1923	10/24	Extratropical	Severe
1924	03/10-11	Extratropical	Minor
	09/18	Extratropical	Moderate
1927	02/19-21	Extratropical	Extremely Severe
1928	09/20	Extratropical	Minor
1929	04/17	Extratropical	Moderate
1932	11/11	Extratropical	Severe
1933	01/26-27	Extratropical	Severe
	08/22-23	Tropical	Extremely Severe
1934	06/20	Extratropical	Minor
1935	11/18	Extratropical	Severe
1936	09/18-19	Tropical	Moderate
1937	04/27	Extratropical	Moderate
1943	10/01	Extratropical	Minor
	10/27	Extratropical	Moderate
1944	09/14-15	Tropical	Severe
	10/21	Extratropical	Minor
1950	11/25-26	Extratropical	Extremely Severe
1951	10/24	Extratropical	Minor
1953	08/15	Extratropical	Minor
1954	09/01	Tropical (Carroll)	Minor
	10/15	Tropical (Hazel)	Moderate
1955	08/13	Tropical (Connie)	Minor
	08/19	Tropical (Diane)	Minor
1956	09/28-29	Tropical (Flossy)	Severe
	10/19	Extratropical	Minor
1957	10/07	Extratropical	Moderate
1960	09/13	Tropical (Donna)	Moderate
1961	10/23-24	Extratropical	Severe
1962	03/06-08	Extratropical	Extremely Severe
	11/05	Extratropical	Severe
	11/12	Extratropical	Moderate
	11/28-29	Extratropical	Severe
1964	01/13	Extratropical	Moderate
1967	09/18	Tropical (Doria)	Minor
1968	05/27-28	Extratropical	Minor
	11/11-13	Extratropical	Moderate
1969	08/20	Tropical (Camille)	Minor
	11/02	Extratropical	Minor
1971	04/06	Extratropical	Minor
	08/26-28	Tropical (Doria)	Minor
	09/02-03	Tropical (Ginger)	Minor
	09/12	Tropical (Heidi)	Minor
	09/23-26	Extratropical	Minor
1972	02/12-13	Extratropical	Minor
	05/14	Extratropical	Minor
	06/20-22	Tropical (Agnes)	Minor
	09/21	Extratropical	Minor
	12/22	Extratropical	Minor
1973	10/25-26	Tropical (Gilda)	Minor
	12/09	Extratropical	Minor
1974	12/01	Extratropical	Severe
1977	10/13-15	Extratropical	Moderate

Table 3. Delaware Coastal Storms: 1923-1977 (Source: Friedlander, et al., 1977).

material. The severe categories indicate extensive but localized structural damage, with most beaches suffering varying amounts of loss, along with numerous washovers and dune breaches. In the extremely severe category, the coastal zone was devastated, with massive destruction of coastal structures, much damage inland, and widespread beach erosion. Classifications were based on contemporary descriptions of damage sustained as recorded in Friedlander, et al. (1977).

Sea-Level Rise

The underlying forcing function behind long-term shoreline retreat is sea-level rise (Leatherman, 1981, 1983a). Some 14,000-17,000 years B.P., at the height of the Wisconsin glaciation, there was enough water tied up in continental ice sheets and caps to lower sea levels more than 300 feet below their present levels (Kraft, et al., 1976). With the waning of the glaciation between 14,000 and 10,000 years B.P., sea levels rose extremely rapidly. Some estimates place that rate as high as 10 feet per century initially (Kraft and John, 1976). From about 10,000 years B.P. until about 2,000 years B.P. the rate of sea-level rise had declined from nearly 1 foot per century to about 0.5 foot per century, remaining fairly constant up to the early part of this century (Belknap, 1975; Figure 13). Tide gauge measurements at Breakwater Harbor

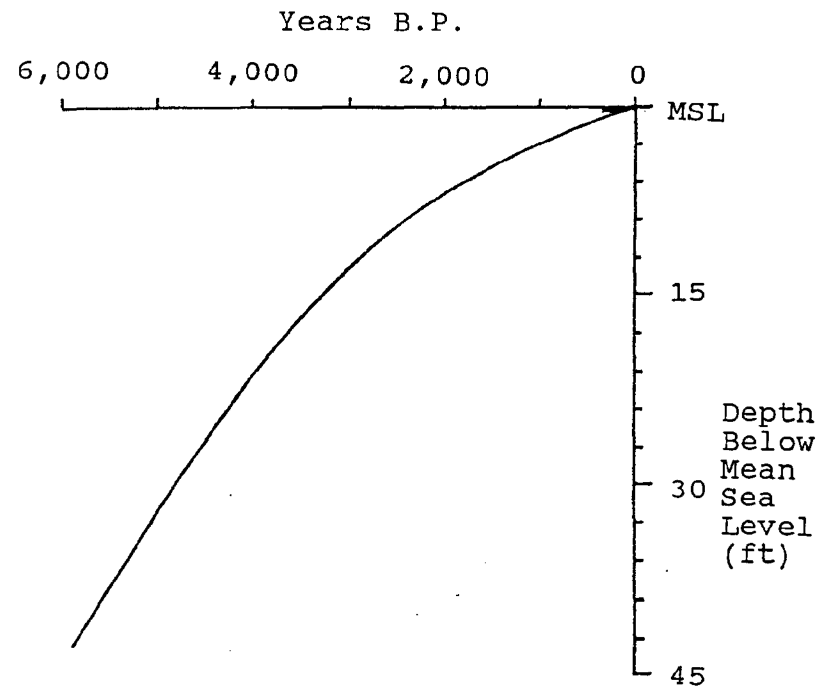


Figure 13. Relative sea-level rise curve for the Delaware Coast (after Belknap, 1975).

indicate nearly 0.7 feet of relative sea-level rise between 1921 and 1986, or just over one foot per century (Lyles, et. al., 1988; Figure 14). While this represents a short time period during which there were many fluctuations, it appears that the present rate of sea-level rise is significantly faster than during the past 2,000 years. This local rate of rise is only slightly higher than the U.S. East Coast average of 0.98 feet over the last century (National Research Council, 1987).

It is unclear how much of the relative sea-level

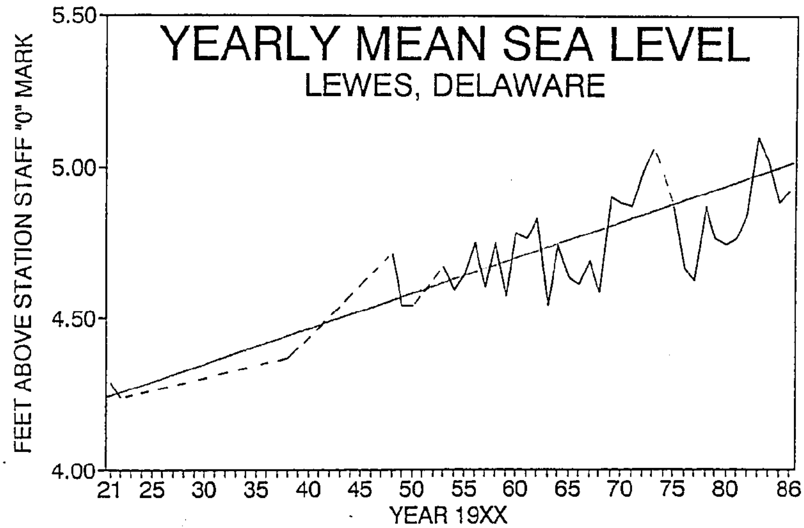


Figure 14. Measured sea levels at Breakwater Harbor (Lyles, et al. 1988)

rise along the Delaware coast is isostatic, resulting from auto-compaction of sediments and localized tectonic subsidence. It is speculated that as much as 180 feet of the total rise in sea-level can be attributed to such phenomena over the past 15,000 years (Kraft and John, 1976). The balance of the rise is eustatic in that it is occurring worldwide.

Considering an idealized, uniform 1 foot/mile (1:5,280) slope of the coastal plain, a 6 inch rise of the water level in 50 years would translate into 0.5 mile of coastal land loss through simple inundation. This idealized example serves to illustrate that even the present rate of sea-level rise poses a potentially severe threat to the flat, low-lying western coast of

Delaware Bay.

Less immediately obvious, however, is the fact that deepening water near the shore (as a result of the rising sea levels) can allow higher storm waves to reach farther inland before expending their energy. In addition, the natural concave upward profile of a beach results in wave energy being dissipated in a smaller volume of water, thereby generating greater turbulence within the surf zone which leads to accelerated coastal recession through erosion (Bruun, 1962; Hands, 1981; Leatherman, 1989a).

This generalized pattern of coastal recession following sea-level rise was described by Bruun (1962) for an idealized, two-dimensional coastline, with no longshore component. The "Bruun Rule," in essence, states that material eroded from the upper beach (due to sea-level rise) is equal in volume to the material deposited on the nearshore bottom, and that the consequent rise of the nearshore bottom is equal to the rise in sea level (Bruun, 1962). The land-water interface, therefore, moves progressively landward with sea-level rise while the nearshore water depth remains relatively constant. This "rule" has been widely applied to a number of coastlines with varying results. Discussion continues as to its validity along open coasts where, in fact, the longshore component of sediment transport does significantly affect shoreline configuration.

METHODOLOGY

Introduction

Shoreline changes through time were examined for the western Delaware Bay. Collection and analysis of the data were directed at: 1) establishment of accurate long-term shoreline erosion and\or accretion rates along the western shore of the Bay; 2) correla-ion of those changes with environmental conditions; and, 3) detection of human influences on those changes at and near developed areas.

Fifty-eight historic shoreline change maps of the west Delaware Bay coast were generated utilizing the Metric Mapping technique. The 58 maps were produced at a scale of 1:6,000 and indicate shoreline changes (erosion or accretion) between Breakwater Harbor and Port Mahon during the period 1842-1977 (Appendix 1).

Numerical rates of shoreline changes were calculated using the TRANSECT sub-routine of the Metric Mapping process. This program projects transect lines perpendicularly across the historic shoreline plots at user-defined intervals. The program then automatically calculates both the net change and per-year rate of change for any two selected years for each of those transect lines. Data output from the TRANSECT program was captured in histogram and tabular format. Tables indicate the numeric computer-measured long- and short-term shoreline changes for each transect (Appendix 2), whereas the histograms graphically express the coastal erosion/accretion rates in a form which aids in visualizing their effects on shoreline planform (Appendix 3). For this study, both long- and short-term shoreline change rates were determined along 192 transects spaced at 1000 foot intervals from Breakwater Harbor to just south of Simons River.

Metric Mapping

The Metric Mapping technique is a system designed to use the high speed data processing capabilities of the computer to emulate the best photogrammetric techniques. Metric Mapping is a package of computer programs which significantly increases the accuracy of standard shoreline mapping procedures. The capabilities include transformation of the original map to State Plane coordinates, space resection of photographs to correct for distortion introduced by flight path irregularities, and a means to plot accurate maps. Data are entered into the computer through X-Y coordinate digitization of control points and shoreline data.

Shoreline change maps generated by this technique are comparable in accuracy to those produced by the stereoplotter and meet National Map Accuracy Standards (Leatherman, 1983b; Clow, 1984). Where many previous shoreline mapping procedures have relied solely on either ground surveys or aerial photography as source data, Metric Mapping allows for the compilation of shoreline change data from all available accurate sources.

The complete Metric Mapping procedure involves four distinct tasks: 1) Data selection and annotation; 2) digitization and data input; 3) data processing; and, 4) map plotting (Leatherman, 1983b; Figure 15).

Data Selection and Annotation

The data sets used to produce the West Delaware Bay shoreline change maps include 23 National Ocean Survey (NOS) "T" sheets and two sets of aerial photographs. NOS "T" sheets are precise coastal maps which were produced by the U.S. Coast and Geodetic Survey (now NOS) dating back to the 1840's. The "T" sheets are considered the most appropriate for historical shoreline mapping for several reasons. First, there is no other source of historical information as accurate as these charts that is generally available for U.S. coastlines (Leatherman, 1983b). Accuracy of stable points on the NOS "T" sheets are within 0.012 inches of their actual location at the scale of the map. The smallest field distance measurable is between 7 and 16 feet (Shalowitz, 1964). Secondly, charts were available for the study area

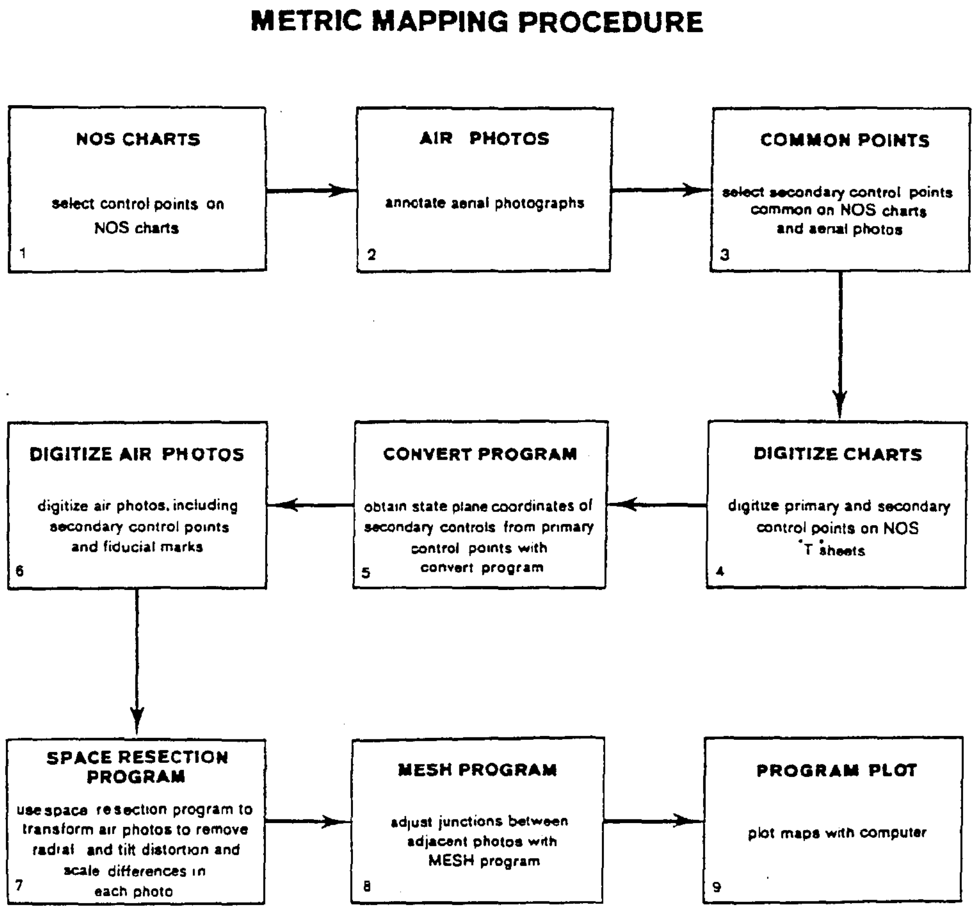


Figure 15. Flow chart of the Metric Mapping process. (From Leatherman, 1983b)

as early as 1842, thereby providing a nearly 150-year window back in time. Third, the decision was made early on by the Survey to use the high water line as the land-sea interface (shoreline) on the charts since it was found that this line could easily be identified in the field by the wetted vs. dry sand. This later became particularly significant with the establishment of the wetted boundary of the high water as the standard interface indicator on aerial photography by Stafford (1971). Fourth, these maps were available for the study area at scales no smaller than 1:20,000, with several (8) available at a scale of 1:10,000, and one at 1:5,000. For historical mapping purposes, 1:20,000 was considered the smallest acceptable scale.

Finally, it was realized early on that the shoreline was a dynamic and changing environment and so the Coast Survey scheduled revisions to occur at periodic intervals (Leatherman, 1988). Consequently, map series for Delaware were available at 23 to 40-year intervals.

Two year groups of good quality aerial photographs were provided by the Delaware Department of Natural Resources. These included a 1954 and a 1977 series, both at the approximate scale of 1:5,000 in a 20" X 20" print format. Each was corrected for radial and tilt distortions, as well as scale differences between photographs by the Space Resection subroutine of the Metric Mapping process (Table 4).

TABLE 4 - SOURCE DATA

WEST DELAWARE BAY SHORELINE CHANGE STUDY

National Ocean Survey "T" Sheets

YEAR	MAP NUMBER	MAP SCALE
1842	T150	1:20,000
1842	T151	1:20,000
1882	T1503	1:20,000
1883	T1547B	1:20,000
1883	T1548A	1:20,000
1884	T1548B	1:20,000
1910	T3087	1:20,000
1943	T8497	1:20,000
1943	T8498	1:20,000
1944	T8499	1:20,000
1946	T8761	1:20,000
1946	T8762	1:20,000
1946	T8763	1:20,000
1946	T8764	1:20,000
1969	TP00052	1:10,000
1969	TP00054	1:10,000
1969	TP00056	1:10,000
1969	TP00058	1:10,000
1970	TP00062	1:10,000
1970	TP00063	1:5,000
1971	TP00059	1:10,000
1971	TP00060	1:10,000
1971	TP00061	1:10,000

Aerial Photographs

CODE	ROLL#	EXPOSURES	DATE	SOURCE
APH	1N	200, 202, 204, 205, 205, 210	7-13-54	Dept. of Agriculture
AHP	3N	32, 34, 36, 94, 96, 97, 103	7-13-54	Dept. of Agriculture
ANH	3N	69, 70	7-20-54	Dept. of Agriculture
ANH	4N	3, 54	7-22-54	Dept. of Agriculture
ANH	4N	61, 62 119, 120	7-30-54	Dept. of Agriculture
ANH	3N	170	8-14-54	Dept. of Agriculture
10001	177	71L-73L, 78L-82L, 83R	5-15-77	DNREC
10005	177	3L, 30R, 30L-31L, 33L, 34R-35R, 69L, 70R	5-15-77	DNREC

Data Preparation

Once all of the available maps and photographs were acquired, they were annotated before the computerization processes began. The first step of the annotation process was to identify the high water level indicator consistent for both maps and photographs. Since the NOS "T" sheets use, as convention, the mean high water line, and indicate it as such by the first solid landward line, there was generally no problem with this step when dealing with the maps. This line was highlighted with an ordinary text highlighter along the entire length of the map in order to avoid the possibility of confusing the actual shoreline with an adjacent or crossing line during the digitizing process.

Stafford (1971) established that the mean high water was also the most satisfactory indicator of the shoreline on aerial photography since the wetted-sand boundary from any previous high tide usually remains visible throughout the low tide periods. An example of a photograph showing the boundary can be seen in Plate I. This line was identified under a magnifying viewer (6X) and marked directly on the photograph with an extremely fine engineering pencil (0.3 mm). This was done to avoid any possibility of drifting from the actual line while digitizing. In addition, it was important to insure that no interpretation or analysis

Plate I. Aerial photograph showing the wetted boundary of the mean high water.

of the photography was attempted during the mentally intensive digitizing process later on.

The next step involved the identification of at least four widely spaced primary control points on each of the T-sheet maps. These are points for which precise geocoordinates are known and serve to spatially place the map area.

This was usually no problem for the more current maps since latitude/longitude lines were generally accurately placed directly on the map. On some of the earlier maps, however, only isolated survey triangulation stations were identifiable with no pattern to their distribution. In addition, on the pre-1929 maps the given geocoordinates for the triangulation stations had to be updated and corrected to the North American Datum (NAD) 27 to eliminate errors inherent in the earlier datums.

Fortunately, most of the triangulation stations had been readjusted to the North American 1927 Datum. Those readjusted coordinates were not on the maps however, and had to be applied from computer data obtained from the National Ocean Survey in Rockville, Maryland, utilizing the Least Squares Fitting, Transformation and Interpolation (LEFTI) program. This program performed the necessary correctional computations automatically and provided a hardcopy output of the old and new coordinates which were then written directly on the map adjacent to the appropriate station.

The next step was the identification of at least four (and up to eight) secondary (registration) control points for each of the photographs to be used in the study. These were points which tied the photographs to the maps and to each other. These points could have been almost anything visible on the photographs provided they met the following basic criteria:

1) The points must be locationally stable through time.

2) The points must be visible on **both** the photographs and the associated maps.

Examples of accepted secondary control points included street intersections, bases of building corners (tall roof corners were not used due to the potential for relief displacement), and dock, pier, and jetty corners. In some cases, even mosquito ditches proved to be reliable control points.

The 1940's map series was chosen as the base maps to which those secondary control points were tied. This was because the 1940's series was the most current complete and unbroken map set covering the study area. In addition, it was that series which provided the greatest amount of cultural information, helpful in identifying the secondary control points. Each of the points were assigned unique identifying numbers and carefully marked on the appropriate maps and photographs.

The final step in data preparation was the assignment of line segments and node points. Line segments are simply segments of the shoreline digitally represented by a dense series of points connected by very short straight lines, ending in nodes. Nodes defined the beginning and end of each line segment, or "arc," to be digitized and were designated as FROM or

TO. There were four types of nodes:

1) Mid Nodes

These nodes were placed at the end of each arc along the shoreline, always between two other arcs within the boundaries of the map/photograph, i.e., a TO node at the end of one line segment will be equivalent to the FROM node of the next adjacent segment.

2) Match Nodes

These nodes were placed at the points where features were broken by the edge of a map or photograph, i.e., a uniquely numbered "TO" match node placed at the end of a shoreline on one map became a "FROM" match node with the same number on the adjoining map.

3) Dangling Nodes

These nodes (designated with a negative (-) sign) were used when a gap in the data existed, either inherently or purposefully, such as at an inlet or between two consecutive sheets which are not of the same year or were otherwise mismatched.

4) End Nodes

These were nodes which began or ended the entire data set.

The procedure for assignment of arcs and nodes was similar, although not identical, with both photographs and maps. The shoreline was digitized as a series of line segments with the points where the ends of the lines join being assigned unique mid-node numbers. Wherever a shoreline reached the edge of a photograph or map, the digitizing ceased and a MATCH node number was assigned. For the maps, the shoreline generally picked up at exact same point on the next adjacent map, with no overlap. That join point had the same number on both maps allowing for the computer to connect, or "tie," the two ends together into an unbroken line.

This was not precisely the case with photographs however. Due to numerous inherent errors in aerial photography, only the approximate center third of each photograph was used whenever possible. Since nearly all vertical aerial photography uses as convention a 60% endlap, this generally posed no problem.

Those node points, however, had to be carefully chosen to be clearly and unmistakably visible on both photographs concerned since the computer could only correct for "under"- or "over-shoot" to a limited, predefined extent. Since the "break" point chosen was directly on the shoreline, positive identification of a reliable point, clearly visible on both photographs, was carefully undertaken.

Due to inherent human limitations and endurance, the shorelines on each of the maps and photographs were broken into smaller, more manageable segments. This was arbitrary and depended largely upon the complexity of the shoreline being digitized. The more complex the shoreline, the shorter each of the line segments were and, consequently, the more individual segments there were for each photograph/map. This was done because of the mentally intensive nature of the process of digitizing. The longer or more complex the line segment, then the more likely it was for digitizing errors to occur. Choosing a higher number of shorter line segments, while somewhat more keyboard-intensive than fewer longer segments, served two functions. First, it allowed frequent breaks for the operator, resulting in fewer errors. Second, in the event of an error, only a small segment of the shoreline had to be redigitized.

Each of the line segments both began and ended with a node, with each of those nodes assigned a unique number. The FROM node of one line segment became the TO node of the next segment. In the case of MATCH nodes at the map/photograph boundaries, the TO MATCH node at the end of the first map/photograph had the same matching number as the next map/photograph's first FROM MATCH node to which it was expected to connect. Finally, there were occasions where a line segment's MATCH node was intentionally not connected to any other line (a "dangling node"). This occurred, for example, when digitizing up a river only a limited distance. It was desired that the line simply end on each side of the river where the digitizing stopped, rather than jump across the river (which is understood to continue beyond the digitized terminus). In these instances, the use of negative numbers was employed, which allowed the program to recognize that the line was to be left unconnected. Each point was clearly marked on the photograph/map exactly where the node point was (using a very fine pencil), along with its identifying number.

<u>Data Entry</u>

Shorelines were transformed into numerical data for computer processing through the use of an X-Y digitizer and keyboard. The process of entering the data into the computer was a largely a straightforward procedure requiring little interpretative or analytical skills. It was, however, a very mentally intensive process requiring much concentration over extended periods making it, in many respects, the most difficult and time-consuming aspect of the entire mapping process.

A PRIME mini-mainframe computer was used for data processing. Data input was through a TEKTRONIX keyboard station, and an ALTEK DATATAB digitizing table, with a resolution of 0.001 inches. Output was through a HEWLETT-PACKARD 7475A 6 color plotter.

The map procedure was to place the map onto the digitizing table and then enter the coordinates of the primary control points into the keyboard. The digitizer cursor was then used to "click-in" the positions of those points on the map, thereby spatially (gegraphically) locating the area to be digitized. If the maps were base maps, then the positions of the secondary control points were then input in a similar manner. The individual line segments were next digitized, with the appropriate identifying data for each being input through the keyboard.

The procedure for the photographs was the same except that no primary control points were input. Instead, secondary control points were input for **every** photograph.

Data Grouping

Since field techniques are comparatively quite slow, and the study area was relatively large, the entire study area was never completely ground surveyed in any one given year. For example, it took from 1943 to 1946 to cover the whole area of interest (see Table 8). Therefore, associated years were grouped together into "year-groups" of 2 to 3 individual years which then constituted one complete shoreline.

This was done for the 1880's, 1940's, and 1969-

1971 groups of maps. The 1842 and 1910 maps were incomplete and without any other temporally close maps; therefore, they stand alone. Each of the sets of photographs were complete and each set shot completely within time spans of only days.

Shoreline change rates and net changes were calculated for the following periods: 1842-1882/83/84 group; 1882/83/84 group-1910; 1910-1943/44/46 group; 1943/44/46 group-1954; 1954-1969/70/71 group; 1969/70/71 group-1977; 1842-1977; and, 1882/83/84 group-1977. (For convenience, the grouped years will hereafter be presented as follows: 1882/83/84 = 1882g; 1943/44/46 = 1943g; 1969/70/71 = 1969g, unless specific reference is made to one of the particular years of a group.)

Data Processing

The digitized data were then run through the Metric Mapping Space Resection program as diagramed in Figure 15. The computer program first performed a two-dimensional transformation on the maps, checking the relationship of the points to determine if there was excessive distortion. The scaling factor was computed first by determining the distances between control points. The distance between any two control points had to be the same on the map as it was between the known state plane or latitude/longitude coordinates of those points.

Next, the rotation was computed by comparing the angles between control points and the vertical axis. Finally, the translation was computed by determining the distance between the center of the controls on the map and the center of the known control. Throughout this process, averages were used to ensure the best fit for all of the control points.

The transformation program forces the use of at least four control points, one more than necessary for a closed form solution, to ensure that the transformation is correct. Any positional displacement of any of the points was displayed on the screen. If the error was found to be excessive (greater than one foot for each 1000 feet of scale), then the map was considered to be excessively distorted and was discarded.

The three-dimensional transformation necessary for aerial photography is considerably more complicated than is the two-dimensional transformation applied to the maps. The photogrammetric method of Space Resection employed to compute the transformation matrix is based in part on the U.S. Geological Survey Simultaneous Model Adjustment Program H256 (U.S.G.S., 1985). This program was developed by the U.S.G.S. in the mid-1970's specifically for the determination of the three angles, flying height, and spatial coordinates, of the camera at exposure time. This information is sufficient to transform the digitizer coordinates to corrected state plane coordinates, pulling, in effect, the digitized shoreline (or whatever feature has been digitized) into correct relative alignment.

For the photographs, the transformation program compared the secondary control points digitized on the photograph with those taken from the planimetrically correct base map. Any deviation of the digitized point from the actual true position was displayed on the computer screen, showing X, Y, and radial displacement in real world scaled feet. Like the maps, an error of 1 foot per 1000 feet of scale was considered to be the maximum acceptable error after the resection is run. Errors in excess of that figure were considered excessive and the photograph was rejected. In the process, tilt, lens distortion, and scale variation among all photographs and maps were corrected to within the 1 foot per every 1000 feet of scale considered to be acceptable. In the final step individual data sets (one for each year-group) were merged together with the MESH program. This adjusted the junctions between adjacent photographs, lengthening or shortening the ends of the under- or over-shot plot lines as necessary.

Map Plots

The final task of the mapping process was the production of hard-copy maps and histograms utilizing the PLOTMAP subroutine. This program allows for the production of various types of shoreline depictions as well as graphical representations of statistical data in the form of histograms of change rates along the shore. Different shoreline "year-groups" were assigned individual line types, with specific years within each group represented by unique markers overprinted on the appropriate year-group plot line.

Map #1 of the 58-map west Delaware Bay series begins at the approximate location of the Breakwater Harbor ferry terminal (map #1), and the series terminates approximately one mile north of the mouth of the Mahon River (map #58). The coordinate system for the maps is the Delaware State Plane, and the maps have been gridded every 2000 feet. Coordinates are printed on the left and top margin of each map sheet. The datum for shoreline positions is the mean high water line as digitized from the NOS "T" sheets and aerial photographs.

The road network for the coastal municipalities has been included on the shoreline change maps where present and are represented by a solid black line. The road network was digitized from the 1970's group of "T" sheets and is only used for spatial referencing (not precise measurement) as the road line widths are generalized and not as precisely positioned as is the mean high water line.

Accuracy Assessment

The Metric Mapping technique, as with all techniques of cartographic comparison, is subject to a number of error sources, most of which are introduced by the source materials themselves or by human factors. However, these errors can be kept to a minimum by applying appropriate standards. Source materials were carefully screened using stringent standards to ascertain the accuracy of the "T" sheets and photographs to insure integrity of the data. The "T" sheets were measured and verified against Polyconic Tables to check for media shrinkage, stretching or distortion. As a result of these procedures, T151 (1842) and TP00063 (1970) were rejected. Each map and photograph were subject to the resection and transformation programs to assess the accuracy of scale, degree of rotation and translation. Aerial photographs were also subjected to checks and corrections for tilt, radial and scale distortions induced by aircraft flight irregularities. Aerial photographs were controlled by linkage to hard ground control features taken from the NOS "T" sheets.

When digitized, the computer calculated the relative positions of control points on both maps and photographs with the known positions of those same points. With the maximum acceptable error envelope of 1 foot per 1000 feet of scale, 10 feet would be the maximum acceptable error for a 1:10,000 scale map. However, for this project, the majority of detectable error was less than 0.5 feet per thousand feet of scale (5 feet for a 1:10,000 map). As a result of this screening, one photo was rejected as being outside of acceptable error tolerances.

Aside from media errors, the other possible source of error in the Metric Mapping technique results primarily from human factors. These include difficulties with map and photograph interpretation and digitizing errors. Photograph interpretation errors were minimized through the use of magnifying devices to determine the mean high water line and identify control features. Human errors were minimized by limiting the length of digitizing sessions and through the use of a backlit digitizing table and cursor magnifying devices. The digitizing table has a precision level of 0.001".

The maximum theoretical error estimate inherent in the Metric Mapping process can be quantified. The conservative, worst case estimate of maximum possible error for the older (1880 and older) approaches 42 feet. However, the careful initial screening of materials for this project clearly make this upper limit unattainable. The theoretical maximum error was attained as follows: (1) inaccurate location of control points due to distortion or cartographic error = 15'; (2) error in location of plotted rodded points relative to control points = 13' (this represents the high estimate of Shalowitz, 1964); (3) error in field interpretation of HWL at rodded points = 13' (the high estimate of Shalowitz, 1964); (4) error in location of HWL as plotted by surveyor between rodded points = unknown (however, probably not significant along most coastal beaches) (Crowell, et al., 1990); and, (5) maximum digitizer error = 0.001" = 10" at a map scale of 1:10,000. Therefore, the total maximum possible error of any feature in the early maps is the sum of these five sources of error, i.e., just under 42'. The worst-case error estimate for later maps produced after 1880 is only 37' because of the higher level of accuracy of those maps (Crowell, et al., 1990).

For aerial photographs at a scale of 1:5,000, the error using the same digitizing equipment equals 32' on the ground. This theoretical maximum error for photographs is equivalent to the sum of the errors in the control points (15'), the error in delineation of MHW from good quality photos (16', as estimated by USC&GS, 1944) and digitizer error (<1') (Crowell, et al., 1990). This theoretical maximum error compares quite favorably with the features on the standard 7.5

minute U.S.G.S. quadrangles.

When the maximum error of 42' (for maps) is distributed across the 135 years of this study, the per-year error range is close to 0.31 feet. This, of course is time-span dependent, with the error ranges increasing with shorter spans. The maximum error for any given span of time can be calculated by dividing 42' by the number of years in the span if both shorelines being compared are from maps. If both shorelines are from photographs, the photograph error maximum of 32' should be divided by the year-span. If one of the two shorelines to be compared is from a photograph and the other from a map, then the average map/photograph error of 37' should be divided by the year-span. In practice, errors in these techniques are believed to range between 0 and 20 feet (Galgano, 1989). Considering the fact that 135 years of data are available, the estimated error is approximately 0.15 feet added to the long-term rate of beach erosion/ accretion values. Therefore, a calculated value of 2 feet per year of beach erosion is more accurately represented as 2.00 ±0.15 feet per year.

RESULTS

Shoreline analysis relied upon historical change maps and transect measurements. These changes were correlated with the various environmental and geological characteristics along the Bay shore. Finally, the effects of shoreline engineering projects were evaluated. A data accuracy assessment and evaluation is presented in Appendix 4.

Shoreline change maps demonstrate an overall transgressive coastline with few areas showing any significant accretion. Average total net change for the entire study area between the years 1882g-1977 was -419.3 feet or approximately -4.5 ft/year (±0.2 ft/yr), considerably higher than the Atlantic coast average of -2.6 ft/yr (National Research Council, 1987). Average net change for the more highly erosive northern half of the study area, north of the Mispillion River Inlet was -978.9 feet (1842-1977). This translates to an average annual rate of erosion of -7.2 ft/yr (±0.1 ft/yr).

The overall averaged annual rate of change of the shoreline for each time span along the entire study area are presented in Table 5. Figure 16 illustrates the rates of change which have taken place along the shoreline during the period 1882g-1977. The 1880's year group was used instead of the earlier 1842 data

Sequential Data Sets						Total Spans	
1842-1882g	1882g-1910	1910-1943g	1943g-1954	1954-1969g	1969g-1977	1842-1977	1882g-1977
-7.9*	-9.1*	-4.8*	+0.5	-7.4	-1.3	-7.2*	-4.5
± Range of Error:							
±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1	±0.2

Table 5. Average Per Year Rates of Change for Each Data Set Time Span and for Total Time Spans (ft/yr) (*These figures represent only the northern half of the study area.)

because the 1880's group represented the earliest complete set of data for the entire study area. Figure 17 shows the change rates for each of the individual complete data spans. Figure 17E shows the long term (1882g-1977) average rates of change.

In general, the highest rate of change occurred during the 1954-1969g time span (Figure 17C), with an average annual rate of erosion of -7.4 feet (±1.2 feet). This was the period of the destructive 1962 Ash Wednesday storm. A similar pattern is found in the 1882g-1943g graph (Figure 17A); a period of increased storminess (Table 3; Friedlander, et at. 1977). The least amount of change occurred during the 1943g-1954 time span, with an average annual rate of change of +0.5 feet (Figure 17B), a period of relatively fewer

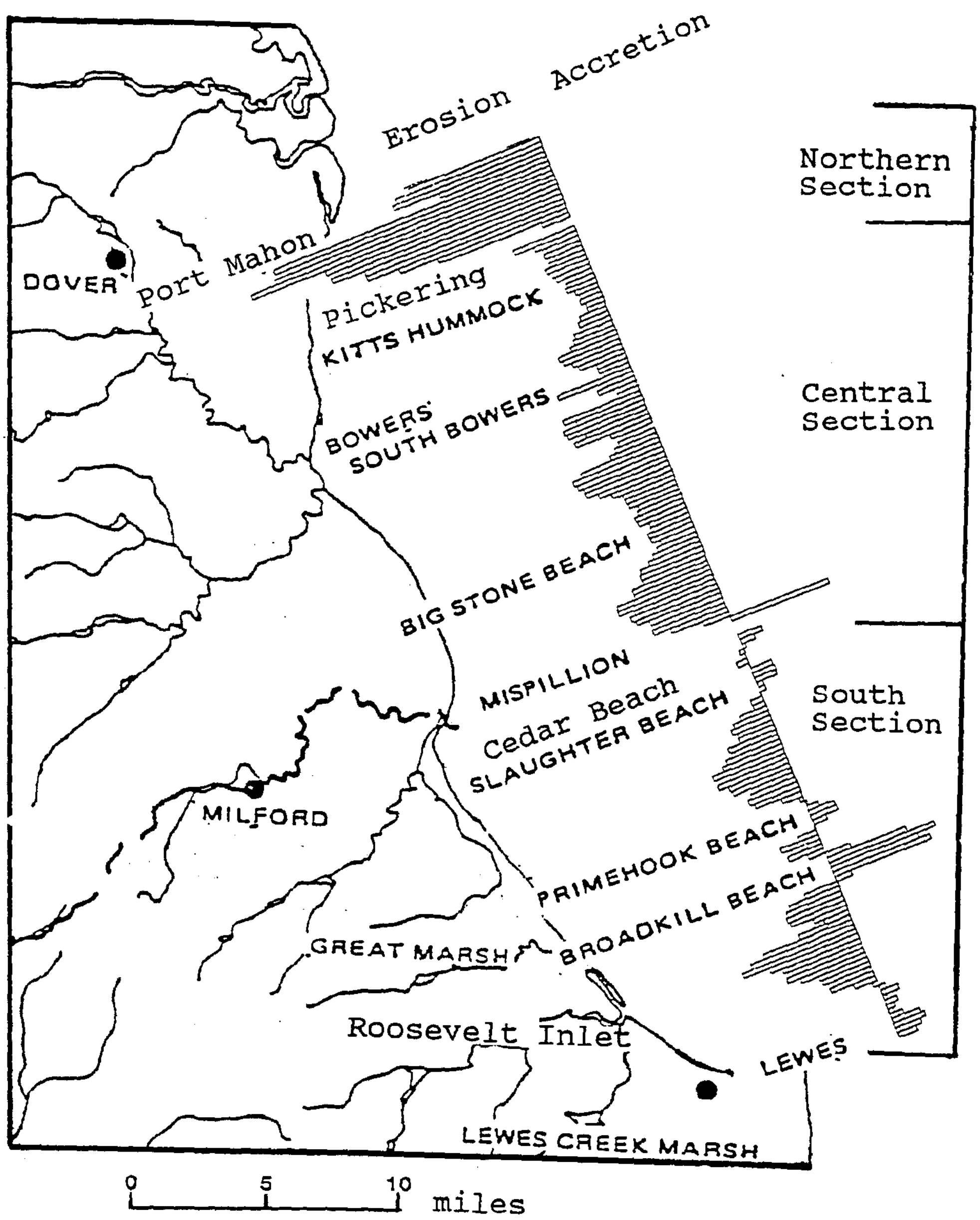


Figure 16. General pattern of shoreline changes along the west Delaware Bay coast: 1882g-1977.

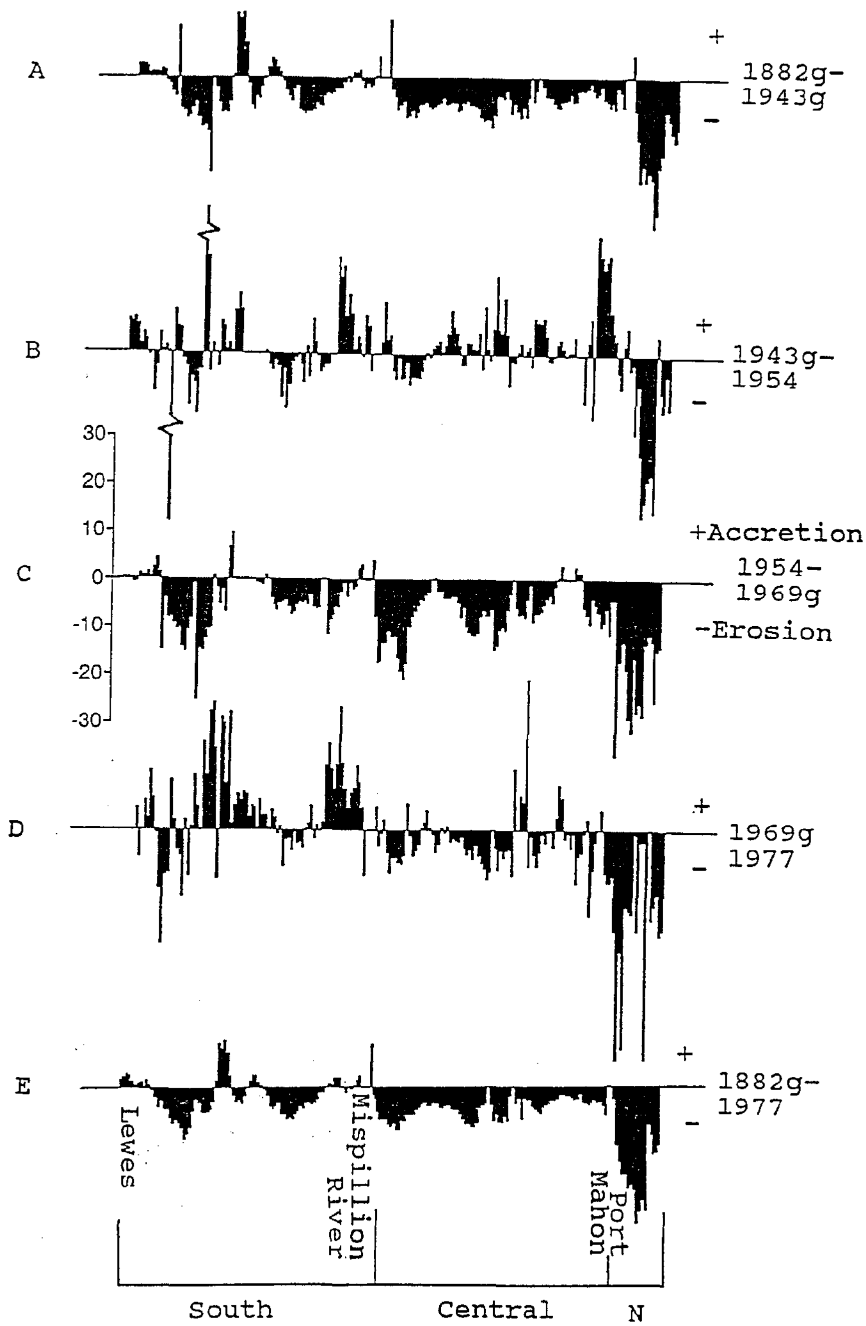


Figure 17. Shoreline change rates for each of the individual discrete study spans in feet per year.

storms. This period also experienced the greatest amount of variability throughout the study area. For all intents and purposes, the +0.5 ft/yr figure indicates no measurable change since 0.5 feet falls well within the established error range of $\pm$1.7 ft/yr. A pattern similar to 1943g-1954 is seen again in the 1969g-1977 graph (Figure 17D), a time during which only one severe storm occurred. It must be considered, when reviewing these rates, that they are averages of all 192 transects. The rate of shoreline recession is highly variable throughout the study area, and is best examined on a more location-specific basis.

The study area may be divided into three distinct coastal units according to geomorphic conditions and shoreline responses (Figure 16): (1) southern section; (2) central section; and (3) northern section. Table 6 lists the average rates of change for each section for each of the available time spans. Those same data are graphically represented in Figures 18 and 19. Full descriptions of each of the three sections follow.

The Southern Section

The southern section extends from Lewes northwestward to the Mispillion River, and includes transect lines #1 to #87. This section has experienced the greatest variability in shoreline change, both

*	Sequential Data Sets						Total Spans	
*	1842-1882g	1882g-1910	1910-1943g	1943g-1954	1954-1969g	1969g-1977	1842-1977	1882g-1977
N	-24.2	-19.3	-11.8	-12.3	-18.9	-25.8	-18.4	-17.2
C	-4.4	-6.1	-4.6	+2.6	-7.2	-2.4	-4.7	-4.8
S	N/A	N/A	N/A	+1.6	-4.7	+4.4	N/A	-1.7
± Range of Error:								
	±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1	±0.2

Table 6. Average rates of change for each of the three sections of the study area for each of the data time spans. *N=North; C=Central; S=South. N/A=Data not available.

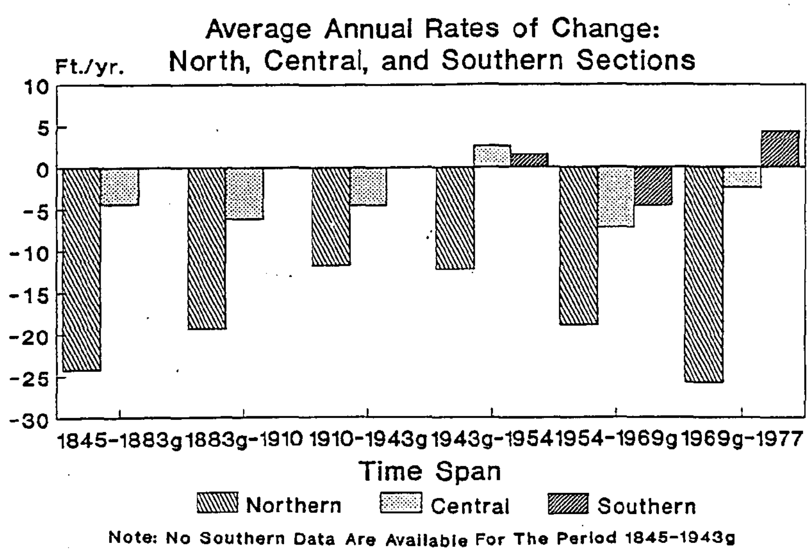


Figure 18. Temporal variations in shoreline change rates of each of the three sections of the study area. Graph depicts differences in shoreline change rates between discrete time frames and between the three sections of the study area.

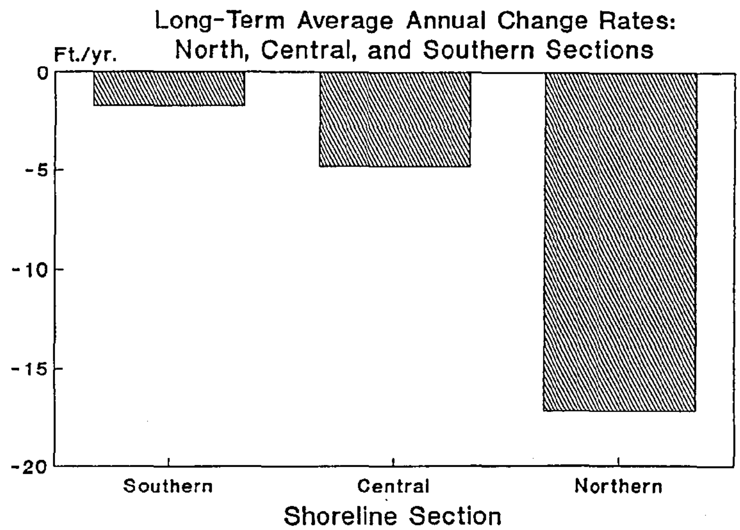


Figure 19. Spatial variations in shoreline change rates for each of the three sections of the study area. Graph depicts differences in long-term (1882g-1977) change rates between the three sections of the study area.

temporally and spatially. Throughout the study span, periods of pronounced erosion alternate with stability/ accretion suggesting that the shoreline is largely storm-driven (Figure 17). This section is comprised of nearly continuous washover barriers up to 450 feet wide (Maurmeyer, 1978). As noted in Chapter 2, several eroding Pleistocene necks and their subaqueous projections (Figures 2 and 3) supply sand to the littoral drift stream.

A qualitative examination of the aerial

photography indicates that the town beaches are almost always wider than those along undeveloped sections. Therefore, it could be inferred that there is a larger net quantity of sand in the developed areas. However, detailed sand volume analyses were not performed for this study.

Because of the overall shape of the Bay, this southern section has the longest fetch from the north through the northeast and, because of proximity to the estuary mouth, it is influenced by ocean swell waves (Figures 10 and 11). This section, therefore, experiences the highest wave energy in the study area, although it is still a relatively low energy coastline when compared with the open Atlantic coast.

The southern section has also experienced the lowest overall long-term erosion rates (Table 6) and even exhibits localized areas of accretion. This section is the most developed shoreline, with approximately 63% of the coastline occupied in some form (based on the most current USGS 7.5' quadrangle maps).

There are five locations within the southern section where long-term accretion has occurred: (A) Lewes/ Breakwater Harbor; (B) Broadkill Beach; (C) Primehook Beach; (D) Slaughter Beach; and (E) Mispillion River Inlet. Each of these areas correspond to the locations of nearby, updrift Pleistocene outcrops. The only area of human development not associated with accretion in the southern section is Roosevelt Inlet, located just west of Lewes Beach (transect lines #14-15; Appendices 2 and 3).

(A) Lewes Beach/Breakwater Harbor. The Lewes Beach/Breakwater Harbor area is the first of the accretionary areas (heading northward), with an average long-term annual growth rate of approximately +1.3 ft/yr (±0.2 ft; Table 7). The area from Lewes eastward has shown moderate overall accretion since the 1880's, with the bayward growth of the shoreline averaging +1.3 ft/yr (±0.3 ft) for transect lines 2-13. Transects measured along the Lewes Beach/ Breakwater Harbor are identified in Figure 20. Long- and short-term shoreline change data are tabulated for each of the transects in Table 7. Each of the periods tabulated suggest some accretion, ranging from a low of +0.5 ft/yr (±1.8 ft) during the period 1945-1969g, to a high of +3.3 ft/yr (±2.3) during the period 1969g-1977, although the error ranges are relatively high.

The southern section has experienced the greatest human development of any of the sections. Consequently, the natural coastal processes have been the most extensively interfered with in this section. At the easternmost extreme of the study area near Breakwater Harbor, rotational gyres caused by the tidal action and refraction of swell waves around Cape Henlopen tend to

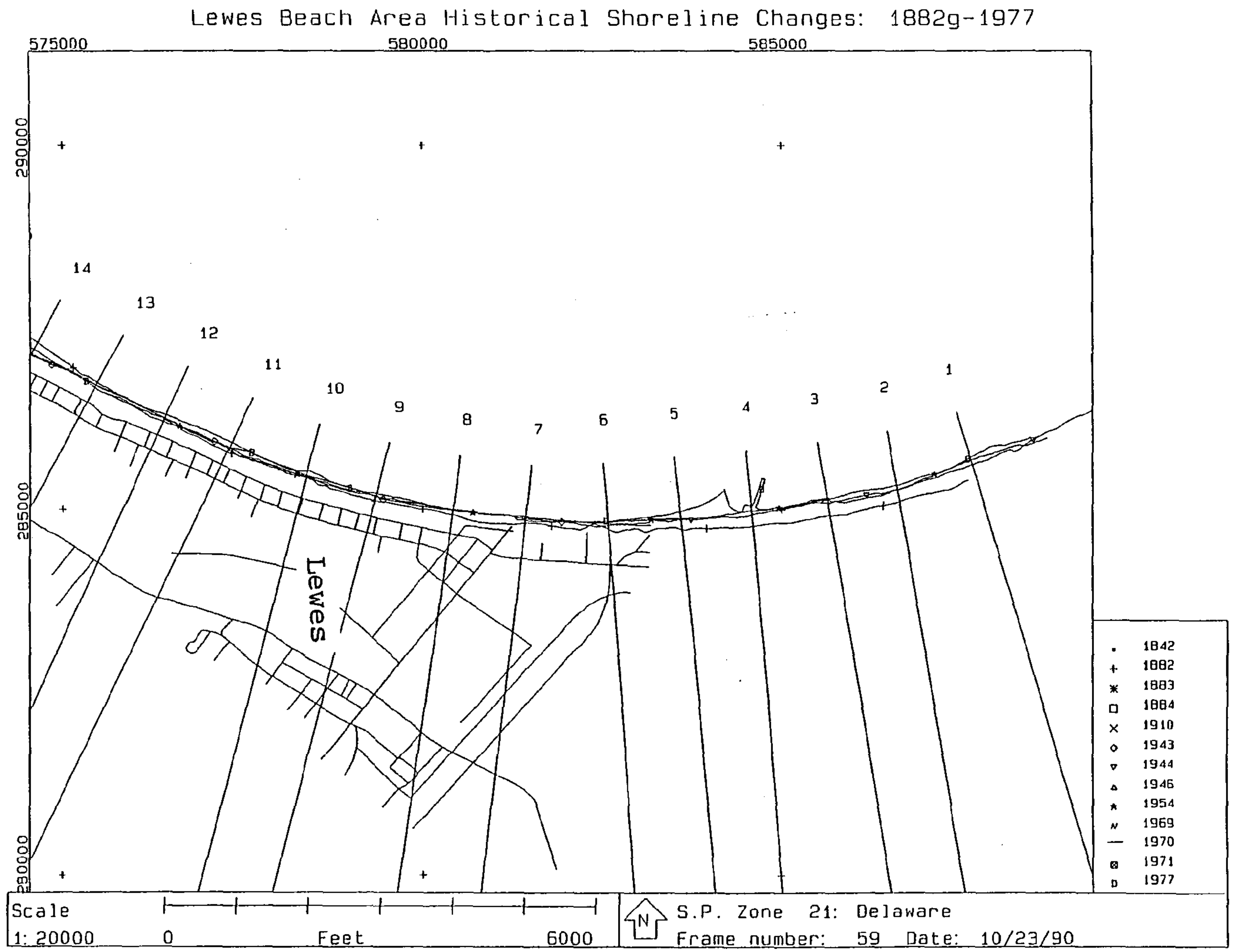


Figure 20. Index map of the Lewes Beach area depicting the locations of the transects.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
1	N/A	6.9	N/A	N/A	N/A
2	2.7	6.1	N/A	N/A	1.7
3	2.8	7.2	N/A	N/A	2.3
4	2.6	5.6	N/A	N/A	3.0
5	2.1	1.6	N/A	N/A	2.6
6	0.8	4.0	-0.9	4.6	1.2
7	1.1	2.6	-0.8	-5.6	0.4
8	1.1	-0.6	0.9	-0.1	0.8
9	1.0	-0.1	0.4	6.1	1.1
10	1.6	-8.4	0.6	2.7	0.3
11	1.3	-2.9	1.3	12.5	1.6
12	-0.6	4.0	0.2	6.7	0.6
13	-1.3	0.5	2.3	-0.6	-0.5
MEAN:	+1.3	+2.0	+0.5	+3.3	+1.3
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 7. Shoreline change data for the Lewes Beach/ Breakwater Harbor area (ft/yr). Locations of transect lines can be seen in Figure 20. N/A=No data available.

form a null area for longshore transport, thereby establishing conditions for deposition and accretion. This is reflected in the first 12 transect lines (Table 7). Construction of two sections of the inner breakwater in 1831 contributed substantially to harbor shoaling by directing flood tidal currents almost directly into this area. By the turn of the century, the gap between the two breakwater sections had been closed in an attempt to reduce the shoaling. This, combined with the construction of the outer breakwater

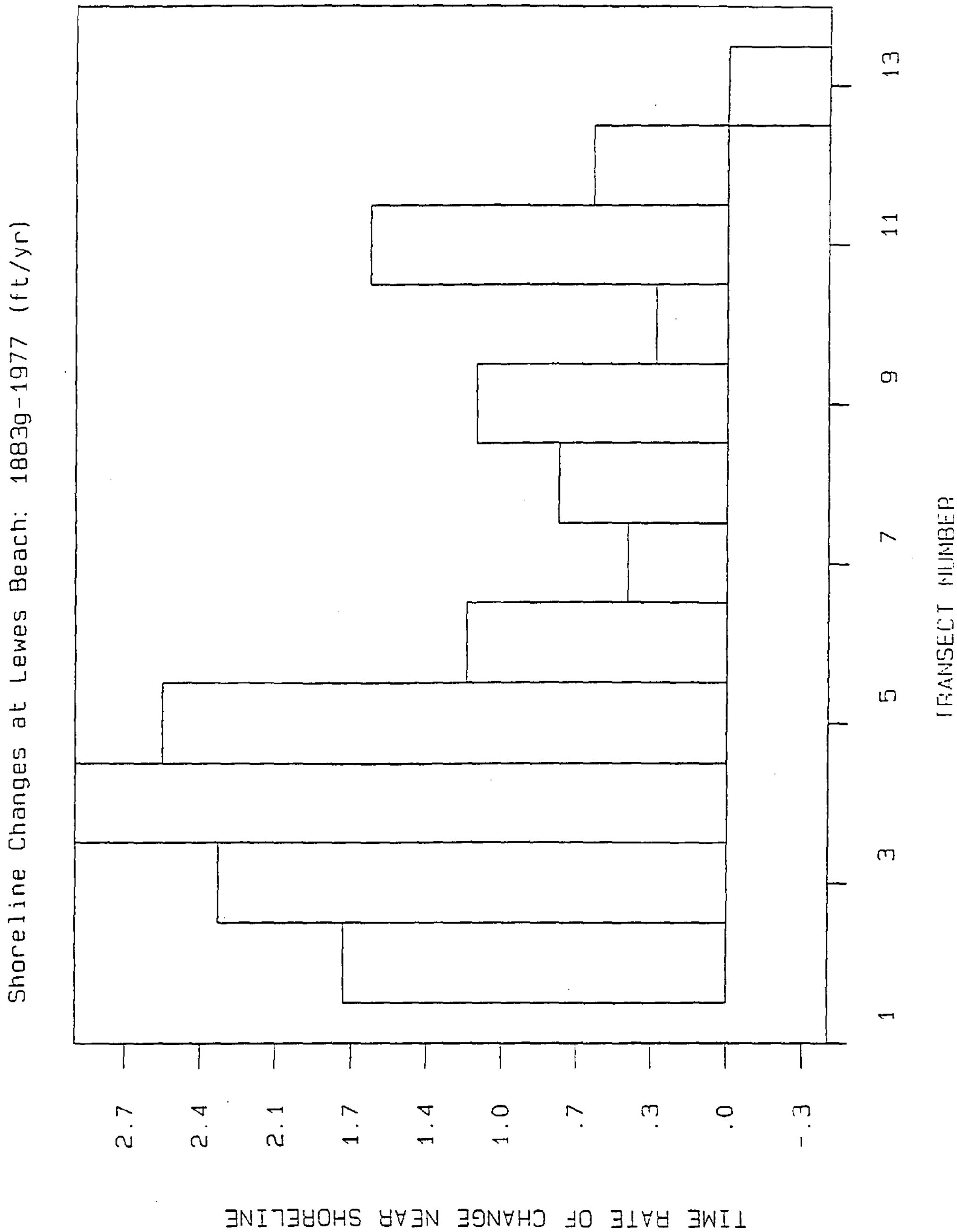


Figure 21. Histogram of the accretion rates along the shoreline of Lewes/Breakwater Harbor.

in 1910 and the extensive northward growth of the Cape, greatly reduced the supply of depositional material to the area (Kraft and Caulk, 1972).

During the period 1948-1950, six groins between 135 and 172 feet in length were placed along 4,200 feet of beach at the eastern end of the study area. This period of time falls within the 1943g-1954 time span which shows an increase in accretion rates (from +1.3 ft/yr (±0.3 ft) to +2.0 ft/yr (±1.7 ft; Table 7).

The Lewes coastline was further modified by the artificial placement of 516,700 cubic yards of sand on the beach between the years 1954 and 1963 (USACOE, 1966). Using the U.S. Army Corps of Engineers rule of thumb of one square foot of new beach for each cubic yard of sand placed (USACOE, 1984), this translates into roughly 50 feet of new beach (assuming 10,000 feet of fill, the approximate length of developed beach; R. Henry and T. Pratt, personal communication, 1990). Interestingly enough, the time period during which this material was placed (1954-1969g) was also the period which showed the lowest rate of accretion of only an average of +0.5 ft/yr (±1.2 ft). The most likely cause for this apparent incongruity was the occurrence of the infamous 1962 northeaster which caused such massive destruction and overall coastal erosion along the U.S. mid-Atlantic coast.

Of the six groins constructed between 1948 and

1950, there is no remaining evidence. With current accretion rates of +3.3 ft/yr (±2.3 ft), those structures could reasonably be expected to be buried by now (1990). Burial of the groins demonstrates that their impact on accretion was secondary and raises the question of why they were built in an area of long-term accretion. An Army Corps of engineers report stated that:

> "...investigations made by the Corps of Engineers in December, 1943...show that erosion and accretion had been in progress since 1843. At the site of the present [Roosevelt Inlet] jetties, the beach eroded approximately 350 feet between 1843 and 1926 [or -4.2 ft/yr, a figure which closely approximates the figures from this study for transect lines 14, 15, and 17, at the location of the inlet; Table 8], while during the same period, about 4,600 feet east of the inlet, the beach moved out into the bay approximately 200 feet from its 1843 location. Between 1937 and 1943 some slight accretion occurred east of the inlet..."
> (USACOE, 1966, p.F-10).

Yet, in the same report, they went on to describe the subsequent placement of the groins (without any apparent justification), concluding by stating that "... the six timber groins are completely covered..." (USACOE, 1966, p.F-11). It is unclear why these structures were constructed in what is an already accretionary area. Doubtless the groins effectively accelerated the trapping of sand from the littoral drift stream for a period of time (therefore accelerating accretion), although it appears that accretion would have occurred in any event.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
14	-3.0	1.3	4.1	-12.2	-2.0
15	-4.0	0.3	1.2	-23.8	-4.1
16	10.8	-55.9	-15.0	-9.5	-2.8
17	-6.4	8.9	-4.2	-9.0	-4.5
MEAN:	-0.6	-11.4	-3.5	-13.6	-3.4
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 8. Shoreline change data for the Roosevelt Inlet area (ft/yr). Locations of transects can be seen in Figure 22.

Approximately two miles west of Breakwater Harbor is Roosevelt Inlet (Figure 22; Plate II). Unlike the other areas of human occupation in this section, the inlet area has experienced a fairly consistent pattern of erosion (Table 8). In 1936-7 the Army Corps of Engineers opened the Broadkill River to the Bay at this point and stabilized the inlet with two 1700 foot jetties (USACOE, 1966). As would be expected, this interrupted the southeastward littoral drift.

It is obvious from the buildup of material on the northeast side of the inlet that the source for the sediment is from the northwest (Figure 22). Additional evidence of a southeasterly flow of drift in this area is apparent less than 2,000 feet northwest where a

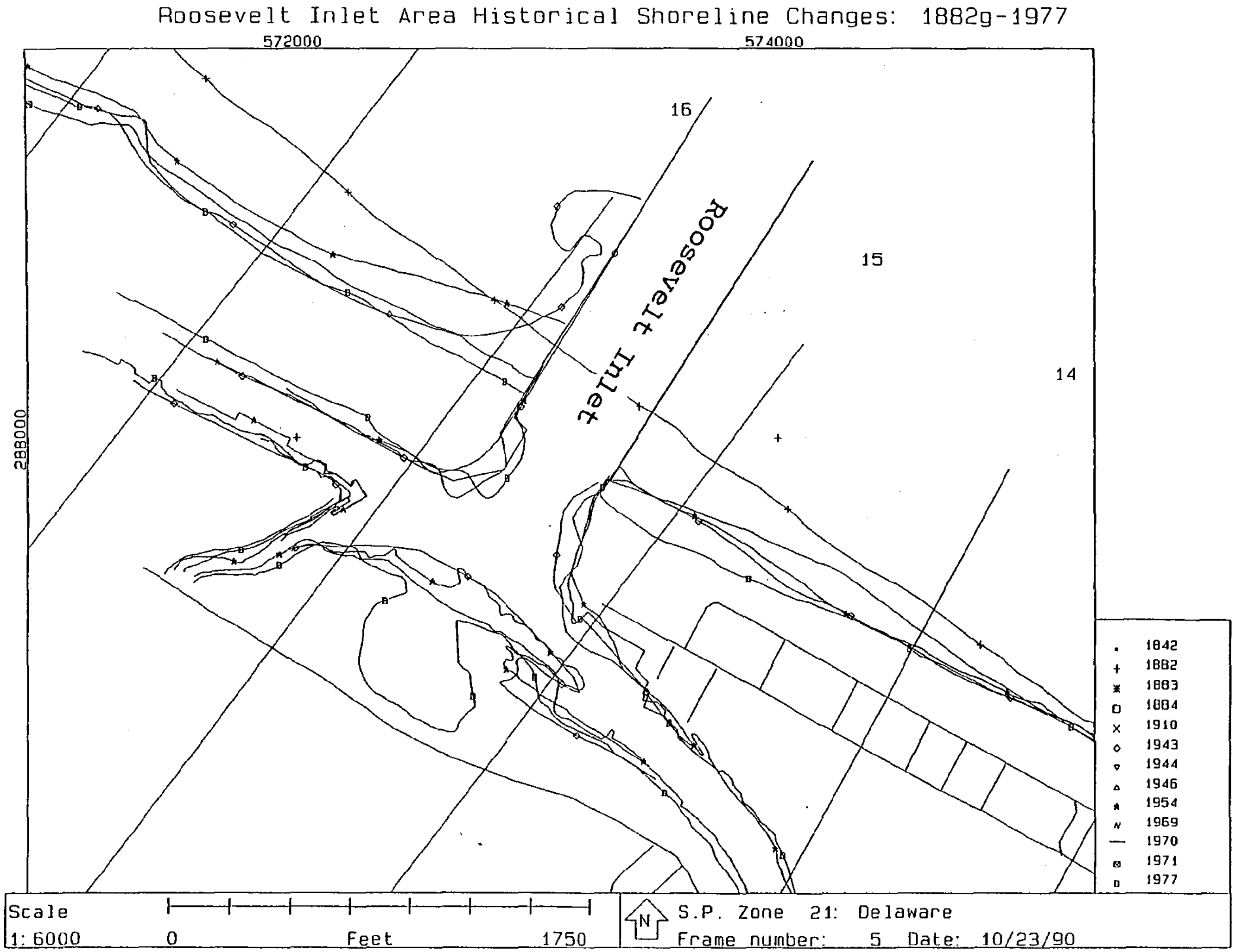


Figure 22. Map of historic shorelines in the area of the Roosevelt Inlet depicting the locations of the transects.

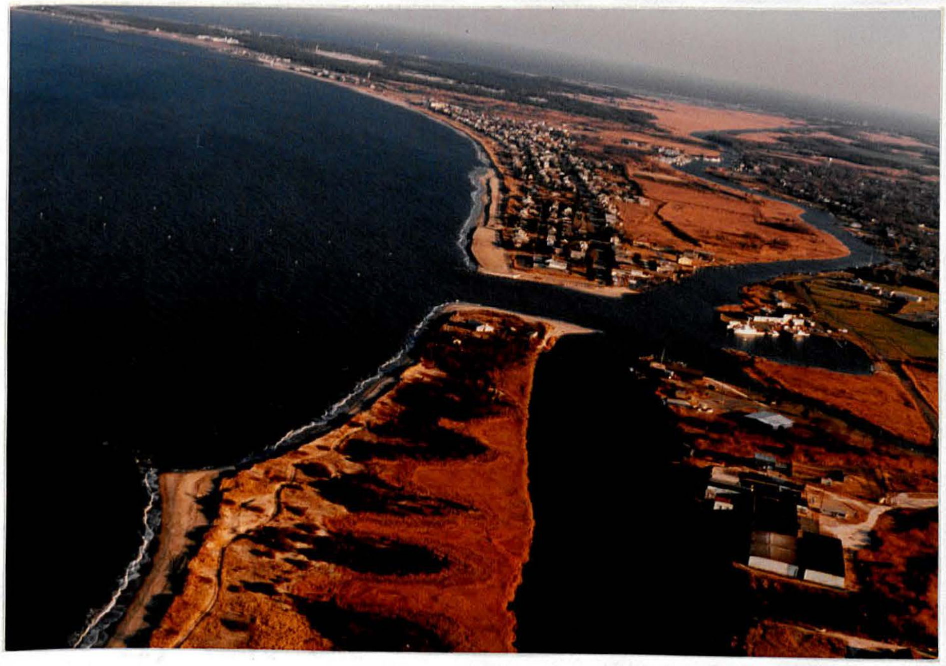


Plate II. Oblique aerial photograph of Roosevelt Inlet and Lewes. The remains of an old shipwreck can be seen in the foreground (December, 1990).

shipwreck between 1882g and 1943g has resulted in a depositional pattern showing updrift growth and downdrift erosion (Figure 22, extreme northwest corner of map; Plate II, foreground).

Net changes just south of Roosevelt Inlet (transect line #15, Table 8) indicates an average of -4.1 feet of recession between 1882g and 1977 (±0.2 ft/yr). However, between the years 1943 and 1963, substantial volumes of inlet-dredged material were placed on the south side of the inlet (USACOE, 1966). This artificial input shows up most clearly in the fluctuations between the 1954, 1969g, and 1977 shorelines where there was a bayward jump of the shoreline between 1954 and 1969g, followed by recurrent subsequent erosion by 1977. This input also appears in the transect data along lines 14 and 15 for those same time periods. Resumption of erosion for that area subsequent to 1969g would suggest that, while not lasting, the effort did have some short-term positive effect on controlling erosion.

Although there is net erosion on both the north and south sides of the inlet, it is clear from the map (Figure 22) that the north shoreline is less eroded than that to the south. This indicates that continual erosion is taking place on both sides of the inlet, but with a slightly higher supply of material from the north. Much of this material is then clearly prevented from subsequently reaching the south side of the jetties, either by entrapment or deflection out into the Bay.

(B) Broadkill Beach. Erosion, averaging -7.4 ft/yr (±0.2 ft/yr) predominates northwestward of Roosevelt Inlet until about one mile south of the town of Broadkill Beach at transect line #27 (map 8, Appendix 1). At this point the juncture of the Broadkill River and Broadkill Sound had been opened to the Bay between 1882g and 1943g with barrier demise. This resulted in the rather astounding, but misleading, net erosion along transect line #27 of -1,206 feet for that single period. The inlet subsequently filled in and closed again between 1943g and 1954. Net accretion along that same transect line for that time period was an equally dramatic +722 feet.

Farther north, in the immediate area of the town of Broadkill Beach itself, closure of another inlet into Broadkill Sound between the years 1882g and 1943g resulted in an anomalous bayward displacement of the shoreline. Total net accretion between transects 35 and 40 for that time span (1882g-1943g) averaged +473 feet, with a maximum net accretion of +815 feet along transect line 38 (Appendix 2).

This, of course, strongly indicates a north-westerly littoral drift as opposed to the obvious southeasterly drift observed only a few miles to the southeast. The presence of a nodal point south of Broadkill would explain the drift reversal. As already noted in Chapter 2, there is a nodal point or reversal in the littoral drift somewhere between Roosevelt Inlet and Broadkill Beach (Strom, 1972; USACOE, 1966; Figure 10). The rapid erosion rates of -10 ft/yr or more at transects #20-27 suggest that this is the location of the nodal point since sediments being lost to the north and south must result in erosion. Thus, at Broadkill Beach, the longshore sediment transport has clearly changed direction toward the northwest.

The displacement of material from southeast to northwest, closing the inlet, is diagrammed in Figure 23. The shoreline change map clearly shows that there was a massive displacement of material in that direction between 1882g and 1943g, as beachfront material was transferred into the open inlet, eventually closing it. Much of the town of Broadkill Beach is today constructed on what amounts to very recently accreted sand. Plate III is an oblique aerial photograph of the Broadkill area looking north. The photograph shows the part of the town which is built on the newly generated land in the distance.

When the Broadkill Beach area is broken down into two distinct zones, the southern erosionary zone and the northern accretionary zone, a dynamic balance between the two becomes quickly apparent during the period 1882g-1943g. Tables 9 and 10 show the average annual rates of change for each of the two areas. Transects measured along Broadkill Beach are identified in Figure 23. A histogram of the entire Broadkill Beach area (lines #31-40), illustrating the abrupt reversal, is shown in Figure 24. Between the years 1882g and 1943g, the southern half of the Broadkill area averaged an annual loss of -6.7 ft/yr ($\pm$0.3 ft/yr), while at the same time the northern half averaged an annual gain of +7.6 ft/yr ($\pm$0.3 ft/yr).

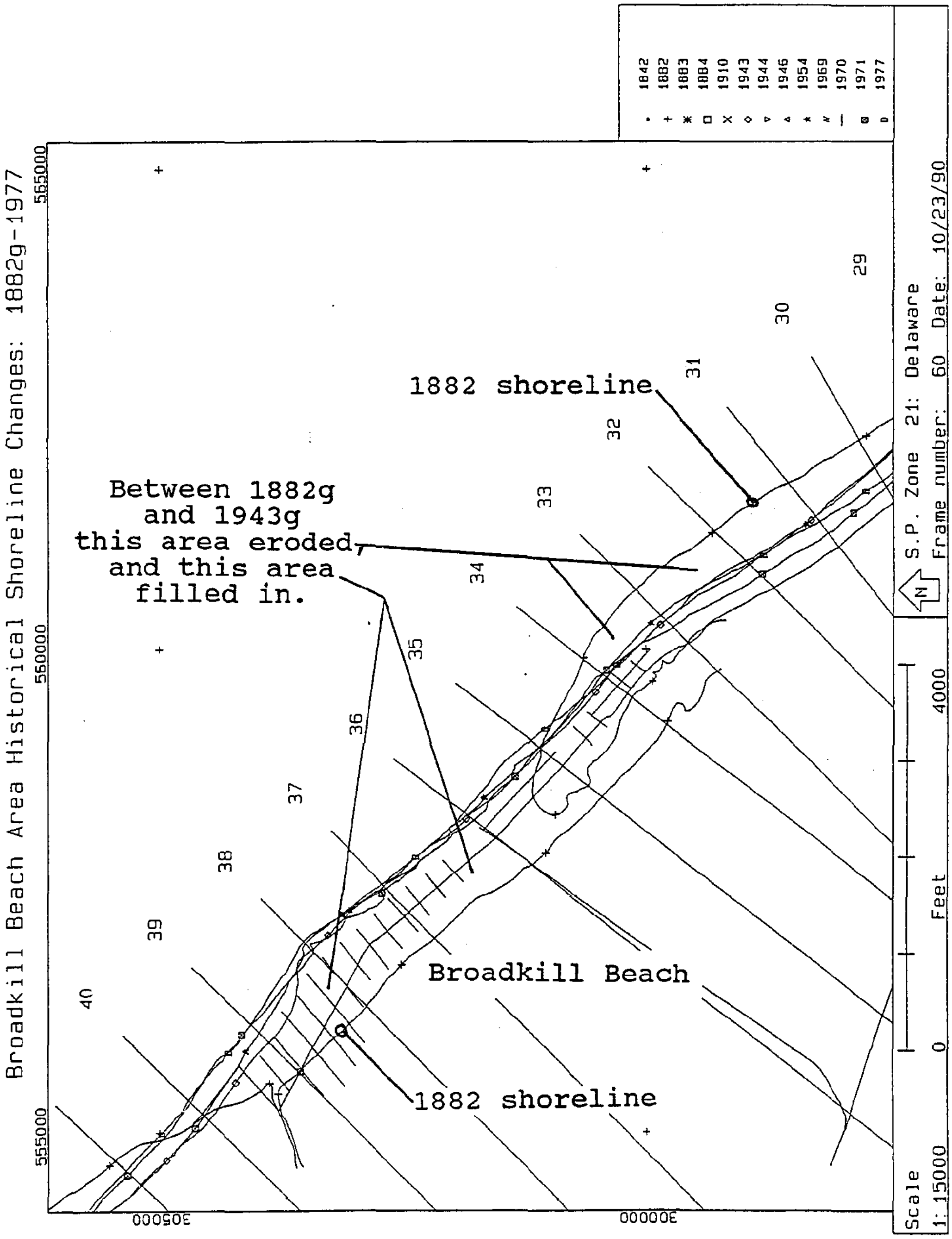


Figure 23. Index map of the area of Broadkill Beach depicting the locations of the transects and the transfer of material during the period 1882g-1943g.

Plate III. Oblique aerial photograph of the town of Broadkill Beach, looking north. The part of the town built on the newly consolidated land is seen in the upper left portion of the photograph. There is no evidence remaining of the groin field (August, 1990).

YEAR GROUPS ARE:
1) 1842; 2) 1882g; 3) 1910; 4) 1943g;
5) 1954; 6) 1969g; 7) 1977

TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
31	-7.3	0.1	-12.7	24.9	-5.4
32	-7.1	-3.0	-10.6	26.8	-5.1
33	-7.3	6.7	-10.2	17.2	-4.7
34	-5.1	5.3	0.6	-10.2	-3.2
MEAN:	-6.7	+2.3	-8.2	+14.7	-4.6
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 9. Shoreline change data for the southern half of the town of Broadkill Beach (ft/yr). Locations of transect lines can be seen in Figure 23.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
35	0.4	0.7	-1.7	23.6	1.5
36	13.3	1.9	-5.4	22.4	9.2
37	12.3	0.4	-2.1	9.8	8.2
38	13.4	8.8	-6.9	24.8	9.9
39	7.2	12.4	6.7	1.5	7.4
40	-1.2	9.1	9.6	5.2	2.4
MEAN:	+7.6	+5.6	0.0	+14.6	+6.4
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 10. Shoreline change data for the northern half of the town of Broadkill Beach (ft/yr). Locations of transects can be seen in Figure 23.

After 1943g, both north and south areas began to experience more uniform rates of change, each area ultimately showing nearly identical accretion of +14.6 and +14.7 ft/yr during the period 1969g-1977 (±2.3 ft/yr). This indicates the continued presence of a sediment source to the south. That source would be at the location of the nodal point where erosion rates are quite high (lines #20-27; Appendix 2). Stratigraphic evidence obtained by Kraft, et al. (1975) indicates that the area had received a relatively large supply of sand and gravel sometime during the last 200 years. It is believed that much of this material came from sediment movement around Cape Henlopen, building

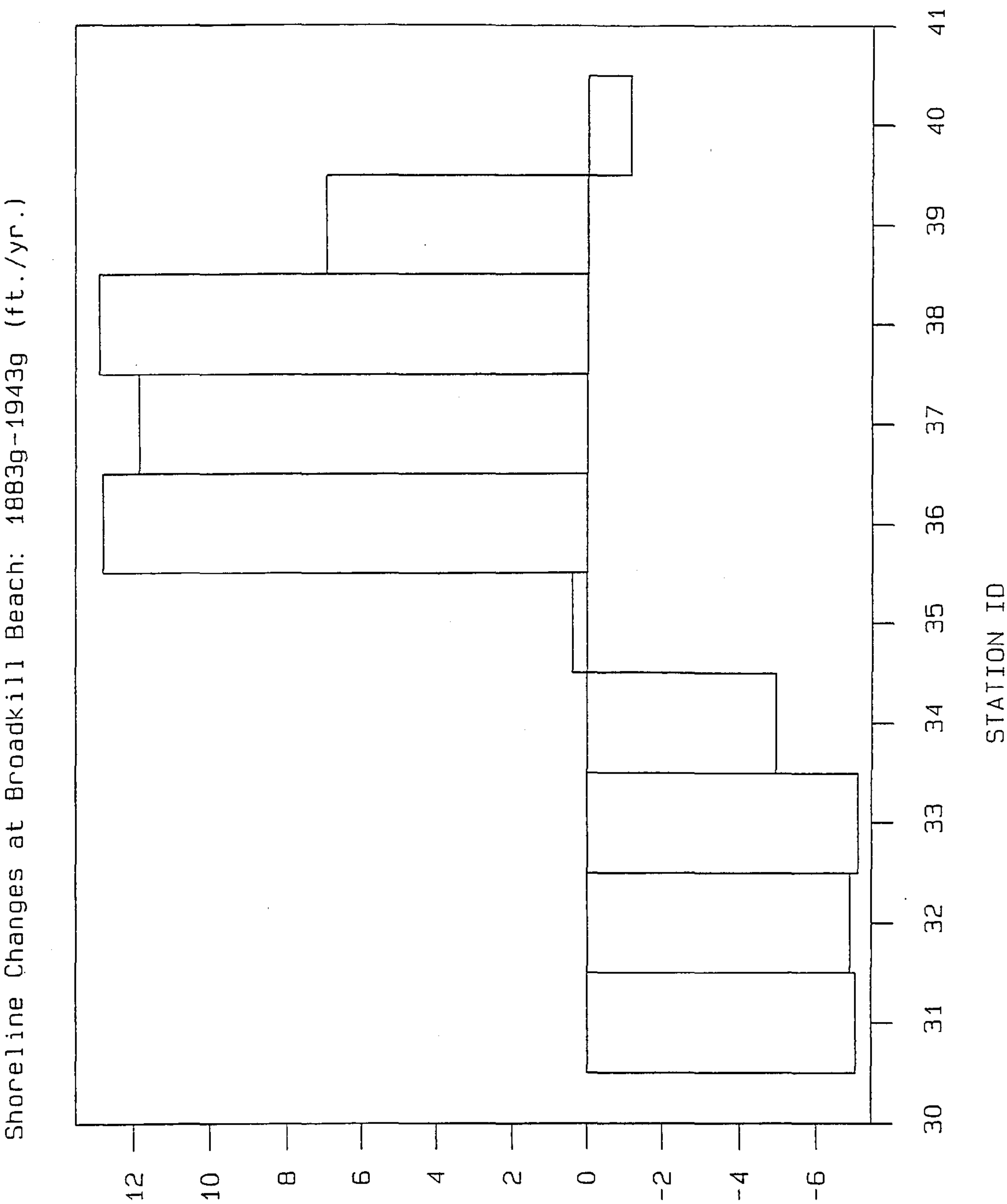


Figure 24. Histogram of transect lines #31-40 located at Broadkill Beach for the period 1882g-1943g.

seaward the area of the present node (Kraft, et al., 1975). Construction of the two breakwaters near the Cape, however, subsequently interrupted that flow causing the current to reverse direction along the southern section. It is this material, combined with erosion of the Broadkill Pleistocene neck, which is presently supplying the sandy material to Broadkill and Lewes (Figure 3).

Placement of a groin field appears to have contributed to a continued general long-term pattern of accretion. The groin field was constructed between 1950 and 1954 and consisted of 5 groins ranging in length from 186 to 199 feet (USACOE, 1966). The historic shoreline maps of the area (maps 10 and 11, Appendix 1) again illustrate the obvious northwest direction of drift. The plot of the most current (1977) shoreline is beyond the most Bayward extension of the groins, suggesting that the structures have been buried. Field examination of the beach in 1990 shows no remaining evidence whatsoever of the groins (Plate III). This suggests that these groins, like those at Lewes, were probably of secondary importance in an already accreting environment.

In addition to the groin field, the State of Delaware also placed nearly 200,000 cubic yards of material on the beach between 1957 and 1961 (USACOE, 1966), adding roughly 50 feet of new beach width. It is interesting to note that the shoreline plots indicate erosion during the 1954-1969g period. The most likely cause for this would, again, be the extraordinarily destructive northeaster which struck the area in 1962. It seems clear that, like Lewes to the south, had this sand not been placed, the erosion rates would have been considerably higher.

(C) Primehook Beach. The area of Primehook Beach is the third of the five areas of accretion. In this area the thickness of the sand suggests a relatively nearby Pleistocene highland undergoing erosion which is supplying the beach (Kraft and John, 1976). This would most likely be the Primehook Neck which approaches to within one-quarter mile of the shoreline and is located just south of the area (Figures 2 and 3). Since the longshore drift here is in a net northwesterly direction, the material eroded from that neck would supply Primehook with ample sand.

This shows up as a small amount of net long-term accretion which occurred between lines 47 and 52 (Table 11), averaging just over 1 ft/yr (±0.2 ft/yr). The highest average annual rate of erosion of -1.8 ft/yr (±1.7 ft/yr) occurred during the period 1943g-1954. This was followed by a -0.6 ft/yr (±1.2 ft/yr) rate of recession which took place during the period 1954-1969g. It was during this latter period that the U.S. Army Corps of Engineers placed over 20,000 cubic yards of dune and beach sand along 3,900 feet of shoreline (USACOE, 1966). It is highly unlikely, however, that this very small amount of sediment had any significant effect on erosion rates. Transects measured along Primehook Beach are identified in Figure 25.

The shoreline northward from Primehook to Slaughter Beach is located along the Slaughter Neck Pleistocene neck (Figures 2 and 3). This segment of shoreline (maps 16-20, Appendix 1) appears to show a fairly consistent pattern of retreat, albeit sporadic in nature.

YEAR GROUPS: 1) 1842; 2) 1882g; 3) 1910; 4) 1943 g 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
47	2.0	N/A	N/A	4.6	1.3
48	3.8	N/A	N/A	0.5	2.4
49	3.3	0.5	-0.8	6.4	2.4
50	2.0	-2.6	-0.9	3.2	1.0
51	1.0	-3.7	-1.3	3.1	0.2
52	-0.7	-1.4	0.7	0.5	-0.4
MEAN:	+1.9	-1.8	-0.6	+3.1	+1.2
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 11. Shoreline change data for the area of Primehook Beach area (ft/yr). Locations of transects can be seen in Figure 25. N/A = No data available.

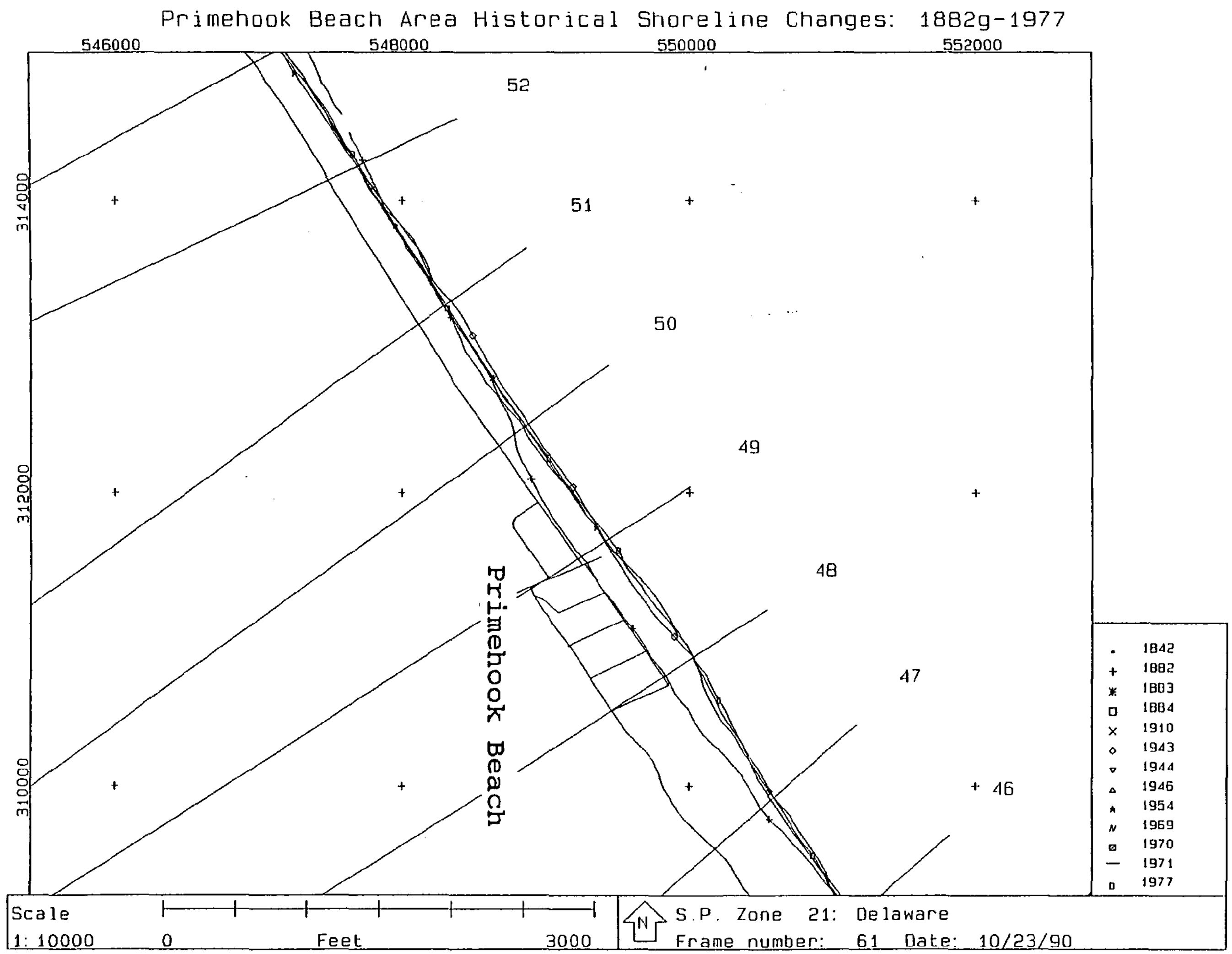


Figure 25. Index map of the area of Primehook Beach depicting the locations of the transects.

(D) Slaughter Beach. Slaughter Beach is the fourth area in the southern section which has experienced some limited long-term accretion. Transect lines #74-80 cross the shorelines of the town of Slaughter Beach. In general, the area experienced an oscillatory pattern of low accretion or limited erosion, followed by periods of substantial accretion. Long-term analysis shows an average annual accretionary rate of +1.0 ft/yr (±0.2 ft/yr). The highest single rate of accretion occurred along transect line #77 during the period 1969g-1977 at +26.0 ft/yr (±2.3 ft/yr). The highest rate of erosion, at -11.5 ft/yr (±1.2 ft/yr) was along line #74 during the period 1954-

YEAR GROUPS ARE:
1) 1842; 2) 1882g; 3) 1910; 4) 1943g;
5) 1954; 6) 1969g; 7) 1977

TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
74	-0.9	20.2	-11.5	12.7	-0.1
75	0.3	16.1	-8.5	8.7	0.6
76	-0.9	18.3	-7.3	13.7	0.5
77	0.9	7.9	-5.7	26.0	1.9
78	1.0	12.5	-5.8	14.1	2.0
79	1.4	8.3	-2.7	8.7	1.9
80	-0.6	0.9	-0.8	4.6	-0.1
MEAN:	+0.2	+12.0	-6.0	+12.6	+1.0
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 12. Shoreline change data for the town of Slaughter Beach (ft/yr). Locations of transect lines can be seen in Figure 26.

1969g. Table 12 lists the shoreline rates for the seven transects which cross the town. The locations of the transects measured are illustrated in Figure 26.

Slaughter Beach is another area where groins and beach replenishment were employed to stabilize the beach. A field of 20 timber groins was built during the 1940's through the 1950's (USACOE, 1966). A significant increase in accretion rates (+12 ft/yr, up from +0.2 for the previous period, Table 12) occurred during that same time period. This, therefore, appears to indicate that the groins contributed to the observed high accretion of the area. Nevertheless, slight apparent (+0.2 ft/yr) accretion can be observed in the shoreline change maps dating as far back as the 1880's, prior to groin construction (Table 12). Since this small short-term figure falls within the ±0.3 ft/yr error range for that time span, some slight erosion may in fact be occurring. In any event, the very small figure indicates that this segment of shoreline was fairly stable during that time period.

The effects of three of the groins placed by 1943g are clearly visible in the plot of that year group, again confirming the drift direction from the southeast (Figure 26). The 1954 shoreline plot appears to show the subsequent effects of the groins through Bayward growth. The later 1977 shoreline has subsequently retreated along the southern half of the town (lines

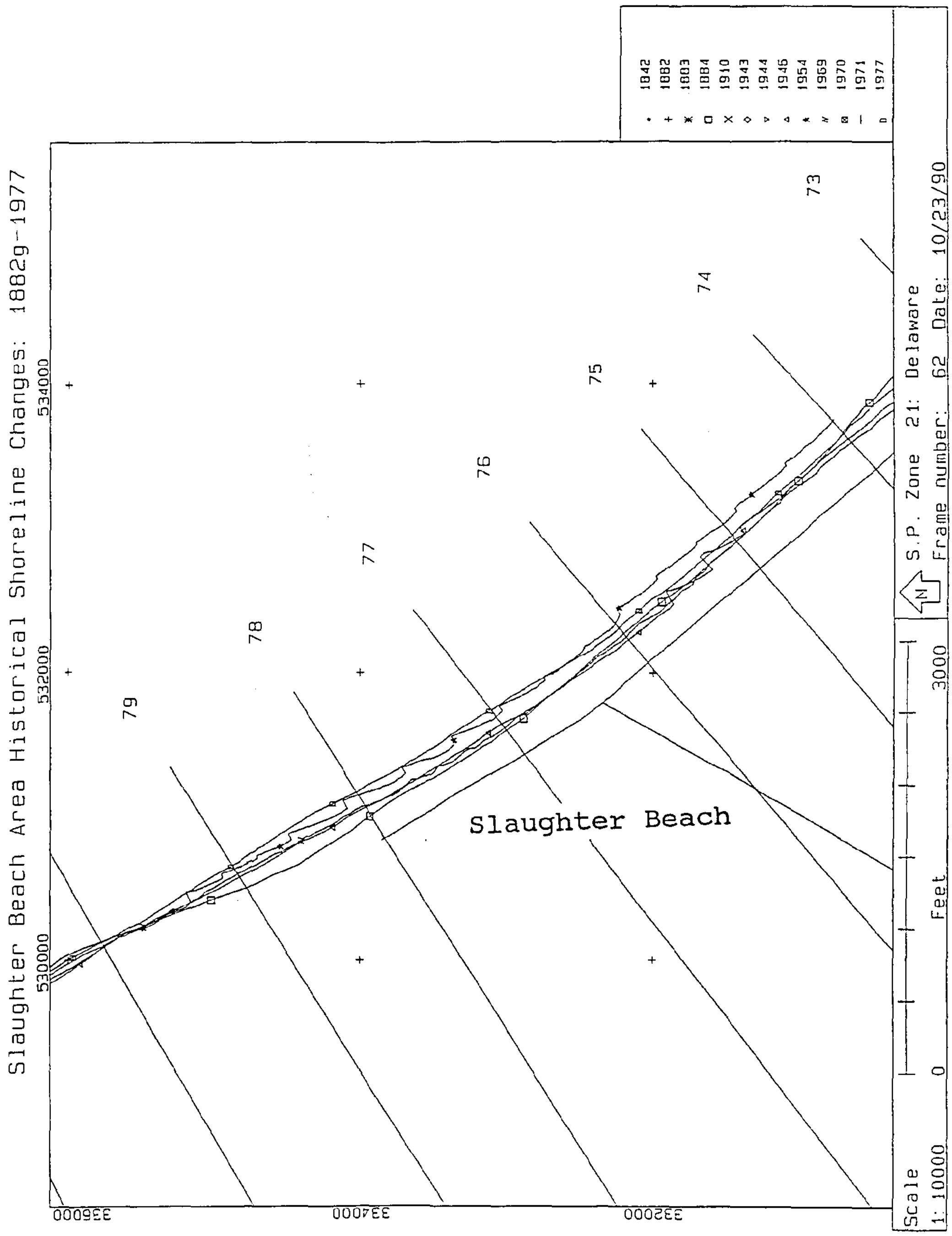


Figure 26. Index map of the Slaughter Beach area depicting the locations of the transects measured.

#74-76), but shows no evidence of the groins. This is probably due to the destruction through time of the wooden groin structures. Field examination of the beach in 1990 shows no evidence whatever of the groins at high tide. The surface photograph in Plate IV was taken at the location of the Slaughter Beach groin field in August 1990.

Between 1958 and 1961, 214,000 cubic yards of sand were placed on the beach, followed by the placement of an additional 57,000 cubic yards in the aftermath of the 1962 storm. This translates into roughly 30 feet

Plate IV. Photograph taken at the location of the groin field at Slaughter Beach. No evidence of the structures remains (August, 1990).

of new beach. That input is not apparently reflected in the transect data as that time period showed an average annual loss of -6.0 ft/yr (±1.2 ft/yr). This pattern of storm-induced recession is much like that seen at Primehook and Broadkill Beaches, which also showed a period of significant erosion between 1954 and 1969g.

The sediments in this area are not particularly erosion-resistant. Under a thin veneer of sands and gravels at the present-day beach, a thick layer of lagoonal muds and peat extends down some 50 feet to the Holocene-Pleistocene boundary (Kraft and John, 1976). In addition, the barrier is backed by nearly a mile of marsh before the Pleistocene highlands are encountered. The erosive nature of the material indicates a relatively nearby source of eroding material to explain the generally positive growth of the area. The source area for the long-term accretionary material is probably the eroding Slaughter Neck Pleistocene headland located just south of the town which, like the Primehook Neck, also approaches to within one-quarter mile of the beach and supplies sand-sized material to the northward flowing littoral drift stream (Figure 2).

(E) <u>Mispillion River</u>. Approximately 1.5 miles north of Slaughter Beach is the Mispillion River Inlet which is stabilized with a pair of jetties extending over one mile out into the Bay. This is the last of the major engineering structures found on the shoreline moving north and is the fifth and last area of long-term accretion (+3.0 ft/yr, ±0.2 ft/yr) observed in this study. However, the relatively high average rate of accretion is largely an artifact of the sudden buildup of material on the north side of the inlet following jetty construction.

Examination of the shoreline plots in Figure 27 clearly shows some of the effects of inlet stabilization. A large area of material grew up along most of the length of the south jetty of the inlet subsequent to its construction in the 1930's. A widening southward growth along the jetty continued until 1954. Since then the shoreline has remained relatively stationary. This is probably due in large part to sediment trapping at Slaughter Beach to the south. Some limited marsh accretion is currently occurring along the south jetty (Plate V). There is no longer any marsh along the north jetty. There is also presently a wide breach between the base of the north jetty and the barrier island. Table 13 lists the measurements taken along the transect lines illustrated in Figure 27. Line #86 is to the south of the inlet and lines #90-91 are to the north. Measurements along the two closest lines to the inlet, while variable, do show long-term accretion occurring on both north and south sides of the jetties.

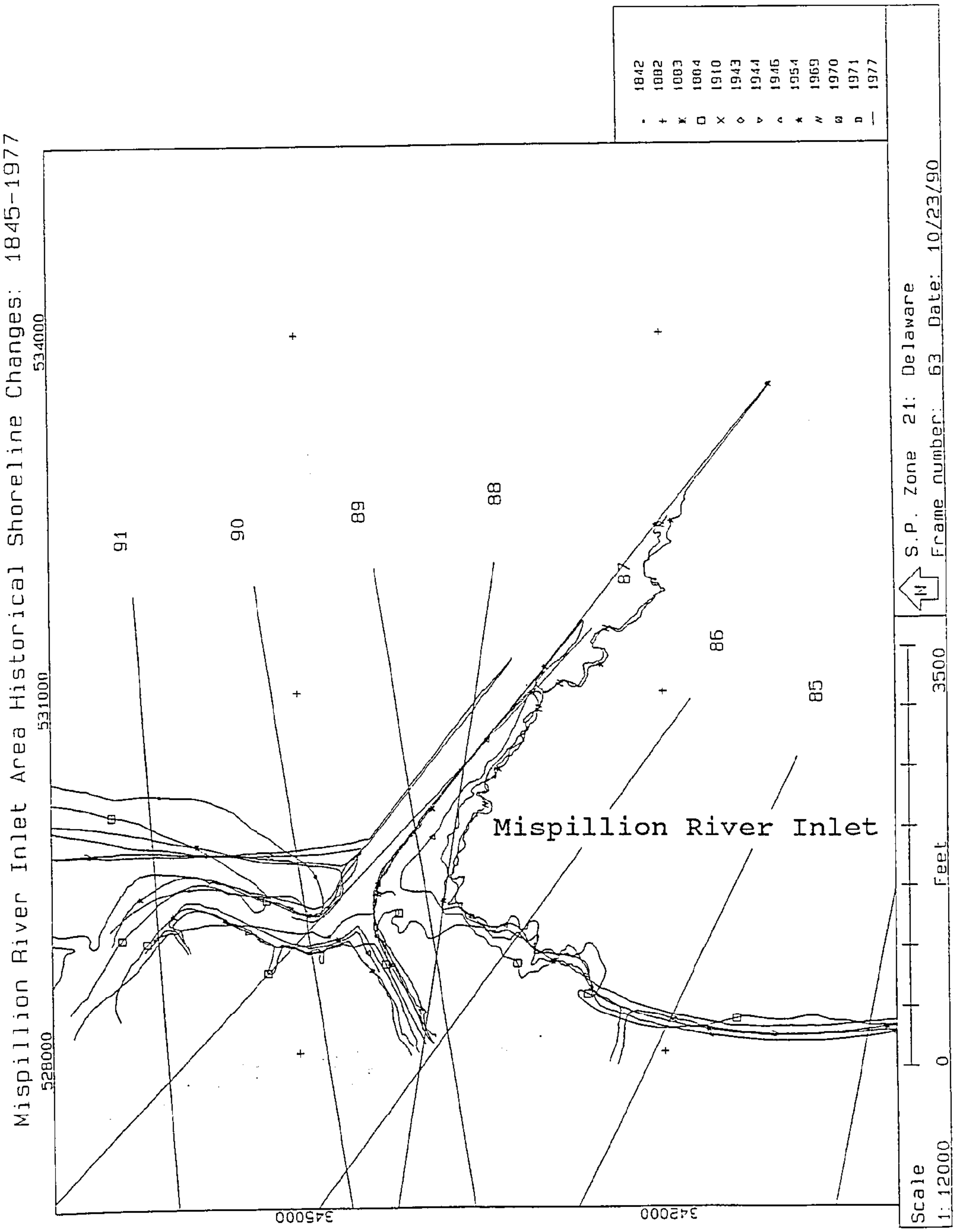


Figure 27. Index map of the Mispillion River Inlet area depicting the locations of the transects.

The large size of the jetties would be expected to have a significant effect on sediment transport, and the inlet area does show some net accretion (Figure 27). In fact, accretion appears to be occurring on both the north and south sides of the jetties (transect lines #84-86 and 90, Appendix 2; maps 24-25, Appendix 1; Figure 27). Cedar Beach, intersected by transect lines #84-86, is located near the tip of the Cedar Neck Pleistocene highland (Kraft, et al., 1975), which is most likely the source area.

The historic build-up on the north side of the inlet is consistent with a southward littoral drift,

Plate V. Oblique aerial photograph of the Mispillion River Inlet. Marsh accretion can be seen along the south jetty. A large breach between the base of the north jetty and the barrier island is visible in the left side of the photograph (August, 1990).

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 2-4	4-5	5-6	6-7	2-7
86	4.2	-3.7	3.0	-9.5	2.2
90	11.9	2.3	3.8	4.9	9.1
91	-2.7	10.8	-7.9	-3.1	-2.4
MEAN:	+4.5	+3.1	-0.4	-2.6	+3.0
	± Range of Error:				
	±0.3	±1.7	±1.2	±2.3	±0.2

Table 13. Shoreline change data for the area of the Mispillion River Inlet (ft/yr). Locations of transects can be seen in Figure 27.

suggesting that this is a convergence point between two littoral cells. In fact, Maurmeyer's (1978) current measurements for Big Stone Beach, approximately four miles to the north, indicated a southerly flow. A statement in a USACOE report (1966) that "The southern migration of the river inlet at the mouth of Mispillion River was halted by the construction of jetties in 1939" (USACOE, 1966, p. 37) would seem to lend further support. The idea finds additional support in the transect data of this study for lines #96-100 which show the relatively high long-term (1882g-1977) average per year rate of recession of -8.4 ft/yr (±0.2 ft/yr). It is, therefore, entirely probable that some of this material is being transported in a net (but probably weak) southerly direction. Why such a reversal in the drift direction might have taken place is unclear.

Field investigations in 1990 revealed a large breach in the barrier north of the north jetty which, according to interviews with long-term residents, occurred during the winter of 1984. The breach was filled in two years later with a rubble wall, but erosion at the southern end has resulted in yet another breach some 500 feet wide which is continuing to widen. There is no discernable erosion at the northern end of the rubble wall. This breach can be seen in the aerial photograph in Plate V.

Clearly, the Mispillion River is presently seeking to migrate to the north as the northern barrier erodes and thins, and will succeed unless some action is taken to permanently close the new inlet. The location of the breach relative to the nearby towns, once protected by the barrier island, indicates that this new opening to the Bay may make those towns substantially more susceptible to storm damage. The extremely poor condition of the jetties themselves is no doubt contributing to this migration.

This situation would now seem to indicate a present northerly direction of drift. Conversely, shoreline changes at Bowers Beach, farther to the north, indicate a southerly migration of the St. Jones River mouth (map 41, Appendix 1), yet spit development and migration of the relict channel between 1842 and 1882g (map 36, Appendix 1) indicate a northerly drift pattern. The pattern is again reversed in the south-oriented development of a spit on the 1977 shoreline (map 37, Appendix 1). It therefore seems likely that the net littoral drift is nearly zero, with the direction periodically changing from north to south. This idea of periodic local reversals in drift direction is supported by Maurmeyer's (1978) field measurements which also indicate numerous reversals in the current direction (Table 2). Furthermore, observations by Kraft and John (1976) indicate that the littoral drift patterns for much of the area are not yet fully understood in terms of direction and magnitude.

Central Section

The central section, extending from Mispillion River Inlet to just north of Pickering Beach (transect lines #90-173), is characterized by progressively narrowing and thinning barriers with intermittent breaks where the backbarrier marsh extends to the shore. Barrier widths in this section range from less than 100 feet up to about 250 feet, with a maximum thickness of around 6 feet (Maurmeyer, 1978). Only about 17% of the shoreline in this section is occupied. Consequently, the extent of shoreline engineering is substantially lower than that which occurs in the southern section.

The earliest (1842) data show this section to be entirely erosional, having experienced no areas of any long-term (1882g-1977) accretion. However, there have been some areas of short-term progradation (Figure 16). This irregular pattern of regression through time suggests that shoreline retreat along this section is, like the southern section, largely storm-event driven.

Because of the distance from the Bay mouth (from approximately 17 to 30 miles), swell waves have little or no effect on local nearshore currents. This leaves locally generated waves as the primary mechanism driving the irregular and variable local longshore drift. Since the Bay begins to narrow along this section, thereby reducing the cross-bay fetch (and winds from the NE quadrant are infrequent), the available onshore wave energy is further reduced.

This section of shoreline is oriented in a general northwest-southeast direction, curving slightly westward from Mispillion River Inlet to Bowers where the shoreline again turns north. Transect lines #92-#109 (Table 14) exhibit representative shoreline change characteristics of all of the more highly erosional, unoccupied areas of the central section. This segment of shoreline has experienced continued erosion, although at temporally erratic rates.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977					
TRANS LINE#	YEAR GROUPS: 1-2	4-5	5-6	6-7	1-7
92	-3.7	3.0	-17.4	-0.7	-4.9
93	-5.9	3.8	-17.1	2.2	-6.6
94	-4.0	-3.6	-13.5	-4.6	-5.9
95	-8.9	-5.3	-13.3	-9.0	-7.5
96	-5.2	-0.7	-11.0	-5.6	-7.1
97	-5.9	-5.3	-12.1	-5.7	-7.5
98	-7.9	-5.2	-12.1	-6.6	-7.7
99	-5.0	-2.0	-16.5	-7.0	-7.8
100	-5.1	-6.5	-19.3	-5.4	-7.8
101	-5.3	-4.8	-21.0	5.6	-6.6
102	-6.7	-5.0	-17.7	-1.3	-7.0
103	-9.9	-5.2	-9.9	-5.3	-7.2
104	-9.4	-3.7	-7.9	-4.2	-7.1
105	-6.6	-1.1	-6.6	-3.0	-6.1
106	-4.4	0.3	-5.5	0.5	-4.8
MEAN:	-6.3	-2.8	-13.4	-3.3	-6.8
	± Range of Error:				
	±0.5	±1.7	±1.2	±2.3	±0.1

Table 14. Measurements along transect lines #92-106. Locations of the transects can be seen on maps 26-30 in Appendix 1.

Several Pleistocene necks find exposure on or near the beach along this section of shoreline (Figures 2 and 3). However, because of low wave energies (and therefore minimal littoral drift), they supply little sand-sized sediment to adjacent areas. Instead, they provide resistance to erosion as evidenced by Figures 2 and 16, which illustrate the correlation between locations of headlands and reduced erosion rates. The three most prominent areas of reduced erosion are: Big

Stone Beach, Bowers Beach, and Kitts Hummock (Figure 16).

Big Stone Beach is a transgressive area, although it shows a noticeably reduced rate of erosion when compared to the areas immediately north and south. In fact, field investigation in 1990 revealed that nothing at all remains of Bennetts Pier, just a few miles to the north, except for a few rotted pilings and an otherwise excellent road going nowhere but to an empty beach. Transect data to the south (Table 14) also exhibited a similar step-wise pattern of retreat as at Big Stone, but at much higher rates.

The most notable difference in rates occurred during the period 1954-1969g, the period of the severe

YEAR GROUPS ARE:
1) 1842; 2) 1882g; 3) 1910; 4) 1943g;
5) 1954; 6) 1969g; 7) 1977

TRANS LINE#	YEAR GROUPS: 1-2	2-3	3-4	4-5	5-6	6-7	1-7
109	-3.4	N/A	N/A	1.7	-3.3	0.5	-3.3
110	-3.1	N/A	N/A	2.7	-2.7	-1.0	-3.8
111	-5.4	N/A	N/A	0.4	-0.1	-4.5	-4.5
112	-3.6	-1.8	-8.2	1.7	0.2	-2.9	-3.7
113	-2.0	-3.1	-7.2	4.2	-2.4	0.4	-3.1
MEAN:	-3.5	-2.5	-7.7	+2.1	-1.7	-1.5	-3.7
	± Range of Error:						
	±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1

Table 15. Shoreline change data for the area of Big Stone Beach (ft/yr). Locations of transects can be seen on map 32 in Appendix 1. N/A = No data available.

1962 storm (Table 14). Where the average for lines #92-#106, just to the south of Big Stone, was -13.4 ft/yr (±1.2 ft/yr), and -10.9 ft/yr (±1.2 ft/yr) at Bennetts Pier (transects #124-128) just to the north, the rate at Big Stone Beach was only -1.7 ft/yr (±1.2 ft/yr; Table 15).

The reason for the significantly lower rate at Big Stone is likely due to the location of the erosion resistant Milford Pleistocene neck. Both areas to the north and south of Big Stone represent shallow ancient valleys filled with soft Holocene muds, whereas Big Stone is located on the Pleistocene neck (Figure 3).

Further confusing the pattern of retreat was the placement of some 26,000 cubic yards of sand in the wake of the disastrous 1962 northeaster. The sand was placed along 3,100 feet of shoreline in an attempt to replace the protective beach. While this is a very small amount of sand, the longshore sediment is also minimal here. Therefore, this limited supply of artificially placed sand could have contributed somewhat to reducing the 1954-1969g erosion rate.

The second area of relatively lower erosion rates in the central section is Bowers Beach (Figure 28). Transect lines #139-142 traverse the local shorelines; Table 16 lists the measurements made along those transects.

Here the Murderkill River finds its way to the Bay

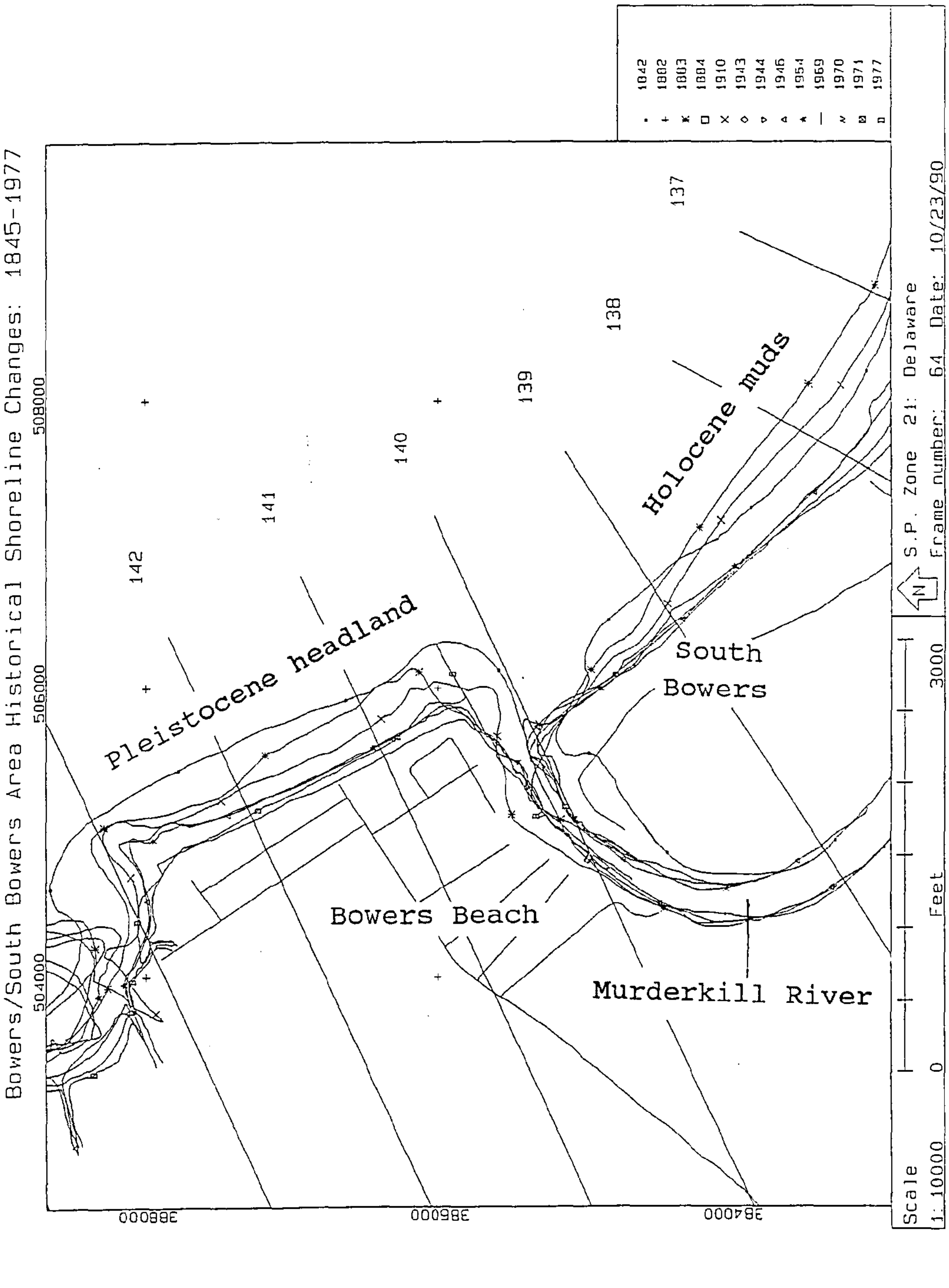


Figure 28. Index map of the Bowers Beach/South Bowers area depicting the locations of the transects measured.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977							
TRANS LINE#	YEAR GROUPS: 1-2	2-3	3-4	4-5	5-6	6-7	1-7
139	-1.3	-5.0	-3.7	2.3	-2.9	12.8	-1.8
141	-1.4	-6.5	-3.9	0.9	-5.9	7.1	-3.0
142	-6.2	-1.4	-3.9	1.6	-7.4	6.0	-3.6
MEAN:	-3.0	-4.3	-3.8	+1.6	-5.4	+8.6	-2.8
	± Range of Error:						
	±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1

Table 16. Shoreline change data for the area of Bowers Beach/South Bowers (ft/yr). Locations of the transects can be seen in Figure 28.

with Bowers Beach located on the north side of the river mouth, and South Bowers located on the south side. It is obvious that the shorelines on both the north side and south sides of the River are highly variable in location (Figure 28). Both shorelines eroded significantly between 1842 and 1943g. This was followed by slight accretion during the period 1943g-1954, and again by erosion between 1954 and 1969g. The final period (1969g-1977), exhibited the highest average annual accretion rate of the entire historical record.

Although the mouth of the river has changed configuration, the river itself has remained locationally stable since 1842, with the flanking beaches eroding uniformly. However, examination of Figure 28 shows that the beach north of the mouth appears to have suffered somewhat greater landward displacement than that of the immediate south. The differences in the shoreline recession between the north and south beaches is less pronounced when transects further to the south are included. It would appear that the 1842 bulge in map frame 38 (transects #134-6, Appendix 1) eroded away and was deposited several thousand feet to the northwest into what had been an indentation in the shoreline. This apparently caused the observed accretion along transect lines #137-137 (map frame 39, Appendix 1) during the span 1842-1882g (again, suggesting a northward drift during that time). After 1882g, the pattern of recession again resembles that observed north of the river. However, the geology of the two areas are quite different.

The town of Bowers Beach is constructed on an Pleistocene upland rather than on a low-lying sandy barrier overlying a coastal marsh (Figures 2 and 3). Strongly compacted and oxidized Pleistocene sandy and silty muds are close to the surface here. The town of South Bowers is located over a deep layer of sandy peats extending down some 20 feet to the Pleistocene horizon of compacted clays (Kraft and John, 1976). In addition, the barrier at this location is, unlike Bowers, backed by extensive marshland.

Littoral drift in this area, like most of the central section, is weak and erratic. It is highly probable that much of the material eroded from the Pleistocene highland under Bowers is being washed back onto the beaches both at Bowers and the immediately adjacent South Bowers. While South Bowers does not stand on a Pleistocene highland, and there is very little littoral drift here, it nevertheless shares this material with Bowers, only 1000 feet north. Thus, the similar retreat patterns of the two geologically different areas.

Like nearly all of the other human occupied areas along the Delaware Bay coast, the Bowers area has experienced artificial modifications to the shoreline. In 1961, 20,000 cubic yards of sand were placed on the beach at South Bowers, and 45,510 cubic yards were placed in 1962 on Bowers and South Bowers beaches in response to the northeaster (USACOE, 1966). With 3,000 feet of beach at Bowers and 2,000 feet at South Bowers, this translates into roughly 13 feet of new beach. The period during which this sand was placed (1954-1969g) also showed the highest average rates of erosion of -5.4 ft/yr (±1.2 ft/yr). Considering the small total amount of sand placed on the beach, it is unlikely that it contributed to any significant degree in reducing those rates.

Presently the mouth of the Murderkill River is stabilized on both sides by large sand-filled canvas bags. A sandbag jetty, approximately 500 feet long, is evident on the 1977 plot (Figure 28), extending into the Bay. Field investigation in 1990 revealed that only tattered remnants of that sand-bag jetty remain, although the sand-bags placed on either side of the mouth itself are in fairly good condition. Currently, there is a new jetty of similar size extending from the south side of the river mouth (Plate VI).

The final significant area of reduced erosion rates is located from Kitts Hummock through Pickering

Plate VI. Oblique aerial photograph of the mouth of the Murderkill River. Bowers Beach, in the far center of the photograph is located on a Pleistocene neck. The smaller South Bowers, in the near center of the photograph, is located over Holocene muds. The jetty on the south (left) side of the Murderkill is just visible (August, 1990).

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977							
TRANS LINE#	YEAR GROUPS: 1-2	2-3	3-4	4-5	5-6	6-7	1-7
154	-4.0	-6.2	-1.8	1.3	-4.8	2.8	-3.2
155	-4.0	-8.3	-2.7	-0.3	-1.4	9.4	-3.2
156	-6.5	-10.2	-0.9	0.4	0.4	6.8	-3.8
157	-10.2	-5.6	-1.1	0.6	2.8	-1.7	-4.3
158	-12.1	-6.6	N/A	3.6	0.2	-0.7	-4.8
159	-14.2	-6.1	-0.7	N/A	N/A	-3.7	-5.7
MEAN:	-8.5	-7.2	-1.4	1.1	-0.6	+2.2	-4.2
	± Range of Error:						
	±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1

Table 17. Shoreline change data for the area of Kitts Hummock (ft/yr). Locations of transects can be seen on map 45, Appendix 1. N/A = No data available.

Beach (maps 45-49, Appendix 1). At Kitts Hummock, the long-term (1842-1977) recession rates average approximately -4.2 ft/yr (±0.1 ft/yr) for transect lines #154-159 (Table 17).

Kitts Hummock is situated on the easternmost tip of the St. Jones Pleistocene neck (Figure 2). In this area a relatively thin sand/gravel beach is overlying a thin (2-5 feet) Holocene marsh. Underlying that are the very deep Pleistocene sands and gravels of the St. Jones Neck. The backbarrier marsh is shallow and narrow with the Pleistocene substrata finding extensive surface exposure relatively near the beach (Kraft and John, 1976).

However, the normal tidal range of over 5 feet almost tops these washover barriers. Naturally, this makes the town extremely susceptible to storm wave attack. While there appears to be no economically reasonable way to protect the area from an extreme storm event, some attempts have been made.

In 1961 the State of Delaware placed 80,000 cubic yards of sand on the beach. In 1962 the Army Corps of Engineers added an additional 30,610 cubic yards of sand. This would translate into roughly 30 feet of new beach, assuming a 4,000 foot fill length. In spite of this placement of over 110,000 cubic yards of sand on the beaches, they nevertheless still lost an average of -0.6 ft/yr (±1.2 ft/yr) during the 1954-1969g time period of the 1962 northeaster. If the additional 30 feet of beach is considered, then the erosion rate might be closer to -2.6 ft/yr. It would appear, therefore, that beach nourishment did have some effect on reducing the erosion rate.

The northernmost hamlet of Pickering Beach has experienced an average, long-term erosion rate somewhat higher than nearby Kitts Hummock (-5.6 ft/yr; ±0.1 ft/yr). This seems to be consistent with the pattern of reduced erosion rates when associated with nearby Pleistocene outcrops. Pickering Beach suffered massive erosion during the 1962 storm. Subsequent to the storm, approximately 40,000 cubic yards of sand were placed on the beach by the Army Corps of Engineers

(USACOE, 1966). While this small amount of sand may have ameliorated the recession rate somewhat, the measured rate of -19.1 ft/yr (±1.2 ft/yr) remains quite high for that period. The most current data set for this site shows a modest progradation of +1.8 ft/yr (±2.3 ft/yr). As of September 1990, the beach was again artificially nourished with approximately 60,000 cubic yards of sand by the State of Delaware. Since this site is clearly quite vulnerable to storm damage, the placement of such sand is prudent.

Northern Section

The northern section (Figure 16) is an area of extensive marsh development extending from the shore several miles inland, with marsh peat deposits reaching down nearly 30 feet to Pleistocene clays (Figure 3; Kraft and John, 1976). There are only a few thin, ephemeral strands of sand found along the shoreline. There are no obvious outcrops of Pleistocene sands and gravels. The available fetch from the north and cross-bay (northeast) is considerably narrower than for the two other sections (Figure 10), and there is little-to-no longshore sediment transport. The only developed area is Port Mahon, which is little more than a large boat ramp and parking area. The only shoreline engineering is a decaying bulkhead on the small road accessing the Port.

This is the most highly erosional section of the study area with long-term erosion rates up to -50 ft/yr occurring at some locations, and rates of -30 ft/yr common. The overall long-term average is -20.5 ft/yr ($\pm$0.1 ft/yr) in the area of Port Mahon. This extremely high figure is due in part to the rapid northward migration of the south point of Kelly Island. This resulted in landward "jumps" of the shoreline as the point eroded away from both sides. This effect is most apparent along transect lines #182-7 (Table 18). Overall long-term erosion rates for the entire north section is -18.4 ft/yr ($\pm$0.1 ft/yr; Table 5).

The south point of Kelly Island (marked by an ⓧ on Figure 29) has migrated northward over 5,000 feet since 1842, which translates to a consistent 37+ ft/yr average across 135 years. The highly erosive south point of Kelly Island, along with the extensive marsh development, is shown in the oblique aerial photograph in Plate VII.

Erosion rates for the Port Mahon/Bombay Hook areas, while fluctuating somewhat between time spans, have remained consistently quite high throughout the entire 135-year time span. These findings contradict those of Rosen (1977), who reported that marshes in the "sister" Chesapeake Bay frequently were eroding more slowly than sandy beaches. This was occurring in spite of the fact that the marsh shorelines in Chesapeake Bay

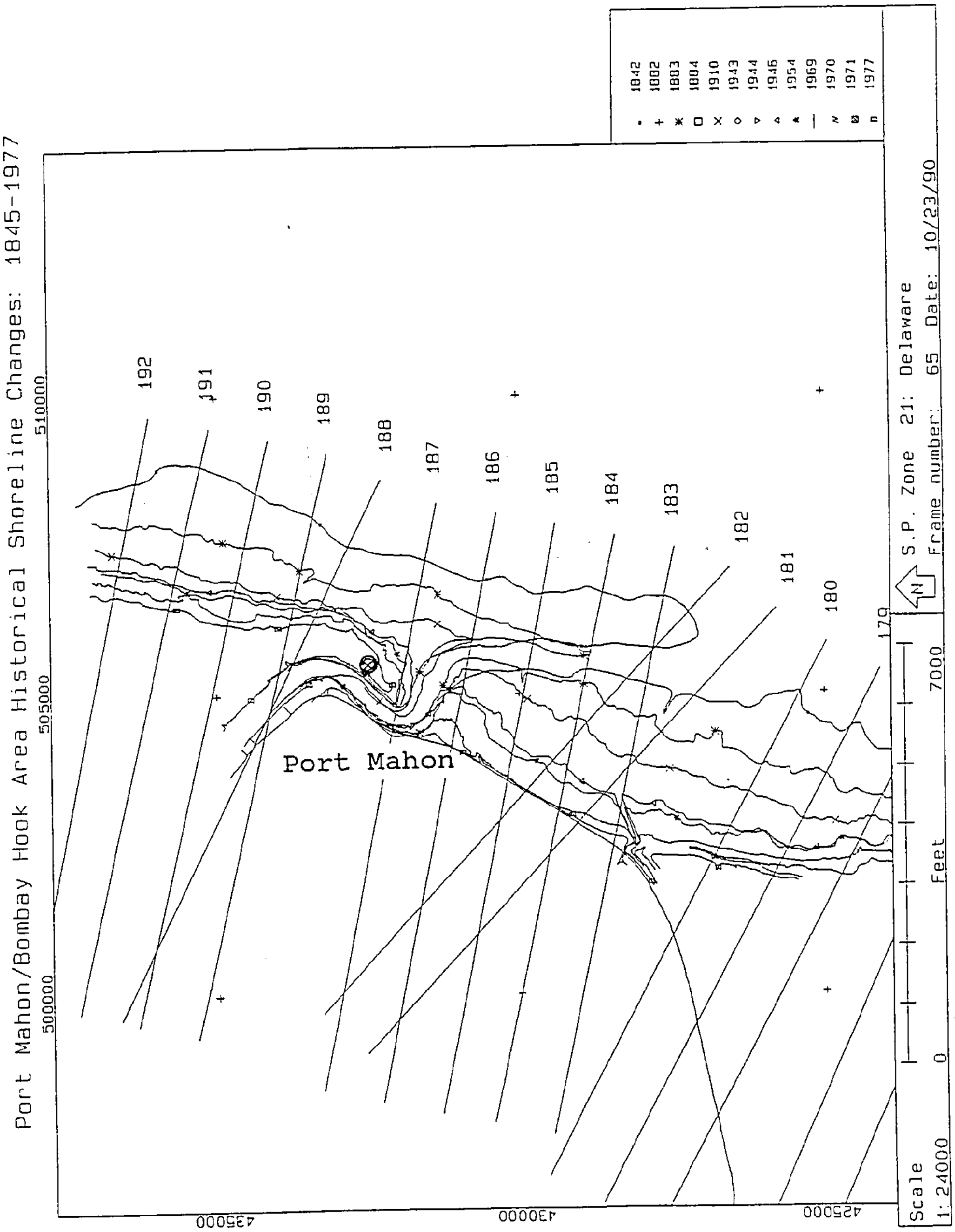


Figure 29. Shoreline map of the Port Mahon/Bombay Hook area illustrating the historic shoreline positions and the locations of the transects measured. The Ⓧ indicates the highly erosive point of Kelly Island.

YEAR GROUPS ARE: 1) 1842; 2) 1882g; 3) 1910; 4) 1943g; 5) 1954; 6) 1969g; 7) 1977							
TRANS LINE#	YEAR GROUPS: 1-2	2-3	3-4	4-5	5-6	6-7	1-7
181	-19.3	-22.6	-21.1	-6.5	-29.0	-17.4	-20.7
182	-50.0	-15.7	-23.5	-21.1	-31.9	-1.0	-29.5
183	-49.6	-24.6	-18.8	-33.9	-16.4	-20.8	-30.1
184	-24.5	-41.9	-23.8	-30.8	-27.7	-2.5	-27.2
185	-16.6	-39.4	-21.1	-26.3	-25.9	-2.3	-23.1
186	-14.6	-14.2	-22.6	-25.3	-28.4	-48.3	-20.8
187	-10.5	-21.4	-12.5	-32.8	-13.6	N/A	-21.1
188	-16.7	-11.9	-3.7	3.8	-11.7	-18.7	-10.6
189	-22.1	-18.4	-1.7	-7.9	-13.1	-15.8	-13.7
190	-22.7	-21.7	-4.2	-11.9	-25.6	-13.5	-16.7
191	-28.5	-20.7	-8.1	-4.3	-15.0	-21.8	-18.2
192	-19.4	-17.6	-5.9	-11.4	-14.2	-20.7	-14.5
MEAN:	-24.5	-22.5	-13.9	-17.4	-21.0	-16.6	-20.5
	± Range of Error:						
	±0.5	±0.8	±0.6	±1.7	±1.2	±2.3	±0.1

Table 18. Shoreline change data for the Port Mahon/ Bombay Hook area (ft/yr). N/A = No data available.

are usually oriented toward the northwest and, therefore, subject to the more severe storm waves which normally come from that direction. The widely held belief that marsh grasses inhibit erosion (Phillips, 1986), while apparently holding true for Chesapeake Bay, is distinctly not the case in Delaware Bay.

Unlike the south and central sections, the pattern of erosion in the north does not exhibit the same step-wise character of retreat. This suggests that this shoreline is not storm-driven, but instead retreats at a relatively regular, albeit high, rate. This is due

Plate VII. Oblique aerial photograph of the highly erosive south point of Kelly Island and the extensive marsh development. Port Mahon is visible in the left center (August, 1990).

to several reasons. The principal reason is the composition and structure of the marsh as opposed a sandy beach. Where sandy beaches are composed of individual, unconsolidated (and therefore easily moved) grains, marsh growth results in a substrate strongly secured together with an extensive network of rhizomes. As a result, the marsh is more resistant to the erosive action of storm waves. In addition, if a storm produces a swell sufficiently high to inundate the marsh completely, the wave energy is no longer expended on the marsh edge. Instead, the wave energy is dissipated on the resilient grass culms.

During normal non-storm periods, the scarped edge of the marsh is continually acted upon biogenically, most notably by various types of crabs and bivalves. The burrows of these animals can extend several inches and promote deep, penetrating cracks in the normally cohesive marsh substrate. Normal wave activity can then cut away the loosened edges of the marsh. As the marsh scarp is eroded back, the clams and bivalves then burrow deeper, continuing the process of marsh edge erosion (Frey and Basam, 1985). When a storm does strike, only those few inches of biogenically loosened material are quickly removed before the storm waves encounter the more resistant, unaltered marsh deposits.

This process may be exacerbated by wave activity attributed to boat wakes. Small boats moving at moderate speeds have been observed generating 18-24 inch waves striking the base of the marsh at low tide, often causing severe undercutting. There have been reports of 5-foot high waves crashing into the shore as a result of large ships moving up the Delaware River to and from Philadelphia (R. Henry and T. Pratt, personal communication, 1990). However, this probably does not fully explain the severe rates of erosion observed during the 1842-1882g time period; a period during which the passage of large vessels would not have been expected.

Clearly, the whole story behind the rapid erosion of this extensive marsh is not yet fully understood. With ever-increasing boat traffic combined with an apparently increasing rate of sea-level rise (along with a general lack of sediment sources in this area), the erosion observed in this study can be expected to continue or possibly accelerate.

DISCUSSION

Influence of Waves and Currents

Wave activity is the primary force causing beach erosion. The west Delaware Bay shoreline is subject both to locally-generated waves and incoming ocean swell. Ocean swell, however, has a significant impact only on the lower Bay, south of the Mispillion River Inlet (Figure 10). North of that point, wave activity is largely dependent upon local wind speed, duration, and fetch. Fetch, in turn, is related to shoreline orientation. Since the Bay is roughly triangularly shaped, narrowing to the northwest, fetch is the greatest along the northwest to southeast axis. Both the cross-Bay (northeast to southwest) and up-Bay (southeast to northwest) fetch become progressively shorter farther northward (Figure 10).

The dominant winds are from the southwest through northwest quadrants (Figure 5) and, therefore, offshore for much of the year. Only during the fall is any significant percentage of the wind onshore from the northeast. Waves follow a similar pattern (Figure 6), and expend much of their energy on New Jersey's shorelines throughout much of the year. Consequently, locally-generated wave energy along the Bay's western shores is low for most of the year.

There is a gradational distribution of wave energy along the shore, with relatively higher energy in the southern areas where fetch from the northwest through northeast is greatest and ocean swell waves reach the shore. Relative wave energy levels progressively decrease toward the north as both the up-Bay and cross-bay fetch decreases and ocean swell energy dissipates.

Incoming ocean swell waves produce a pattern of large "master" littoral drift cells (here defined by distinct reversals in drift direction, either by divergence or convergence) which appear to be particularly well displayed in the southern regions of the study area (Figures 10 and 30). Incoming swell waves refracting around Cape Henlopen and diffracting around the breakwaters turn to approach the lower Bay coastline from an approximately shore-normal direction (Figure 10).

Between Roosevelt Inlet and Broadkill Beach (Figure 3), there is a nodal point where the net littoral drift reverses (Figure 30). This reversal in the drift directions is clearly visible in the accretion patterns observed at such shore-normal structures as the jetties at Roosevelt Inlet (southward-directed drift) and the groins at Broadkill Beach (northward-directed drift) only a few miles away (Figures 22 and 23, respectively). The result is two distinct drift cells: one between the node point and the Cape with a southeasterly net littoral drift; one

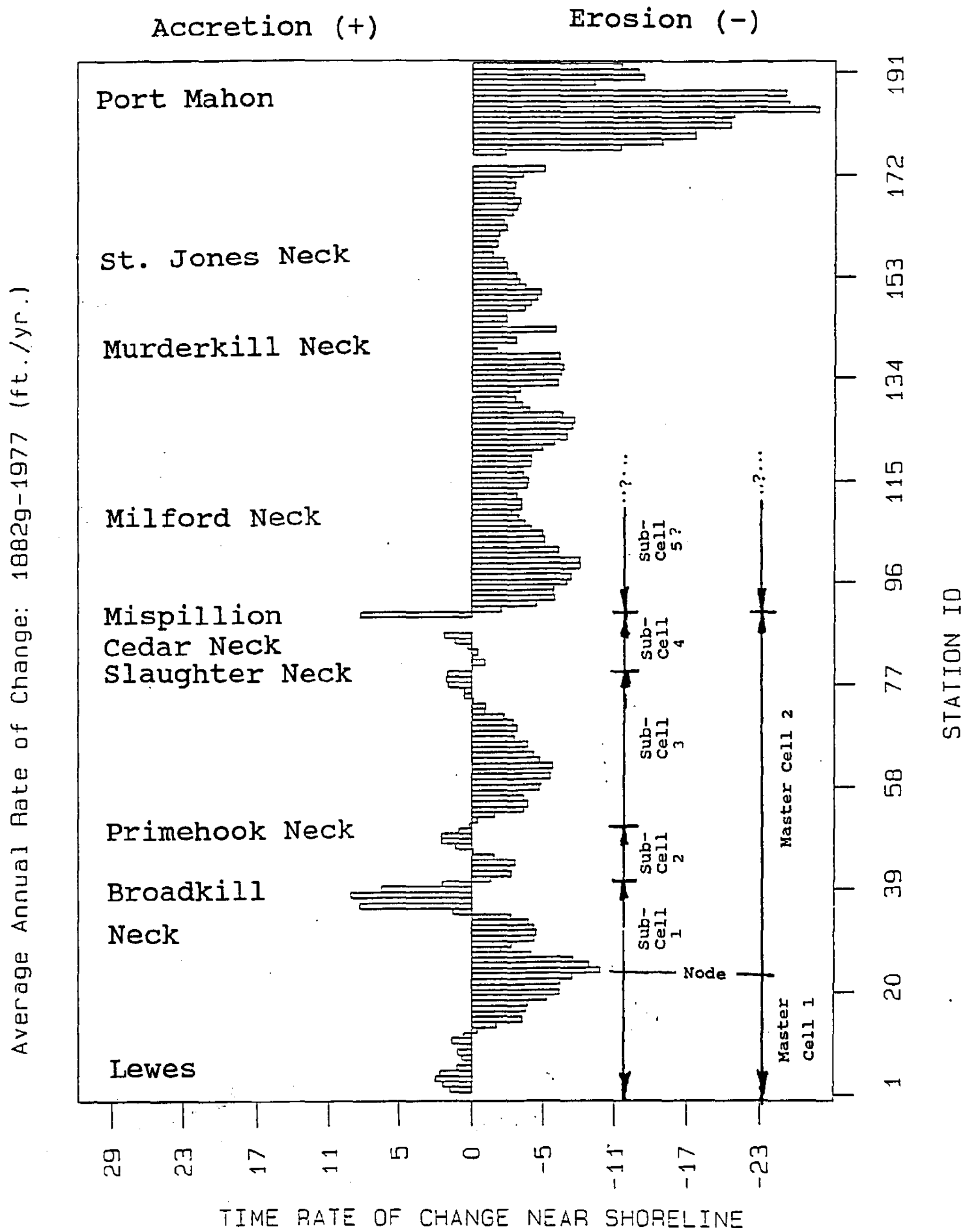


Figure 30. Histogram of long-term shoreline change illustrating the locations of the littoral drift cells and sub-cells as determined by this study. Arrows indicate direction of littoral drift.

between the node and the Mispillion River with a northwesterly net littoral drift (Figure 30).

Net rate of littoral drift is considerably lessened by the time Mispillion River Inlet is reached, as evidenced by the limited buildup of material along the southern jetty. Because there is also buildup of material on the north side of the north jetty, it appears that this is a convergence point between the Broadkill-Mispillion "master" cells. The jetties extend over one mile into the Bay, effectively blocking any transfer of material between the two cells and stabilizing the location of the convergence point (Figure 30). However, north of the inlet, where wave energies are quite low, the limited littoral drift is highly variable in direction and poorly defined.

Within the well-defined "master" cell #2, there are four sub-cells within which there is a clear pattern of updrift erosion and downdrift deposition (Figure 30). Sub-cell #5 just north of, and including, Mispillion River Inlet is less well defined at its northern end. These sub-cells are defined as including a source area from which material is eroded and an adjacent sink where much of that material is deposited with limited transfer of material from one erosion/deposition cell to another (Tanner, 1973; Carter, 1988). This definition does not require drift reversal which defined the "master" cells.

Each of the sub-cells observed in the southern section of the study area have a Pleistocene headland as the eroding source which is supplying sandy material to adjacent, downdrift accretionary beaches. "Master" cells are, therefore, defined by wave activity in this situation, whereas the sub-cells are defined largely by geology.

This, of course, requires varying longshore energy within each sub-cell, with higher longshore wave energy at the eroding headland to transport material and lower longshore wave energy downdrift allowing the material to accumulate in the depositional areas. The causes of these variations in longshore energy along the shoreline are unclear, although it is probably due to subtle variations in the angle of wave approach to the shoreline resulting from varying nearshore bathymetry and coastal orientation. It is also possible that the subaqueous erosion-resistant Pleistocene outcrops provide slight topographic highs, concentrating the erosional force of the waves somewhat through refraction (Bascom, 1980). Offshore shoals from the eroding headlands may well contribute to this effect.

Understanding of at least the location, direction, and morphology of these littoral drift "master" cells and sub-cells is of particular significance to coastal planning as they delimit natural coastal units (Nicholls and Webber, 1987). Recognition and interpretation of these patterns of sources and sinks can help guide coastal development by allowing planners to make future projections of geomorphic change for specific areas.

Influences of Geology and Sediments

Beach erosion is rarely a simple situation where coastal material is stripped off in a one-way process. Erosion might better be described as a net imbalance between material removed from an area and the material supplied to that area. Shoreline stability under a given energy regime is dependent upon both the physical resistance of the shore material and the rate of supply of material to that shore.

The southern and central sections of the Delaware Bay coast are characterized by a series of washover barriers backed by salt marshes. Underlying the barriers are a series of pre-Holocene valleys and interfluves (Kraft, et al., 1971). Several erosion-resistant Pleistocene highlands find exposure at or near the shore (Figure 2), while numerous others have subsurface exposure offshore throughout the study area (Maurmeyer, 1978). In the southern section, those erosional headlands are consistently flanked by areas of reduced erosion or accretion, whereas in the central section, the headlands are instead flanked by increased erosion rates (Figure 16). It seems, therefore, that these outcrops serve two distinctly different functions depending on location within the study area.

In the relatively higher energy southern section, the continual erosion of these outcrops of Pleistocene sands and gravel supply material to adjacent barriers due to the fairly strong littoral drift. This is observed in the littoral drift sub-cell pattern previously discussed. Farther north, along the much lower energy central section, fewer of these Pleistocene highlands are present. Because of the low littoral drift in this area, the principal effect of these outcrops is to slow erosion locally. In this section, much of the material eroded from the highland is apparently either lost offshore or even moved back onto the same beach with little moving in a longshore direction.

Because there are fewer available outcrops of Pleistocene sands and gravel, coupled with an inadequate longshore current to move what is eroded, the shoreline from approximately mid-Bay north frequently does not have that narrow strand of protective barriers. Instead, the coastline becomes progressively more one of broad estuarine marshes directly in contact with the Bay waters as sediment supplies decrease northward (Kraft, et al., 1971).

This pattern shows up quite clearly in the distribution of erosion rates (Figure 16). Areas in the southern section which are just downdrift of eroding Pleistocene outcrops, such as at the Broadkill, Slaughter and Primehook beaches, frequently show limited accretion, particularly when the littoral drift is intercepted by artificial structures such as groins. Areas in the central section which are on or very near Pleistocene necks, such as Kitts Hummock and Bowers Beach, tend to be more erosion-resistant than adjacent areas lacking the close proximity of such compacted, resistant sands and gravels. Yet, in this section there is no indication that the eroded material reaches adjacent shorelines in any significant amount, and the nearby shorelines have consistently exhibited higher erosion rates. With weak longshore currents to redistribute the materials to adjacent beaches, varying resistance to erosion then becomes the chief controlling factor in shoreline recession.

Quantitative measurements of sand volumes were not undertaken in this study. However, qualitative examination of the aerial photography shows that the beaches consistently appear to be wider along the developed areas than along adjacent, undeveloped areas. This means that in the southern section the locations of the Pleistocene necks have narrower beaches, and in the central section, the necks have wider beaches. This may be due in part to human modifications of the local shorelines.

The stable patterns of high to low erosion or erosion to accretion observed along the more southern shorelines are not apparent in the northern section. There are no Pleistocene headlands here, either to resist erosion or to provide sand-sized materials to nearby areas. This section, composed almost exclusively of marsh deposits has experienced fairly uniformly high erosion rates throughout historical time (Table 6). There are few sources of sediment here and the littoral drift is so low and variable that little or no material reaches the area from elsewhere.

Sea-level rise may well be the underlying cause for much of the erosion of the marsh, which is, by nature, normally an accretionary feature. Current rates of sea-level rise are over one foot per century (Lyles, et al., 1988), double the rate over the past 2,000 years (Belknap, 1975). The most obvious result would be increased erosion at the water's edge (National Research Council, 1987).

The more immediate causes of the erosion are, however, probably low sediment supply to the area combined with the biogenic activity of clams and bivalves. These animals can burrow several inches into the scarp at the marsh edge. This burrowing loosens the normally cohesive substrate sufficiently to allow normal wave activity to erode the edge. As the marsh edge erodes away, the animals burrow deeper, continuing

Plate VIII. Surface photograph illustrating the highly erosive nature of the rapidly eroding marsh deposits near Port Mahon (August, 1990).

the erosion process (Frey and Basam, 1985). This, combined with the observed erosive effects of boat wakes, will cause continued retreat of the marsh edge. At current average erosion rates of -20.5 ft/yr (±0.1 ft/yr), the entire marsh behind Port Mahon will be gone in less than 500 years. If sea-level rise rates triple over the next 100 years (National Research Council, 1987), then the local rate of erosion could reach as much as 100 ft/yr, eliminating the marsh in only 100 years. This estimate, however, reflects only marsh edge erosion. Extensive marsh loss due to inundation and internal ponding would result in a much reduced life for the marsh (Orson, et al., 1985; Kearney, et al., 1988).

Beachface sediment samples from throughout the entire study area were compared to long-term (1882g-1977) shoreline change rates in order to determine if the expected correlation existed since, in general, beach material of a coarser nature tends to be more resistant to erosion than are finer materials. In addition, beach sediment size was correlated against physical location along the shore to determine if there was any gradation in size along the Bay shore.

Maurmeyer (1978) analyzed beachface sediment samples from all along the southwestern coast of the Bay (Table 1). Where several samples were taken from a single beach, the sizes were averaged. These mean sediment sizes were then plotted against the erosion rates measured in this study (Figure 31).

There is indeed a weak correlation between sediment size and long-term erosion rate (Figure 31). A time-trend line analysis more clearly illustrates the association (Figure 32). As might be expected, where particle size increases, erosion rates generally decrease, suggesting that the coarser beaches are more resistant to erosion and/or that there are relatively good supplies of larger sediment. On the whole, there

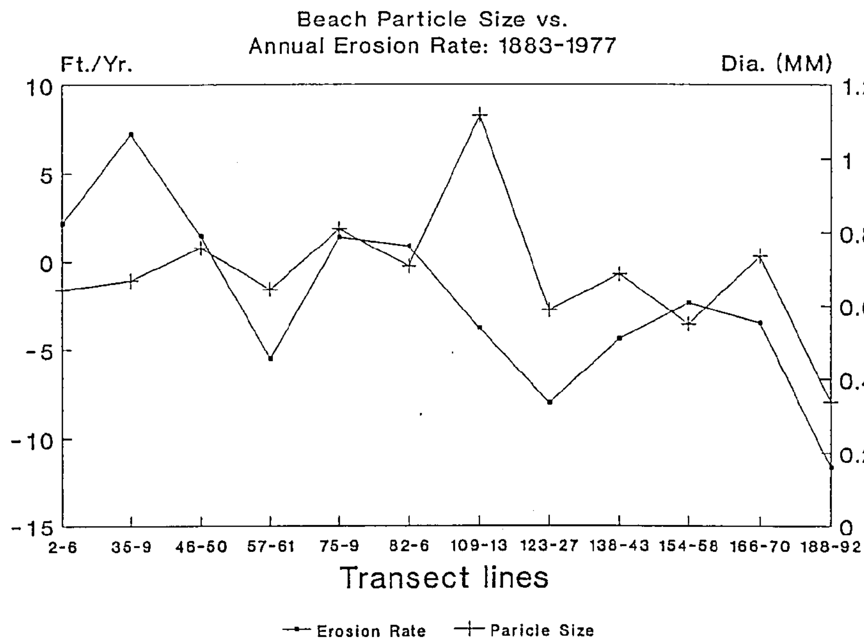


Figure 31. Beachface sediment size (in mm) plotted against rates of erosion.

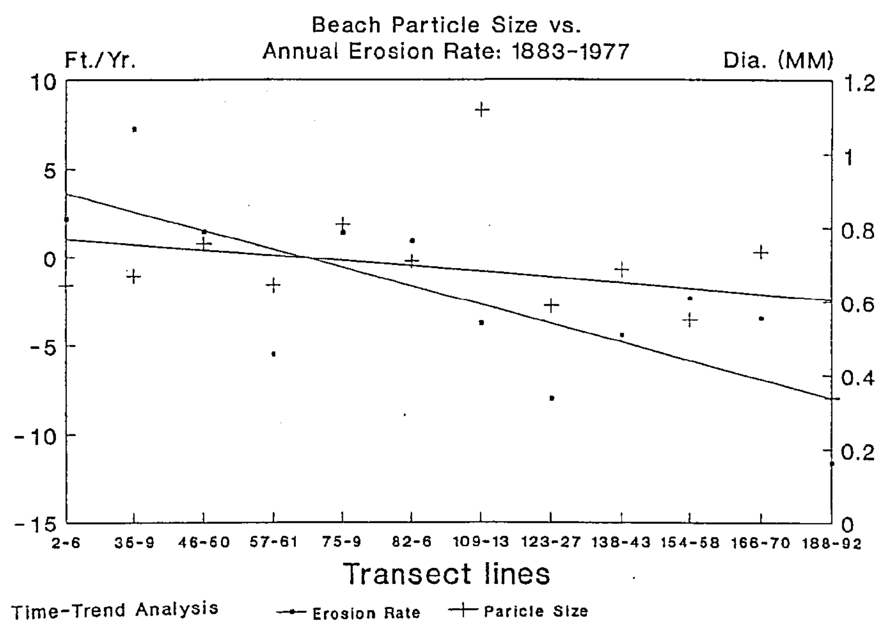


Figure 32. Trend line analysis graph of the same data in Figure 31.

was virtually no gradation of sediment size with distance up-Bay. In the south section, this may be due to sorting of sediments along the longshore energy gradient of the individual sub-cells (Tanner, 1973), with the larger materials being deposited in the downdrift areas. In the central section, the consistently medium-to-large materials found on the beaches may be due to the onshore-offshore transfer processes moving fines out of the nearshore area. It should be noted that there were probably too few samples, taken at inconsistent times, for an accurate trend to be apparent.

The Role of Storms

Shoreline changes can often go unnoticed during human time frames. However, a major storm can result in substantial destruction and beach recession. The massively destructive Ash Wednesday northeaster of March 5-8, 1962, was shown to have caused about 100 feet of erosion along Delaware's ocean coast (Galgano, 1989). This shoreline recession amounts to what would be decades of "normal" erosion. The effects of this storm were equally evident in Delaware Bay with the extremely high rates of erosion occurring during the time period of 1954-1969g (Figure 17C).

Many factors affect shoreline position. Sea-level rise, wave energy and sediment supply are all components in the balance of forces and materials which determine where and how quickly a particular segment of shoreline will change and in what direction. Yet, it is the storms which perform the bulk of the work of erosion in very short spans of time. Since these storms are probabilistic in occurrence, short-term rates of shoreline change can vary considerably from one time span to the next. Such temporal variability in shoreline change rates are clearly evident along the Delaware Bay coast during the 135-year study span. In spite of a long-term average erosion rate of -4.5 ft/yr (±0.2 ft/yr), the shoreline has retreated and prograded at overall average extremes of -7.4 ft/yr (±1.2 ft/yr), and +0.5 ft/yr (±1.7 ft/yr; full study area averages, Table 5). An example of the general pattern of shoreline change along an undeveloped segment of the Delaware Bay coast is illustrated in Figure 33.

Seldom does the shoreline exhibit uniform rates of retreat through time; rather, recession is cyclic in nature. The shoreline shows periods of relative positional stability with alternating minor erosion and accretion. On the other hand, significant shoreline recession is largely driven by major storm events.

The pattern of retreat shown along transect line #101 (Figure 33) is representative of the undeveloped shoreline retreat patterns found along much of south

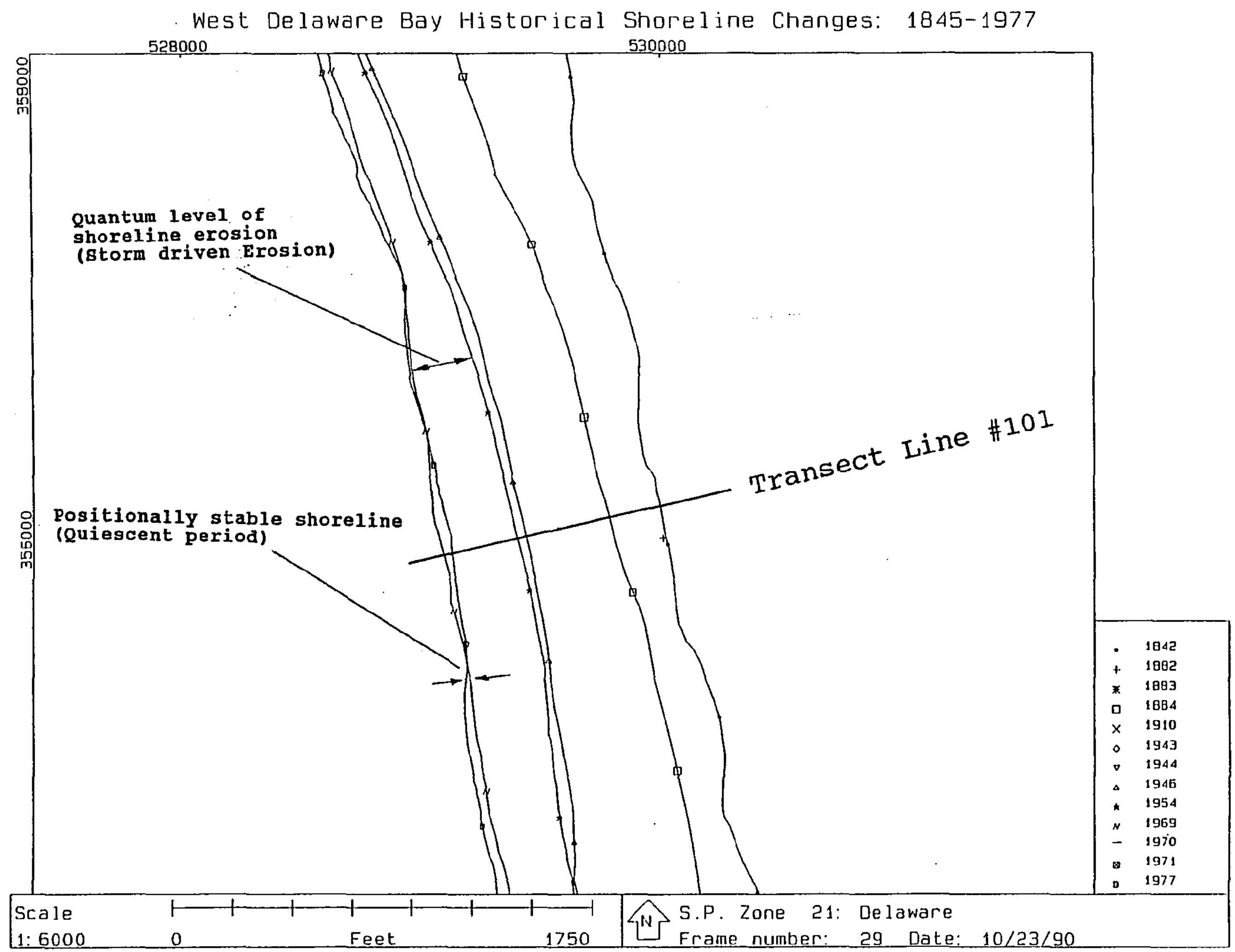


Figure 33. Shoreline change map illustrating the general pattern of episodic shoreline change along west Delaware Bay.

and central sections. In this example, the shoreline retreated by 222 feet during the period 1842-1882g. That translates to -5.3 ft/yr (±0.5 ft/yr). The pattern of similar rates of -5.8 ft/yr (±0.3 ft/yr) and -4.8 ft/yr (±1.7 ft/yr) continued for the following two time spans. The pattern was then broken by a period of severe erosion between 1954 and 1969g, the time during which the 1962 Ash Wednesday storm struck. Erosion during that period increased by a factor of 4, to average -21.0 ft/yr (±1.2 ft/yr). This high annual rate is, however, an artifact of the time interval. The actual distance that the shoreline moved back during that 15-year period was calculated in this study to be approximately 315 feet (Appendix 3). If the pattern of storm-induced erosion was similar to that found for the Atlantic Coast (Galgano, 1980), then perhaps one-third of that 315-foot figure, or about 100 feet, was directly attributable to the storm.

The 1954-1969g time period was then followed by an accretionary period during which the shoreline prograded at a rate of +5.6 ft/yr (±2.3 ft/yr) for the span 1969g-1977, the final span of the study. Despite the subsequent accretion, however, the net effect was some 270 feet of erosion from the 1954 (pre-storm) position to 1977, which translates to a misleadingly high annual loss rate of approximately -11.25 ft/yr for 24 years. This is a pattern similar to those exhibited in the southern and central study sections (Table 6).

The northern marsh section differs from this pattern in that the storm period 1954-1969g is only the fourth most erosive span of record at -18.9 ft/yr (±1.2 ft/yr). It was the time period which followed the storm (1969g-1977) that experienced the highest rates of erosion. Therefore, unlike the more southerly areas, erosion of this section of shoreline is not storm-driven. This is largely due to the structure and composition of the marsh, as opposed to the sandy beaches to the south. The sandy beaches are composed of easily moved individual grains of material, whereas the marsh substrate is securely held together by an extensive system of rhizomes. Rapid erosion at the marsh edge during a storm will extend only to the depth of biogenic activity before the resistant, cohesive rhizome network is encountered, after which the rate of erosion will slow significantly. In addition, if the storm surge is sufficiently high, the marsh may be inundated completely. If this occurs, the wave energy will no longer be expended on the marsh edge, but will instead be dissipated among the culms of the marsh grass. Another factor behind the apparently minimal effect of storms on the marshy coast may simply be the distance up-Bay (30-35 miles) of this area, combined with the shorter fetch.

Variations in short-term sandy shoreline change rates are influenced in large part by both storm frequency and, of course, storm intensity. Figure 34 illustrates the close relationship between rates of shoreline recession and storm frequency. The first time period may be somewhat misleading because accurate storm records were not kept prior to the 1920's (Friedlander, et al., 1977), and the erosion rate given (-6.4 ft/yr, ±0.6 ft/yr), is for the period from 1910 to 1943. In addition, that figure is only for the northern half of the study area since no reliable southern shoreline data for 1910 were available. Therefore, it may appear that fewer storms caused a high degree of erosion. The final year group, 1969g-1977, may be somewhat skewed because increased coastal development during this period may have artificially increased the number of storms reported as causing damage (Friedlander, et al., 1977).

The effects of storm intensity are illustrated in Figure 35 which correlates subjective evaluations of levels of damage caused by each storm (Table 3) against annual erosion rates during the same time span. It can be seen that as the total number of severely and extremely severely damaging storms increases so do the rates of erosion for that same time period.

In addition to the caveats expressed for the previous graph, it should be cautioned that these are largely subjective, damage-level evaluations as expres-

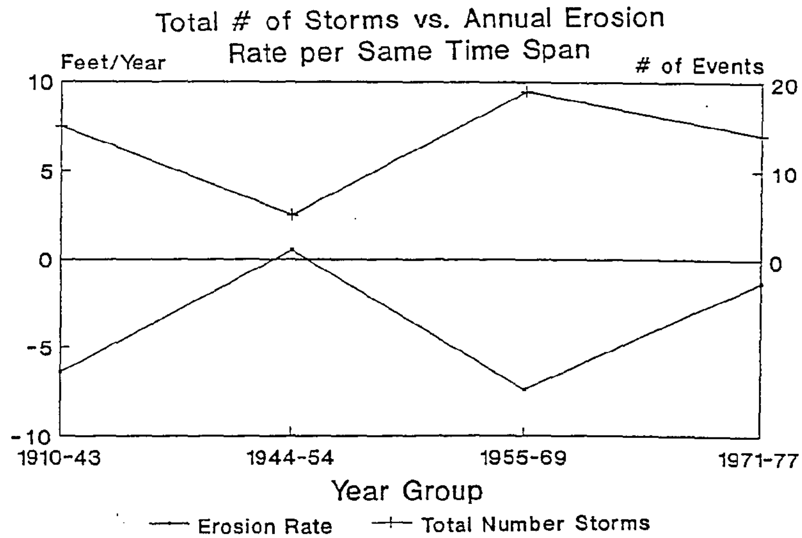


Figure 34. Graph illustrating the relationship between storm frequency and coastal change. Periods of erosion coincide with periods of increased storm frequency (compiled from Friedlander, et al., 1977).

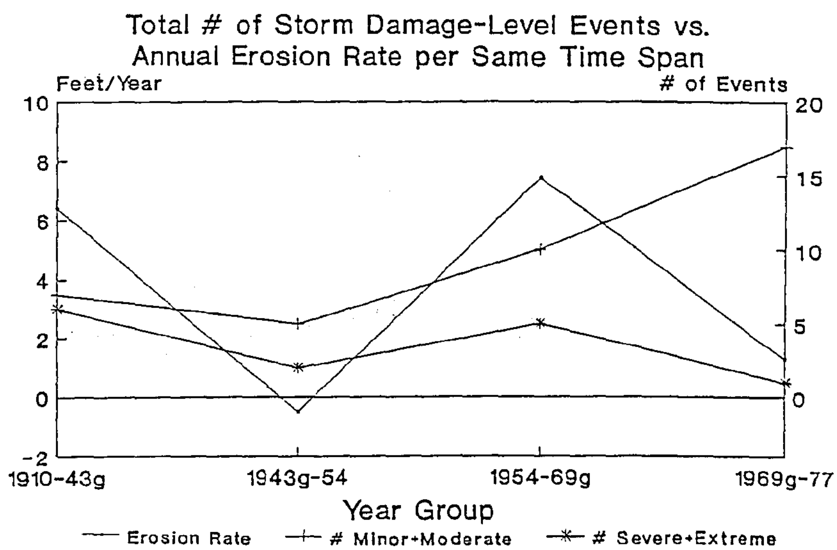


Figure 35. Graph illustrating the relationship between the total number of storms causing a particular level of damage and the annual rates of shoreline change for that same time period. It is clear that when the total number of intensely damaging storms increases, so does the average rate of erosion (storm damages as described in Friedlander, et al., 1977)

sed by Friedlander, et al. (1977). An attempt to "normalize" the descriptions was made in that damage was categorized as minor through extremely severe. This categorization was based more on beach and overwash damage as opposed to net building destruction which, of course, would be expected to increase through time as human occupation of the coast increased. In spite of these limitations, the relationship between storm activity and erosion is quite clear. The sandy western shores of Delaware Bay are largely storm-driven and retrograde in a step-wise fashion, rather than in a smooth pattern of transgression with rising sea level. This pattern is consistent with that found for the open-ocean coastline of Delaware (Galgano, 1989).

Shoreline Engineering

While natural phenomena account for the majority of the temporal and spatial variation in the shoreline changes observed along the undeveloped shores of west Delaware Bay, human-induced changes have had some degree of influence on the rates along much of the developed shorelines. Of the three sections of this study area, the southern section is by far the most developed with approximately 63% of the coastline affected. Approximately 17% of the shoreline in the central section is occupied. The northern section, with its extensive marsh development, has less than 1%

of its shores inhabited. The degree to which the coastline has been engineered closely follows the same pattern. The effects of shoreline engineering (e.g., groins, beach nourishment, and jetties) on coastal change were examined in this study.

Groins have been used extensively at nearly every area of human occupation in the south and central sections. At least 32 individual groins ranging in length from 98 feet to 199 feet have been installed along these sections of shoreline (USACOE, 1966). Their effects are often apparent in the shoreline plots (Appendix 1), and it was possible to establish a qualitative estimate of their effectiveness.

Groins are designed to trap sediment in the littoral stream by interrupting the longshore flow, resulting in a characteristic pattern of accretion behind the updrift side of the structure and erosion immediately downdrift. It has been demonstrated that there are, in fact, littoral drift streams functioning in the lower segments of west Delaware Bay. Yet, with only the exception of the Roosevelt Inlet (which is not a groin), no such downdrift acceleration in erosion was observed. Some of those areas experienced accretion resulting in the most recent shoreline (1977) being displaced bayward of the ends of the groins. This phenomenon is most clearly visible in the Broadkill and Slaughter Beach areas (Figures 23 and 26, respectively). This strongly suggests that groins were of secondary importance, having been placed in already accreting areas. After a groin is filled to capacity, sediments will be transported around the end and continue downdrift to the next obstruction (USACOE, 1984). The fact that the groins have apparently become buried at several areas (Figures 23 and 26) suggests that these areas were already experiencing accretion.

Further evidence of this apparent groin-independent accretion can be found in the transect data (Appendix 2). At Slaughter Beach, a field of 20 groins was built during the 1940's through the 1950's (USACOE, 1966). This was, by far, the most extensive application of this shore stabilization technique in the study area. The data show, however, that the shoreline prior to that installation (1882g-1943g, Table 12) had accreted at a rate of +0.2 ft/yr (±0.3 ft/yr). While this figure is within the data error range, it clearly indicates that this was not a highly erosional shoreline during that period of time. Accretion has continued long after the construction of the groins. Field examinations in 1989 and 1990 of each of the areas discussed failed to disclose any evidence of groins.

This is not to say that these groins have had no effect at all. For example, during the period of time when the groins were installed at Slaughter Beach, the previous accretion rate of +0.2 ft/yr (±0.3 ft/yr) jumped to +12.0 ft/yr (±1.7 ft/yr). In a similar, albeit less dramatic pattern, accretion rates at Lewes' six groins accelerated slightly from +1.3 ft/yr (±0.3 ft/yr) to +2.0 ft/yr (±1.7 ft/yr) between the 1940's and 1950's (Table 7). No doubt these groins have been effective in accelerating the local rates of accretion in the short term, particularly at Slaughter Beach. But apparently they became quickly filled and buried in what were already progradational areas over the long term. The structures were presumably constructed because those areas had experienced episodes of local, short-term erosion (too short to be seen in these data), which was quickly responded to with an engineering approach.

Every beach with groins was also nourished at some time (USACOE, 1966). Often the nourishment coincided with the time period of groin construction. This probably contributed to the observed post-groin accretion, making it difficult to separate the effects of each. Fill volumes were usually quite small (most between 20,000 and 80,000 cubic yards; Table 19), and, therefore, did not create much new beach area. Exceptions include Lewes with over 500,000 cubic yards being placed between 1954 and 1963. Assuming a 10,000-foot fill length (the approximate length of developed beach; R. Henry and T. Pratt, personal communications, 1990), this would translate into roughly 50 feet of new beach width (USACOE, 1984). Another exception is Slaughter Beach, with over 270,000 cubic yards pumped onto the beach between 1958 and 1962 (approximately 45 feet of beach accretion, assuming a 6,000-foot fill length). Broadkill also received a relatively large quantity of sand (nearly 196,800 cubic yards, or roughly 30 feet of new beach) between 1958 and 1961 (Table 19).

LOCATION	QUANTITY (cu.yds.)	YEAR(S) PLACED
Pickering Beach	39,630	1962
Kitts Hummock	80,000 30,160	1961 1962
Bowers and South Bowers	20,000 45,510	1961 1962
Big Stone Beach	25,980	1962
Slaughter Beach	49,000 165,000 56,630	1958 1961 1962
Primehook Beach	20,190	1962
Broadkill Beach	76,800 120,000	1957 1961
Lewes	48,000 400,000 20,000 48,700	1954 1957 1961 1963

Table 19. Artificial beach nourishment locations, volumes, and dates along west Delaware Bay (USACOE, 1966).

All told, over 1.2 million cubic yards of sand were distributed among nine beaches within the 1954-1969g study span. Yet seven of the nine experienced erosion during that same period. There is no doubt that the disastrous Ash Wednesday storm of 1962, which lasted over five high tides, was responsible for these sand losses. In fact, virtually the entire study area suffered severe erosion during that period (Figure 17C).

There is a continuing controversy over the cost effectiveness of beach nourishment (Pilkey, 1987; Jarrett, 1987). While expensive, it is often considered the most desirable form of beach stabilization (National Research Council, 1990). It is, therefore, up to the individual communities and those responsible for the necessary funding to decide if this is the route to pursue for any given location.

The effects of jetties were also examined in this study. Jetties are not considered a type of beach stabilization but instead maintain inlet and river channels at three locations along the western shore of Delaware Bay: Roosevelt Inlet, Mispillion River Inlet, and the Murderkill River at Bowers/ South Bowers.

Roosevelt Inlet was stabilized in 1937 with two parallel, 1,700-foot jetties (USACOE, 1966). As would be expected, they have interrupted the eastward longshore drift. The downdrift side of the inlet has shown the accelerated pattern of erosion typical of such structures built in areas with a significant littoral drift stream (Figure 22). Since the town of Lewes is just downdrift of the inlet, it is likely that the immediate area will require continued maintenance (most probably in the form of beach nourishment).

On the other hand, the Mispillion River Inlet has experienced intermittent accretion on both sides. The stabilization of this inlet was completed in 1939 with a parallel pair of jetties over one mile long (USACOE, 1966). The great length of the structures block completely any transfer of littoral material from one side to the other. However, in spite of the long length, accretion on either side is only slight. In addition, there is no clear evidence of sand starvation on either side of the inlet. This indicates that there is relatively little material available for littoral drift and/or that the longshore currents are weak. Under these circumstances, even structures as large as these do not appear to have caused any significant damage to adjacent shorelines since there is little longshore drift to interfere with. However, any natural morphologic changes which would have normally occurred here, such as the migration of the suspected low energy cellular convergence zone, have essentially been locked into place by the jetties.

Presently there is a large (1,000 ft+) gap between the landward end of the north jetty and the barrier island to which it had been attached. This is clearly the most efficient route for the tidal currents. The result is that the south end of the island is continuing to be scoured away and is receding to the north (R. Henry and T. Pratt, personal communications, 1990). There is no evidence of this eroded material being redistributed on nearby beaches or against the jetty, which further suggests that there is little or no longshore drift here.

This breach at the base of the north jetty is now exposing numerous homes and businesses which had been protected by the barrier. There is every reason to expect the opening to grow. If this opening is not stabilized or closed before the next major storm, then those homes and businesses will experience much more damage than if they still had the barrier protection.

The third area where jetties are employed is at the mouth of the Murderkill River between the towns of Bowers Beach and South Bowers (Figure 28). The 1977 shoreline plot shows the location of a 500-foot sandbag jetty stabilizing the north side of the river. There is no indication of any significant buildup of material which is indicative of a general lack of an established littoral drift stream. Field investigation in 1990 showed the jetty to be in extremely poor repair, with only a few tattered fragments of burlap bagging remaining, although the sand bags placed on either side of the mouth itself are in fairly good condition. The south side of the mouth has now been jettied with another sandbag structure which is presently in good condition (Plate VI). Again, there is no clear pattern of accretion at this structure.

Since the path of the Murderkill River has been locationally stable since 1842, these structures serve only to stabilize the somewhat more mobile mouth. This is, of course, important in that both sides of the mouth of the river are presently occupied right up to the water's edge and are, therefore, subject to damage with even a slight shift in the shoreline.

CONCLUSIONS

This study represents the first instance where high resolution, long-term historical shoreline data have been used to trace and interpret shoreline trends along a relatively low energy, non-oceanic coast. The computerized methodology employed in this study has previously been used successfully in a number of open-ocean coastal areas (Galgano, 1990; Leatherman, 1983b). While any process of digitizing and computerized processing is subject to certain inherent errors, the maximum error for a given shoreline in this study has been determined to be less than 42 feet. In practice, errors encountered with this methodology probably range between 0 and 20 feet (Galgano, 1989).

Previous attempts to measure long-term shoreline trends in Delaware Bay have typically employed simple map and photograph comparisons, often supplemented by anecdotal records (Kraft and Caulk, 1972; Weil, 1977). While those attempts have produced generalized results which are in accordance with the results of this study, those earlier techniques lack the spatial and temporal resolution necessary to assess accurately the more subtle variations occurring in an environment of low and variable wave energy such as Delaware Bay.

The western shore of Delaware Bay has historically been retreating at an average annual rate of -4.5 ft/yr

($\pm$0.2 ft/yr). This figure is significantly higher than the average -2.6 ft/yr for the open Atlantic coast as a whole (National Research Council, 1987). Yet, the long-term record exhibits significant temporal and spatial variations in shoreline behavior which were found to be important in the analysis of changes occurring along this shoreline.

Three distinct shoreline segments were identified based on geomorphic responses to such varying environmental forcing factors as wave energy, currents, and storms, as well as antecedent geology and human interference. The southern section, with the lowest average annual erosion rate, has the highest wave energy and greatest number of exposed pre-Holocene sources of sand and gravel.

The patterns of recession observed in the southern section clearly indicate a well-defined and stable cellular and sub-cellular pattern of littoral drift. The two larger "master" cells result from tidal gyres and incoming ocean swell waves refracting around Cape Henlopen, striking the beach, and splitting into two opposite directions south of Broadkill Beach. Those cells are, therefore, controlled primarily by wave activity. Within the northern "master" cell there are four sub-cells. Each of the sub-cells include an area of eroding Pleistocene sand and gravel, and a depositional area some distance downdrift over Holocene marsh deposits. They are, therefore, partly controlled by geology, although the underlying wave control is not clear. This results in a pattern of higher erosion occurring at the Pleistocene source areas, and lower erosion or accretion occurring along the depositional areas overlying Holocene deposits.

There were five areas which exhibited some limited long-term accretion in what is an overall transgressive shore: Lewes, Broadkill, Primehook, Slaughter and Mispillion. The existence of long-term accretionary areas along an otherwise transgressive shore contradicts the classical Bruun rule which states, in essence, that rising sea-levels must necessarily result in shoreline retreat (Bruun, 1962). While this study has shown the Bruun rule to be correct in general, it has also shown that the rule cannot always be used on a site-specific basis since the accretion observed in this study is totally opposite that predicted by Bruun. The long-term accretion observed at each of these locations can be attributed to specific and varying combinations of the factors of geology and longshore wave energy, amplified by human engineering. The strategic location of the towns in downdrift areas in the southern section capitalize on the natural littoral drift pattern. Groin construction has allowed the coastal residents to further take advantage of the littoral conditions by trapping that sediment.

In the central section, where the longshore currents are weak and variable, the patterns of shoreline change observed in the southern section are reversed. Here Pleistocene sediments are not transported in an alongshore direction to any great degree. As a result, the eroding Pleistocene headlands retreat at a less rapid rate than the areas composed of Holocene marsh deposits. Consequently, where towns in the south tend to be located downdrift of Pleistocene sediment source areas, human development occurs almost exclusively directly over Pleistocene necks in the Central section.

Shoreline engineering appears to have exaggerated the trends of shoreline change. Both the south and central sections have been subjected to extensive beach nourishment and groin emplacement, which has either reduced the "natural" rates of erosion, or has contributed to limited accretion. Since there are significant quantities of sediment in the longshore current in the southern section, groins have been shown to be effective in trapping that material. In the central section, nourishment has been the beach stabilization technique of choice. Since there is little littoral drift in that section, groins would have limited effectiveness.

In the south and central sections, examination of shorter, individual time spans have revealed a pattern of moderate erosion and some limited accretion punctuated by severe, storm-dominated beach erosion. Both tropical (hurricane) and migratory, mid-latitude storms (northeasters) affect the Delaware Bay shore. Although hurricanes are generally much more powerful, as measured by central pressures, overall wind speeds, and (usually) storm surge levels, it is probable that northeasters, due to their relatively high frequency, often cause the greatest damage.

The northern section differed significantly from the two other areas. This section is composed almost exclusively of marsh extending to the shore's edge. There is no evidence of any established longshore currents and little source of sand-sized sediment. This section has experienced the highest rates of erosion of the entire study area (e.g., -18.4 ft/yr; ±0.1 ft/yr). This high rate of erosion contradicts the findings of Rosen (1977) who, working in the nearby Chesapeake Bay, reported that marshes generally eroded more slowly than sandy beaches, which is usually what is considered the norm (Phillips, 1986). Accelerating sea-level rise is probably the underlying driving mechanism behind this high rate of erosion. The rate of sea-level rise over the past century is more than double the rate of the past 2,000 years (Belknap, 1975; Lyles, et al., 1988), the period during which these marshes formed. The most obvious expected response to the increased water levels would be erosion at the water's edge (National Research Council, 1990). However, the more immediate reason for this high rate is probably the general deficiency of sediments in the area combined with the lack of any transport mechanism.

Another possible cause of erosion in the northern section may be anthropogenically-generated waves (i.e., boat wakes) striking the marsh edge. These waves have been observed causing undercutting and subsequent slumping of relatively large blocks of marsh vegetation (R. Henry and T. Pratt, personal communications, 1990). This process has been increasing through time due to increasing ship traffic, and there is every reason to expect it to continue into the future.

Based only on the present rate of shore erosion, the entire marsh west of Port Mahon (which took thousands of years to develop) could be completely lost in less than 500 years. There is strong evidence suggesting that the rate of sea-level rise may, in fact, increase by as much as a factor of three by the middle of the next century (National Research Council, 1987), in which case the marsh could disappear completely in less than 100 years. When the processes of submergence and wetlands loss by ponding are factored in, that rate could be much higher (Orson, et al., 1985).

It is clear from the time-dependent variability observed in this study, particularly in the south and central sections, that analyses of shoreline change require long-term data to assess accurately shoreline behavior. Therefore, shoreline changes can be misleading if long-term data are not available to establish trends. For example, an average 116 feet of recession along the entire study area was observed during the period 1954-1969g, the period during which the 1962 Ash Wednesday northeaster occurred. Yet, this is not to be construed as representing a trend of -7.7 feet of erosion per year. In fact, much of that 116 feet of recession occurred in a very short time (days) as a result of a single storm. The actual trend becomes apparent upon examination of the 135-year record which reveals the long-term rate of recession to be -4.5 ft/yr (±0.2 ft/yr).

Any attempt to plan beach development based on short time spans (a few decades or less) could well lead to expensive over-reaction. On the other hand, it has been 28 years since a storm of such magnitude has struck this shoreline. Planning based only on the post-storm period of time could well result in complacency. Thus, the need for long-term historical shoreline change data.

There are many factors which must be considered when examining any shoreline segment. Knowledge of antecedent geology, combined with an understanding of coastal processes, can explain the long-term patterns of shoreline change and allow realistic projections into the future. The identification of littoral cell patterns can be particularly important in coastal planning since they delimit natural coastal units and contribute to the definition of stable areas vs. areas of potentially significant change (Nicholls and Webber, 1987).

This kind of holistic geomorphic insight can have broad application in coastal planning. Oftentimes setback laws establish a single setback standard per local unit of government or by large data-averaging procedures (National Research Council, 1990). Yet, this study has shown that areas experiencing long-term recession can coexist with areas of relative stability only a few thousand feet away. Thus, the need for spatially high resolution data.

Clearly, it is not enough to make decisions solely on generalized recessional rates, as has so often been done in the past. Cycles of shoreline stability, followed by severe erosion, have significant consequences for coastal communities. There has not been a major coastal storm to affect Delaware Bay for nearly three decades. Belief that a few groins and some sand pumped onto the beach will hold the encroaching waters at bay can further color thinking on the dynamics of this coastline. This is the fallacy of relying upon short-term data to interpret shoreline vulnerability. The fact remains that local sea levels are currently rising at a over one foot per century, which translates into a general pattern of continued shore recession.

This study has shown that a broad-brush approach of using existing classic geomorphic models and generalized concepts on a low-energy coastline can be flawed and is not applicable everywhere. In summary, the findings of this study can be stated as follows:

1. Shoreline change rates are closely allied with the underlying Pleistocene morphology and local energy conditions. When Pleistocene outcrops are exposed to an established littoral drift stream, they serve as sediment feeders to adjacent areas, reducing the rates of erosion of those areas, and, in some cases, resulting in accretion that is in contradiction to the Bruun rule. When such resistant materials outcrop in areas without any established littoral drift, these outcrops serve only to limit erosion locally and have little effect on adjacent areas which erode at higher rates.

2. Spatially high resolution data must be employed to reveal subtle variations occurring along a dynamic shoreline. Generalized categorization of large segments of shoreline, as has frequently been employed

in the past, can result in inaccurate assessments of specific shoreline behavior.

3. Shoreline changes observed along the sandy Bay shore are not a smoothly continuous process in time and space, but instead are largely storm-driven.

4. Shoreline changes observed along the marsh shore exhibited little storm-induced change but instead eroded in a relatively continuous pattern through time. Erosion rates along the marsh shore were consistently much higher than those of the sandy shores which contradicts both conventional understanding of marsh erosion as well as earlier findings within the nearby Chesapeake Bay.

5. Erosion control practices in low energy environments can have a positive effect on shoreline stability. Groins intercepting littoral drift can accelerate accretion if there is sufficient sand-sized material in the drift stream. Beach nourishment can be used to supply sacrificial material to counter storm-induced recession and feed downdrift beaches, or used to replace beach material after storm losses.

6. In order to place the dynamics of shoreline changes into proper perspective, long-term (100 + years)

historical shoreline change data are required to interpret short-term changes as well as to identify the actual trends of change.

A future possible direction of research would involve the collection of field data in the form of profile measurements through time to measure not only the mean high water but also changes along the entire profile. Those data could then be compared with the results of this mapping study to better understand the sediment transport processes. This should be done in conjunction with detailed analyses of sediment sources and sinks to arrive at a true sediment budget. These data should ideally be updated every five years to further trace and interpret the shoreline evolution of a low-energy coast. This would serve to benefit basic understanding of coastal processes in general and sediment transport budgets in particular.

REFERENCES CITED

Anders, F.J., and M.R. Byrnes. 1990. Potential Measurement Errors and the Accuracy of Shoreline Change Rates. Shore and Beach, in press.

Bascom, W., 1980. Waves and Beaches. Anchor Press, New York, 366 pp.

Belknap, D.F., 1975. Dating of Late Pleistocene and Holocene Relative Sea Levels in Coastal Delaware. Masters Thesis, Department of Geology, University of Delaware, Newark, 95 pp.

Belknap, D.F., and J.C. Kraft, 1977. Holocene Relative Sea-Level Changes and Coastal Stratigraphic Units On the Northwest Flank of the Baltimore Canyon Trough Geosyncline. Journal of Sedimentary Petrology, Vol. 47, No. 2, pp. 601-629.

Bruun, P., 1962. Sea-Level Rise As A Cause of Shore Erosion. Journal of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, 1: pp. 117-130.

Carter, R.G., 1988. Coastal Environments, An Introduction to the Physical, Ecological and Cultural Systems of Coastlines. Academic Press, New York, pp. 199-212.

Clow, J.B., and S.P. Leatherman, 1984. Metric Mapping: An Automated Technique of Shoreline Mapping. Proc. of ASP-ACSM Convention, Washington, D.C., pp. 309- 317.

Crowell, M., S.P. Leatherman, and M.K. Buckley, 1991. Historical Shoreline Change: Error Analysis and Mapping Accuracy. Journal of Coastal Research, in press.

Davis, A.J., 1985. Beach and Nearshore Zone. Coastal Sedimentary Environments, R.A. Davis, Jr., Ed., Springer-Verlag, New York, pp. 225-301.

Dean, R.J, 1987. Managing Sand and Preserving Shorelines. Oceanus, Vol.31, pp. 49-55.

Demarest, J.M., 1978. The Shoaling of Breakwater Harbor, Cape Henlopen Area, Delaware Bay, 1842 to 1971. Delaware Sea Grant Technical Report DEL-SG-1-78, College of Marine Studies, University of Delaware, Newark, 169 pp.

Drew, K.S., 1981. The Influence of Geological Structure and Historical Changes In Morphology of Delaware Bay: Communities on Environmental Planning. Unpublished report by the University of Delaware to the Office of Coastal Zone Management, National Oceanic and Atmospheric Administration, 186 pp.

Frey, R. and P. Basan, 1985. Coastal Salt Marshes, Coastal Sedimentary Environments, R.A. Davis, Jr., Ed., Springer-Verlag, New York, pp. 225-301.

Friedlander, S.C., S.E. Jackson, J.S. Landsdale, J.R. Mather, D.A. Murray, P.W. Rees, E.A. Schellhardt, and J.J. Swaye, 1977. Delaware Coastal Storm Damage Report: 1923-1974. Technical Report No. 4. Delaware Coastal Management, Budget and Planning, 442 pp.

Galgano, F.A., 1989. Shoreline Recession and Nearshore Response, Atlantic Coast of Delaware. Masters Thesis, Department of Geography, University of Maryland, College Park, 161 pp.

Hands, E.B., 1977. Implications of Submergence For Coastal Engineers. Coastal Sediments '77, American Society of Civil Engineers, pp. 149-166.

Hands, E.B., 1981. Predicting Adjustments in Shore and Offshore Sand Profiles on the Great Lakes. CERC Technical Aid No. 81-4, U.S. Army Corps of Engineers, 25 pp.

Henry, R. and T. Pratt, 1990. Personal Communications, Delaware Department of Natural Resources, Dover, DE.

Jarrett, J.T., 1987. Beach Nourishment - A Corps Perspective, Coastal Engineering Research Board, 48th Meeting, Savannah, GA District, 3 pp.

Jordan, R.R., 1964. Columbia (Pleistocene) Sediments of Delaware: Delaware Geologic Survey Bulletin No. 12, 69 pp.

Kearney, M.S., R.E. Grace, and J.C. Stevenson, 1988. Marsh Loss in Nanticoke Estuary, Chesapeake Bay. Geographical Review, Vol. 78, No. 2, pp. 205-220.

King, P.B., 1977. Evolution of North America. Princeton University Press, Princeton, NJ, 197 pp.

Kraft, J.C., and R.L. Caulk, 1972. The Evolution of Lewes Harbor. Trans. of the 1971-72 Meeting of the Delaware Academy of Science, Newark, 60 pp.

Kraft, J.C., R.E. Sheridan, R.D. Moose, R.N. Strom, and C.B. Weil, 1975. Middle-Late Holocene Evolution of the Morphology of a Drowned Estuary System: The Delaware Bay. Technical Report No. 34, College of Marine Studies, University of Delaware, Newark, 10 pp.

Kraft, J.C., and C.J. John, 1976. The Geological Structure of the Shorelines of Delaware. College of Marine Studies, University of Delaware, Newark, 107 pp.

Kraft, J.C., E.A. Allen, D.F. Belknap, C.J. John, and E.M. Maurmeyer, 1976. Delaware's Changing Shoreline. Technical Report Number 1. Dover, DE, Delaware State Planning Office, 319 pp.

Kraft, J.C., C.J. John, and P.R. Marx, 1981. Clastic Depositional Strata in a Transgressive Coastal Environment: Holocene Epoch. Northeastern Geology, V. 3, nos. 3/4, pp. 268-277.

Leatherman, S.P., 1979. Migration of Assateaque Island, Maryland, by Inlet and Overwash Processes. Geology, V.7, pp. 104-107.

Leatherman, S.P., 1981. Barrier Beach Development: A Perspective on the Problem. Shore and Beach, V. 49, pp. 3-9.

Leatherman, S.P., 1983a. Barrier Dynamics and Landward Migration With Holocene Sea-Level Rise. Nature, Vol. 301, No. 5899, pp. 415-418.

Leatherman, S.P., 1983b. Shoreline Mapping: A Comparison of Techniques. Shore and Beach, V. 51, pp. 28-33.

Leatherman, S.P., 1985. Geomorphic Effects of Accelerated Sea-Level Rise on Ocean City, MD (J. Titus, Ed.), U.S. Environmental Protection Agency, Washington, D.C., pp. 33-65.

Leatherman, S.P., 1987. Beach and Shoreface Response to Sea-Level Rise: Ocean City, Maryland, U.S.A. Prog. Oceanog. 18: pp. 139-149.

Leatherman, S.P., 1988. Barrier Island Handbook. University of Maryland, College Park, MD, 92 pp.

Leatherman, S.P., 1989a. Impact of Accelerated Sea Level Rise on Beaches and Coastal Wetlands. Global Climate Change Linkages, J.C. White, Elsevier Science Publishing Co., Inc., pp. 43-57.

Leatherman, S.P., 1989b. Response of Sandy Beaches to Sea-Level Rise. Late Quaternary Sea-Level Correlation and Applications, D.B. Scott, et al., Eds., Kluwer Academic Publishers, Netherlands, pp. 57-69.

Leatherman, S.P., and J.B. Clow, 1983. UMD Shoreline Mapping Project. IEEE Geo-Science and Remote Sensing Society Newsletter, 22, pp. 5-8.

Leatherman, S.P., and J.J. McDonald, 1988. America's Eroding Beaches - NOS Data May Hold the Key. The Military Engineer, No. 520. pp. 143-144.

Lyles, S.D., L. E. Hickman, Jr., and H.A. Debaugh, Jr., 1987. Sea-Level Variations for the United States: 1885-1986. Rockville, MD: U.S. Department of Commerce, NOAA-NOS, 84 pp.

Maurer, D., and H. Wang, 1973. Environmental Vulnerability of The Delaware Bay Area to Supertanker Accommodation, Vol. III: Chemistry, Engineering, Geology, and Physical Oceanography: N.T.I.S. Pub. PB-29-803, 311 pp.

Maurmeyer, E.M., 1978. Geomorphology and Evolution of Transgressive Estuarine Washover Barriers Along the Western Shore of Delaware Bay. Ph.D. Dissertation. University of Delaware, 275 pp.

National Research Council, 1987. Responding to Changes in Sea Level: Engineering Implications. Washington, D.C.: National Academy of Science, 135 pp.

National Research Council, 1990. Managing Coastal Erosion. National Academy of Science, Washington, D.C., 182 pp.

Nicholls, R.J., and N.B. Webber, 1987. Coastal Erosion in the Eastern Half of Christchurch Bay, Planning and Engineering Geology, Culshaw, M.G., et al., Eds, Geological Society Engineering Geology Special Publication No.4, pp. 549-554.

Phillips, J.D., 1986. Spatial Analysis of Shoreline Erosion, Delaware Bay, New Jersey, Annals of the Association of American Geographers, V.76, #1, pp. 50-62.

Orson, R., W. Panageotou, and S.P. Leatherman, 1985. Response of Tidal Salt Marshes of the U.S. Atlantic and Gulf Coasts to Rising Sea Levels. Journal of Coastal Research, Vol.1, No.1, pp. 29-37.

Pilkey, O.H., 1987. A Review of East Coast Beach Replenishment. Coastal Engineering Research Board, 48th Meeting, Savannah, GA District, 4 pp.

Rosen, P.S., 1978. A Regional Test of The Bruun Rule on Shoreline Erosion. Marine Geology, V.26, 10 pp.

Strom, R.N., 1972. Sediment Distribution in Southwestern Delaware Bay. Technical Report No. 18, College of Marine Studies, University of Delaware, Newark, 118 pp.

Stumpf, R.P., 1983. The Process of Sedimentation on the surface of a Salt Marsh. Estuarine Coastal and Shelf Science, V.17, No.5, pp.495-508.

Tanner, W.F., 1973. Advances In Near-Shore Physical Sedimentology: A Selective Review. Shore and Beach, V. 41, pp. 22-27.

U.S. Army Corps of Engineers (USCE), 1966. Beach Erosion Control and Hurricane Protection Along the Delaware Coast. Philadelphia District, U.S. Army Corps of Engineers, Philadelphia, PA, 71 pp., Appendices a-k.

U.S. Army Corps of Engineers (USCE), 1977. Shoreline Erosion Control Demonstration Program: Pickering Beach, Delaware. Philadelphia District, U.S. Army Corps of Engineers, Philadelphia, PA, 49 pp., Appendices a-b.

U.S. Army Corps of Engineers (USCE), 1984. Shore Protection Manual, Volume 1. CERC, Vicksburg, VA.

U.S. Department of Commerce, 1977. Tide Tables: High and Low Water Predictions of North and South America: U.S. Department of Commerce, 288 pp.

U.S. Department of Commerce, 1990. 50 Years of Population Change Along the Nation's Coasts: 1960-2010. National Oceanic and Atmospheric Administration, Rockville, MD, 41pp.

Vellinga, P., and S.P. Leatherman, 1989. Sea Level Rise, Consequences and Policies, Climatic Change 15, pp. 175-189.

Weil, C.B., Jr., 1975. A Model For The Distribution, Dynamics, and Evolution of Holocene Sediments and Morphologic Features of Delaware Bay. Ph.D. Dissertation, Department of Geology, University of Delaware, Newark, 408 pp.

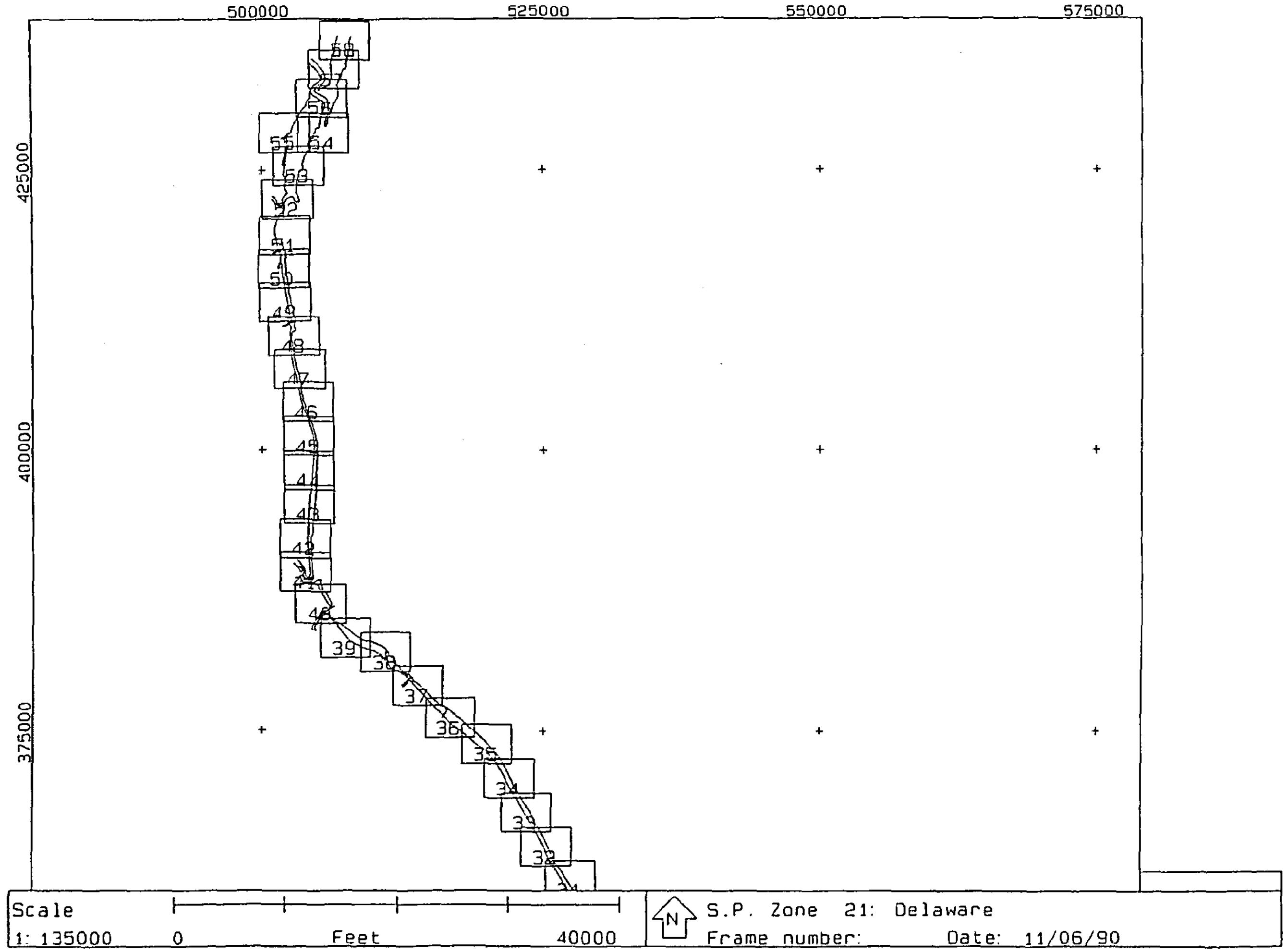
Weil, C.B., Jr., 1977. Sediments, Structural Framework, and Evolution of Delaware Bay: A Transgressive Estuarine Delta. Delaware Sea Grant Technical Report DEL-SG-4-77, College of Marine Studies, University of Delaware, Newark, 199 pp.

Walton, T.L., 1977. Calculation Of Equilibrium Shorelines In Florida and Applications to Coastal Structure Design. Coastal Sediments '77, pp. 1-16.

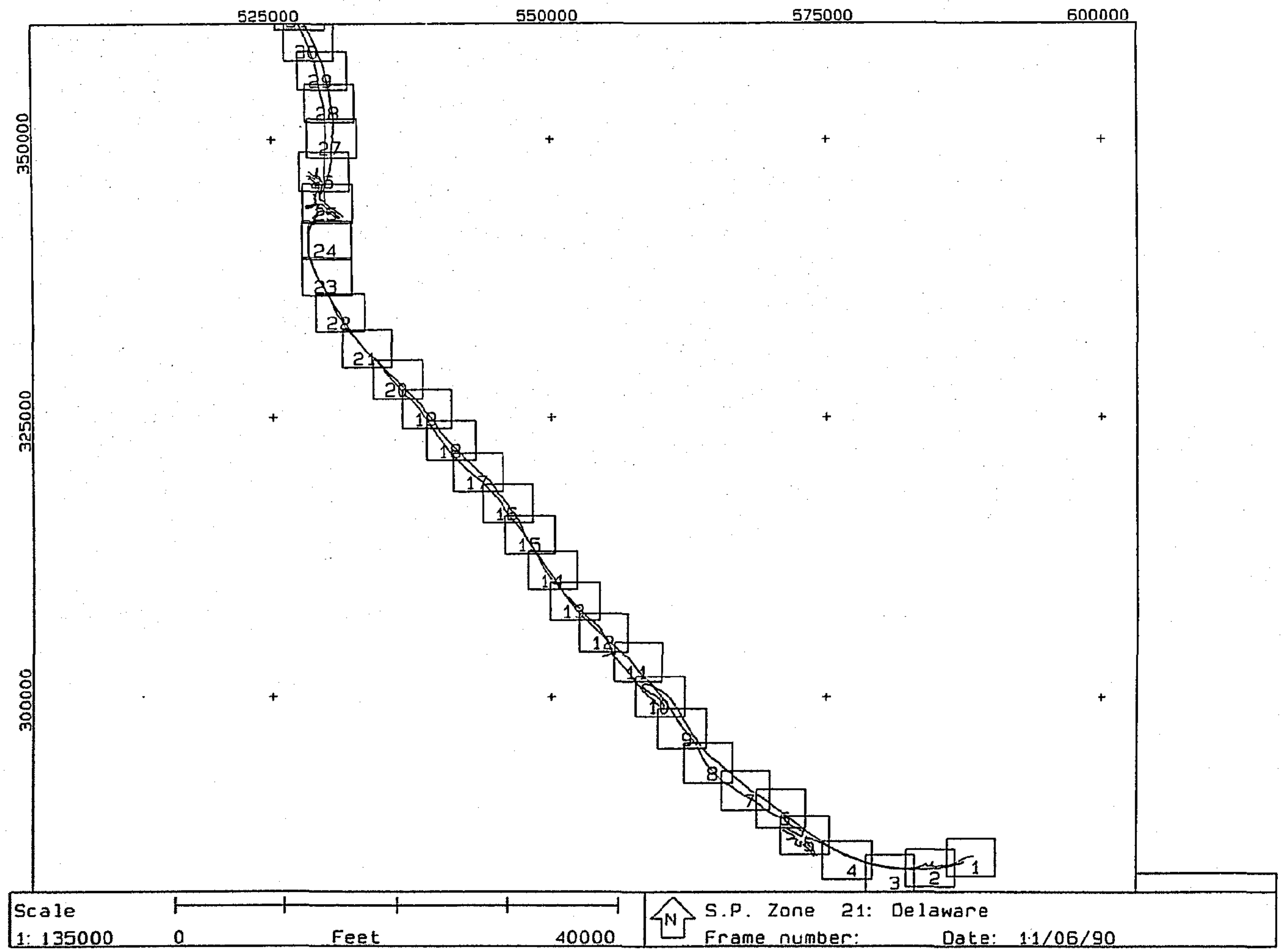
APPENDIX 1

This appendix contains 58 historical shoreline change maps and two index maps depicting the positions of the western shorelines of the Delaware Bay as they were in the years 1842, 1882/1883/1884, 1910, 1943/1944/1946, 1954, 1969/1970/1971, and 1977. The maps were generated at a scale of 1:6000. Straight lines projected approximately perpendicular to the shorelines represent computer-generated transect lines at which locations positional change calculations were made. The results of those calculations are seen in Appendices 2 and 3.

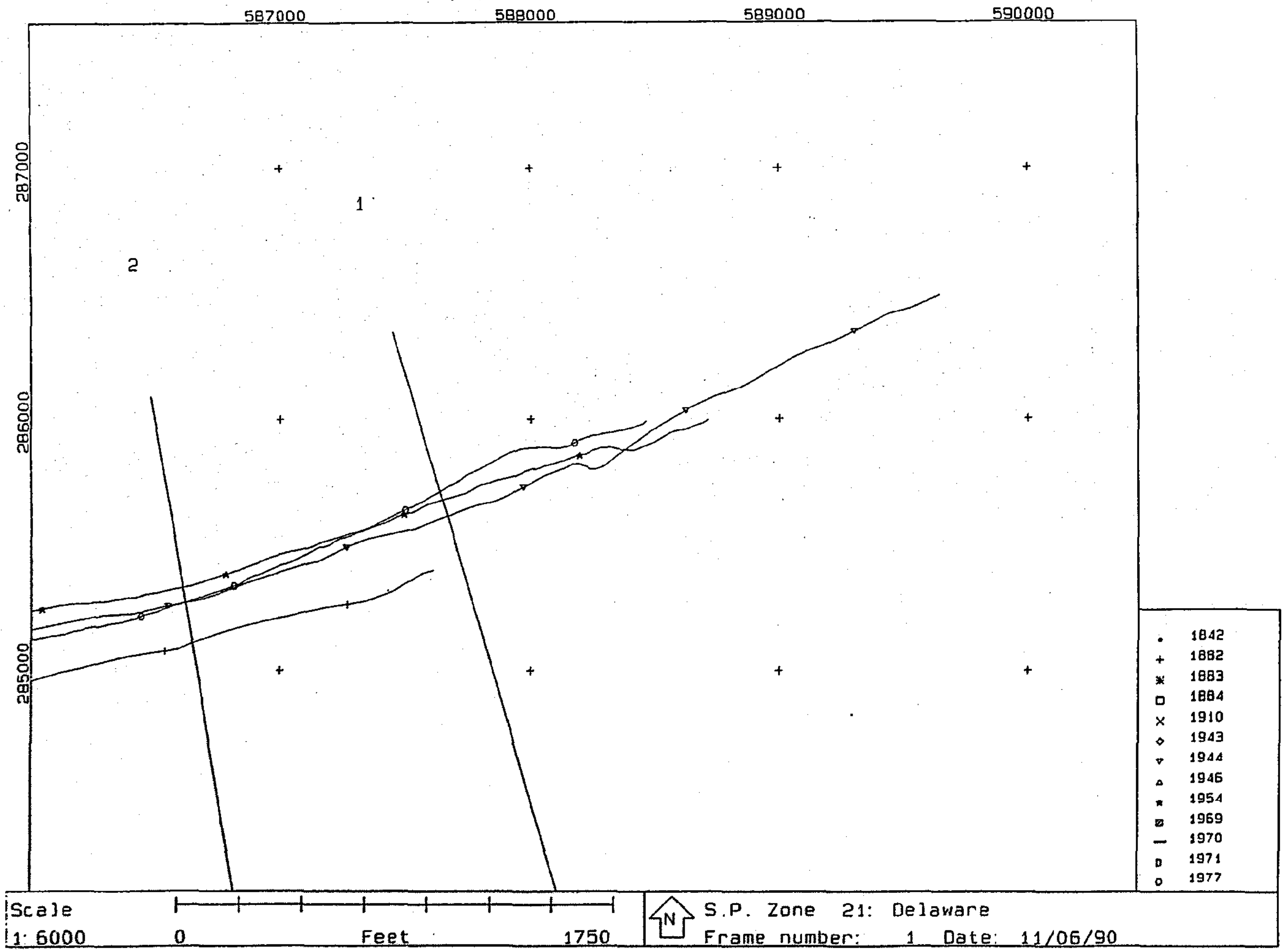
INDEX TO MAP FRAME LOCATIONS: WEST DELAWARE BAY, NORTHERN HALF



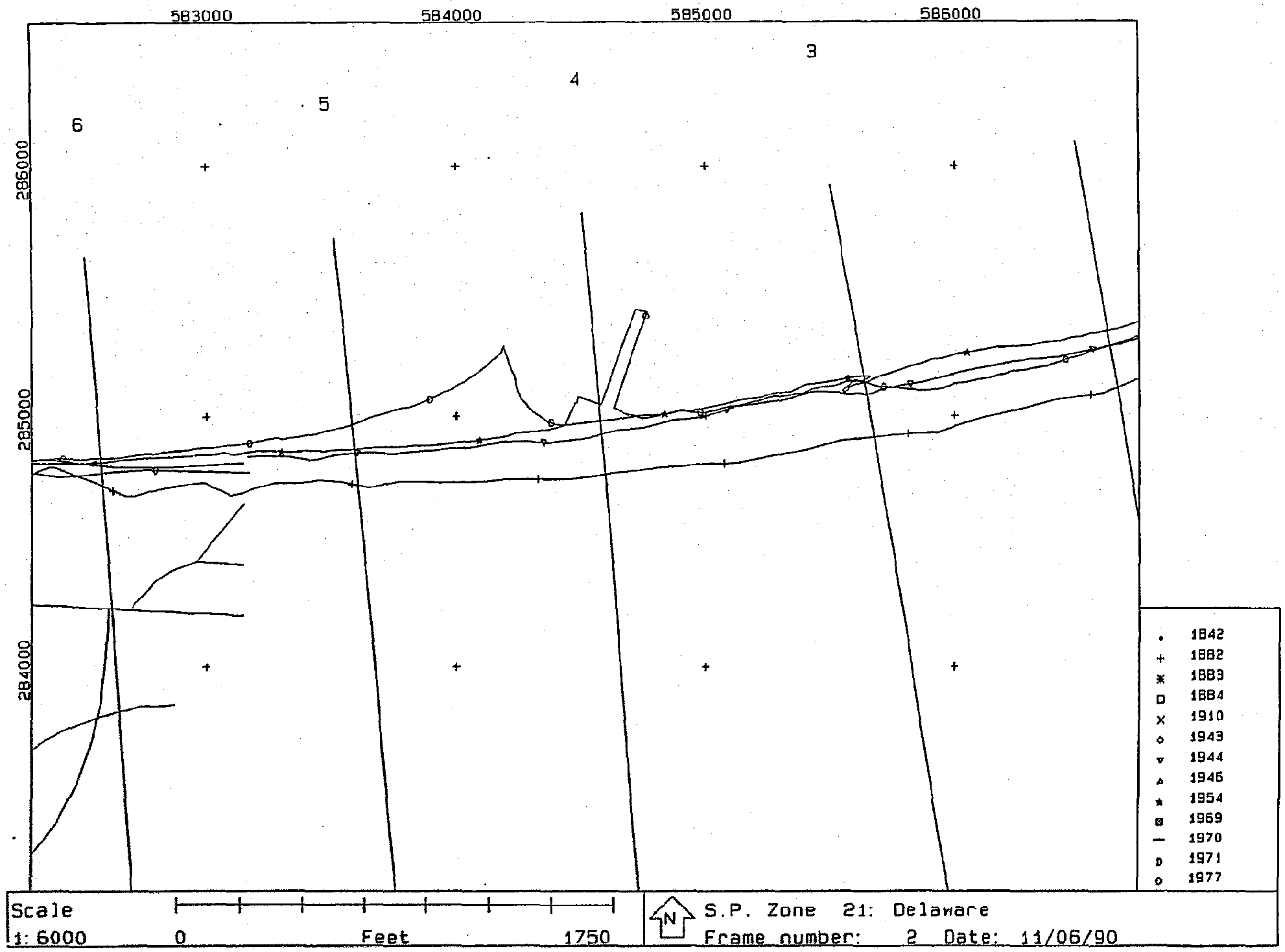
INDEX TO MAP FRAME LOCATIONS: WEST DELAWARE BAY, SOUTHERN HALF



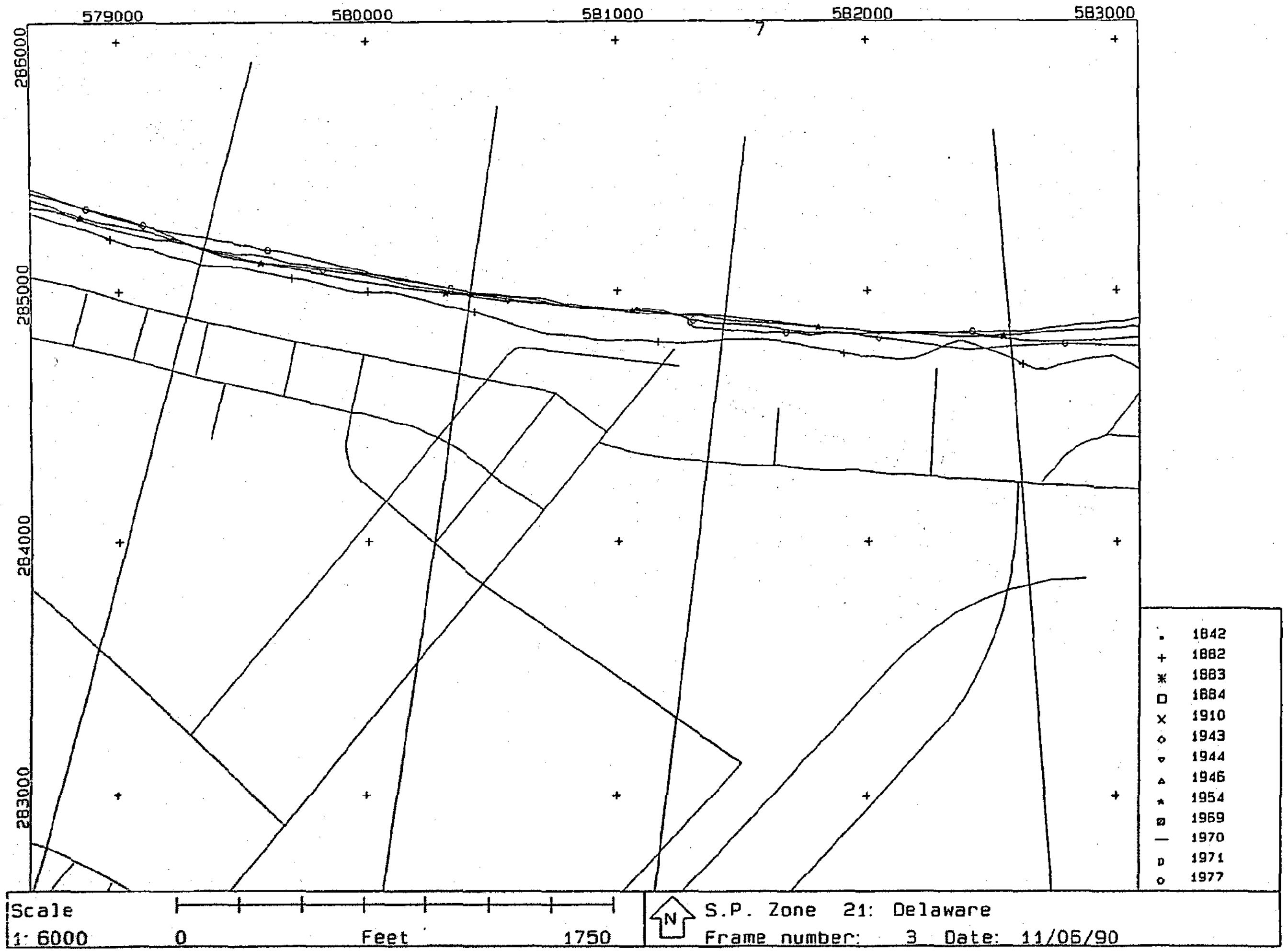
West Delaware Bay Historical Shoreline Changes: 1842-1977



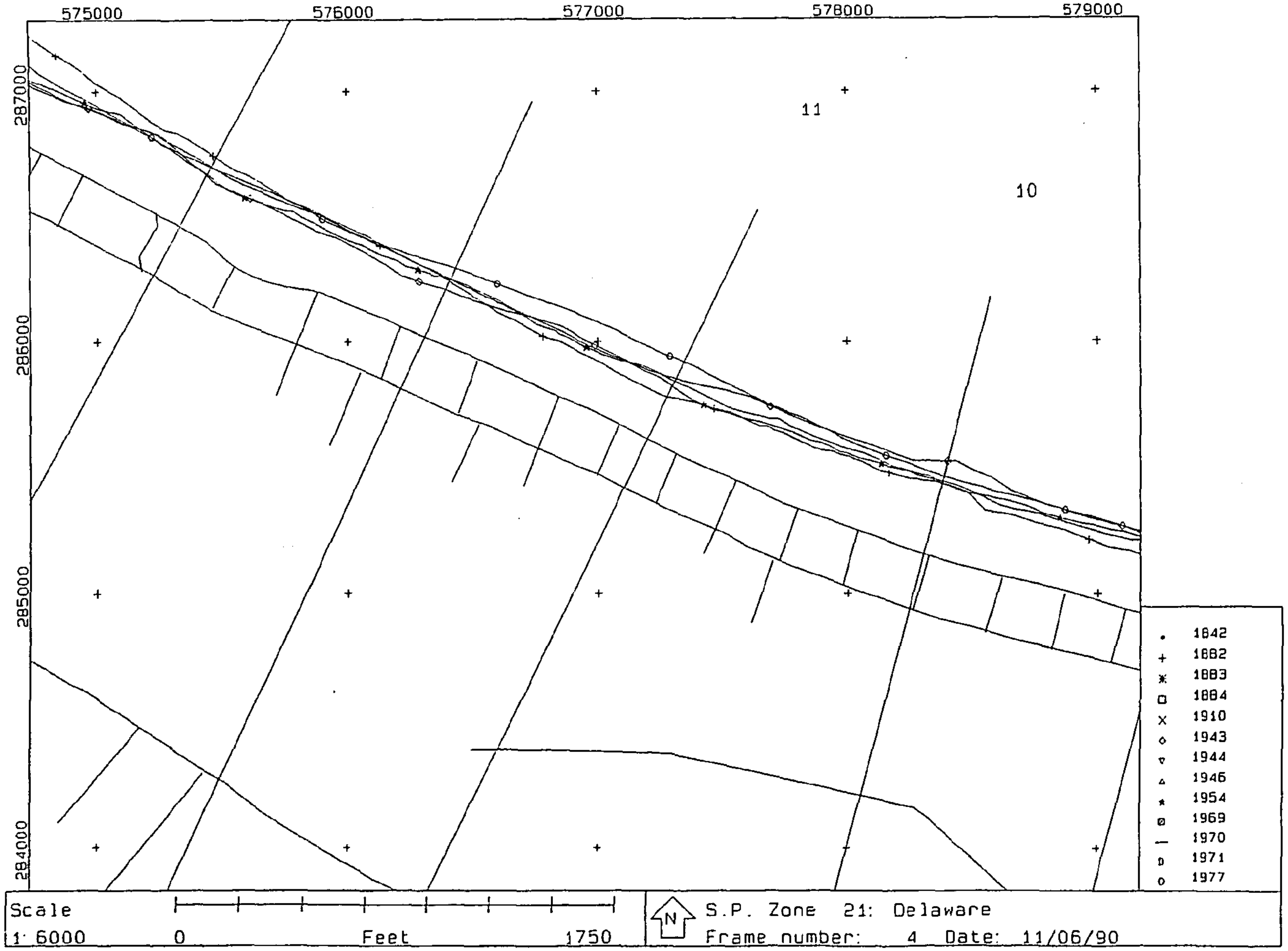
West Delaware Bay Historical Shoreline Changes: 1842-1977



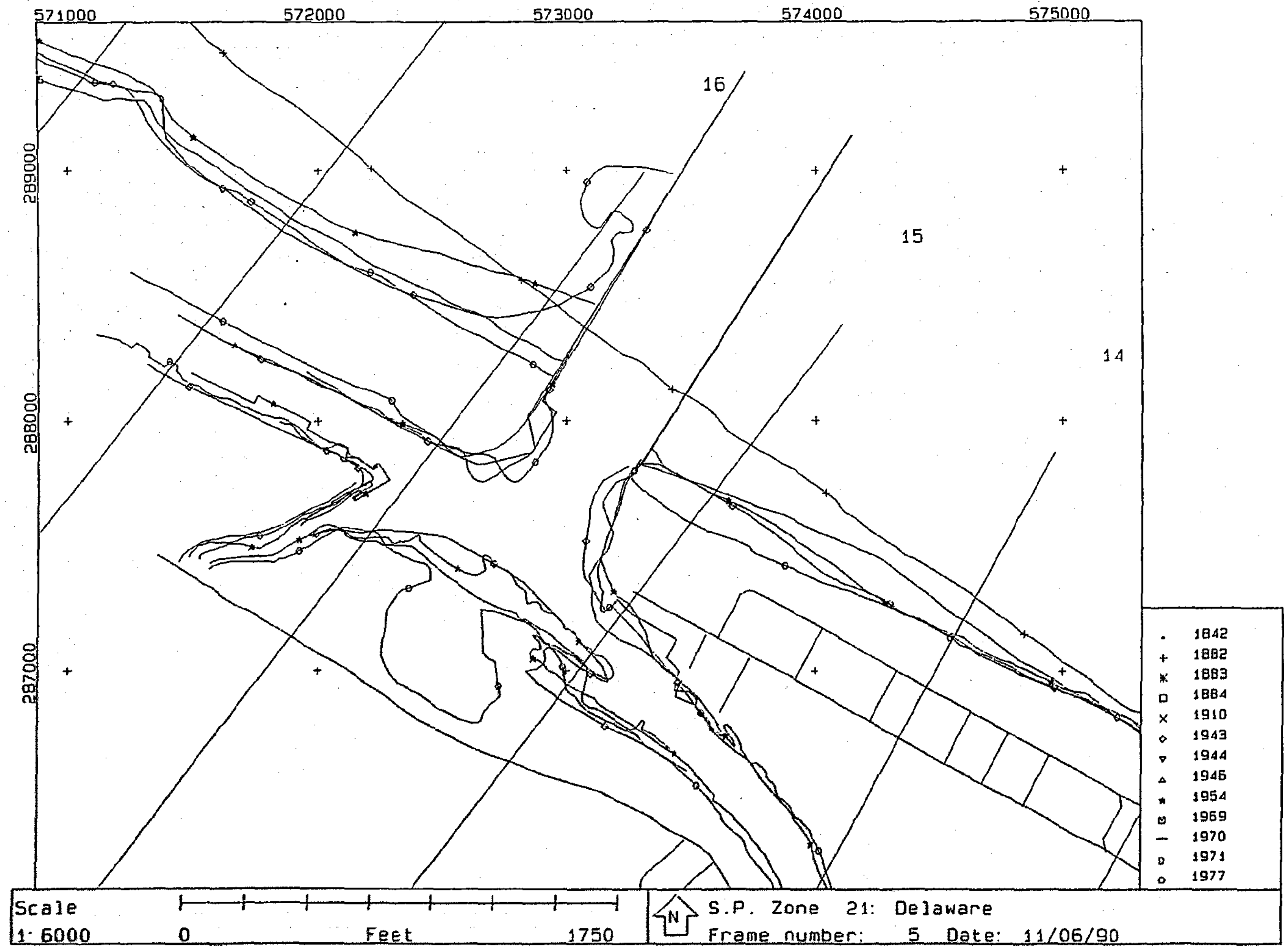
West Delaware Bay Historical Shoreline Changes: 1842-1977

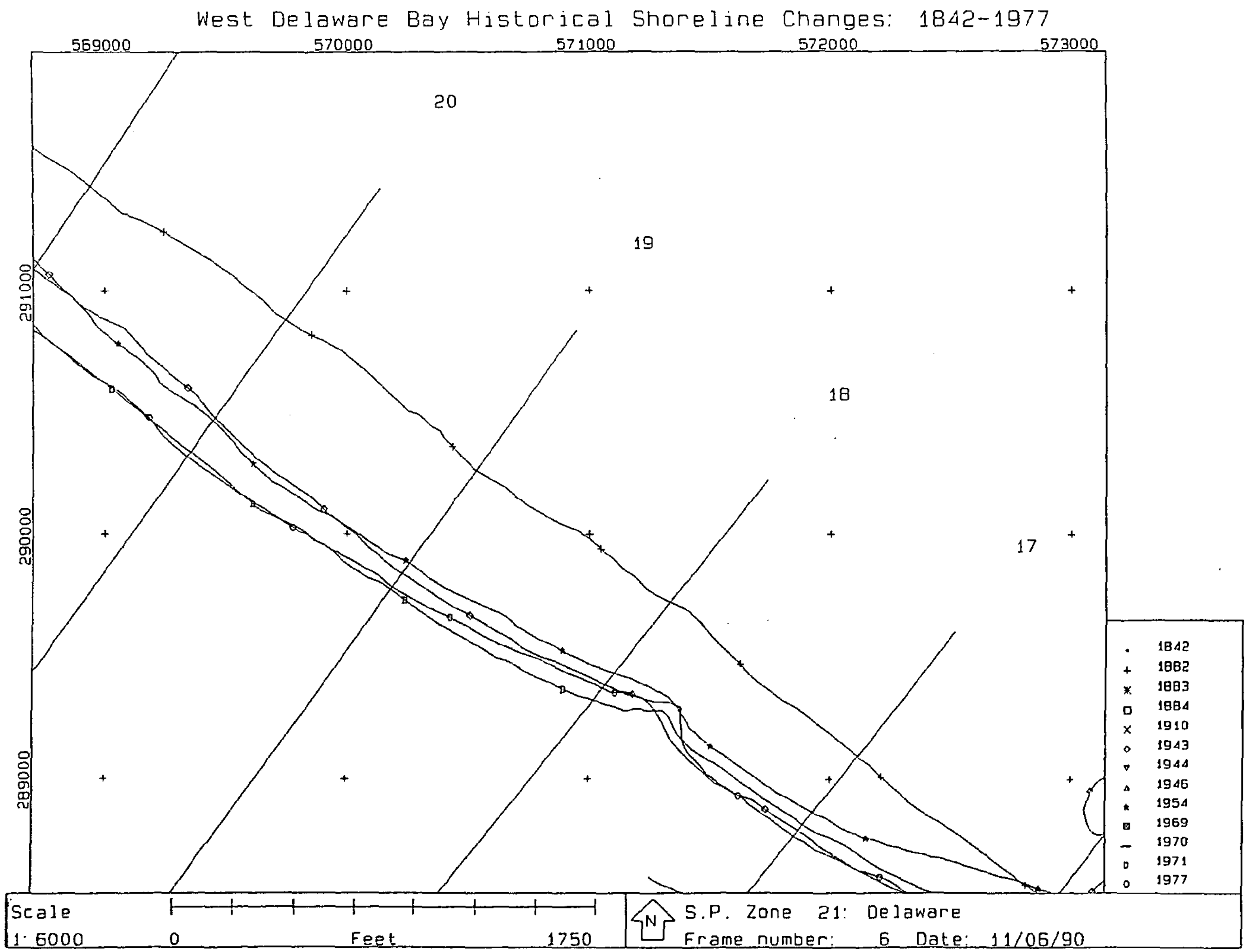


West Delaware Bay Historical Shoreline Changes: 1842-1977

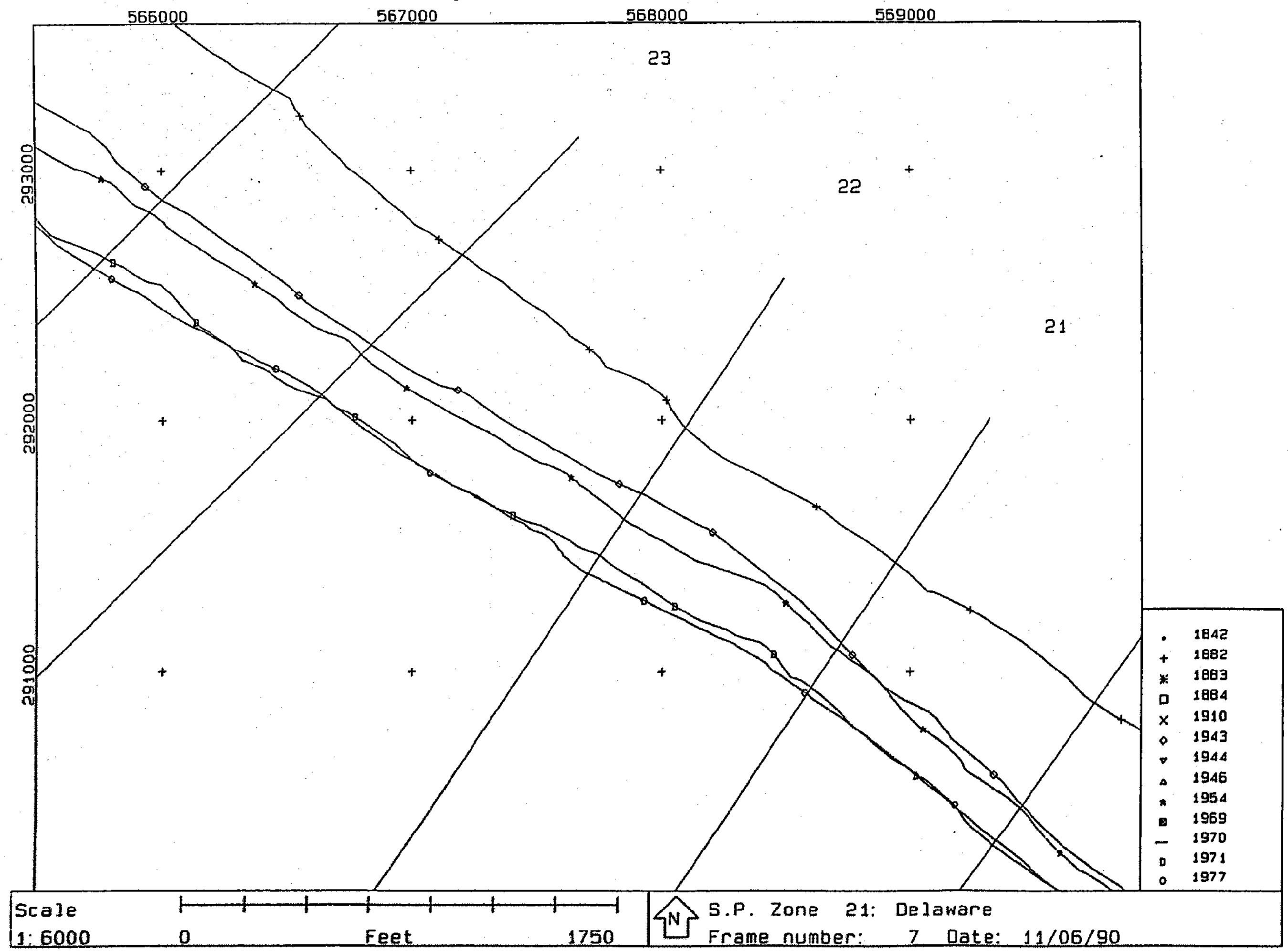


West Delaware Bay Historical Shoreline Changes: 1842-1977

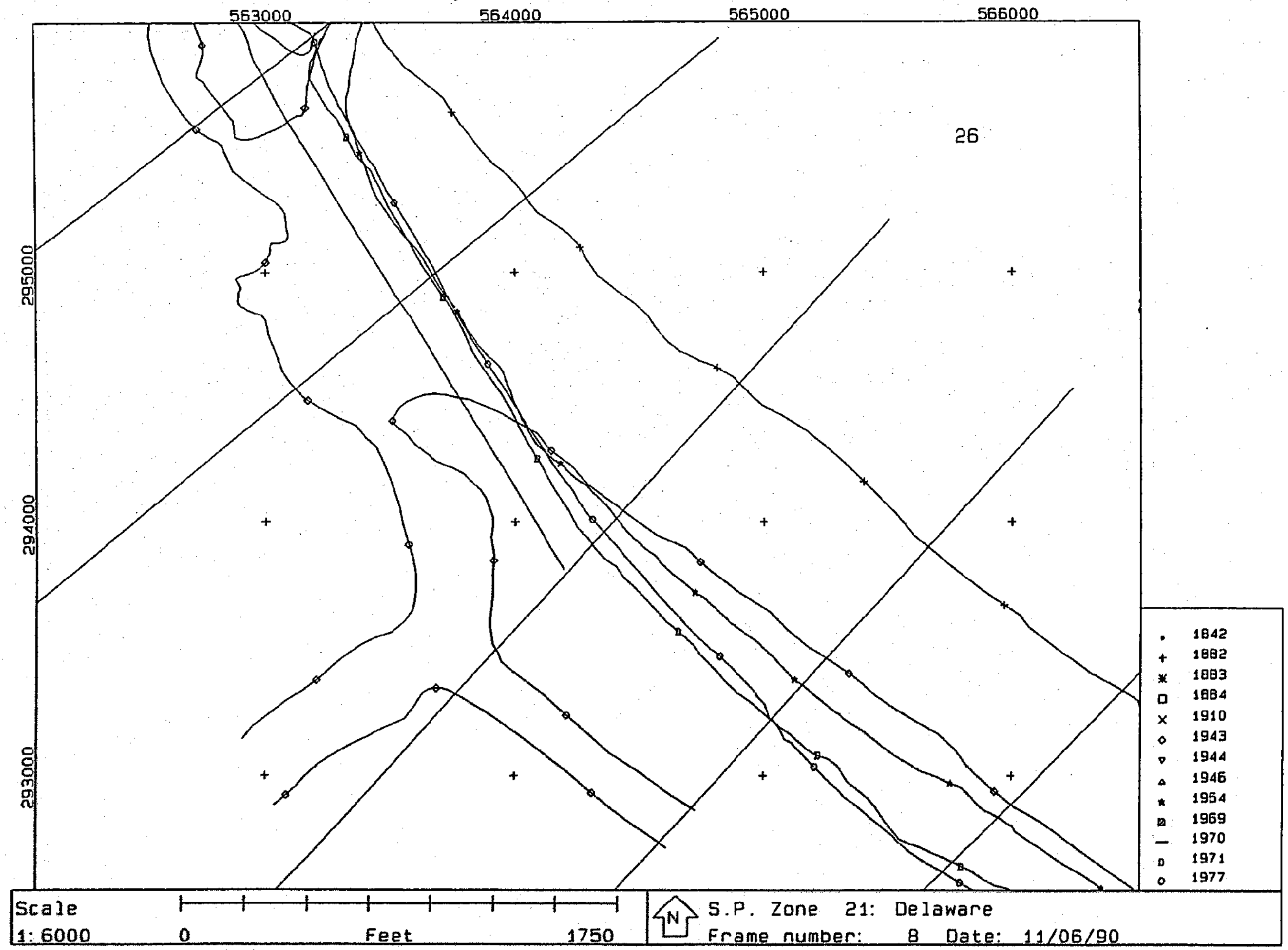



West Delaware Bay Historical Shoreline Changes: 1842-1977
569000
570000
571000
572000
573000
20
19
18
17
291000
290000
289000
1842
1882
1883
1884
1910
1943
1944
1946
1954
1969
1970
1971
1977
Scale
1: 6000
0
Feet
1750
N
S.P. Zone 21: Delaware
Frame number: 6 Date: 11/06/90

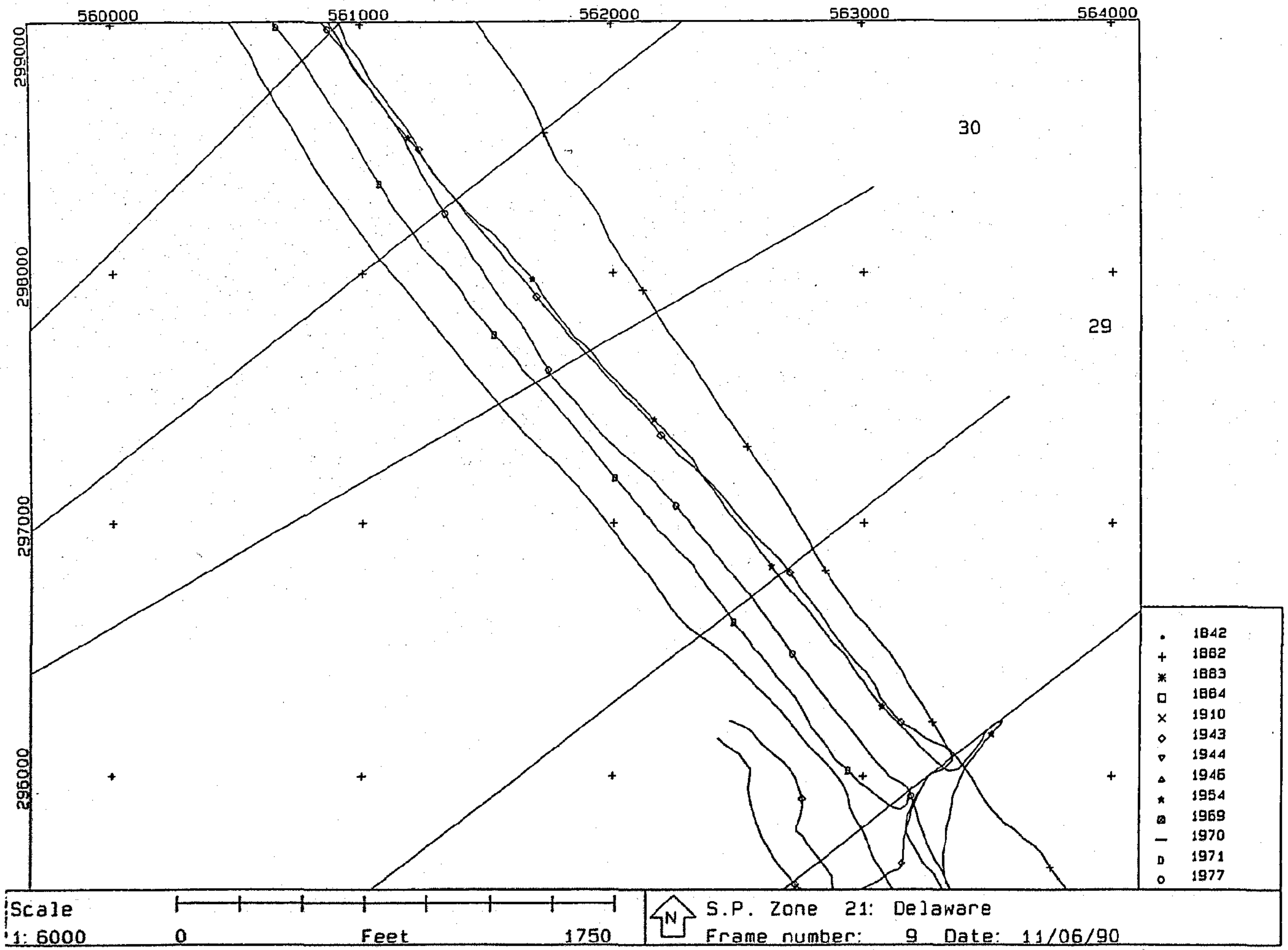
West Delaware Bay Historical Shoreline Changes: 1842-1977



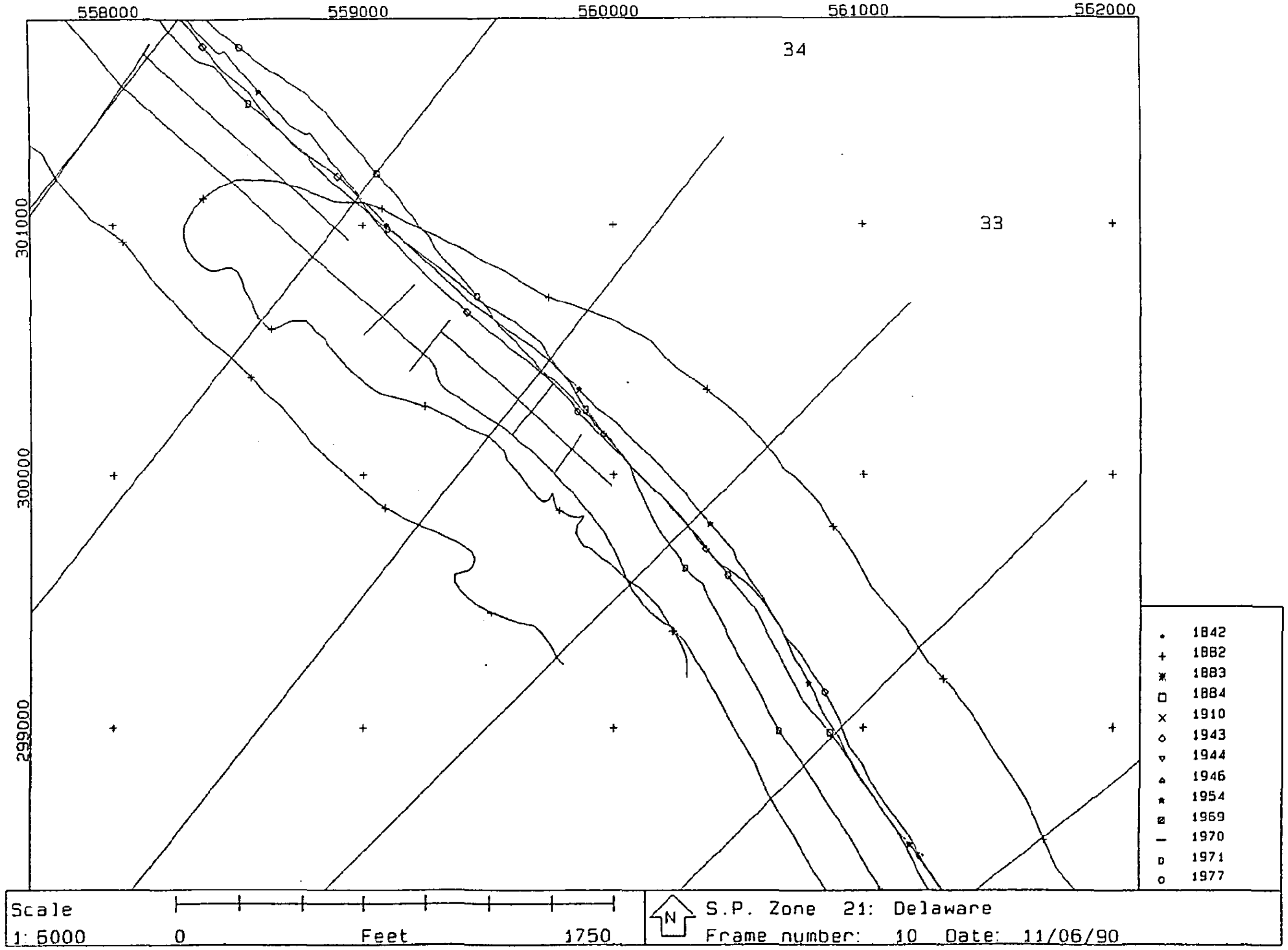
West Delaware Bay Historical Shoreline Changes: 1842-1977



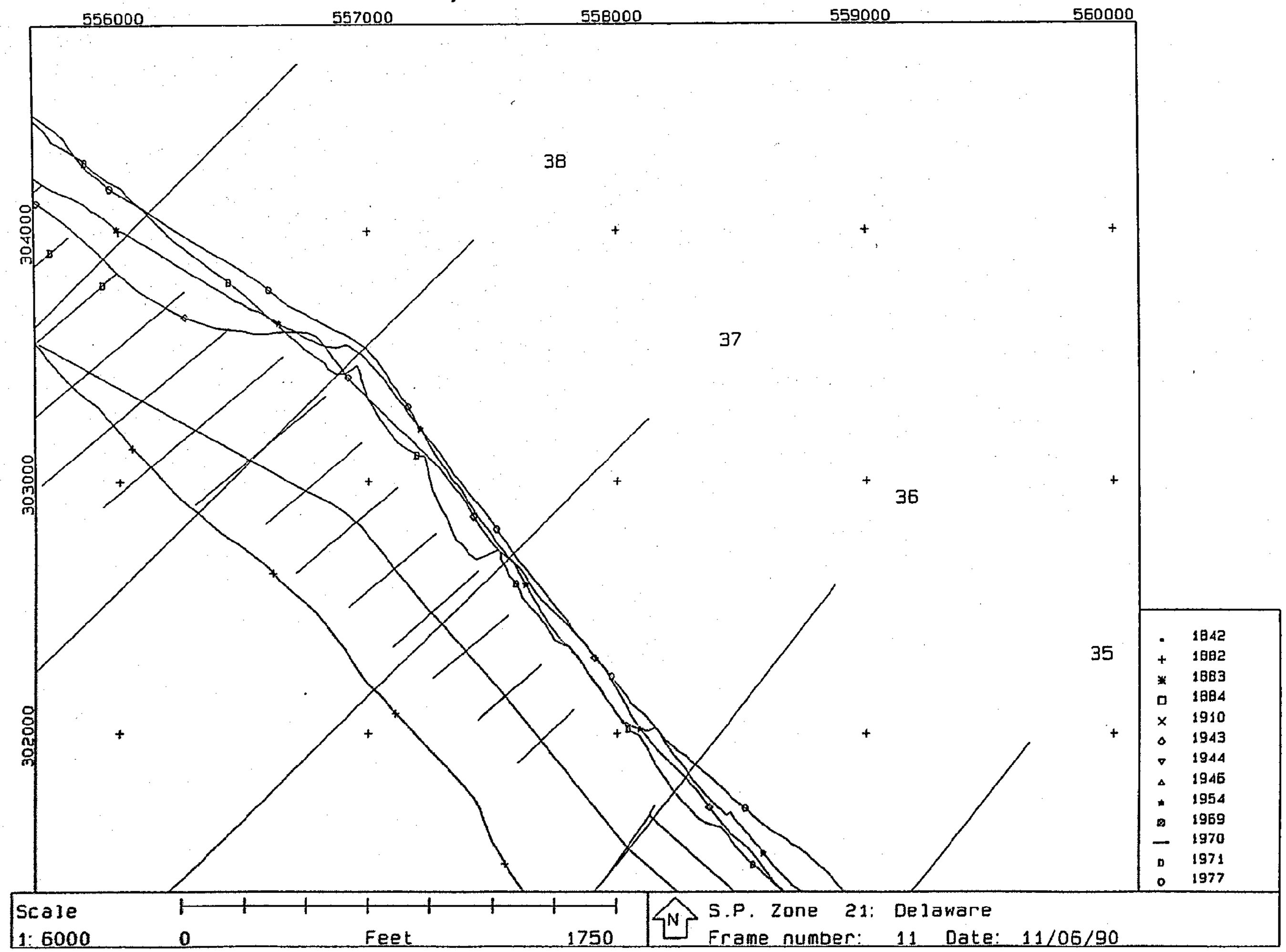
West Delaware Bay Historical Shoreline Changes: 1842-1977



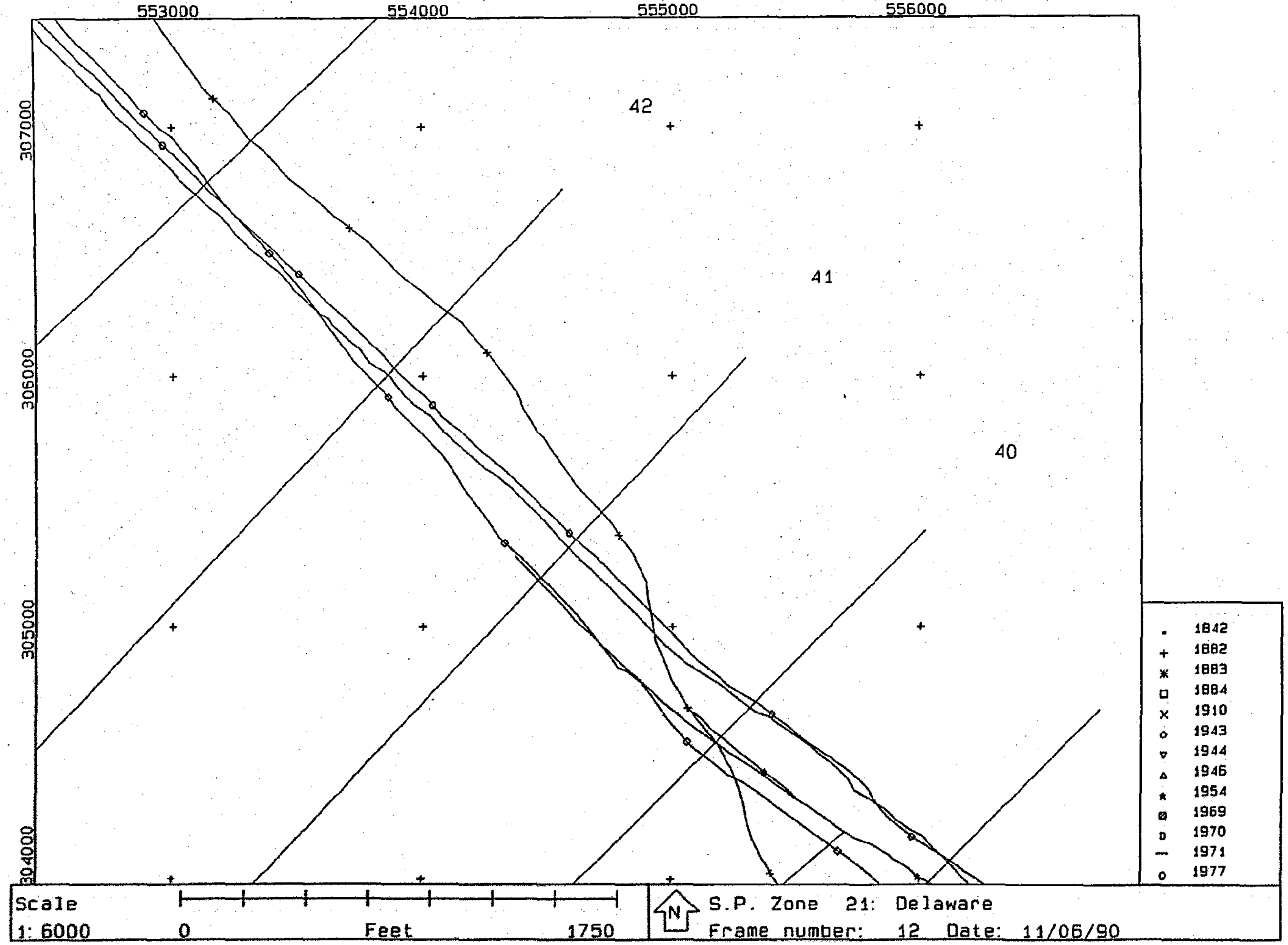
West Delaware Bay Historical Shoreline Changes: 1842-1977



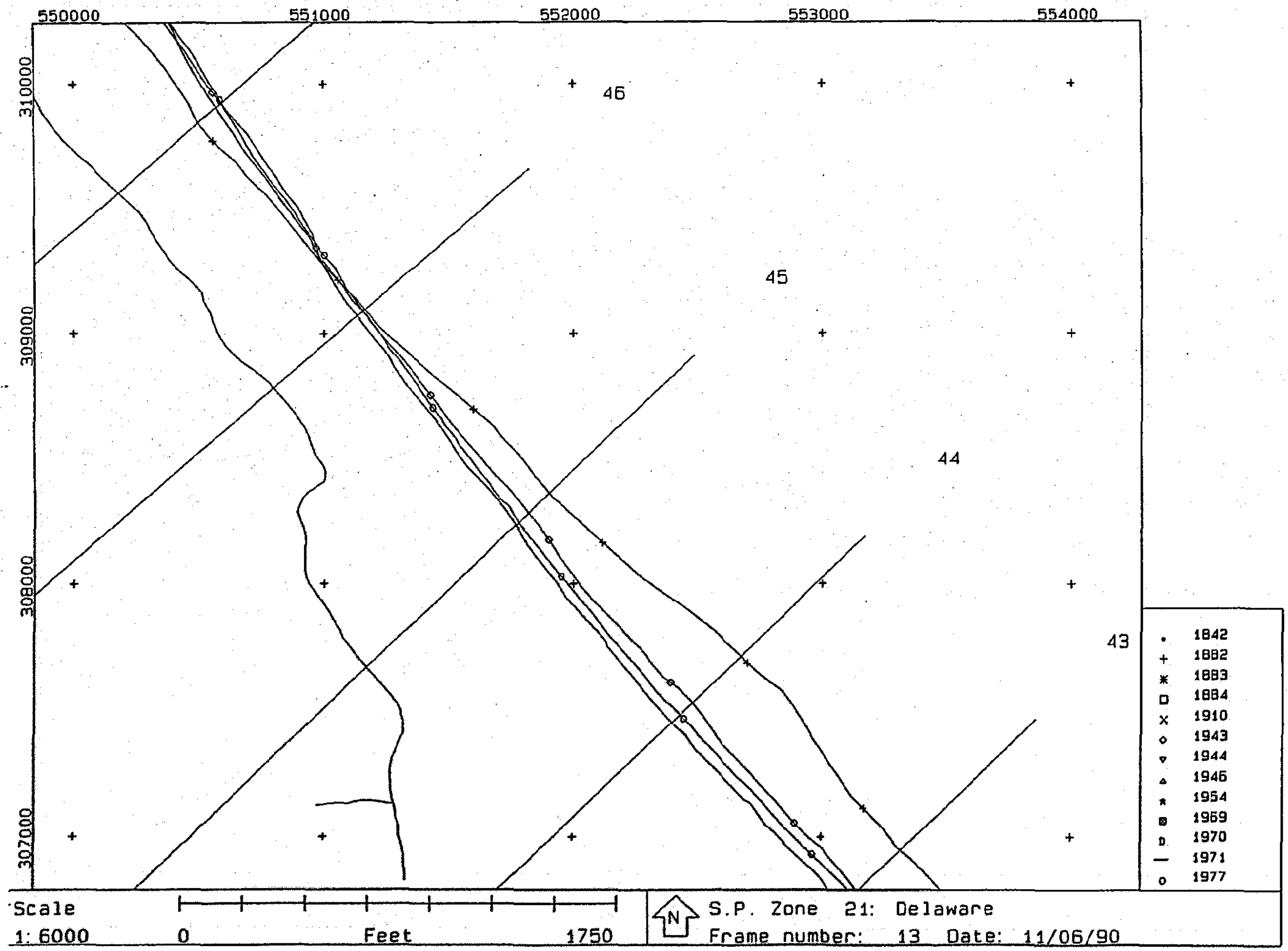
West Delaware Bay Historical Shoreline Changes: 1842-1977



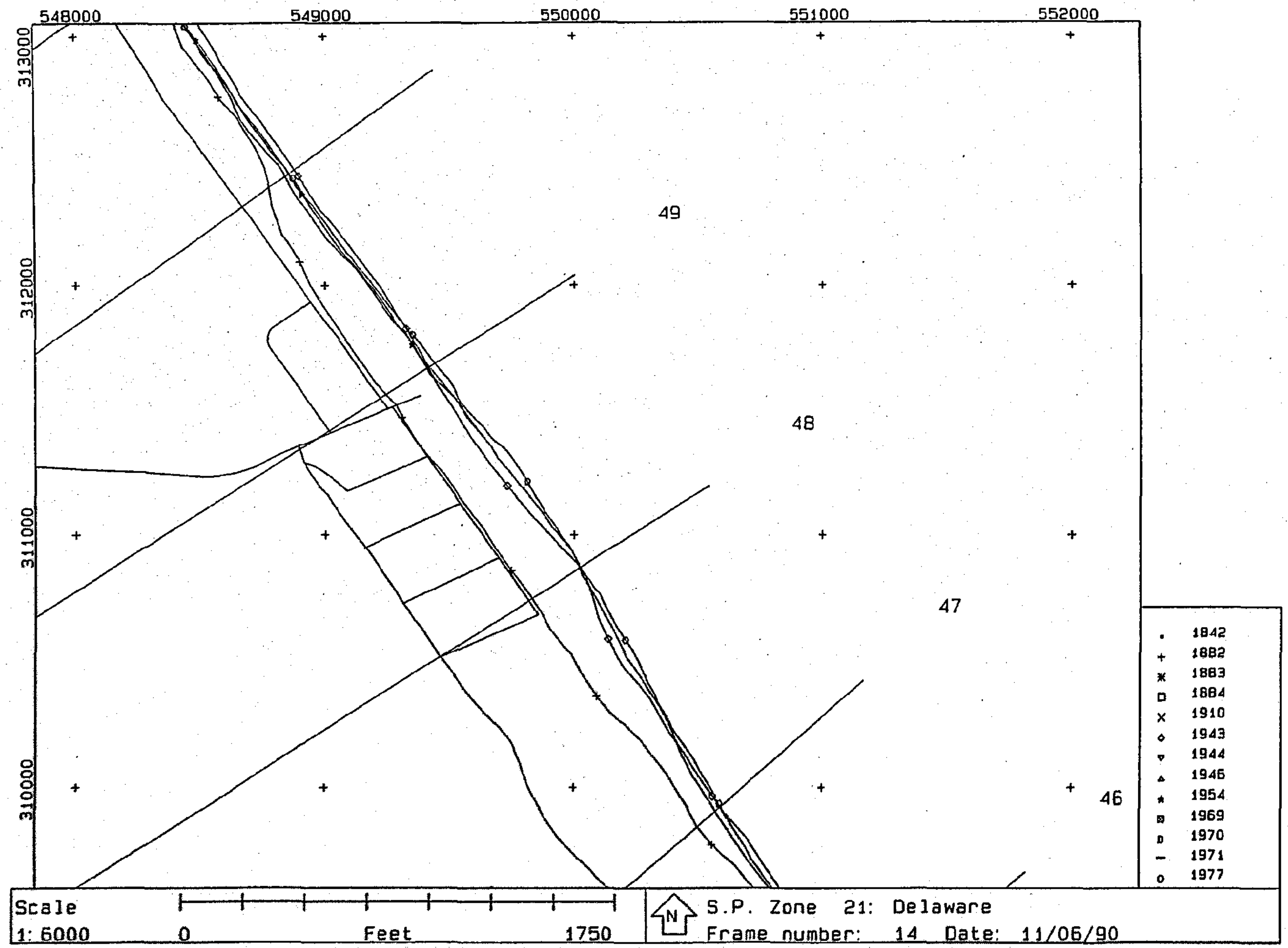
West Delaware Bay Historical Shoreline Changes: 1842-1977



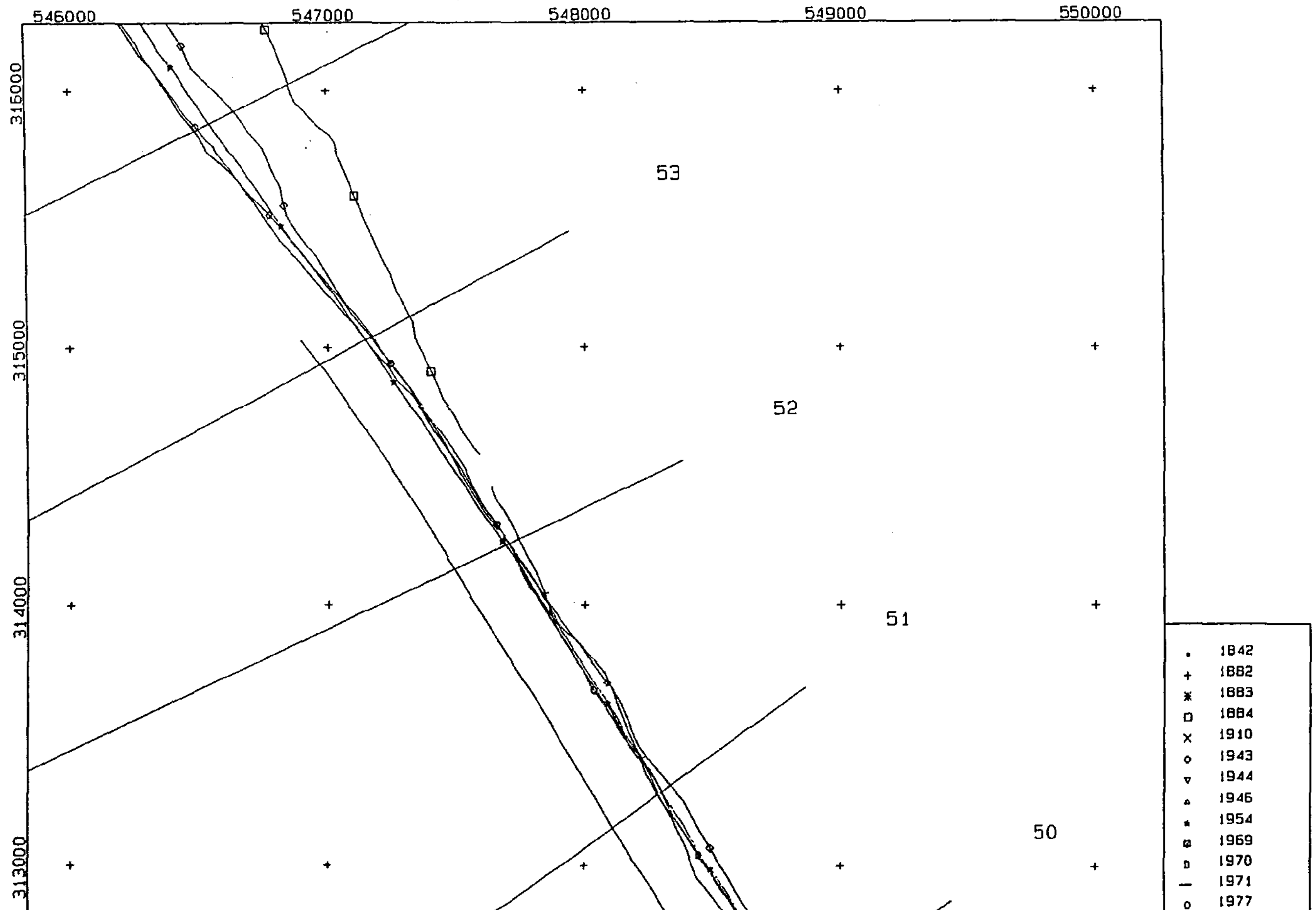
West Delaware Bay Historical Shoreline Changes: 1842-1977



West Delaware Bay Historical Shoreline Changes: 1842-1977

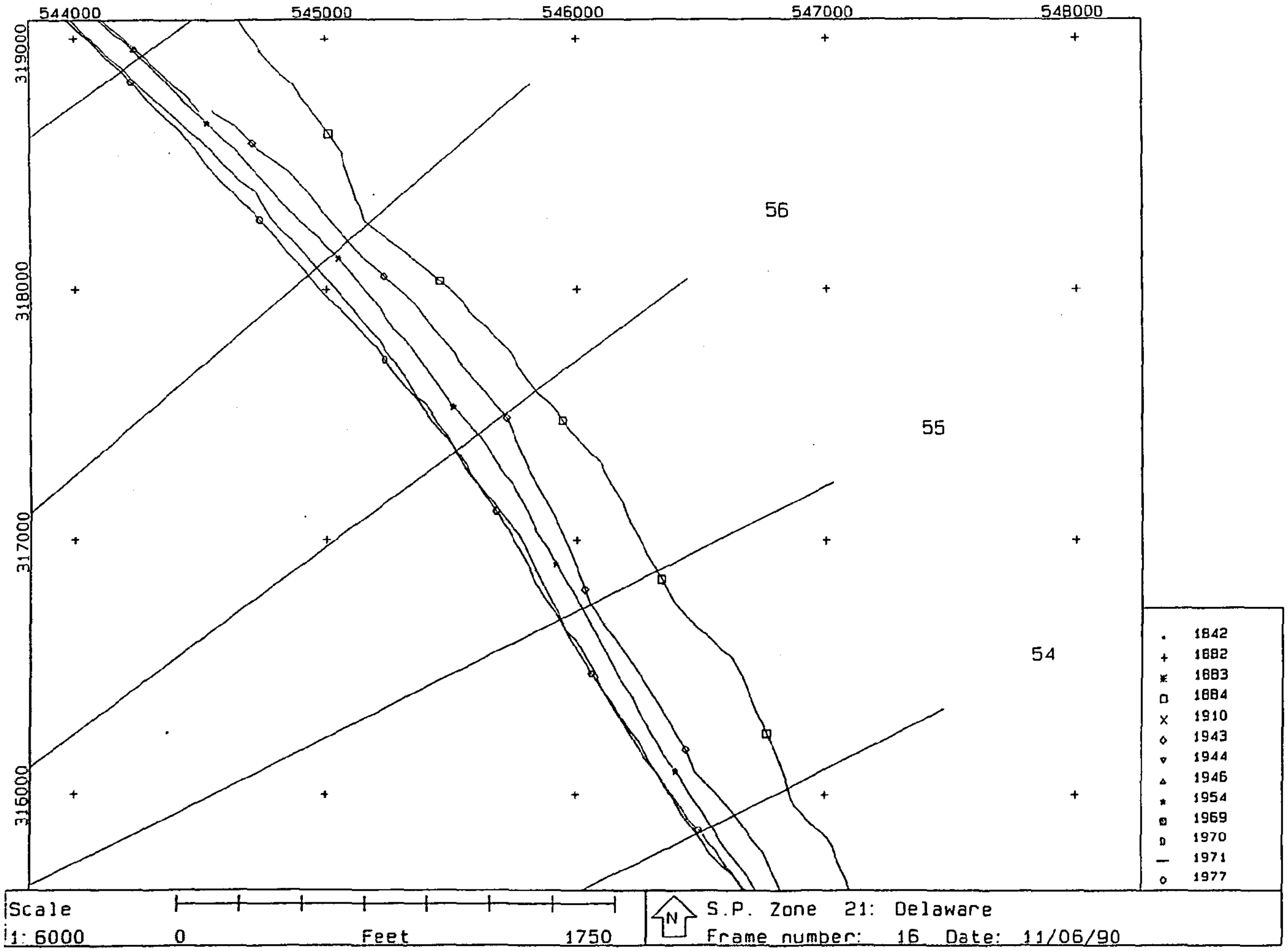


West Delaware Bay Historical Shoreline Changes: 1842-1977

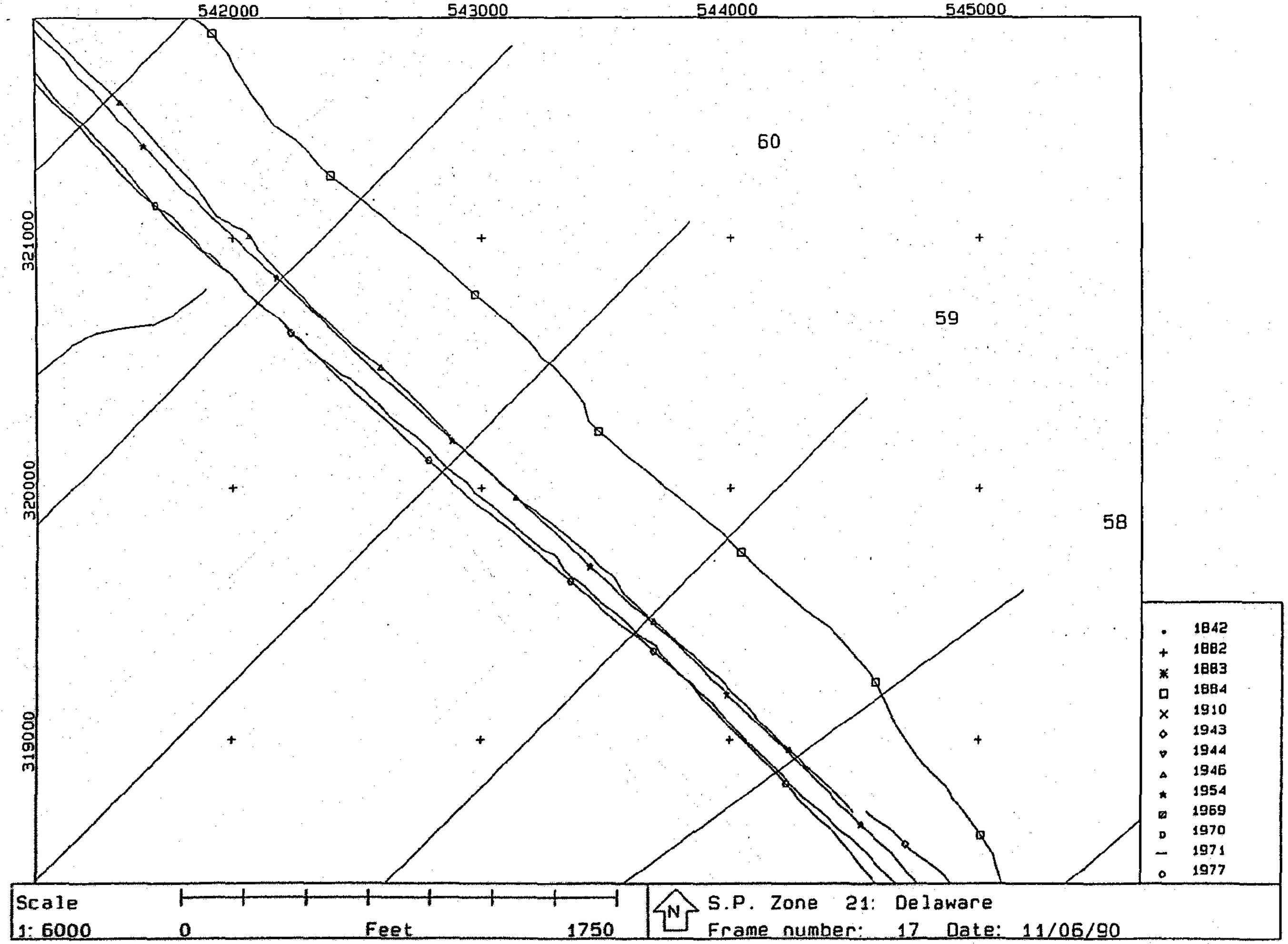


Scale 1: 6000	0 Feet 1750	S.P. Zone 21: Delaware Frame number: 15 Date: 11/06/90

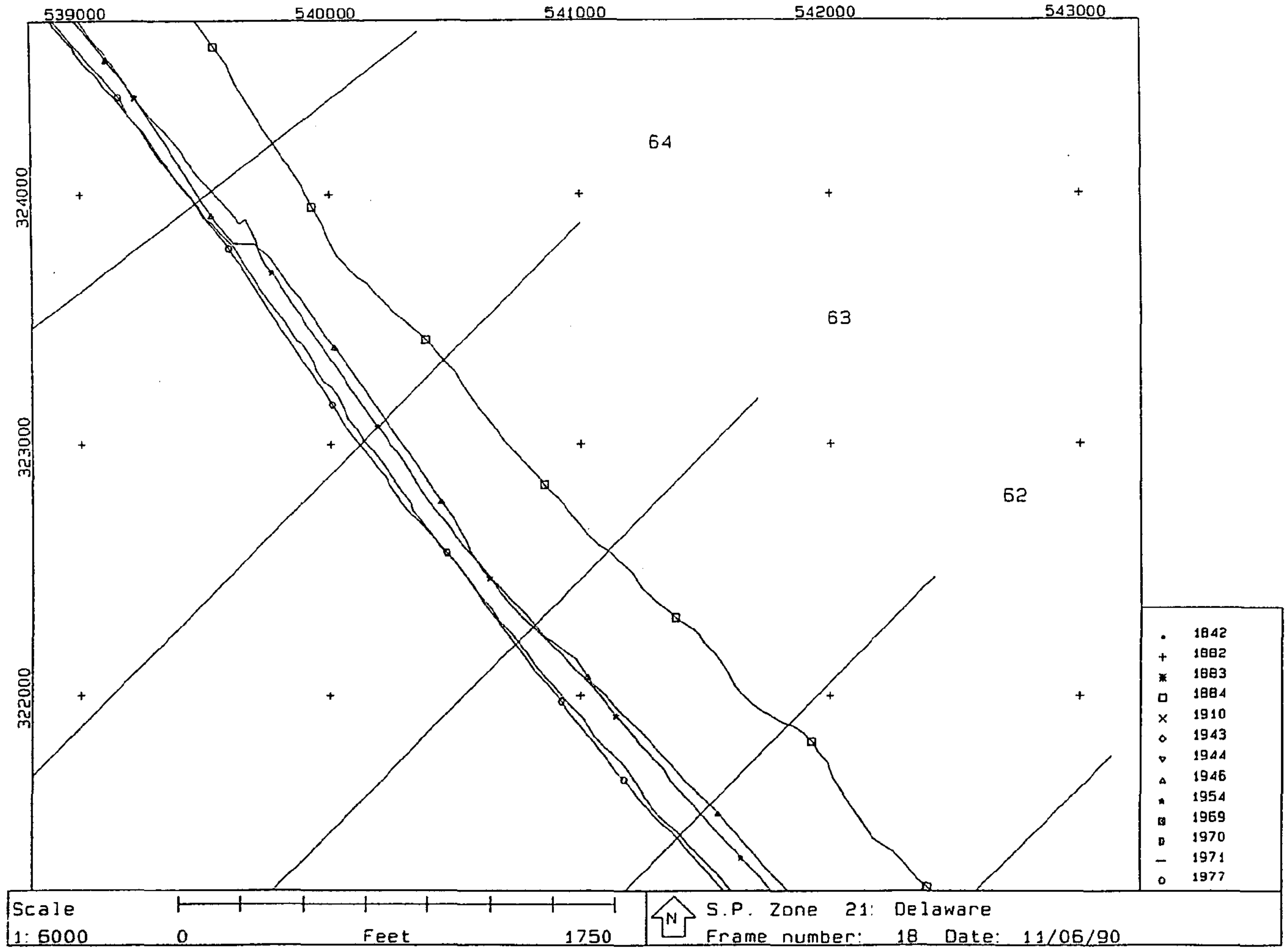
West Delaware Bay Historical Shoreline Changes: 1842-1977



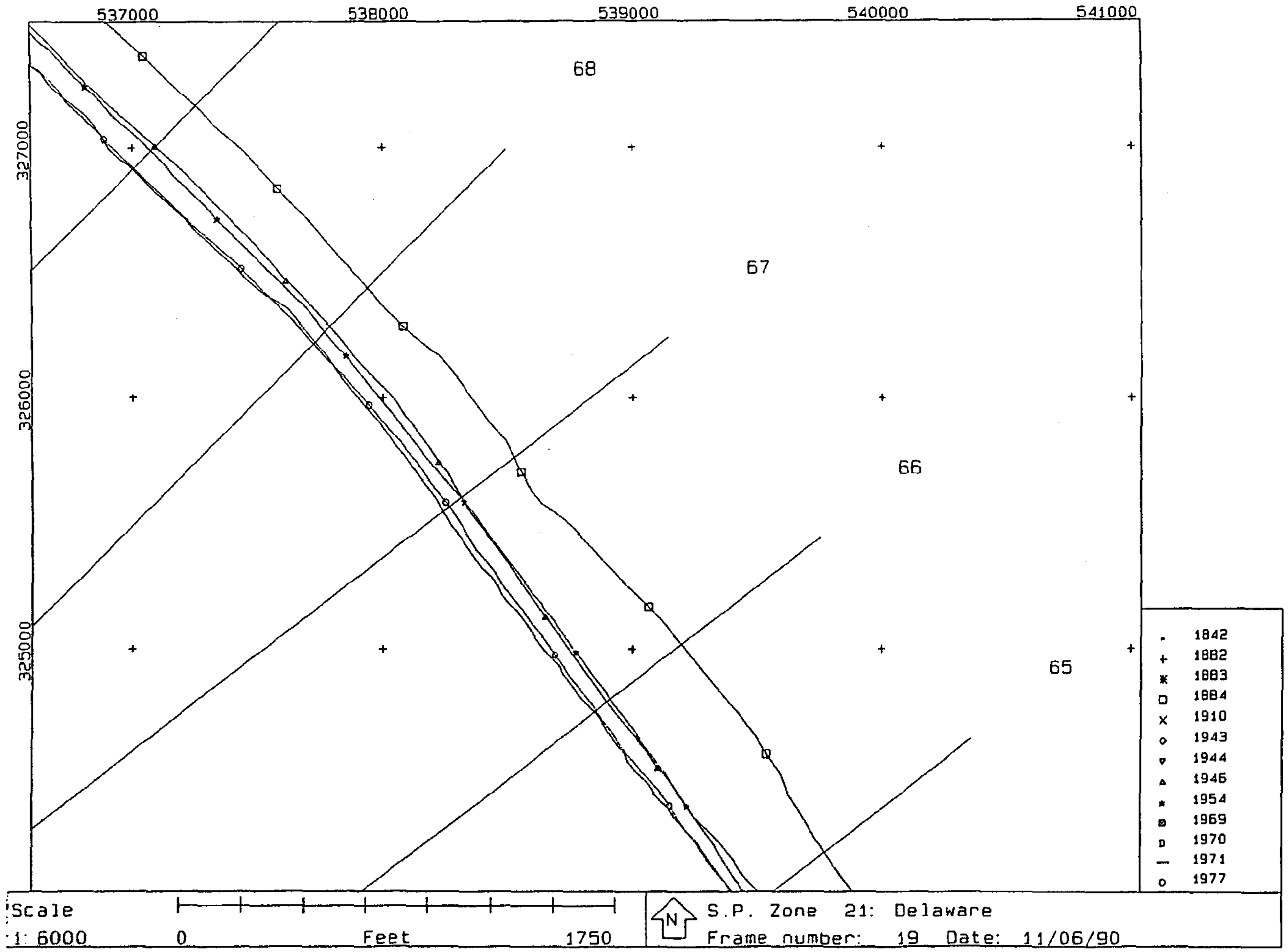
West Delaware Bay Historical Shoreline Changes: 1842-1977



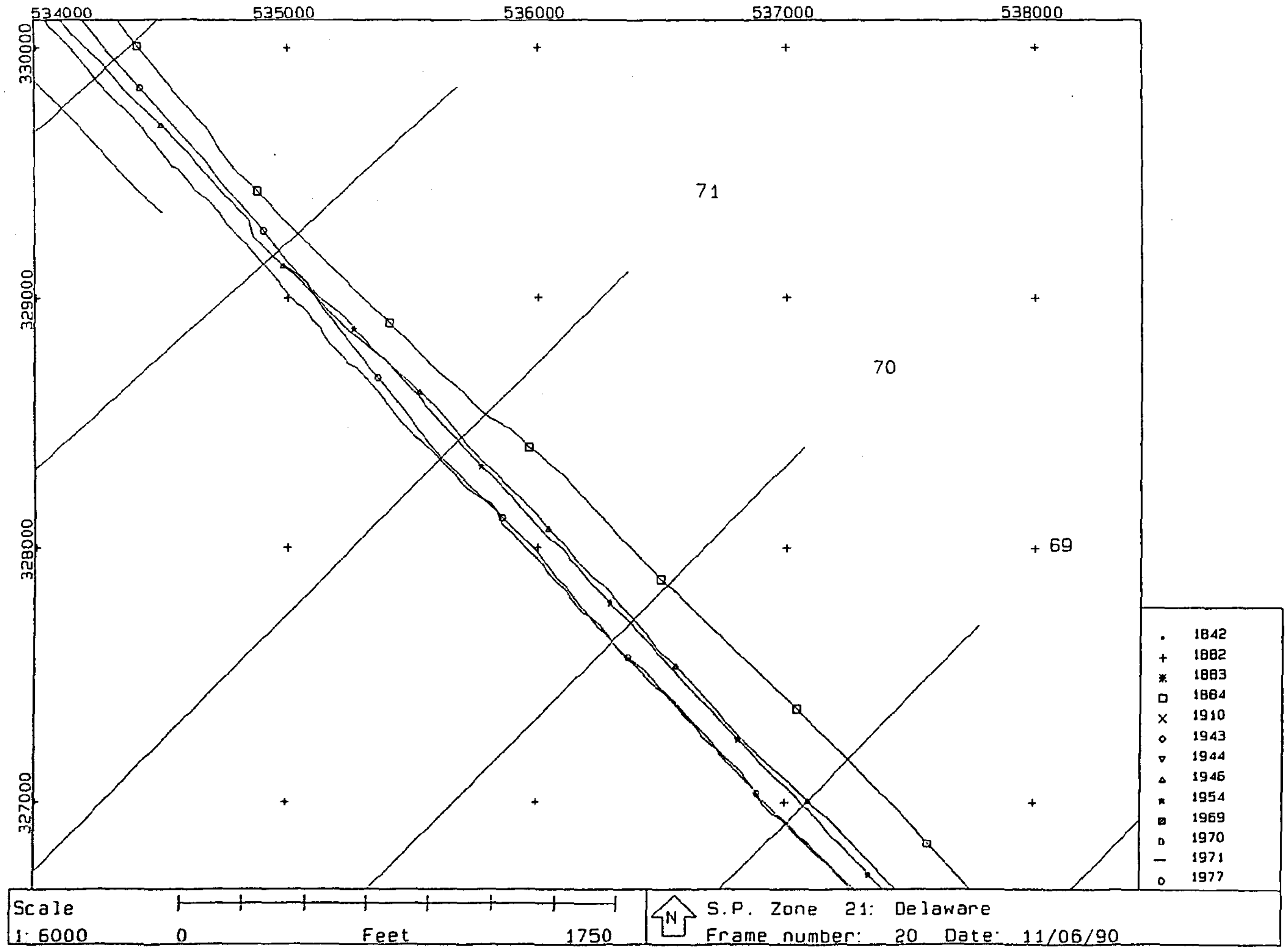
West Delaware Bay Historical Shoreline Changes: 1842-1977



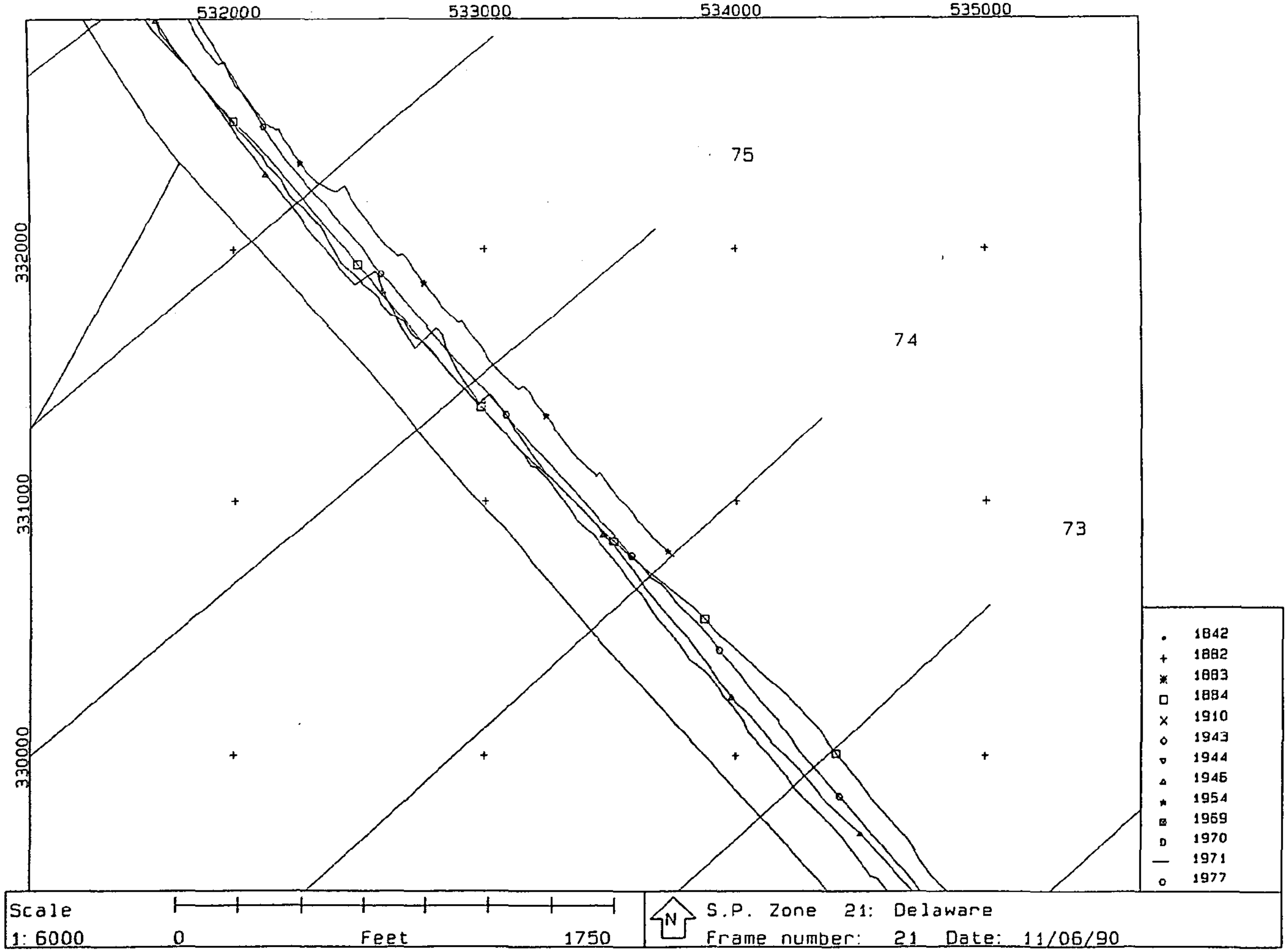
West Delaware Bay Historical Shoreline Changes: 1842-1977



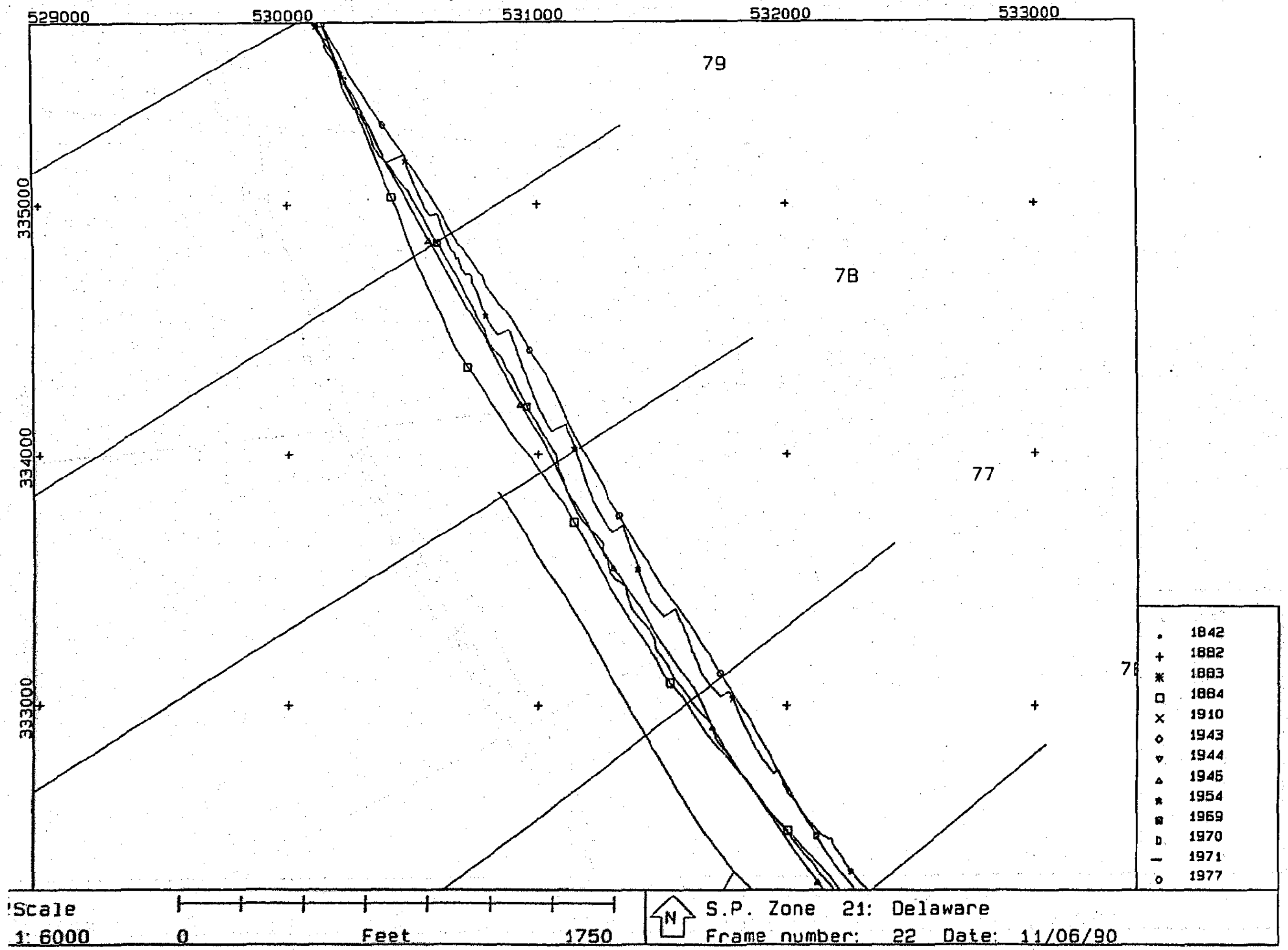
West Delaware Bay Historical Shoreline Changes: 1842-1977



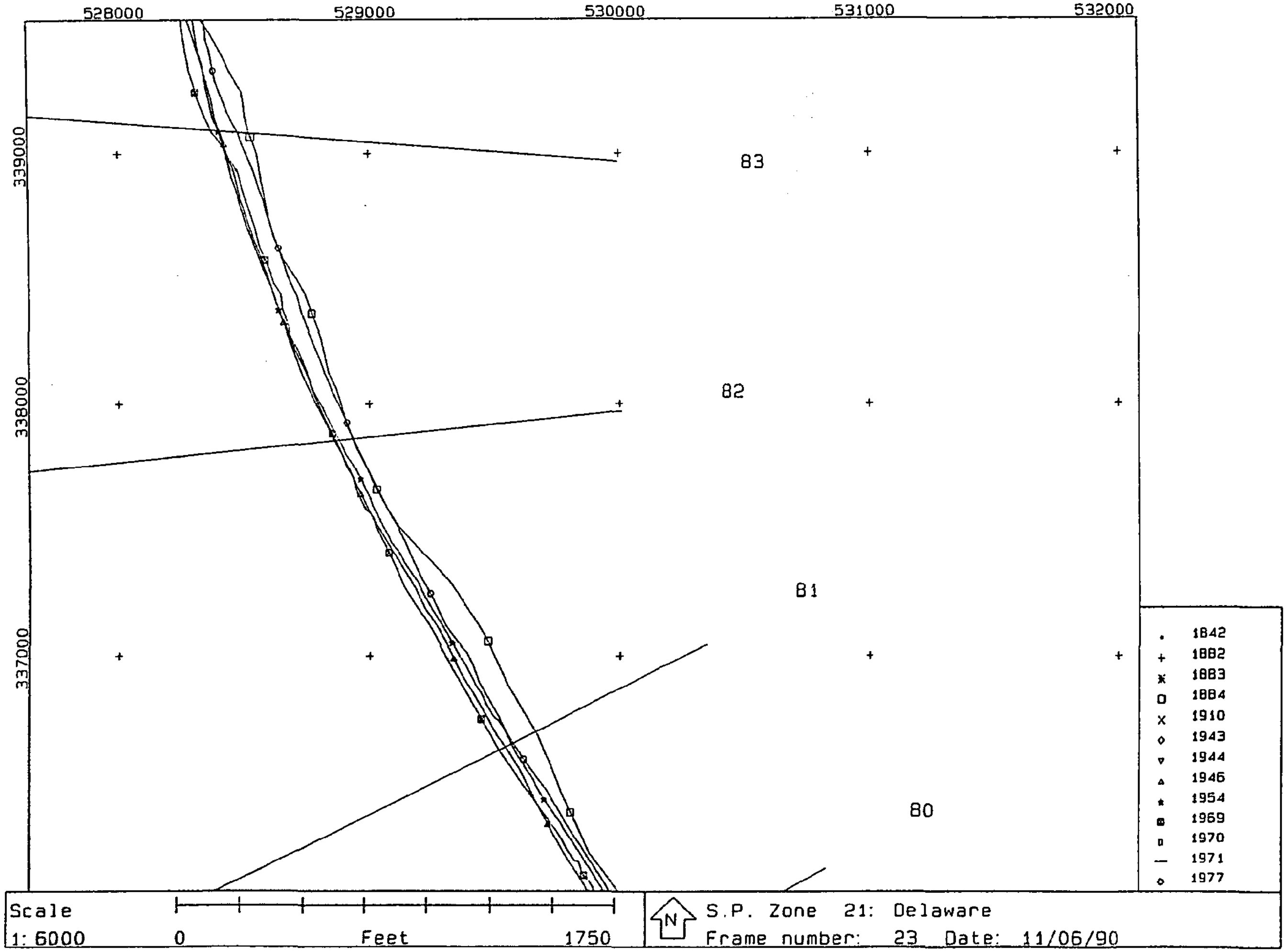
West Delaware Bay Historical Shoreline Changes: 1842-1977



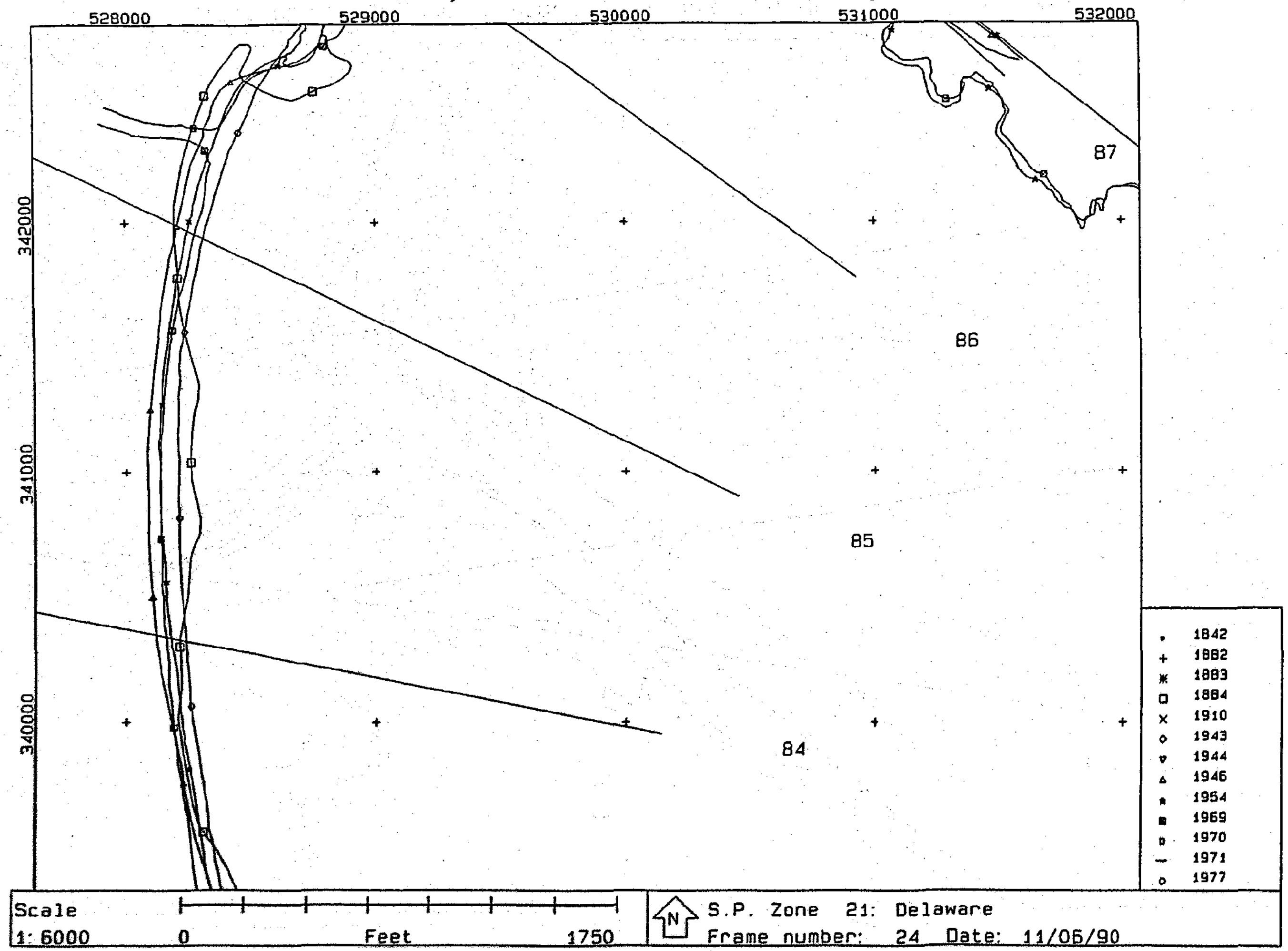
West Delaware Bay Historical Shoreline Changes: 1842-1977



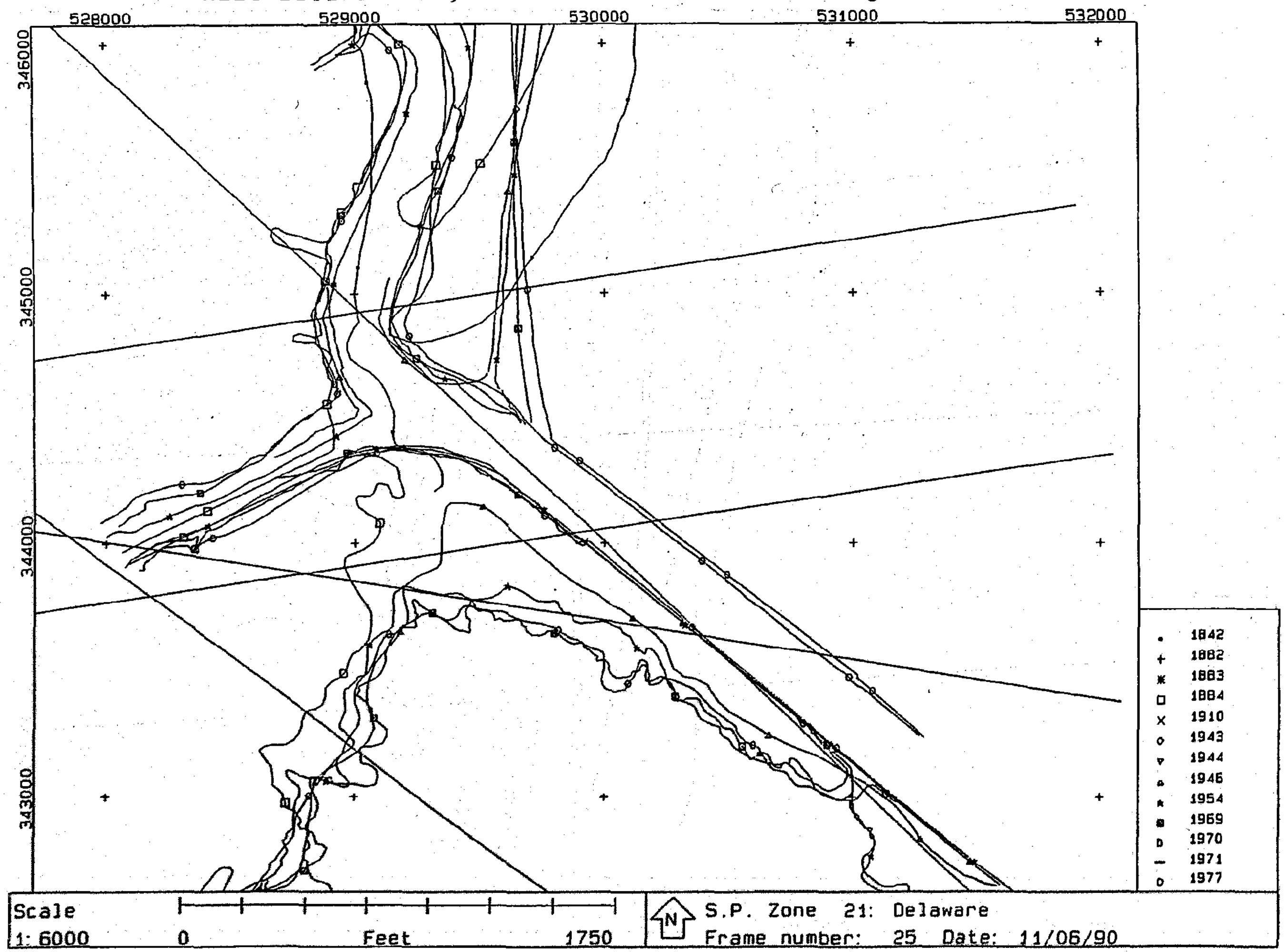
West Delaware Bay Historical Shoreline Changes: 1842-1977



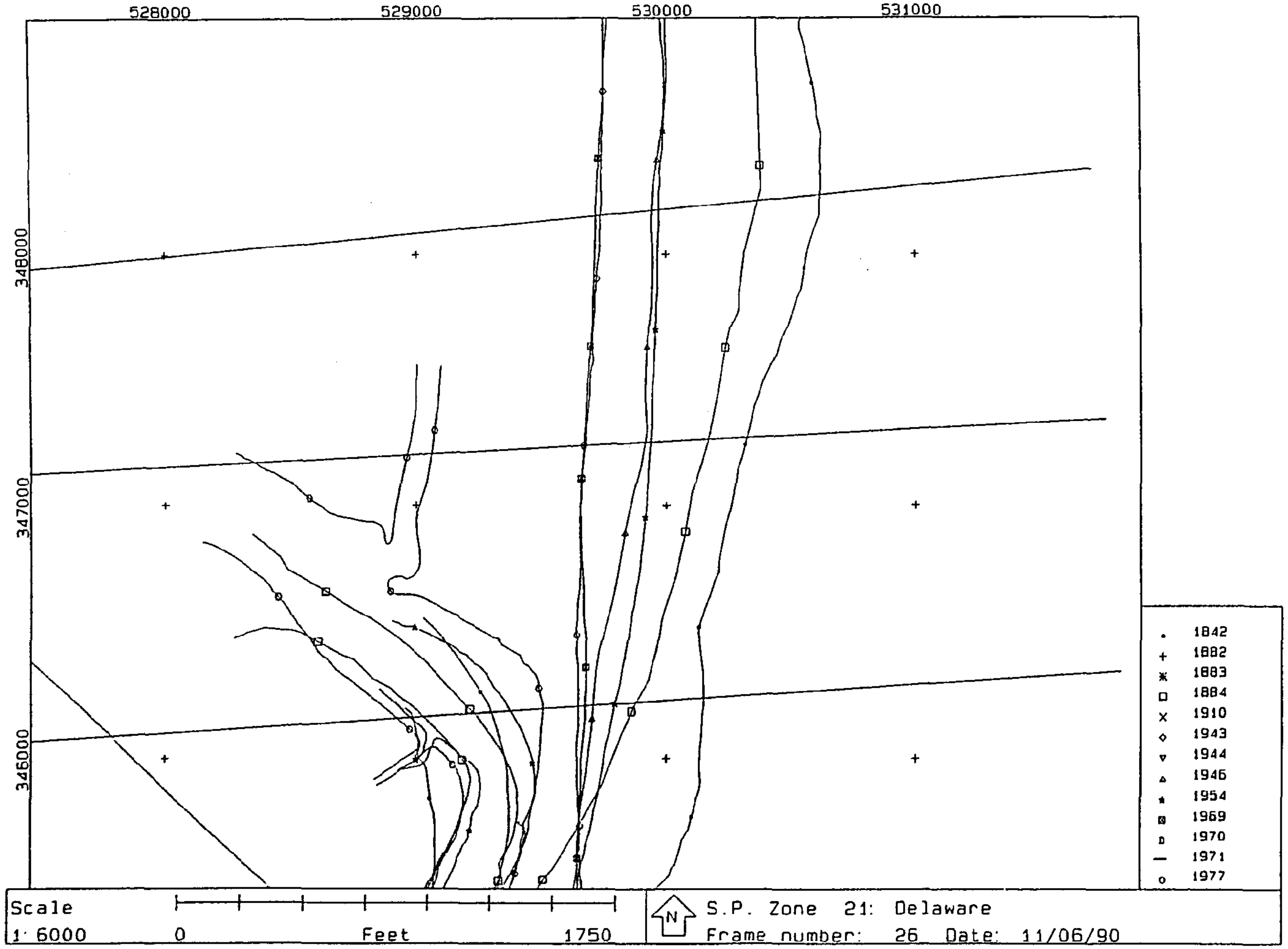
West Delaware Bay Historical Shoreline Changes: 1842-1977



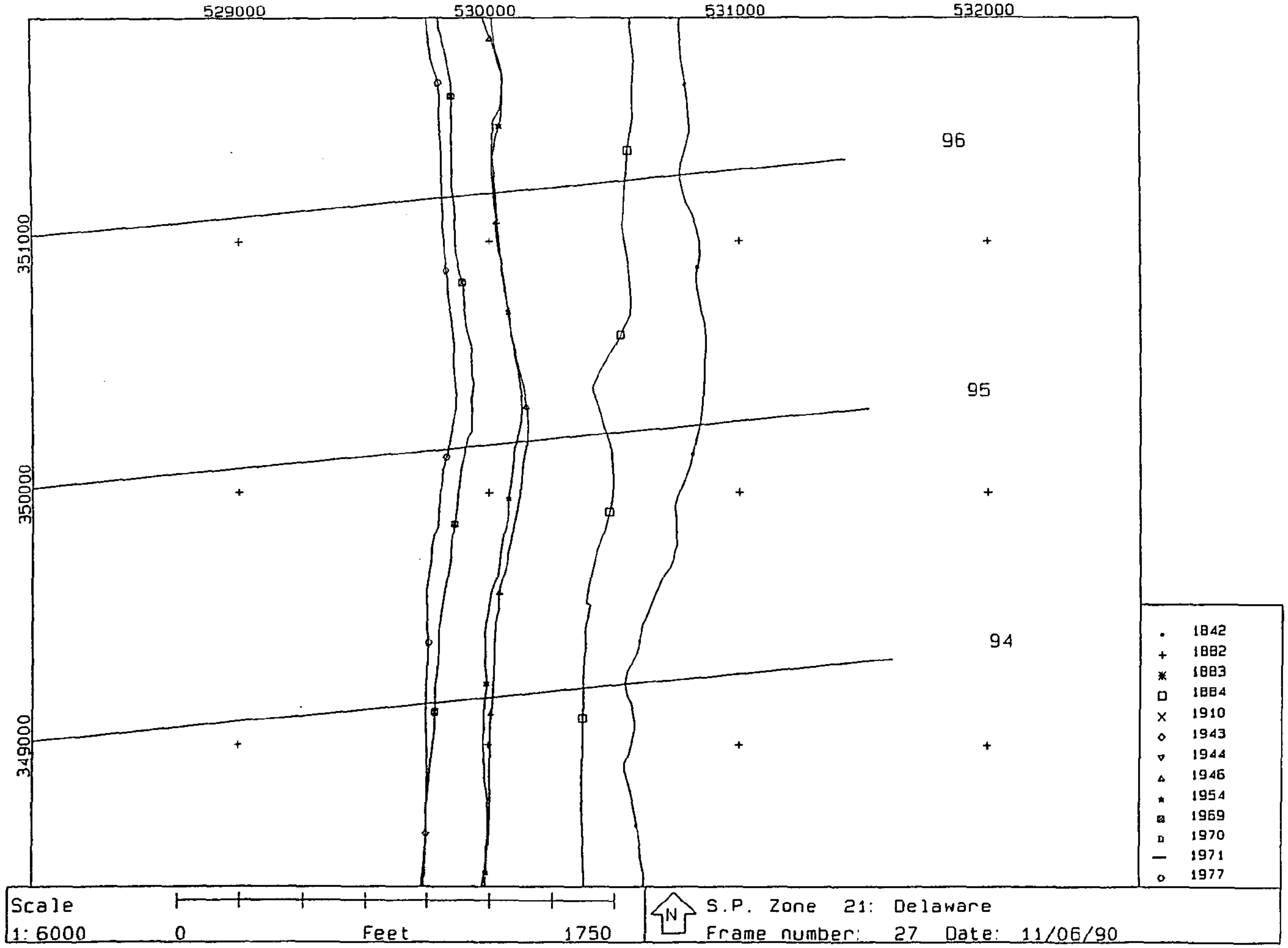
West Delaware Bay Historical Shoreline Changes: 1842-1977



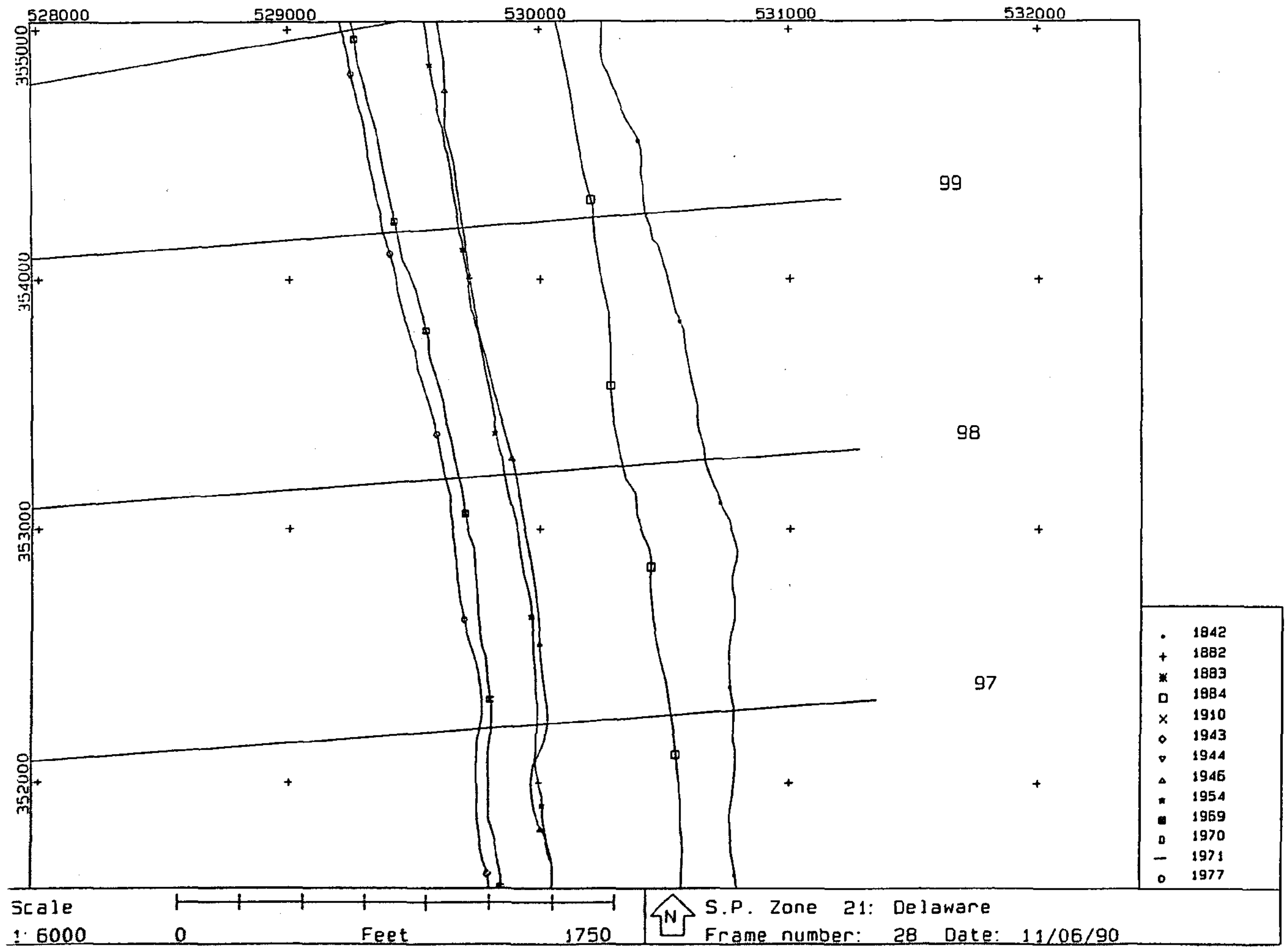
West Delaware Bay Historical Shoreline Changes: 1842-1977



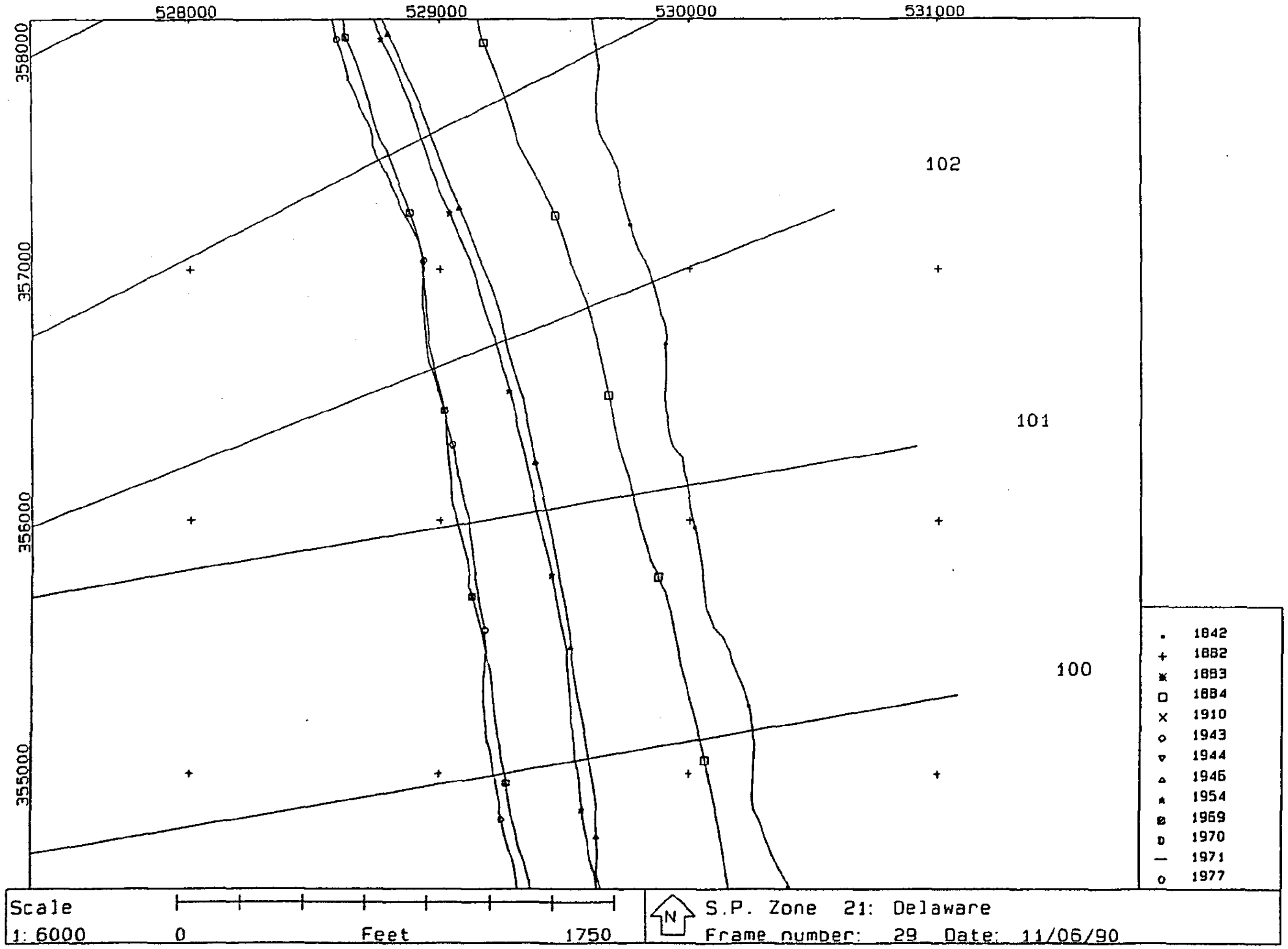
West Delaware Bay Historical Shoreline Changes: 1842-1977



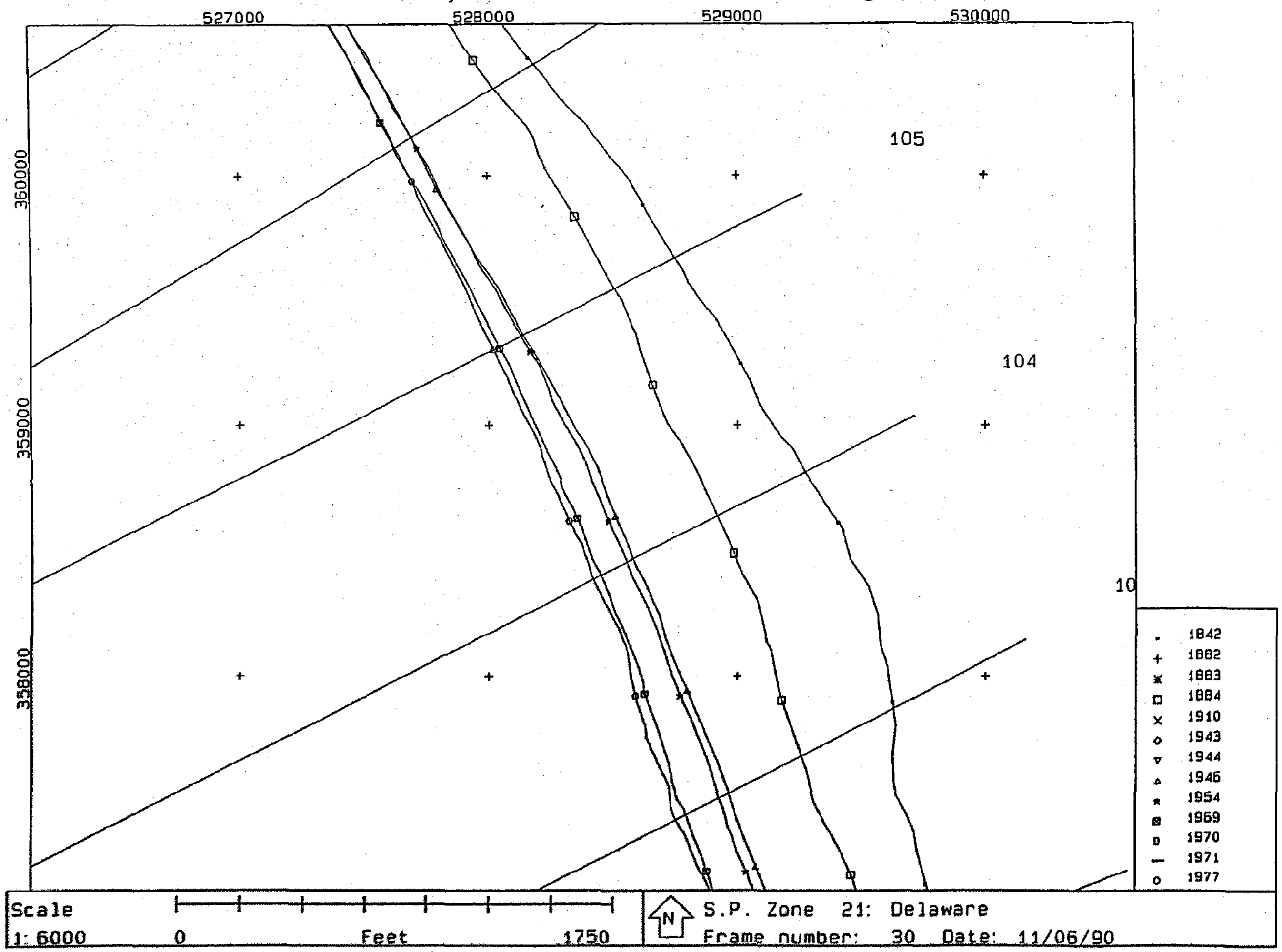
West Delaware Bay Historical Shoreline Changes: 1842-1977



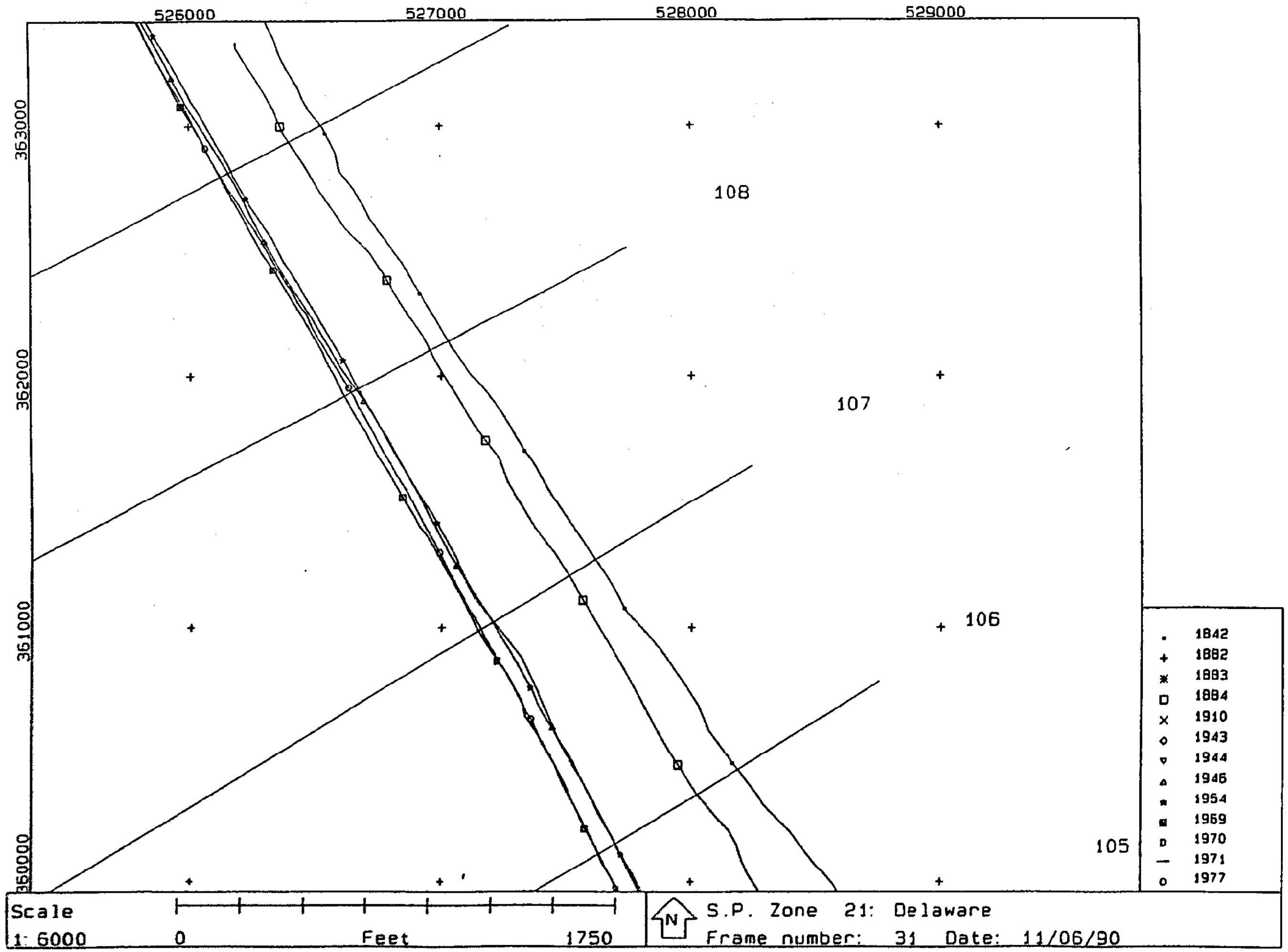
West Delaware Bay Historical Shoreline Changes: 1842-1977



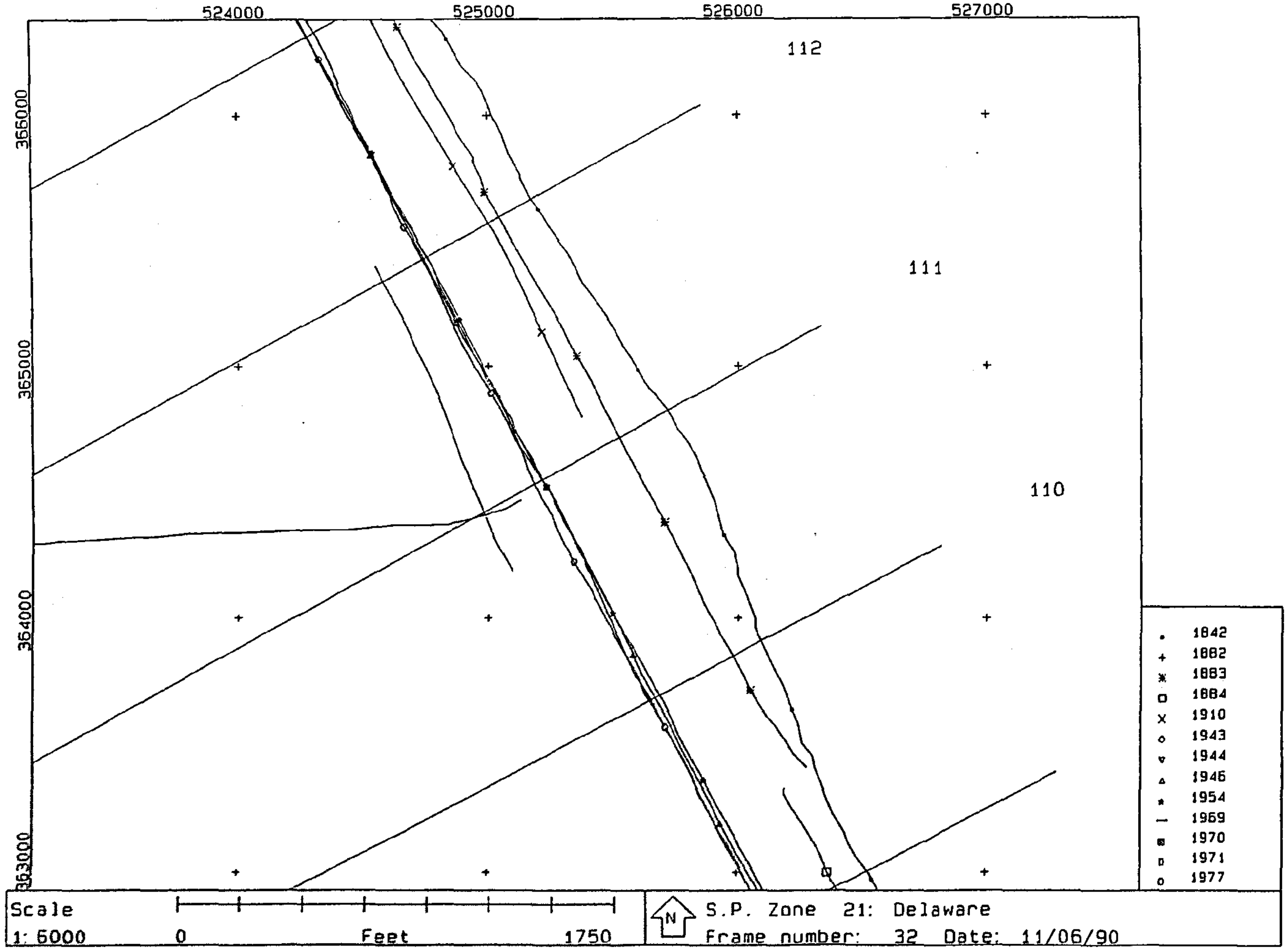
West Delaware Bay Historical Shoreline Changes: 1842-1977



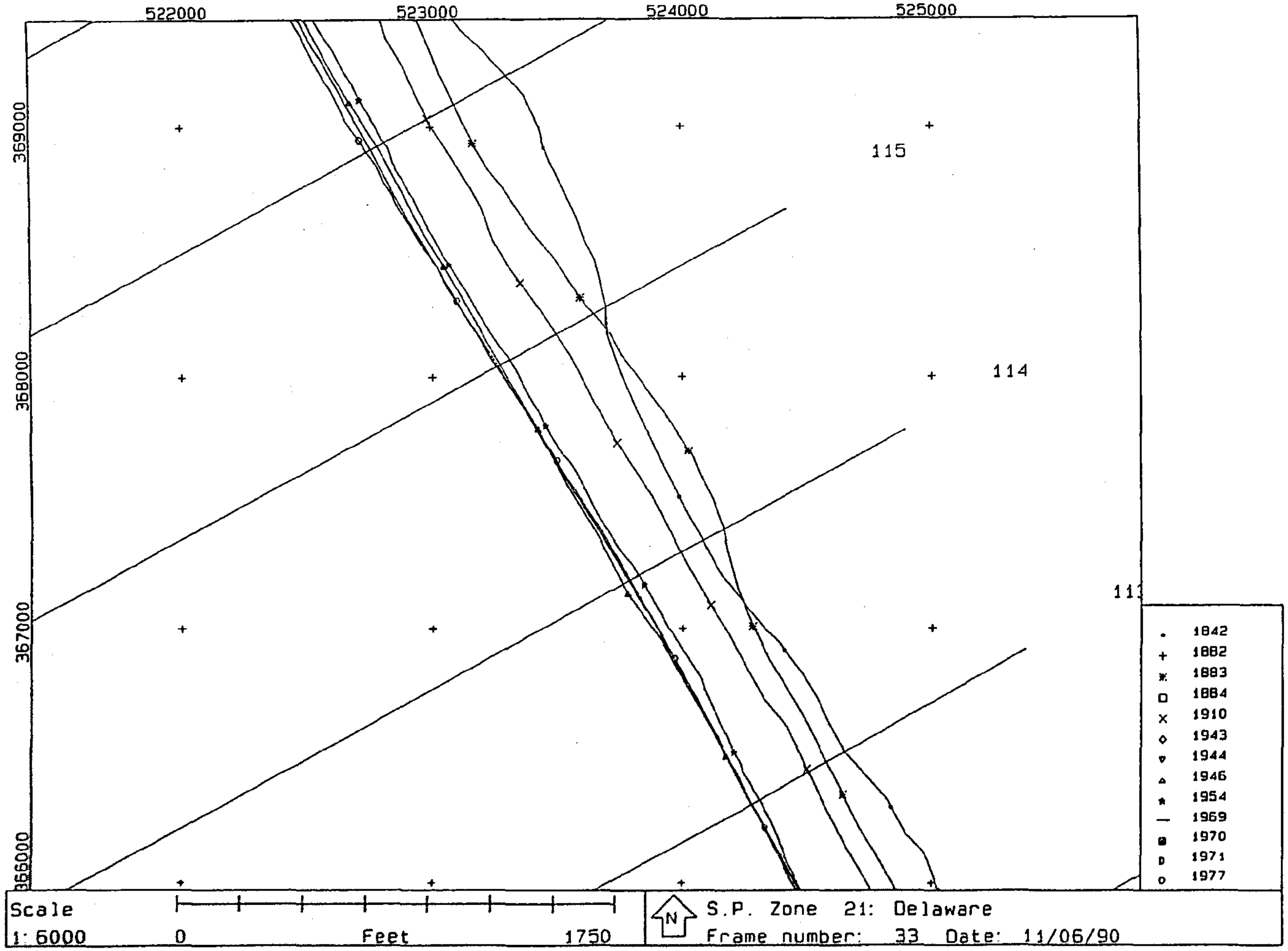
West Delaware Bay Historical Shoreline Changes: 1842-1977



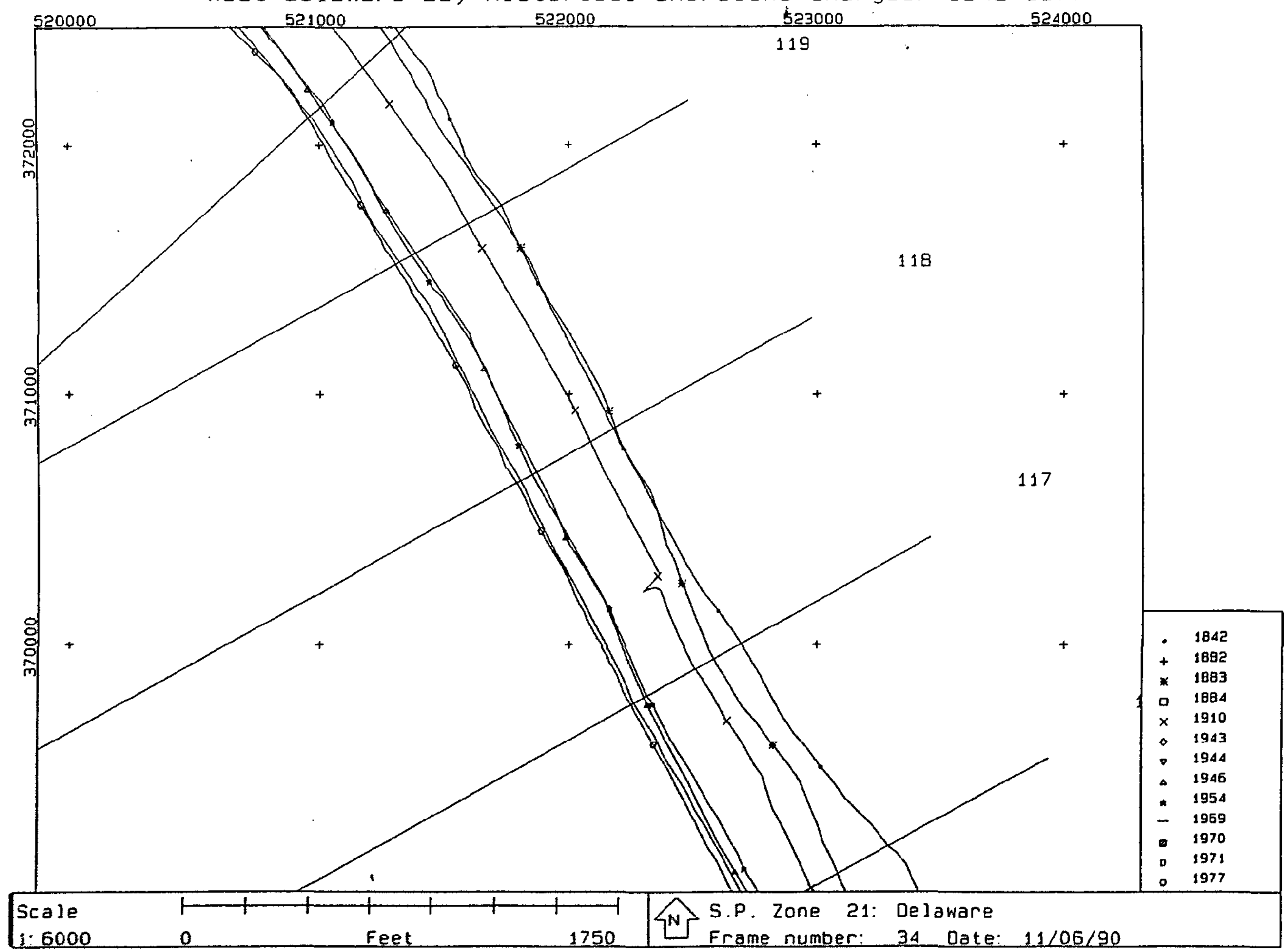
West Delaware Bay Historical Shoreline Changes: 1842-1977



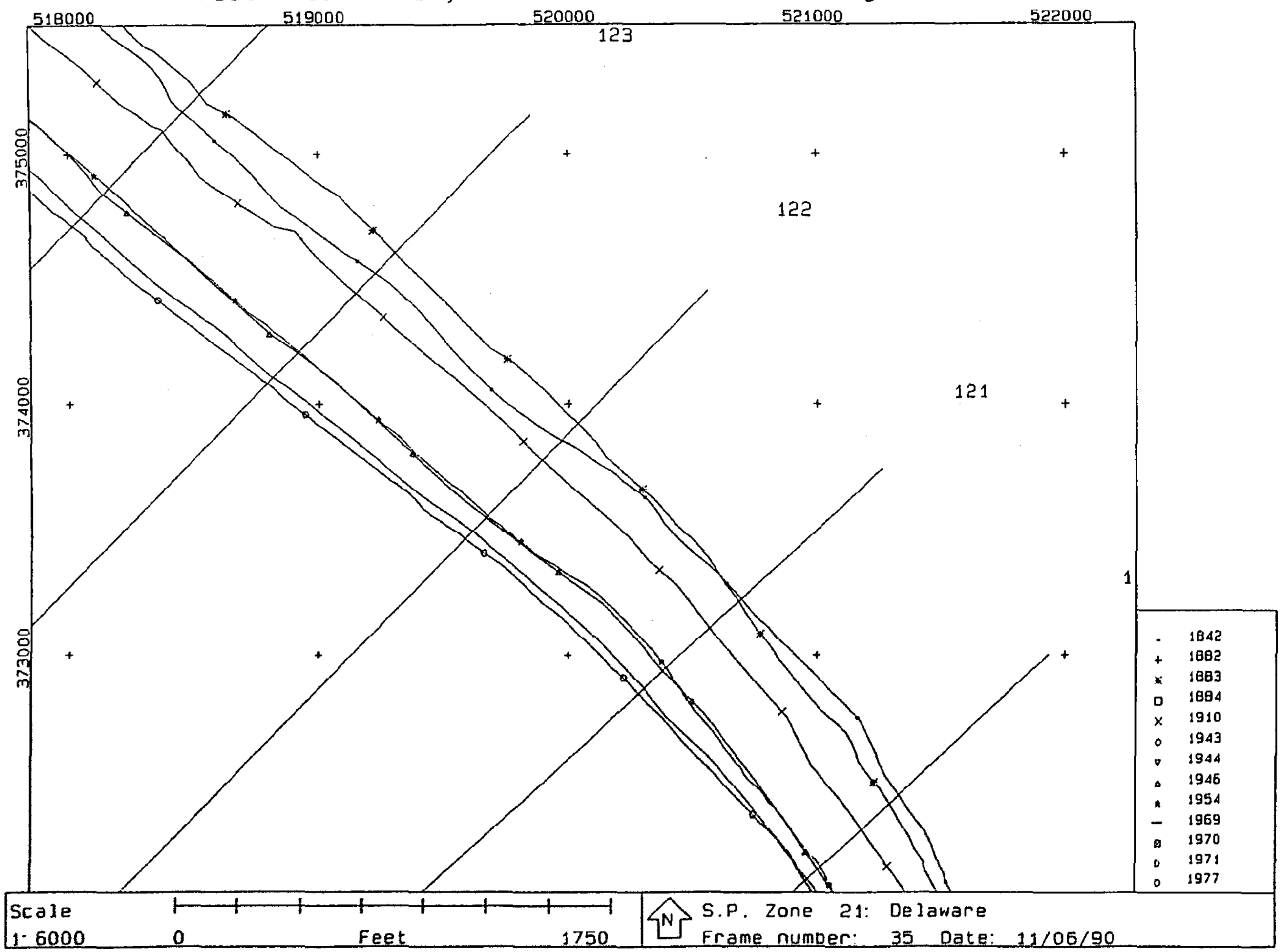
West Delaware Bay Historical Shoreline Changes: 1842-1977



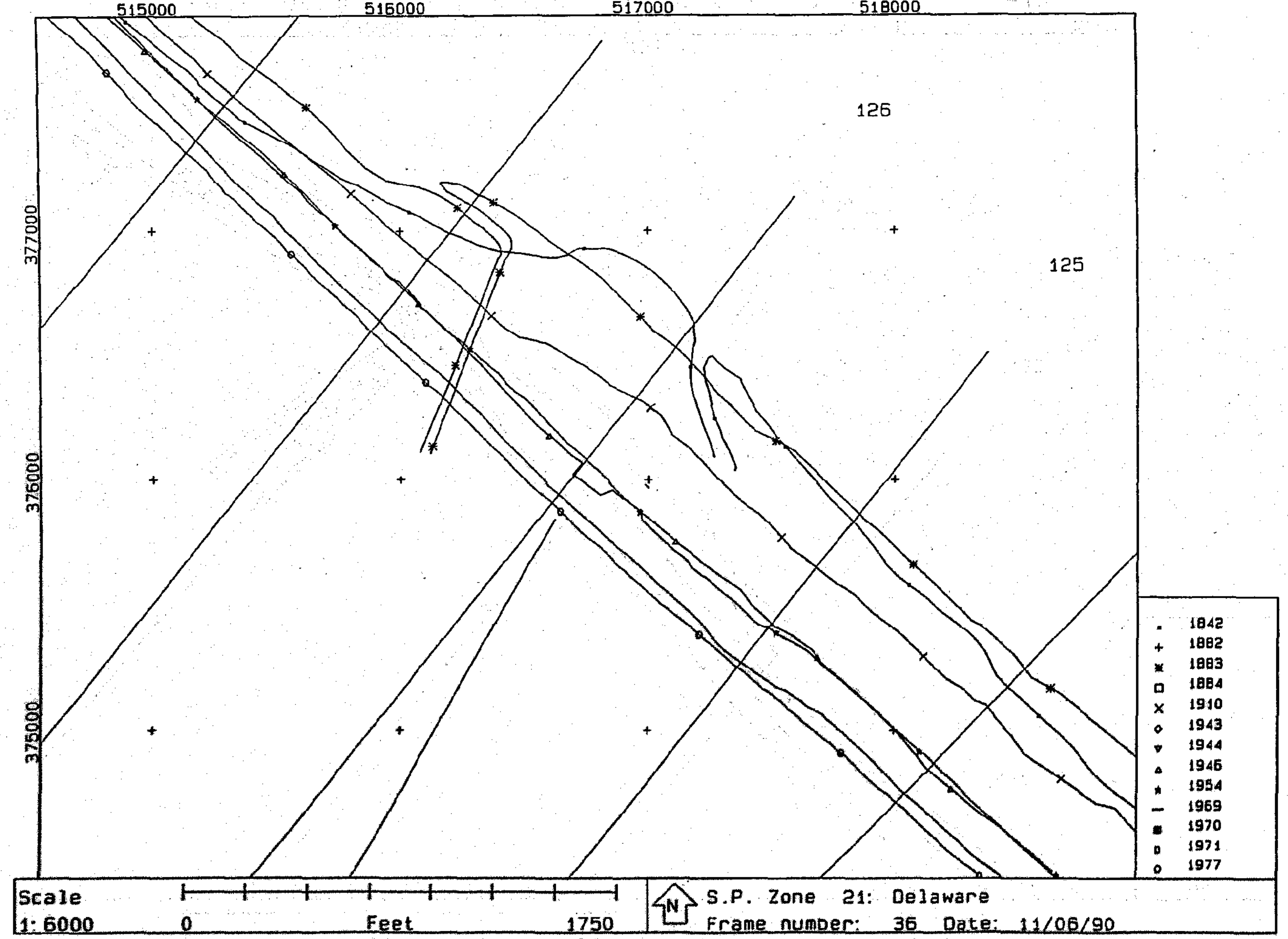
West Delaware Bay Historical Shoreline Changes: 1842-1977



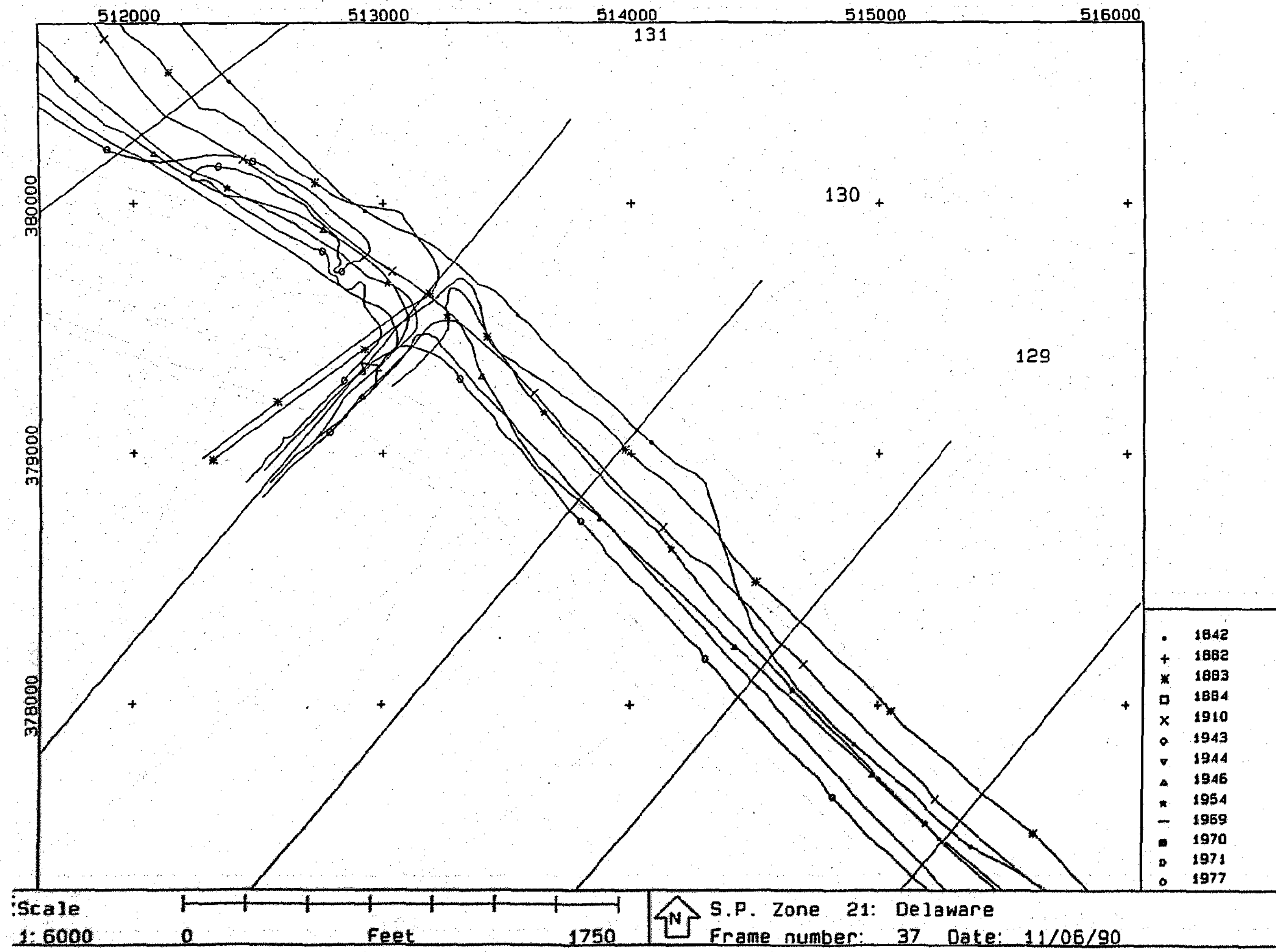
West Delaware Bay Historical Shoreline Changes: 1842-1977



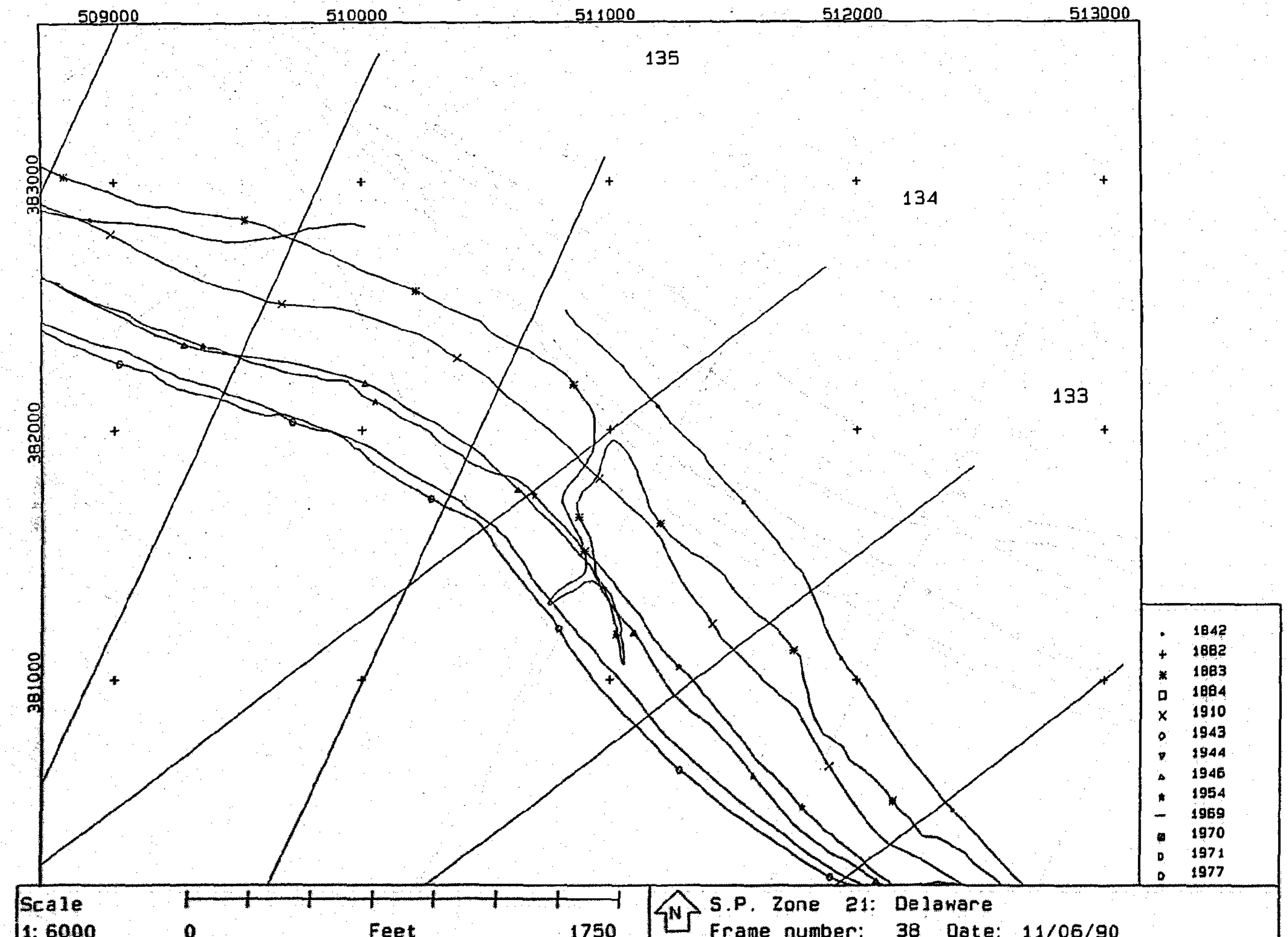
West Delaware Bay Historical Shoreline Changes: 1842-1977



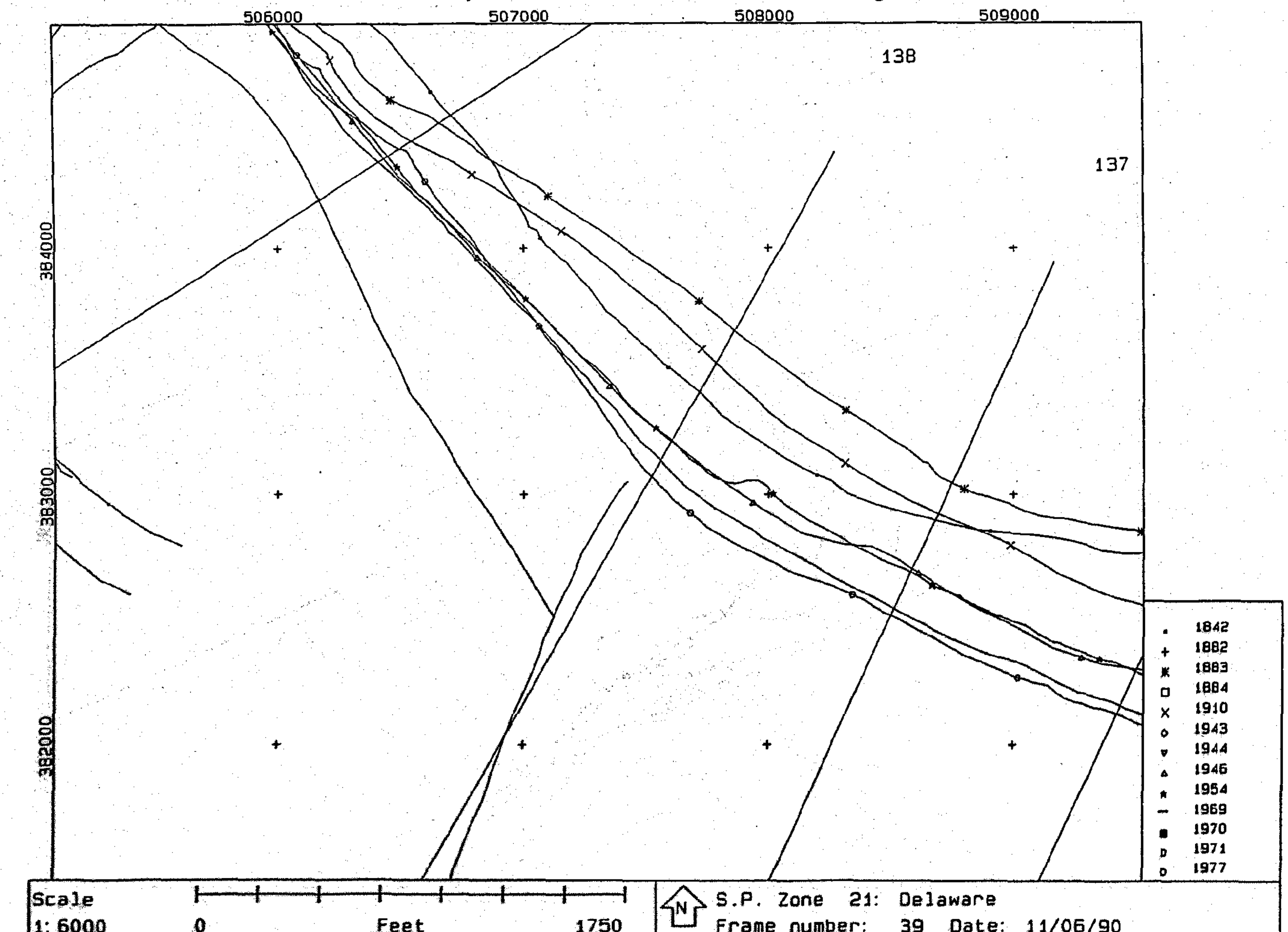
West Delaware Bay Historical Shoreline Changes: 1842-1977



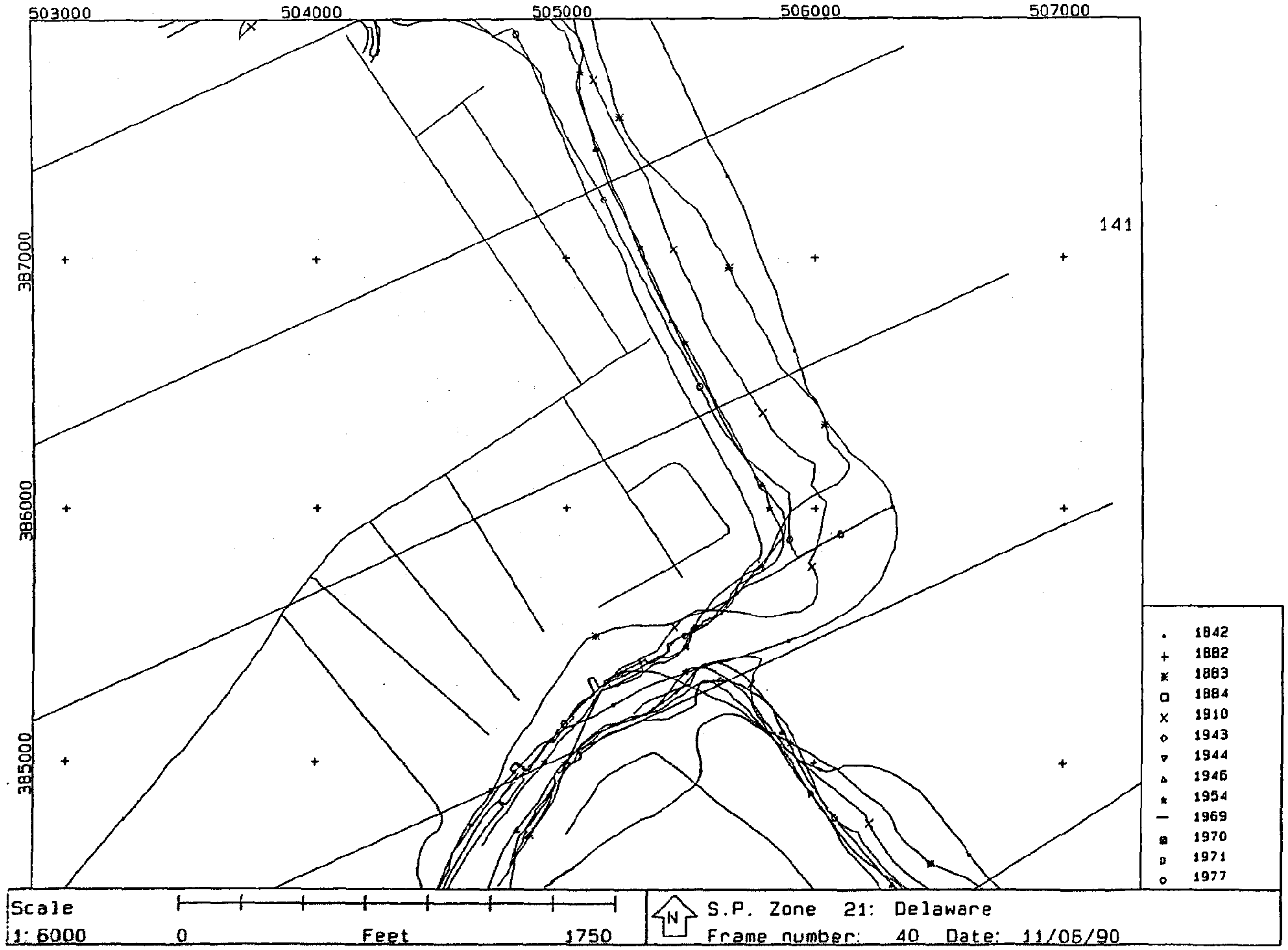
West Delaware Bay Historical Shoreline Changes: 1842-1977



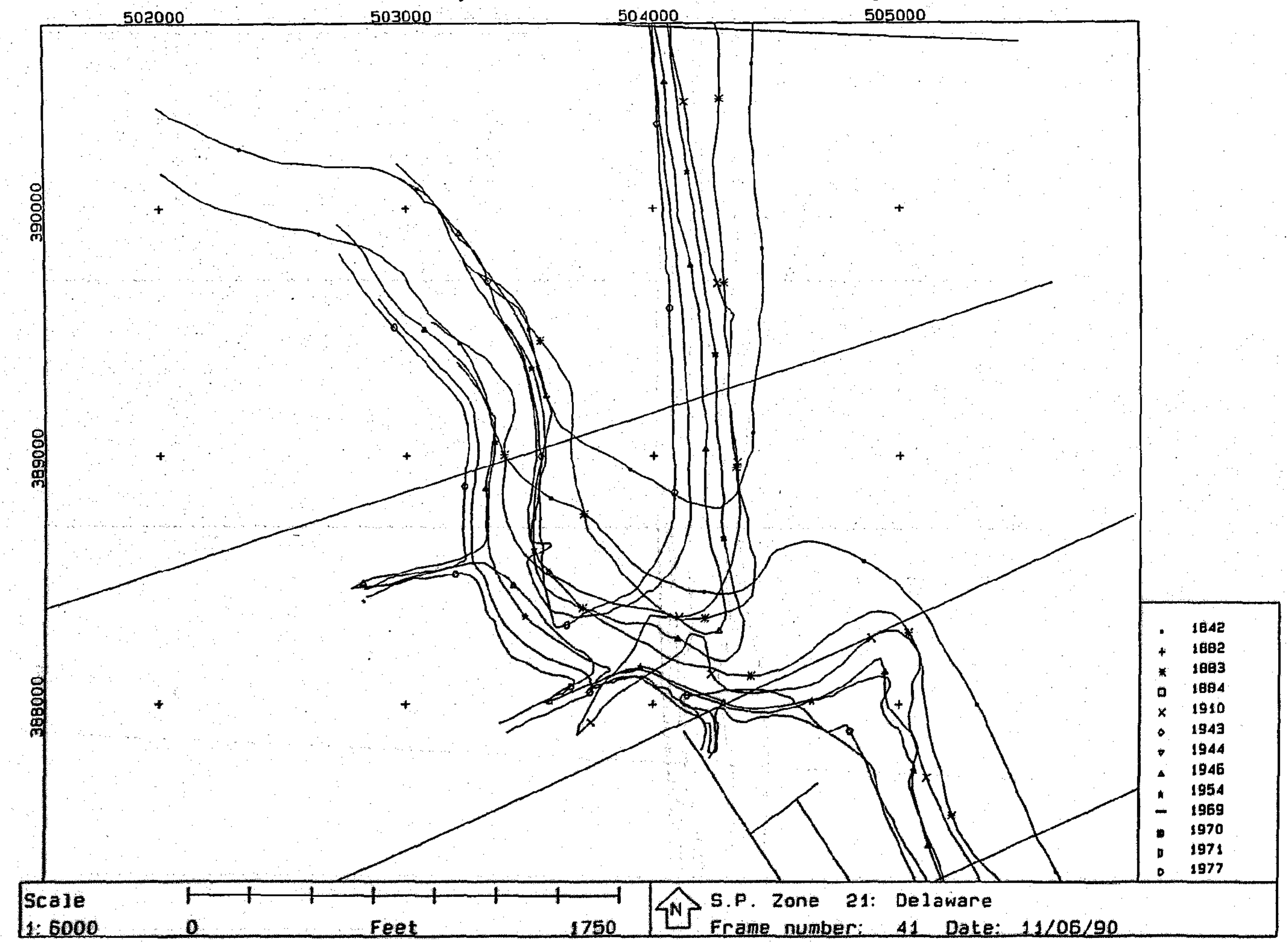
West Delaware Bay Historical Shoreline Changes: 1842-1977

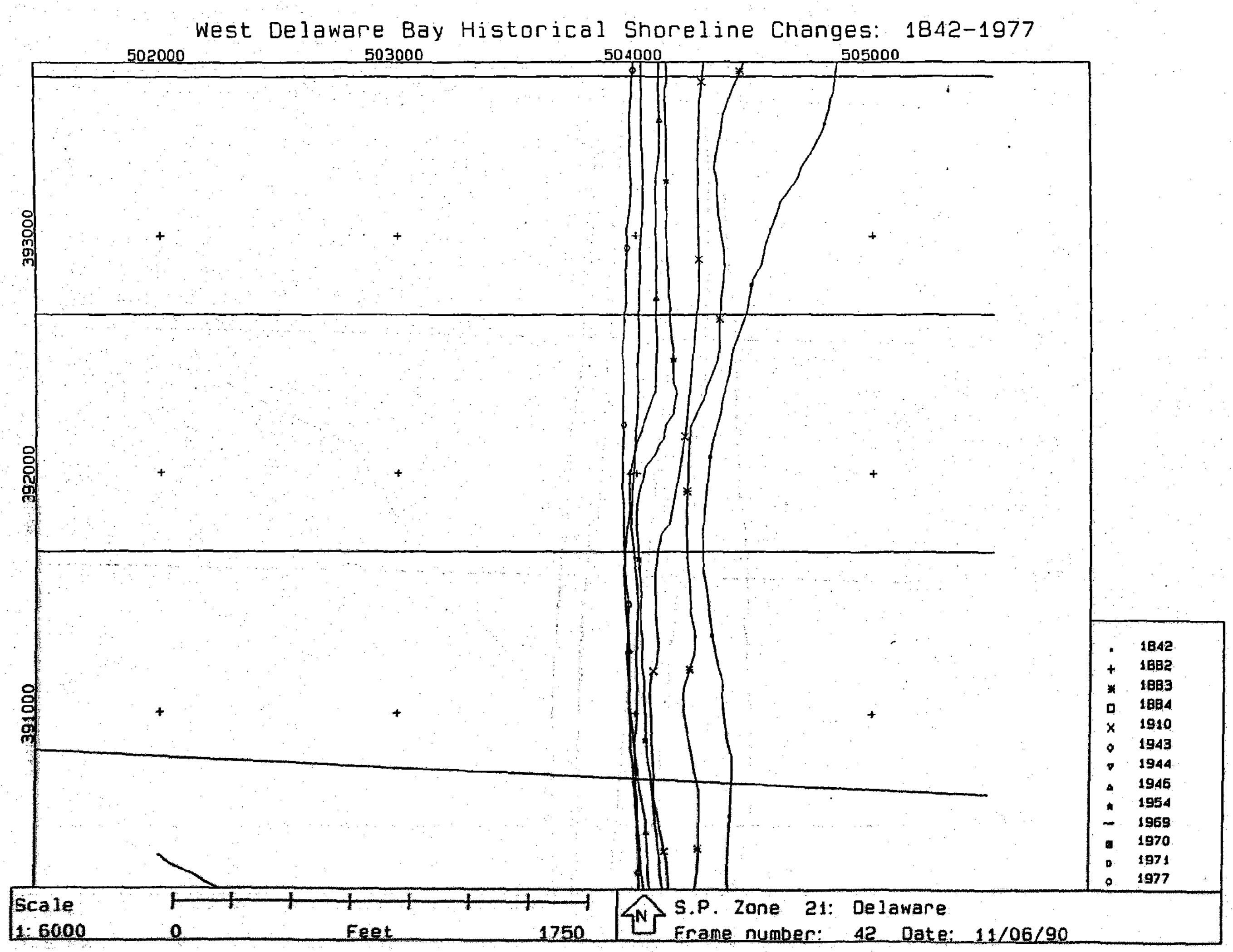


West Delaware Bay Historical Shoreline Changes: 1842-1977

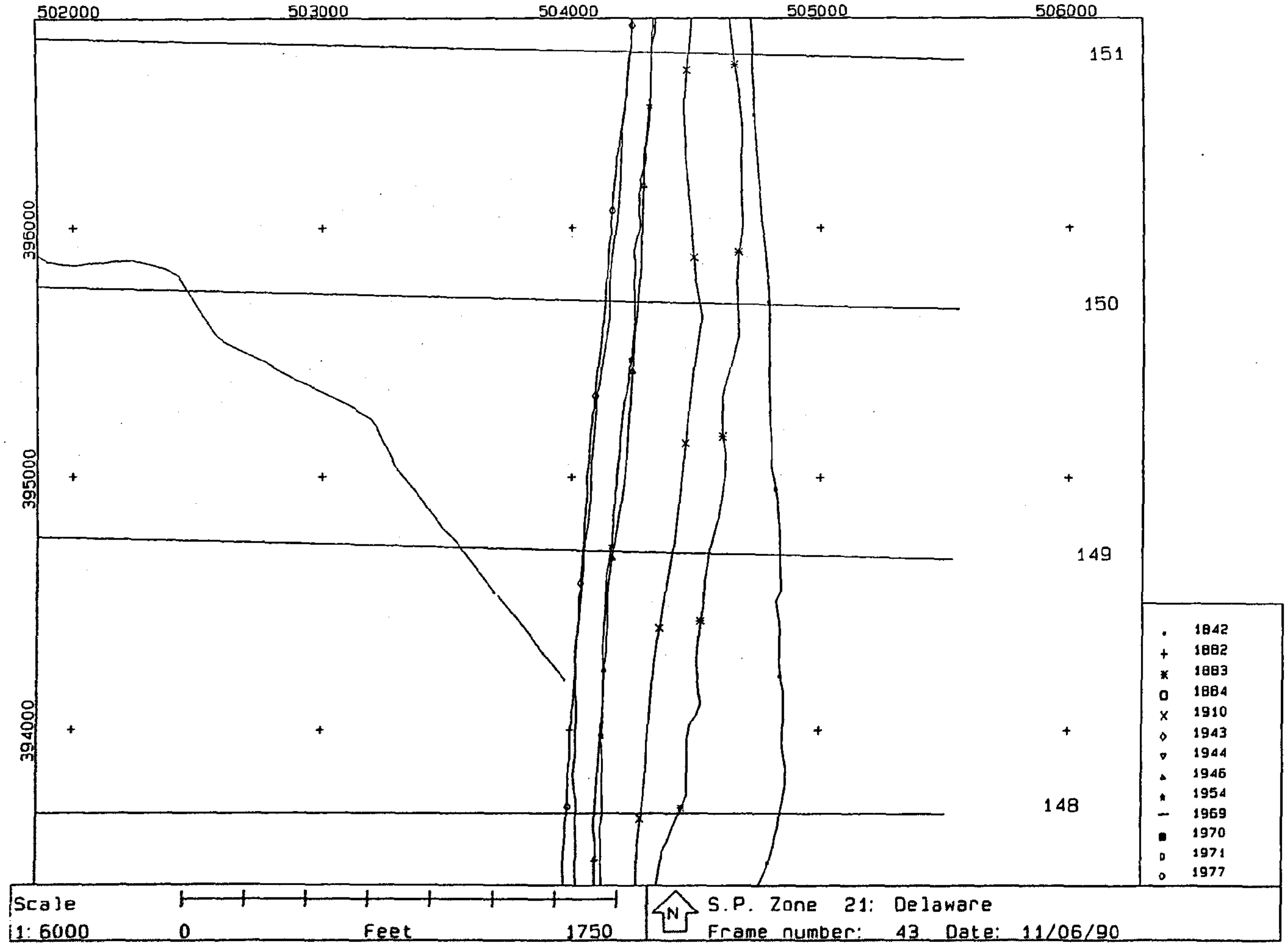


West Delaware Bay Historical Shoreline Changes: 1842-1977

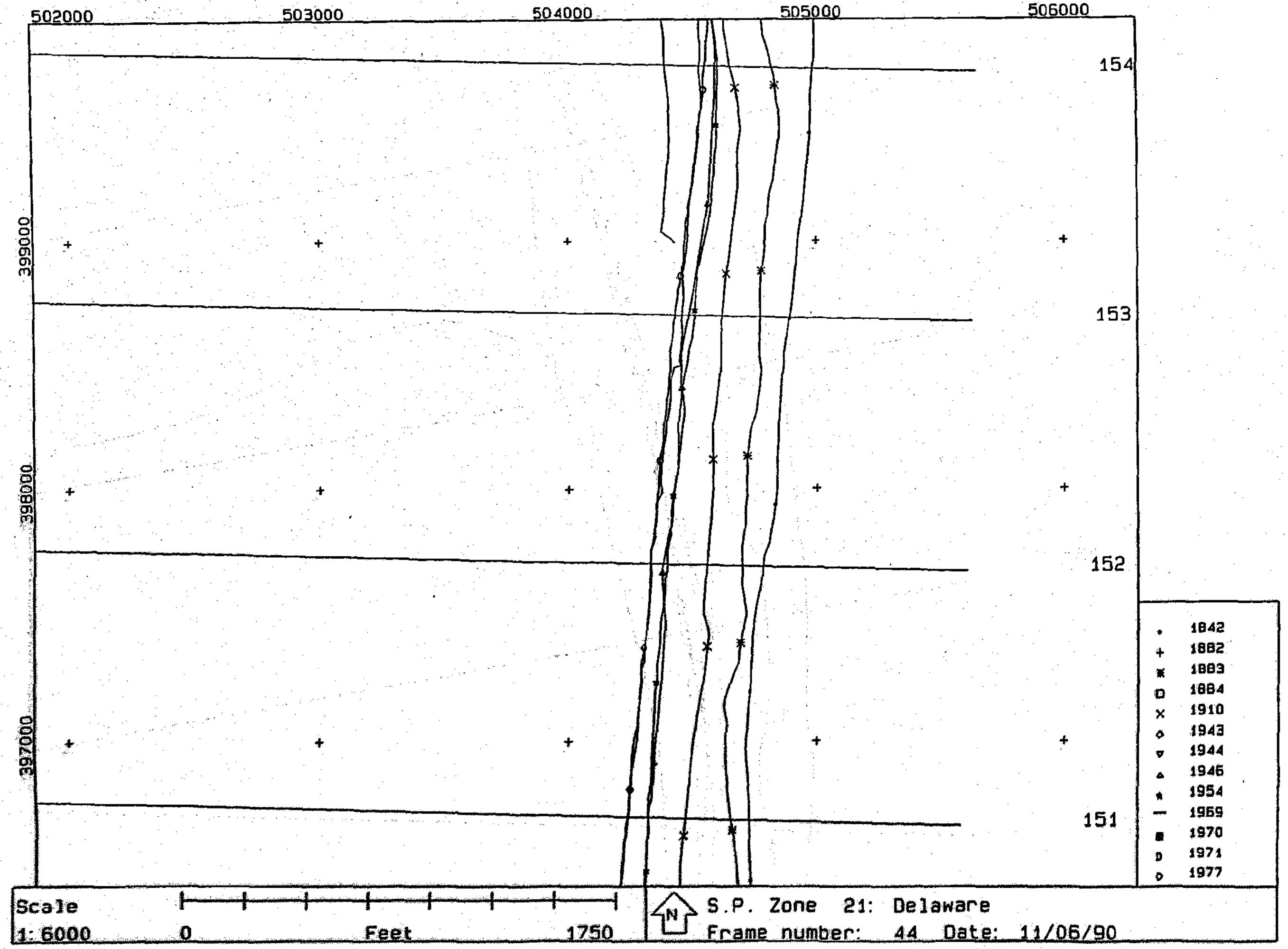



West Delaware Bay Historical Shoreline Changes: 1842-1977
502000
503000
504000
505000
393000
392000
391000
1842
1882
1883
1884
1910
1943
1944
1946
1954
1969
1970
1971
1977
Scale
1: 6000
0
Feet
1750
N
S.P. Zone 21: Delaware
Frame number: 42 Date: 11/06/90

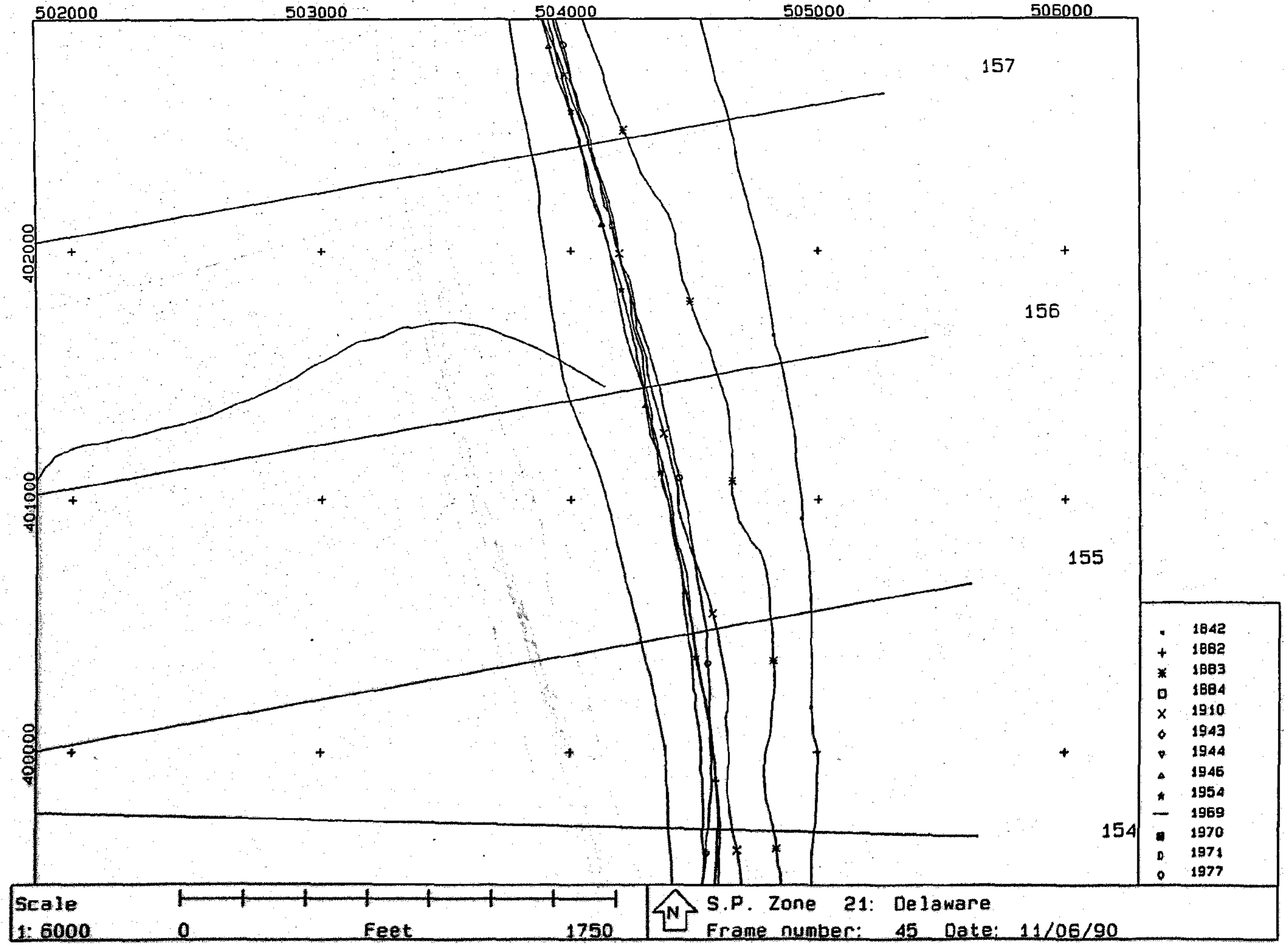
West Delaware Bay Historical Shoreline Changes: 1842-1977

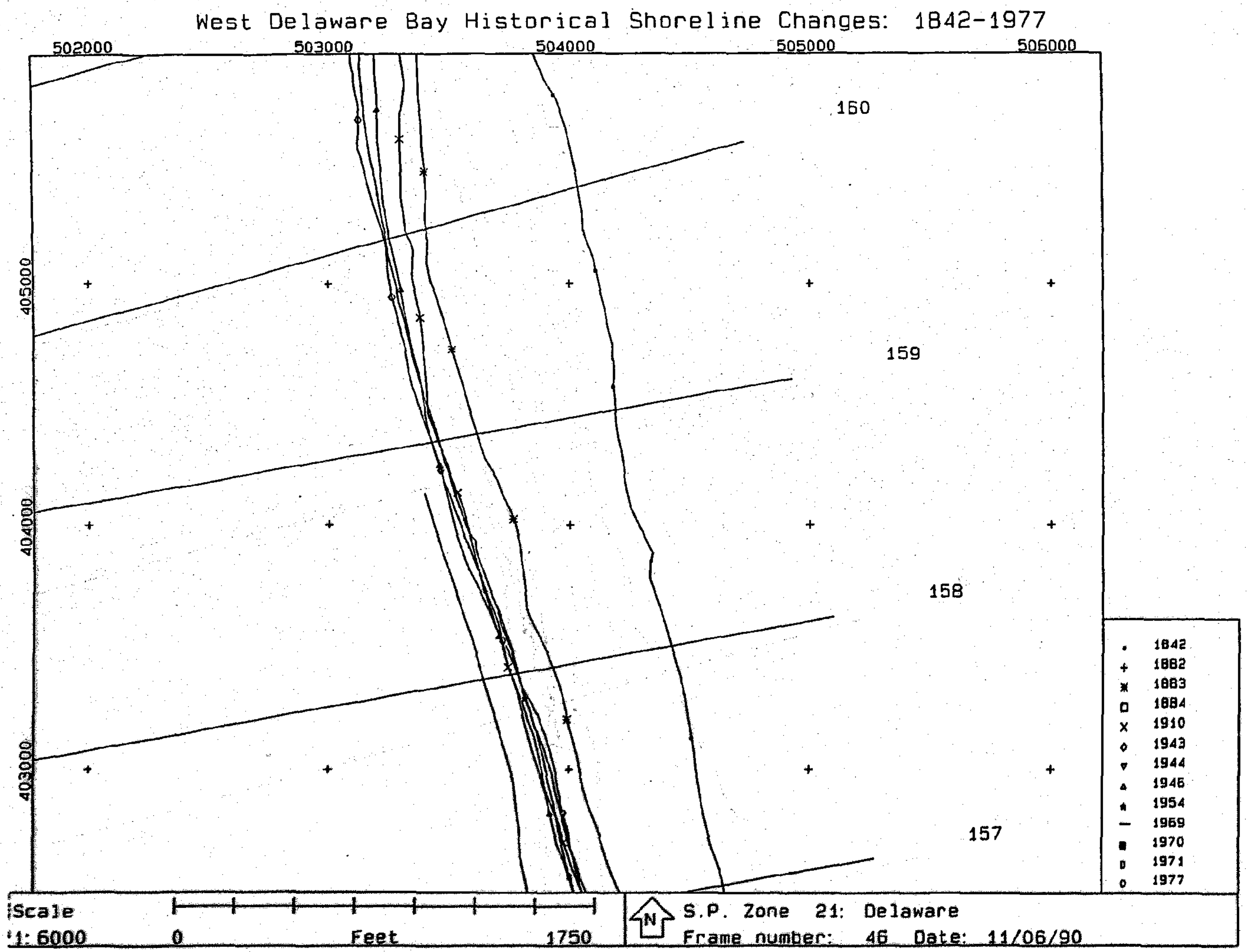


West Delaware Bay Historical Shoreline Changes: 1842-1977

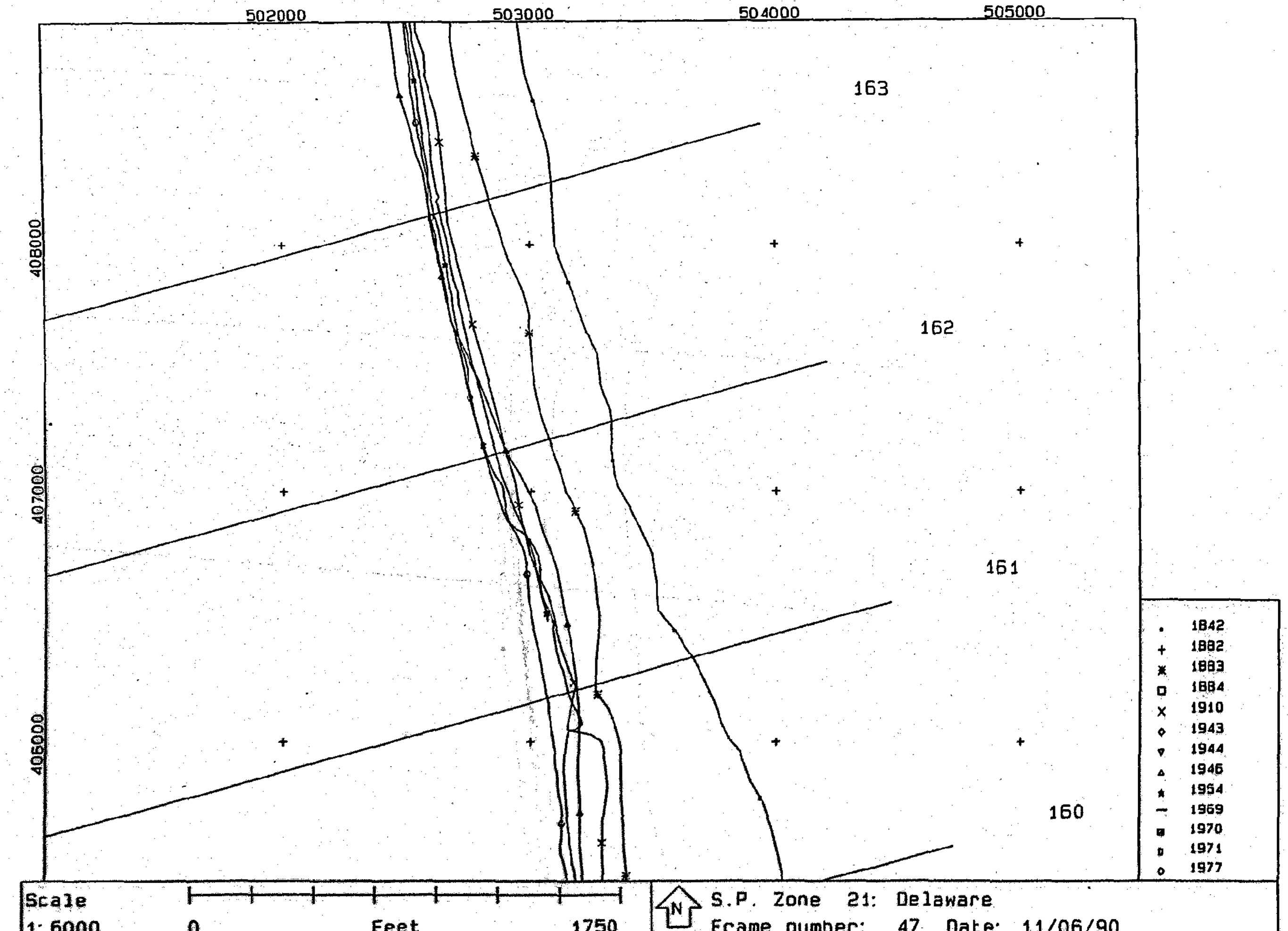


West Delaware Bay Historical Shoreline Changes: 1842-1977

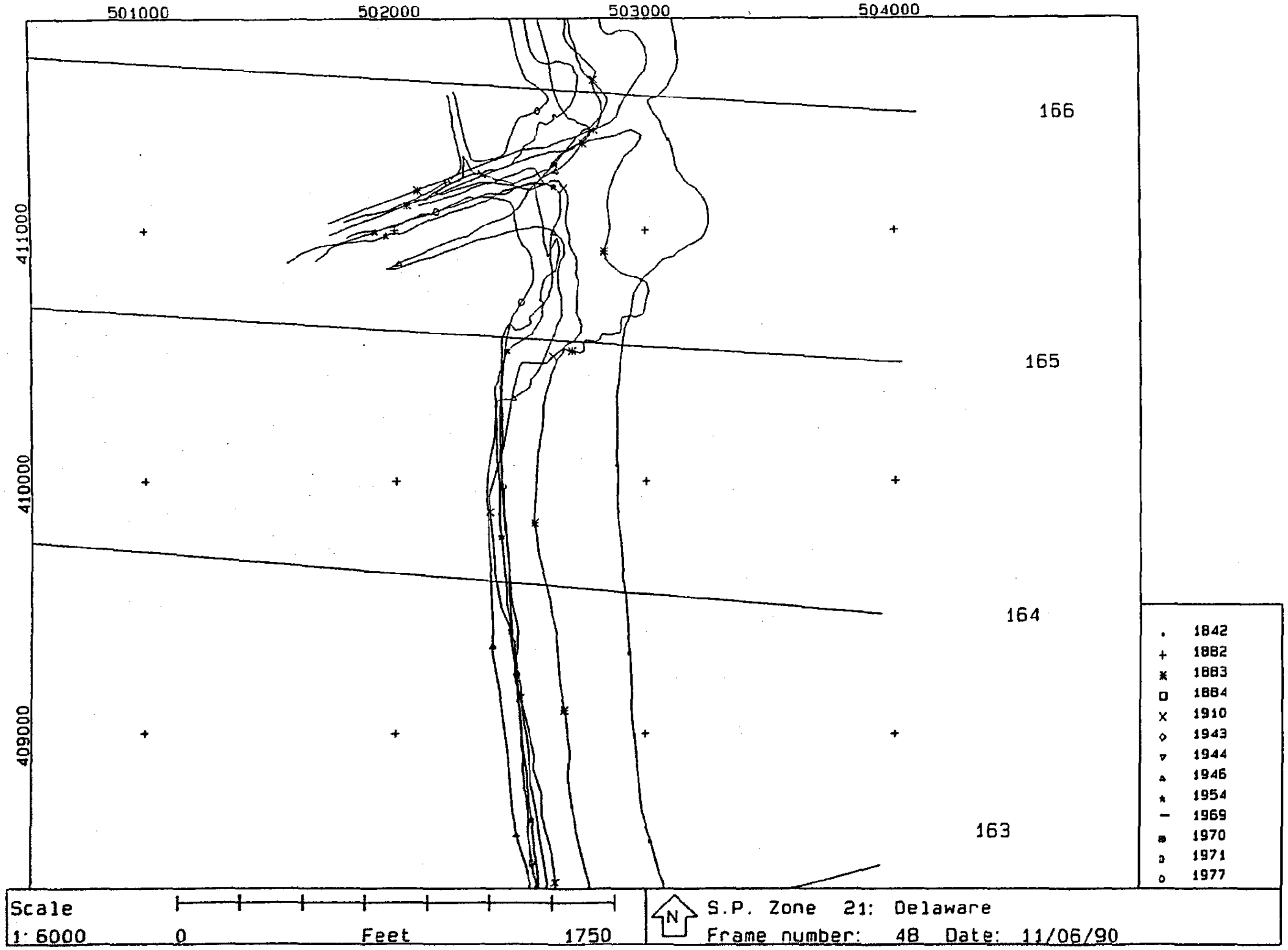



West Delaware Bay Historical Shoreline Changes: 1842-1977
502000
503000
504000
505000
506000
405000
404000
403000
160
159
158
157
1842
1882
1883
1884
1910
1943
1944
1946
1954
1969
1970
1971
1977
Scale
1: 6000
0
Feet
1750
N
S.P. Zone 21: Delaware
Frame number: 46 Date: 11/06/90

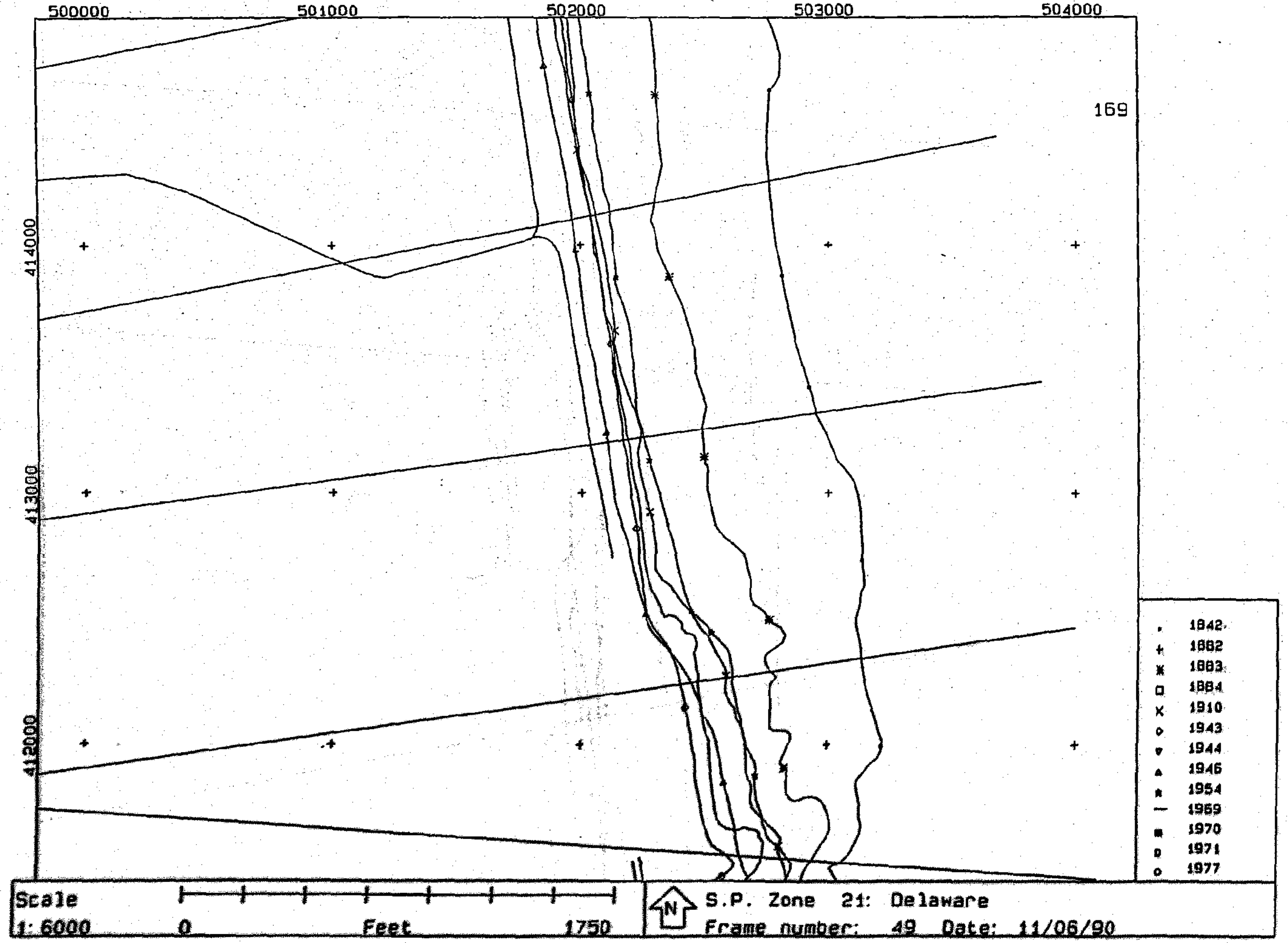
West Delaware Bay Historical Shoreline Changes: 1842-1977



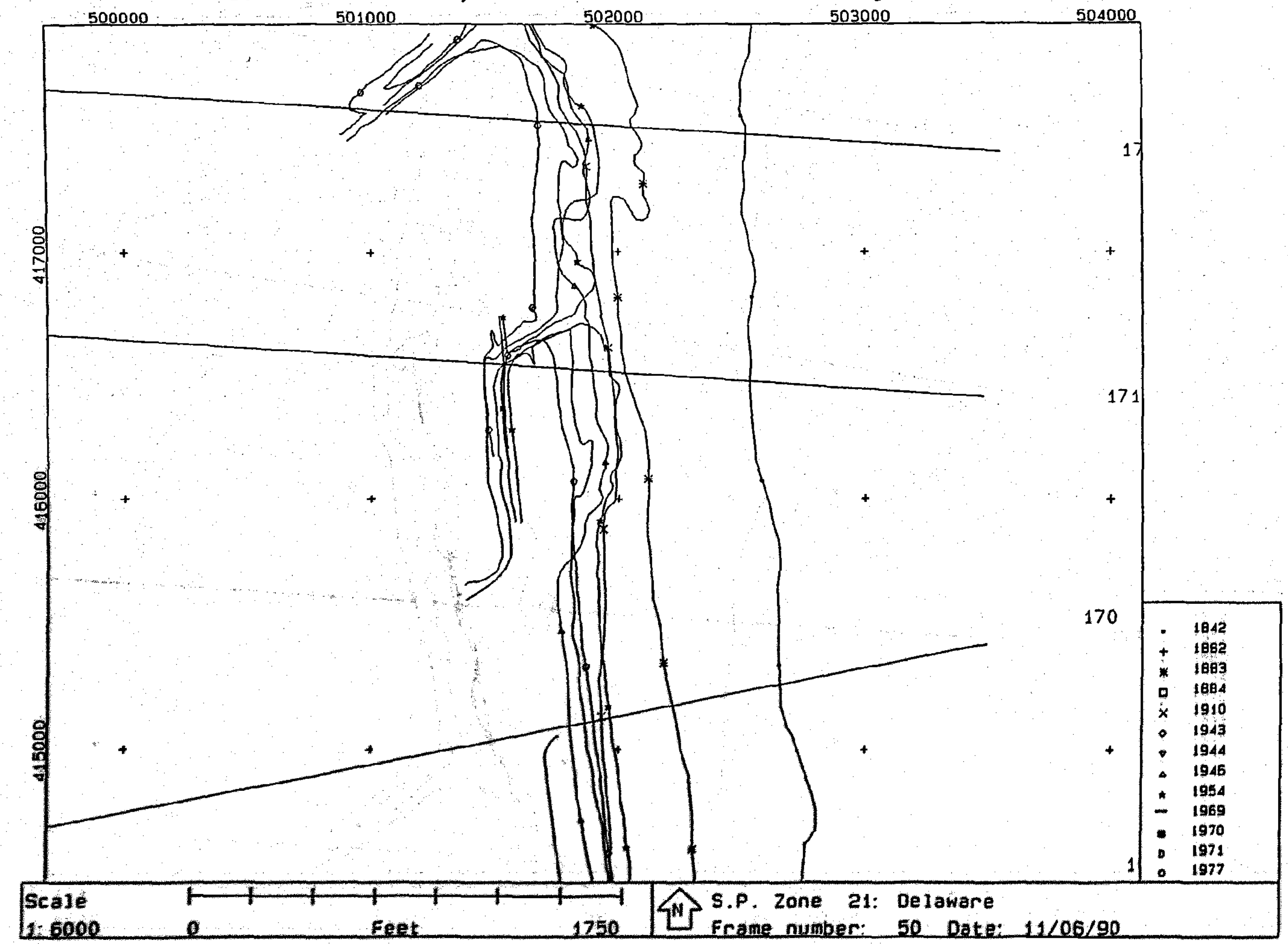
West Delaware Bay Historical Shoreline Changes: 1842-1977



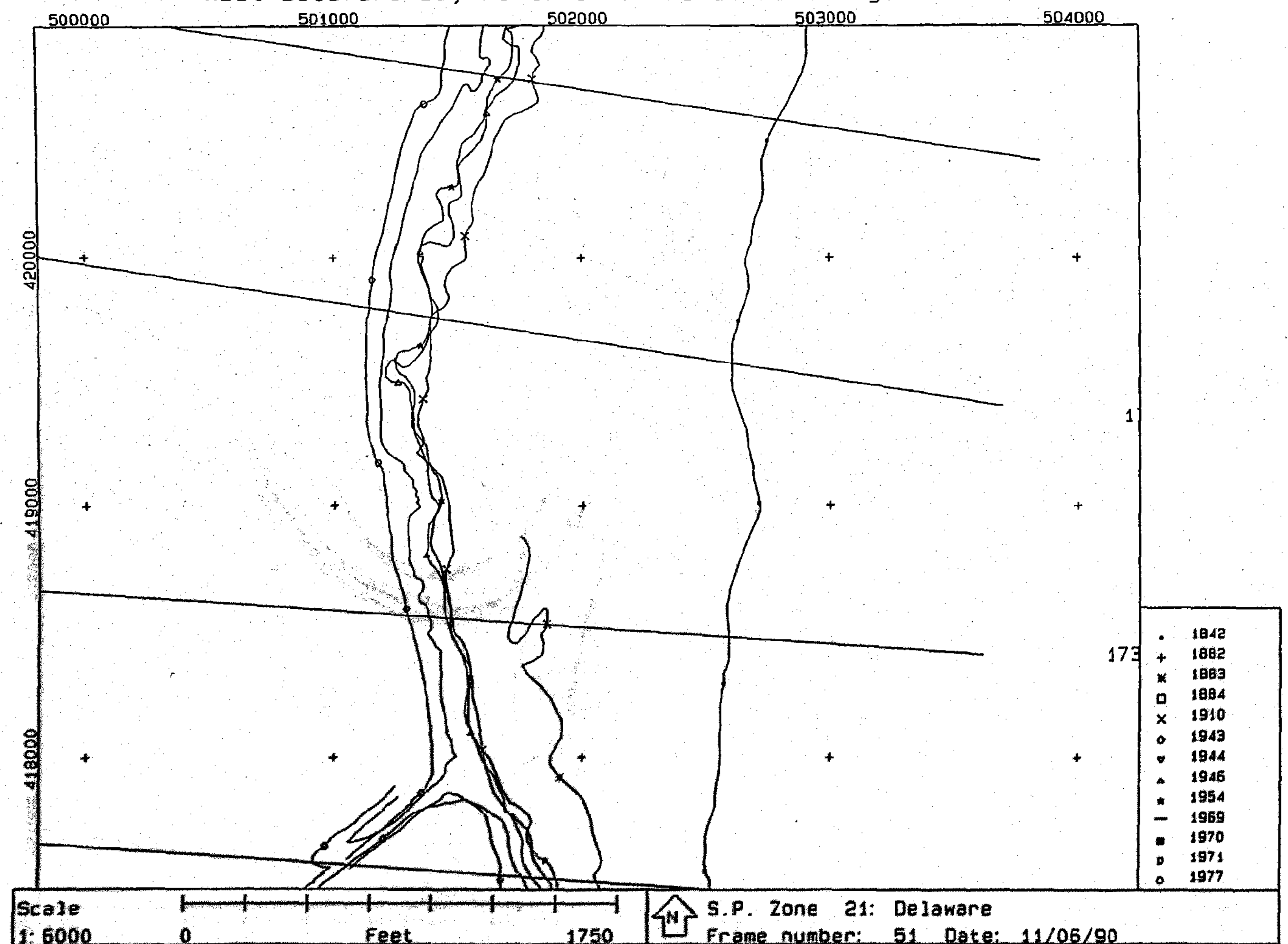
West Delaware Bay Historical Shoreline Changes: 1842-1977



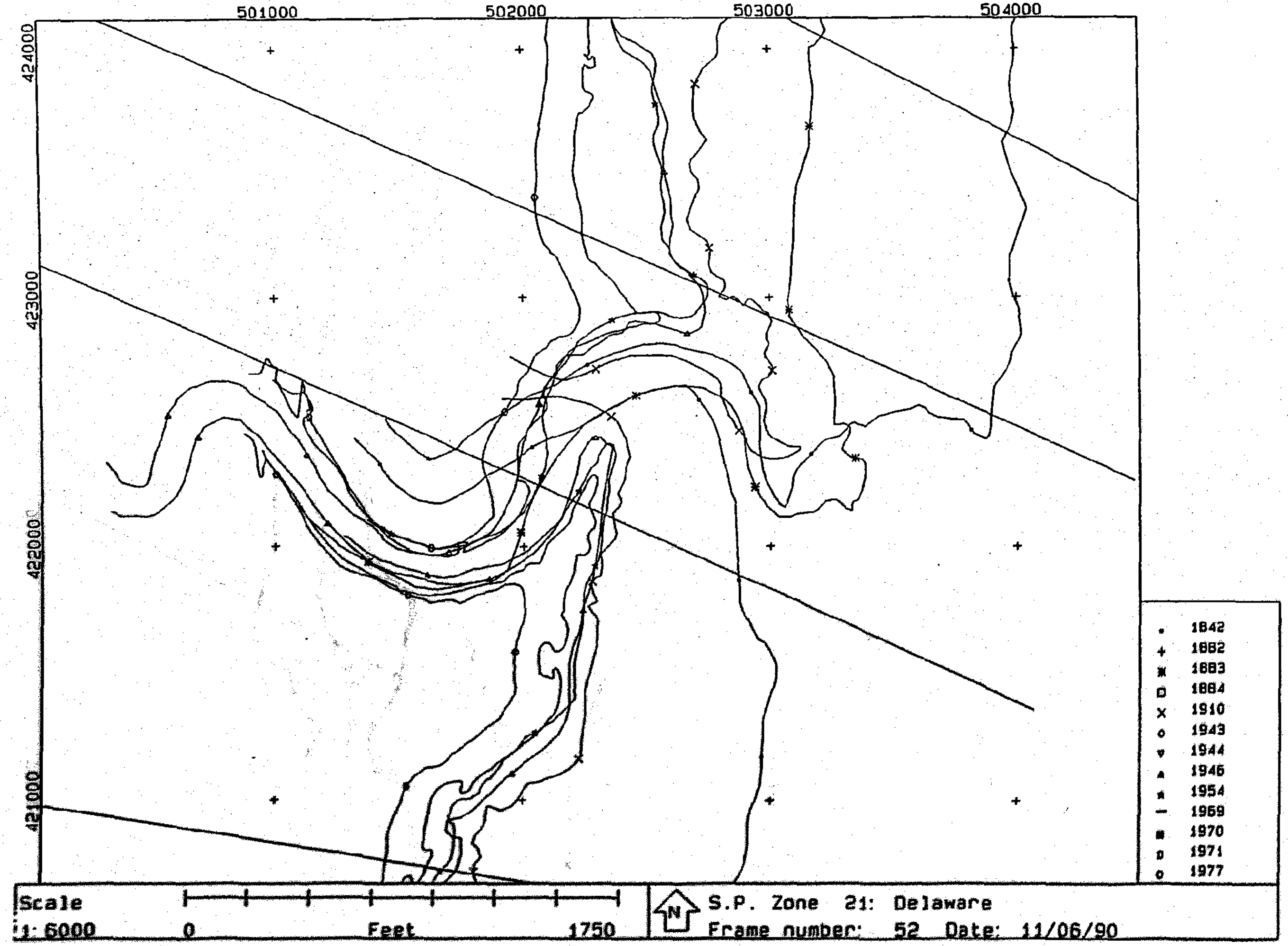
West Delaware Bay Historical Shoreline Changes: 1842-1977



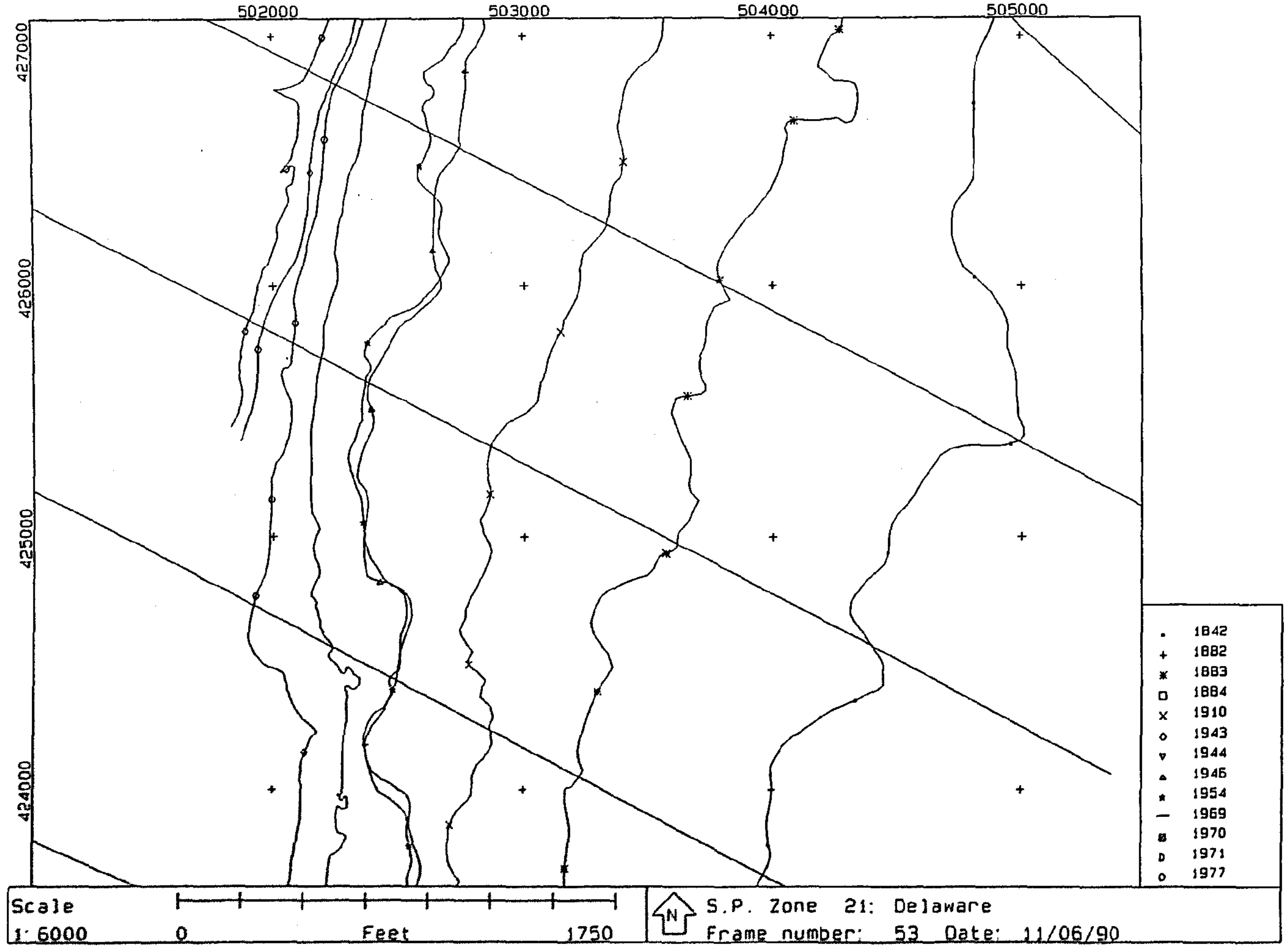
West Delaware Bay Historical Shoreline Changes: 1842-1977



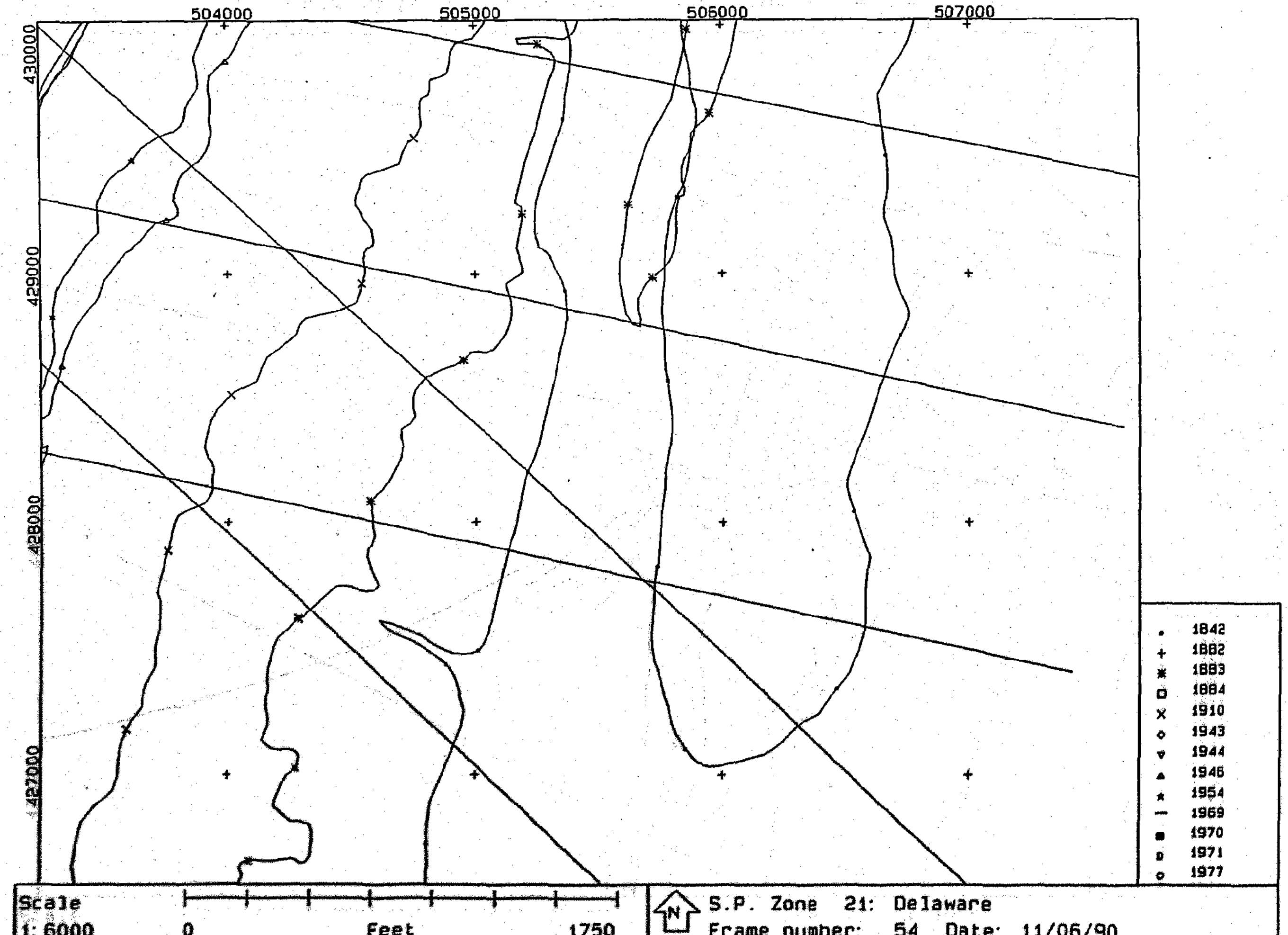
West Delaware Bay Historical Shoreline Changes: 1842-1977



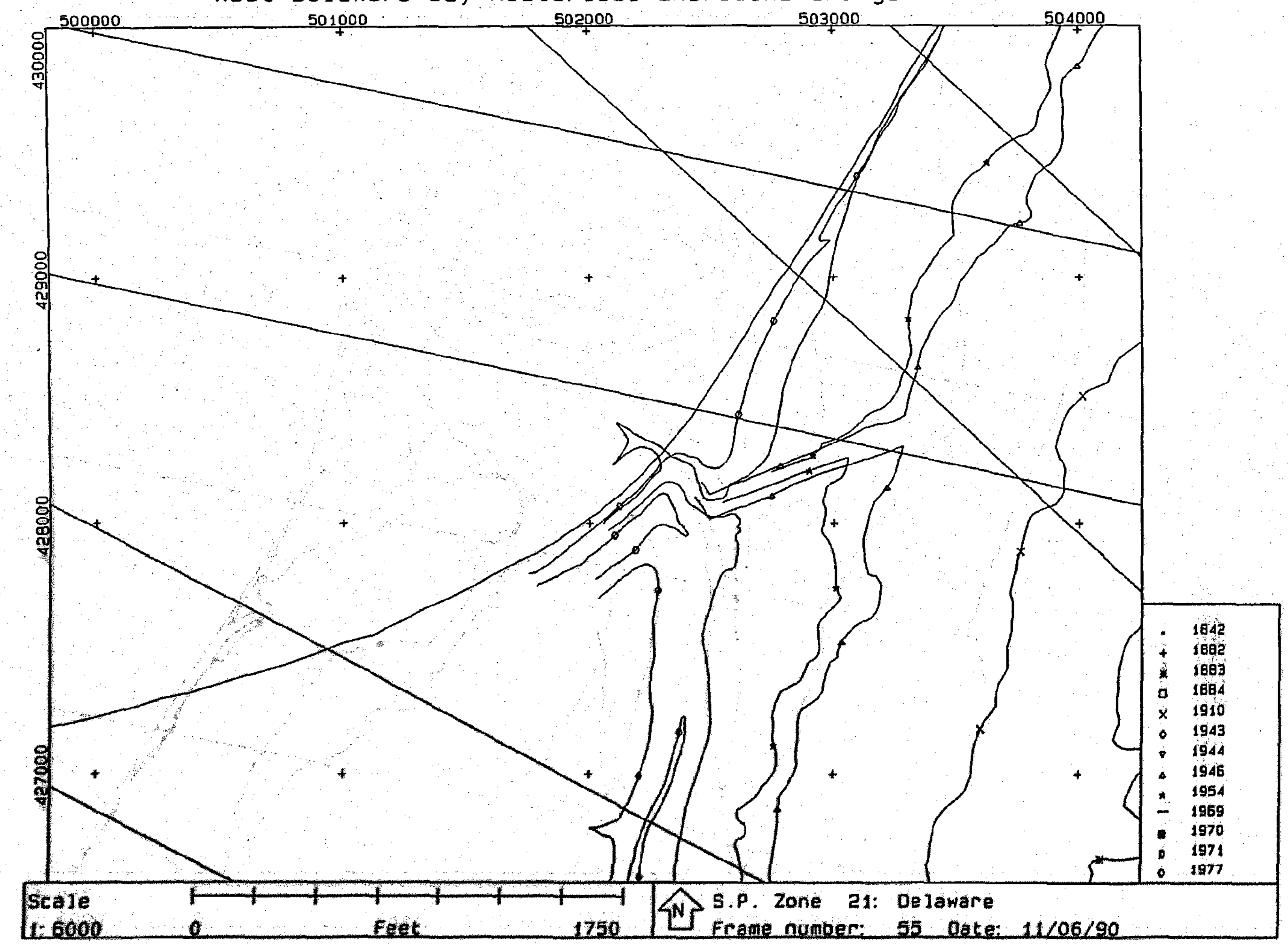
West Delaware Bay Historical Shoreline Changes: 1842-1977

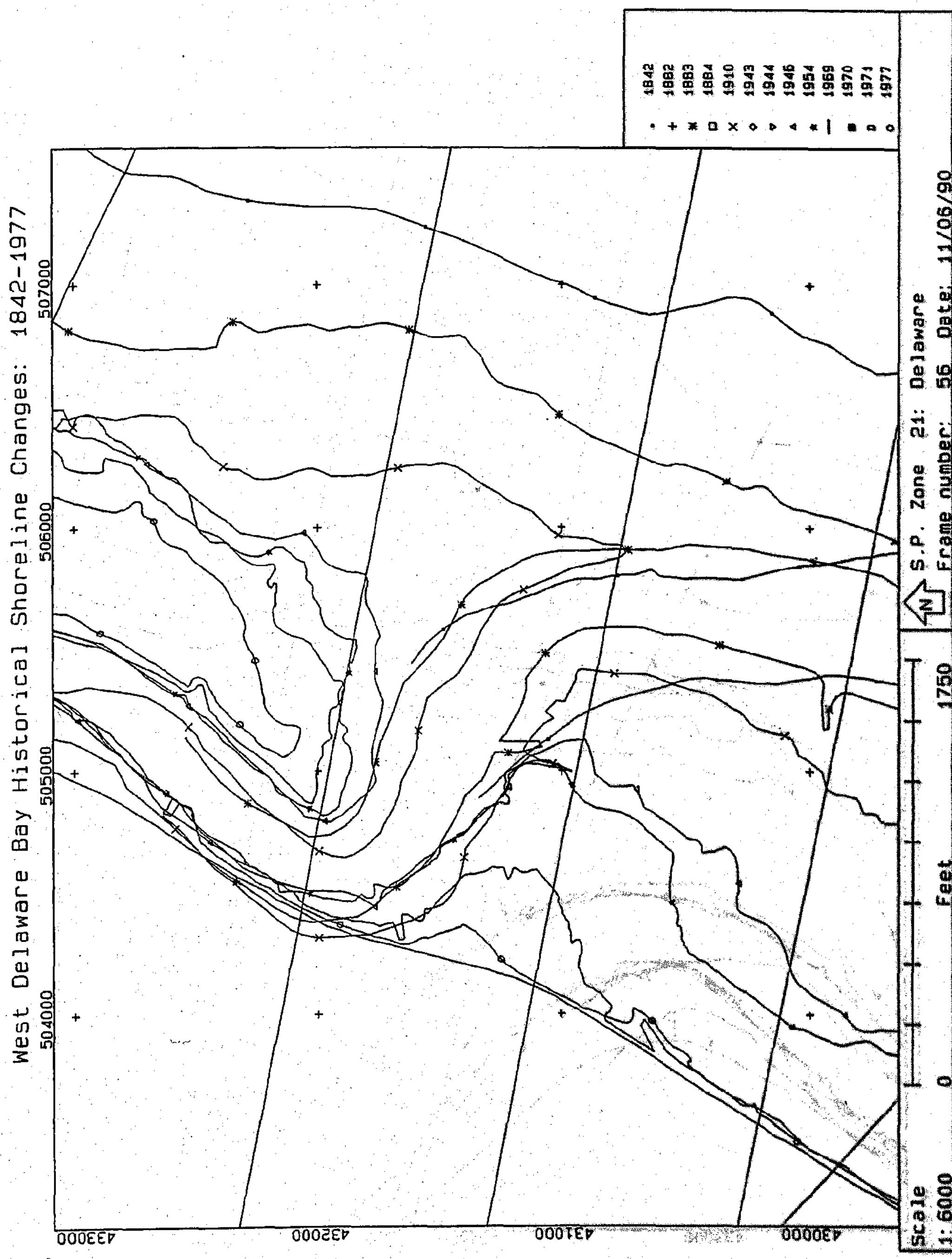


West Delaware Bay Historical Shoreline Changes: 1842-1977

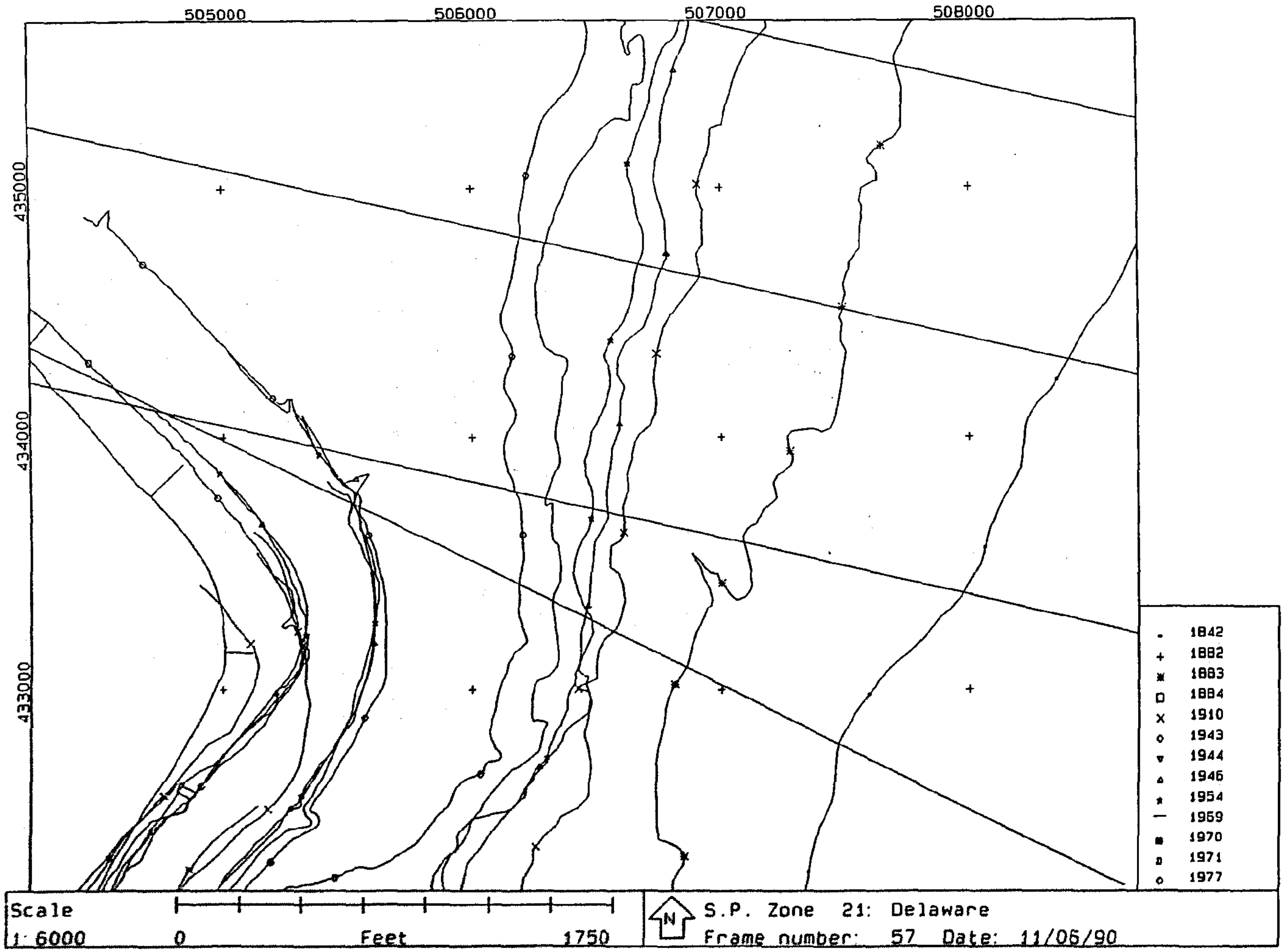


West Delaware Bay Historical Shoreline Changes: 1842-1977

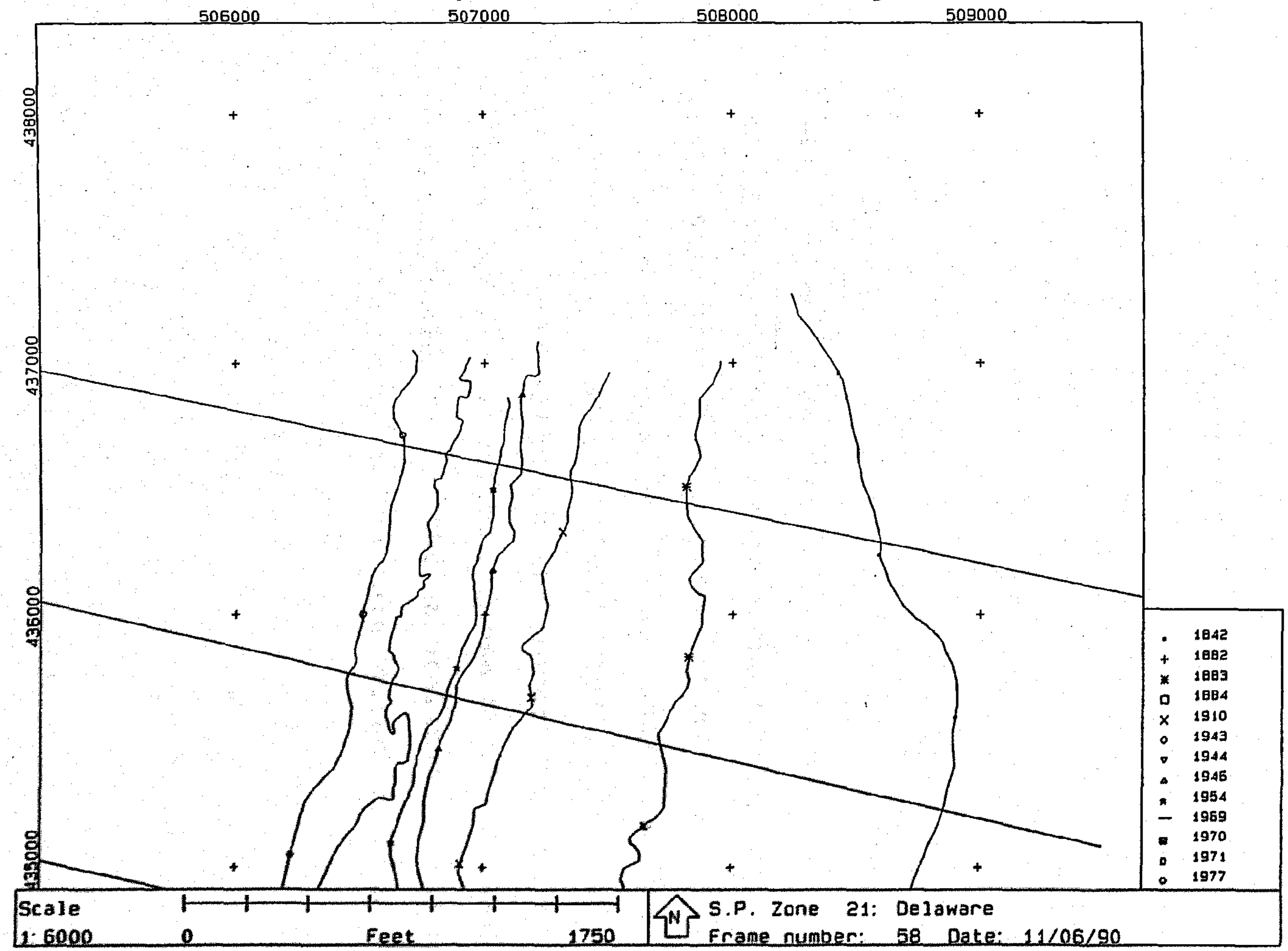



West Delaware Bay Historical Shoreline Changes: 1842-1977
504000
505000
506000
507000
433000
432000
431000
430000
1842
1882
1883
1884
1910
1943
1944
1946
1954
1969
1970
1971
1977
S.P. Zone 21: Delaware
Frame number: 56 Date: 11/06/90
Scale
1:6000
0
Feet
1750

West Delaware Bay Historical Shoreline Changes: 1842-1977



West Delaware Bay Historical Shoreline Changes: 1842-1977



APPENDIX 2

This appendix contains the tabulated results of computer-calculated rates of change along the shoreline of the west Delaware Bay between the following successive years or year-groups: 1842, 1882/1883/1884, 1910, 1943/1944/1946, 1954, 1969/1970/ 1971, and 1977. These values were calculated at the locations of the correspondingly-numbered straight transect lines seen projecting perpendicularly to the shorelines on the maps in Appendix 1. The values are given in feet.

YEARS or YEAR GROUPS:

1: 1842; 2: 1882/1883/1884; 3: 1910; 4: 1943/1944/1946; 5: 1954;
6: 1969/1970/1971; 7: 1977

Dashed line indicates no data available.
Blank lines indicate faulty datum points.

TRANSECT NUMBER #	1-2	2-3	2-4	3-4	4-5	5-6	6-7	2-7	1-7
1	---	---	---	---	6.9	---	---	---	---
2	---	---	2.7	---	6.1	---	---	1.7	---
3	---	---	2.8	---	7.2	---	---	2.3	---
4	---	---	2.6	---	5.6	---	---	3.0	---
5	---	---	2.1	---	1.6	---	---	2.6	---
6	---	---	0.8	---	4.0	-0.9	4.6	1.2	---
7	---	---	1.1	---	2.6	-0.8	-5.6	0.4	---
8	---	---	1.1	---	-0.6	0.9	-0.1	0.8	---
9	---	---	1.0	---	-0.1	0.4	6.1	1.1	---
10	---	---	1.6	---	-8.4	0.6	2.7	0.3	---
11	---	---	1.3	---	-2.9	1.3	12.5	1.6	---
12	---	---	-0.6	---	4.0	0.2	6.7	0.6	---
13	---	---	-1.3	---	0.5	2.3	-0.6	-0.5	---
14	---	---	-3.0	---	1.3	4.1	-12.2	-2.0	---
15	---	---	-4.0	---	0.3	1.2	-23.8	-4.1	---
16	---	---	10.8	---	-55.9	-15.0	-9.5	-2.8	---
17	---	---	-6.4	---	8.9	-4.2	-9.0	-4.5	---
18	---	---	-7.0	---	5.4	-8.2	10.6	-4.7	---
19	---	---	-8.6	---	5.0	-7.8	2.1	-6.2	---
20	---	---	-8.1	---	-1.3	-9.4	-3.9	-7.3	---
21	---	---	-6.3	---	-2.9	-10.6	-5.4	-6.6	---
22	---	---	-5.2	---	-11.2	-10.3	-14.0	-7.4	---
23	---	---	-8.4	---	-5.2	-14.2	2.2	-8.4	---
24	---	---	-10.3	---	-6.4	-15.1	-9.7	-10.7	---
25	---	---	-9.9	---	-13.0	-10.8	0.8	-9.7	---
26	---	---	-11.3	---	-3.7	-8.4	11.6	-8.4	---
27	---	---	-19.8	---	65.7	-0.9	5.0	-4.9	---
28	---	---	-0.2	---	20.2	-25.4		-2.4	---
29	---	---	-2.1	---	-4.0	-14.6	18.7	-3.3	---
30	---	---	-5.4	---	1.8	-15.0	11.6	-5.2	---
31	---	---	-7.3	---	0.1	-12.7	24.9	-5.4	---
32	---	---	-7.1	---	-3.0	-10.6	26.8	-5.1	---
33	---	---	-7.3	---	6.7	-10.2	17.2	-4.7	---
34	---	---	-5.1	---	5.3	0.6	-10.2	-3.2	---
35	---	---	0.4	---	0.7	-1.7	23.6	1.5	---
36	---	---	13.3	---	1.9	-5.4	22.4	9.2	---
37	---	---	12.3	---	0.4	-2.1	9.8	8.2	---
38	---	---	13.4	---	8.8	-6.9	24.8	9.9	---
39	---	---	7.2	---	12.4	6.7	1.5	7.4	---
40	---	---	-1.2	---	9.1	9.6	5.2	2.4	---
41	---	---	-5.8	---	---	---	7.6	-1.6	---
42	---	---	-6.6	---	---	---	6.3	-3.2	---
43	---	---	-3.9	---	---	---	8.1	-2.7	---
44	---	---	-4.4	---	---	---	7.5	-3.5	---
45	---	---	-1.9	---	---	---	2.8	-1.8	---
46	---	---	-0.2	---	---	---	5.1	-0.1	---
47	---	---	2.0	---	---	---	4.6	1.3	---
48	---	---	3.8	---	---	---	0.5	2.4	---
49	---	---	3.3	---	0.5	-0.8	6.4	2.4	---
50	---	---	2.0	---	-2.6	-0.9	3.2	1.0	---
51	---	---	1.0	---	-3.7	-1.3	3.1	0.2	---
52	---	---	-0.7	---	-1.4	0.7	0.5	-0.4	---
53	---	---	-2.8	---	-2.8	---	4.2	-1.8	---
54	---	---	-4.0	---	-9.5	-3.9	2.6	-4.2	---
55	---	---	-5.0	---	-3.4	-5.5	-1.0	-4.6	---
56	---	---	-2.7	---	-11.7	-6.5	0.7	-4.2	---
57	---	---	-1.8	---	-6.9	-5.2	-7.5	-3.4	---
58	---	---	-6.7	---	-1.7	-4.8	-2.0	-5.6	---
59	---	---	-7.1	---	-0.9	-4.4	-1.8	-5.7	---
60	---	---	-7.7	---	-0.3	-5.9	-4.3	-6.6	---

61	---	---	-7.2	---	-2.4	-7.3	-0.5	-6.3	---
62	---	---	-7.1	---	-6.2	-6.9	-2.8	-6.7	---
63	---	---	-6.9	---	1.4	-5.5	-2.4	-5.6	---
64	---	---	-5.4	---	-5.0	-4.8	-3.7	-5.1	---
65	---	---	-5.9	---	7.1	-4.9	0.3	-4.2	---
66	---	---	-6.0	---	2.2	-4.7	1.5	-4.6	---
67	---	---	-4.2	---	-0.4	-5.3	5.1	-3.5	---
68	---	---	-3.5	---	-3.9	-3.3	-1.7	-3.4	---
69	---	---	-3.7	---	-3.2	-5.9	1.1	-3.8	---
70	---	---	-3.1	---	-2.4	-6.1	-0.2	-3.4	---
71	---	---	-2.2	---	-2.3	-6.0	1.6	-2.6	---
72	---	---	-2.1	---	---	---	13.5	-1.1	---
73	---	---	-2.5	---	---	---	18.4	-1.1	---
74	---	---	-0.9	---	20.2	-11.5	12.7	-0.1	---
75	---	---	0.3	---	16.1	-8.5	8.7	0.6	---
76	---	---	-0.9	---	18.3	-7.3	13.7	0.5	---
77	---	---	0.9	---	7.9	-5.7	26.0	1.9	---
78	---	---	1.0	---	12.5	-5.8	14.1	2.0	---
79	---	---	1.4	---	8.3	-2.7	8.7	1.9	---
80	---	---	-0.6	---	0.9	-0.8	4.6	-0.1	---
81	---	---	-2.2	---	3.4	-3.7	7.9	-1.1	---
82	---	---	-1.2	---	2.1	-0.8	8.8	---	---
83	---	---	-1.9	---	-0.6	-2.0	13.4	-0.5	---
84	---	---	-1.6	---	8.0	-1.4	10.0	0.3	---
85	---	---	0.2	---	5.7	2.2	4.6	1.4	---
86	---	---	4.2	---	-3.7	3.0	-9.5	2.2	---
87									
88									
89									
90	-18.8	---	11.9	---	2.3	3.8	4.9	9.1	0.5
91	-6.5	---	-2.7	---	10.8	-7.9	-3.1	-2.4	-3.7
92	-3.7	---	-4.1	---	3.0	-17.4	-0.7	-5.4	-4.9
93	-5.9	---	-6.9	---	3.8	-17.1	2.2	-6.9	-6.6
94	-4.0	---	-5.9	---	-3.6	-13.5	-4.6	-6.8	-5.9
95	-8.9	---	-5.2	---	-5.3	-13.3	-9.0	-6.8	-7.5
96	-5.2	---	-8.4	---	-0.7	-11.0	-5.6	-7.9	-7.1
97	-5.9	---	-8.1	---	-5.3	-12.1	-5.7	-8.3	-7.5
98	-7.9	---	-7.0	---	-5.2	-12.1	-6.6	-7.7	-7.7
99	-5.0	---	-8.4	---	-2.0	-16.5	-7.0	-9.0	-7.8
100	-5.1	---	-7.3	---	-6.5	-19.3	-5.4	-9.0	-7.8
101	-5.3	---	-5.8	---	-4.8	-21.0	5.6	-7.2	-6.6
102	-6.7	---	-5.7	---	-5.0	-17.7	-1.3	-7.2	-7.0
103	-9.9	---	-5.3	---	-5.2	-9.9	-5.3	-6.0	-7.2
104	-9.4	---	-6.1	---	-3.7	-7.9	-4.2	-6.0	-7.1
105	-6.6	---	-6.7	---	-1.1	-6.6	-3.0	-5.9	-6.1
106	-4.4	---	-6.2	---	0.3	-5.5	0.5	-5.0	-4.8
107	-2.9	---	-5.6	---	-0.6	-4.3	1.6	-4.4	-3.9
108	-1.9	---	-5.4	---	1.1	-4.4	4.1	-3.8	-3.2
109	-3.4	---	-4.4	---	1.7	-3.3	0.5	-3.3	-3.3
110	-3.1	---	-5.6	---	2.7	-2.7	-1.0	-4.1	-3.8
111	-5.4	---	-5.6	---	0.4	-0.1	-4.5	-4.1	-4.5
112	-3.6	-1.8	-5.4	-8.2	1.7	0.2	-2.9	-3.7	-3.7
113	-2.0	-3.1	-5.5	-7.2	4.2	-2.4	0.4	-3.7	-3.1
114	2.3	-7.1	-7.2	-7.3	9.0	-2.5	-0.6	-4.5	-2.5
115	-1.5	-6.3	-6.8	-7.2	5.5	-4.0	0.7	-4.7	-3.7
116	-5.7	-4.5	-5.5	-6.3	4.3	-4.2	-2.5	-4.2	-4.7
117	-3.0	-3.0	-5.0	-6.6	1.7	-4.0	-1.8	-4.0	-3.7
118	0.2	-4.3	-5.8	-7.0	-2.4	-3.6	-2.1	-4.8	-3.3
119	-0.6	-4.8	-5.8	-6.6	-2.3	-3.7	-2.4	-4.9	-3.6
120	-1.3	-5.6	-6.2	-6.6	2.2	-4.9	-1.5	-4.9	-3.8
121	-0.3	-6.0	-6.5	-7.0	2.1	-8.1	-3.7	-5.8	-4.1
122	2.3	-7.5	-8.3	-8.9	1.1	-5.8	-5.2	-6.8	-4.1
123	2.9	-8.5	-9.0	-9.4	0.9	-9.8	-4.2	-7.9	-4.6
124	2.4	-7.9	-8.8	-9.6	4.3	-11.2	-6.0	-7.9	-4.7
125	0.9	-10.1	-8.9	-8.0	-3.1	-11.7	-3.1	-8.3	-5.5
126	-2.9	-9.7	-10.4	-11.0	9.8	-11.9	-5.4	-8.5	-6.8
127	4.9	-12.5	-7.8	-4.3	1.1	-11.4	-6.8	-7.5	-3.8
128	4.8	-5.3	-3.9	-2.9	-1.1	-8.1	-8.1	-4.7	-1.8
129	4.2	-4.3	-3.9	-3.7	5.2	-6.5	-10.4	-4.1	-1.6
130	-2.1	-4.6	-4.5	-4.4	16.5	-7.7	-8.8	-3.6	-3.1
131	-2.2	-2.8	-3.0	-3.2	5.1	-7.5	---	---	---

132	-3.8	-4.6	-4.5	-4.5	4.5	-6.3	-3.7	-4.0	-3.9
133	-5.2	-6.7	-7.6	-8.2	11.8	-14.8	-8.3	-7.1	-6.5
134	-7.2	-3.0	-5.5	-7.4	4.1	-14.0	-4.2	-5.9	-6.3
135	---	-6.8	-7.0	-7.1	-6.5	-10.7	-5.7	-7.4	---
136	-0.8	-10.2	-8.3	-6.8	-1.2	-10.0	-4.3	-7.6	-5.5
137	4.1	-5.1	-6.1	-6.8	-1.8	-10.8	-3.9	-6.3	-3.1
138	7.0	-5.5	-8.2	-10.1	0.6	-6.3	-9.6	-7.2	-2.9
139	-1.3	-5.0	-4.3	-3.7	2.3	-2.9	12.8	-2.0	-1.8
140									
141	-1.4	-6.5	-5.0	-3.9	0.9	-5.9	7.1	-3.6	-3.0
142	-6.2	-1.4	-2.8	-3.9	1.6	-7.4	6.0	-2.4	-3.6
143	-2.3			-2.7	-2.5	-7.1	31.5	-6.9	-5.5
144	-2.8	---	-1.8	-3.1	7.5	-8.1	-7.5	-2.5	-2.6
145	-3.6	-6.7	-3.9	-1.8	6.7	-4.3	-1.3	-2.8	-3.1
146	-1.6	-4.6	-4.1	-3.7	6.5	-1.1	-4.9	-2.8	-2.5
147	-2.7	-3.6	-4.3	-4.8	7.5	-8.9	-7.4	-4.3	-3.8
148	-9.9	-5.7	-5.4	-5.2	4.0	-7.1	-4.5	-4.8	-6.3
149	-7.0	-5.4	-6.1	-6.5	-1.1	-7.1	-1.0	-5.4	-5.9
150	-3.1	-5.7	-6.3	-6.8	-1.5	-6.7	-2.6	-5.7	-4.9
151	-1.8	-6.6	-5.2	-4.1	-0.2	-5.4	-0.4	-4.4	-3.6
152	-2.1	-5.2	-5.0	-4.9	2.1	-4.2	-0.2	-3.9	-3.3
153	-2.9	-5.7	-4.6	-3.7	3.1	-3.4	-3.5	-3.6	-3.4
154	-4.0	-6.2	-3.7	-1.8	1.3	-4.8	2.8	-2.9	-3.2
155	-4.0	-8.3	-5.1	-2.7	-0.3	-1.4	9.4	-2.9	-3.2
156	-6.5	-10.2	-4.9	-0.9	0.4	0.4	6.8	-2.6	-3.8
157	-10.2	-5.6	-3.0	-1.1	0.6	2.8	-1.7	-1.7	-4.3
158	-12.1	-6.6	-2.8	---	3.6	0.2	-0.7	-1.6	-4.8
159	-14.2	-6.1	-3.0	-0.7	---	---	-3.7	-2.0	-5.7
160	-16.0	-3.1	-2.5	-2.0	---	---	-0.8	-1.9	-6.2
161	-9.9	-3.3	-1.2	0.3	---	---	-11.0	-2.2	-4.5
162	-6.5	-6.7	-2.8	0.2	-10.2	2.5	-5.3	-2.8	-3.9
163	-6.4	-6.5	-3.9	-2.0	2.5	1.5	-4.7	-2.6	-3.7
164	-7.8	-7.4	-3.5	-0.6	7.3	1.4	-0.8	-1.6	-3.5
165	-3.7	-1.6	-2.1	-2.5	-13.5	-6.0	2.2	-3.3	-3.4
166	-2.9	-4.7	-4.7	-4.7	25.0	-7.3	-17.8	-3.7	-3.4
167	-9.1	-6.8	-5.1	-3.9	20.5	-9.3	-8.4	-3.9	-5.5
168	-11.4	-9.2	-6.1	-3.7	18.2	-4.2	-2.5	-3.4	-5.8
169	-11.5	-8.8	-5.4	-2.8	19.7	-5.3	-0.1	-2.8	-5.4
170	-10.9	-10.9	-6.7	-3.6	20.7	-6.9	4.2	-3.5	-5.7
171	-12.3	-2.3	-2.2	-2.1	8.8	-10.1	-9.1	-3.1	-5.9
172	-11.2	-9.7	-3.2	1.6	4.6	-9.1	-10.9	-4.1	-6.3
173	-18.0	-14.4	-6.4	-0.4	2.9	-6.2	-10.9	-6.0	-9.6
174	---	---	---	0.9	-3.7	-11.6	-9.7	---	-11.0
175	---	---	---	-2.0	-7.0	-4.4	-20.9	---	-10.1
176	-21.5	12.2	4.4	-1.4	2.0	-4.4	-59.8	-2.7	-8.4
177	-21.0	-4.5	-7.0	-8.9	5.5	-36.7	-25.1	-12.2	-14.9
178	-20.5	-14.8	-13.1	-11.8	-3.1	-17.2	-45.2	-15.6	-17.1
179	-21.6	-31.1	-22.0	-15.2	-2.1	-13.2	-15.9	-18.4	-19.4
180	-32.9	-19.3	-18.7	-18.3	-16.6	-18.9	-16.6	-18.4	-22.8
181	-19.3	-22.6	-21.8	-21.1	-6.5	-29.0	-17.4	-21.2	-20.7
182	-50.0	-15.7	-20.2	-23.5	-21.1	-31.9	-1.0	-20.5	-29.5
183	-49.6	-24.6	-21.3	-18.8	-33.9	-16.4	-20.8	-21.6	-30.1
184	-24.5	-41.9	-31.5	-23.8	-30.8	-27.7	-2.5	-28.4	-27.2
185	-16.6	-39.4	-28.9	-21.1	-26.3	-25.9	-2.3	-26.0	-23.1
186	-14.6	-14.2	-19.0	-22.6	-25.3	-28.4	-48.3	-23.5	-20.8
187	-10.5	-21.4	-16.3	-12.5	-32.8	-13.6		-25.7	-21.1
188	-16.7	-11.9	-7.2	-3.7	3.8	-11.7	-18.7	-8.0	-10.6
189	-22.1	-18.4	-8.9	-1.7	-7.9	-13.1	-15.8	-10.1	-13.7
190	-22.7	-21.7	-11.7	-4.2	-11.9	-25.6	-13.5	-14.1	-16.7
191	-28.5	-20.7	-13.5	-8.1	-4.3	-15.0	-21.8	-13.7	-18.2
192	-19.4	-17.6	-10.9	-5.9	-11.4	-14.2	-20.7	-12.3	-14.5
MEAN:	-7.9	-9.1	-4.8	-6.4	+0.5	-7.4	-1.3	-4.5	-7.2

APPENDIX 3

This appendix contains the tabulated results of computer-calculated net shoreline positional change measurements along the west Delaware Bay shoreline between the following successive years or year-groups: 1842, 1882/1883/1884, 1910, 1943/1944/1946, 1954, 1969/1970/ 1971, and 1977. The individual values were calculated at the locations of the correspondingly-numbered straight transect lines seen projecting perpendicularly to the shorelines on the maps in Appendix 1. The values are given in feet.

YEARS or YEAR GROUPS:

1: 1842; 2: 1882/1883/1884; 3: 1910; 4: 1943/1944/1946; 5: 1954;
6: 1969/1970/1971; 7: 1977

Dashed line indicates no data available.
Blank lines indicate faulty datum points.

TRANSECT LINE #	1-2	2-3	2-4	3-4	4-5	5-6	6-7	2-7	1-7
1	---	---	---	---	68.8	---	---	---	---
2	---	---	166.3	---	60.8	---	---	166.2	---
3	---	---	172.5	---	72.3	---	---	219.7	---
4	---	---	160.3	---	55.8	---	---	281.9	---
5	---	---	128.6	---	16.0	---	---	244.1	---
6	---	---	51.2	---	43.6	-13.8	31.9	112.9	---
7	---	---	66.2	---	29.0	-13.5	-39.0	42.7	---
8	---	---	65.6	---	-6.7	14.6	-0.7	72.7	---
9	---	---	60.7	---	-1.5	6.5	42.8	108.6	---
10	---	---	94.7	---	-92.2	9.0	19.2	30.6	---
11	---	---	78.8	---	-32.1	20.8	87.5	155.0	---
12	---	---	-36.7	---	44.0	3.8	46.9	58.0	---
13	---	---	-80.5	---	5.0	36.2	-3.9	-43.2	---
14	---	---	-184.4	---	13.9	65.0	-85.5	-191.0	---
15	---	---	-246.4	---	3.5	19.0	-166.9	-390.8	---
16	---	---	656.8	---	-615.3	-240.7	-66.4	-265.5	---
17	---	---	-391.2	---	98.0	-68.0	-62.8	-424.0	---
18	---	---	-425.5	---	59.0	-139.2	63.4	-442.3	---
19	---	---	-526.3	---	54.7	-132.5	12.5	-591.6	---
20	---	---	-491.8	---	-14.6	-160.4	-23.6	-690.4	---
21	---	---	-385.1	---	-31.7	-180.1	-32.3	-629.2	---
22	---	---	-316.7	---	-123.6	-174.6	-84.2	-699.0	---
23	---	---	-512.3	---	-56.7	-241.9	13.4	-797.5	---
24	---	---	-630.2	---	-70.3	-256.8	-57.9	-1015.3	---
25	---	---	-603.3	---	-143.1	-183.5	5.0	-924.8	---
26	---	---	-689.1	---	-40.6	-142.3	69.8	-802.2	---
27	---	---	-1205.7	---	722.2	-15.0	29.8	-468.7	---
28	---	---	-11.5	---	221.8	-431.3	-227.3	---	
29	---	---	-129.2	---	-43.7	-248.6	111.9	-309.7	---
30	---	---	-328.3	---	19.7	-254.2	69.5	-493.3	---
31	---	---	-444.0	---	1.6	-215.6	149.3	-508.9	---
32	---	---	-434.5	---	-33.1	-179.9	160.9	-486.6	---
33	---	---	-447.6	---	73.4	-174.1	102.9	-445.4	---
34	---	---	-312.7	---	58.0	10.9	-61.0	-304.8	---
35	---	---	25.4	---	7.3	-28.8	141.5	145.5	---
36	---	---	809.1	---	21.1	-91.1	134.3	873.3	---
37	---	---	748.3	---	4.1	-35.1	58.5	775.8	---
38	---	---	815.0	---	96.5	-117.2	149.0	943.4	---
39	---	---	439.0	---	136.8	113.9	8.8	698.6	---
40	---	---	-71.3	---	100.3	163.0	31.5	223.4	---
41	---	---	-354.3	---	---	---	45.8	-149.0	---
42	---	---	-405.2	---	---	---	38.1	-307.9	---
43	---	---	-239.5	---	---	---	48.6	-258.7	---
44	---	---	-265.9	---	---	---	44.9	-335.1	---
45	---	---	-116.6	---	---	---	17.0	-171.6	---
46	---	---	-10.9	---	---	---	30.7	-10.4	---
47	---	---	121.5	---	---	---	27.6	122.8	---
48	---	---	229.4	---	---	---	2.7	230.4	---
49	---	---	199.4	---	5.4	-13.1	38.2	229.9	---
50	---	---	123.0	---	-28.2	-16.1	19.1	97.8	---

51	---	---	59.0	---	-41.2	-21.6	18.7	14.9	---
52	---	---	-40.0	---	-15.0	11.4	3.2	-40.4	---
53	---	---	-165.3	---	-31.0	-0.5	25.3	-171.4	---
54	---	---	-238.3	---	-104.1	-66.0	15.6	-392.9	---
55	---	---	-295.6	---	-37.1	-93.9	-5.9	-432.4	---
56	---	---	-158.6	---	-129.2	-110.9	4.4	-394.4	---
57	---	---	-108.1	---	-75.5	-88.1	-45.0	-316.7	---
58	---	---	-414.6	---	-13.3	-81.4	-11.8	-521.1	---
59	---	---	-442.2	---	-7.0	-74.5	-10.8	-534.5	---
60	---	---	-480.3	---	-2.3	-101.1	-25.7	-609.3	---
61	---	---	-444.3	---	-19.0	-123.8	-3.3	-590.3	---
62	---	---	-441.9	---	-49.6	-118.0	-16.9	-626.4	---
63	---	---	-424.8	---	10.9	-93.3	-14.1	-521.4	---
64	---	---	-334.7	---	-40.1	-81.8	-22.0	-478.6	---
65	---	---	-364.5	---	57.0	-83.6	2.0	-389.0	---
66	---	---	-374.6	---	17.4	-80.7	8.8	-429.2	---
67	---	---	-261.8	---	-3.4	-89.6	30.7	-324.2	---
68	---	---	-215.3	---	-31.1	-55.5	-10.1	-312.0	---
69	---	---	-230.2	---	-25.8	-101.1	6.7	-350.4	---
70	---	---	-194.0	---	-19.1	-103.1	-1.1	-317.2	---
71	---	---	-133.8	---	-18.0	-101.7	9.3	-244.2	---
72	---	---	-132.6	---	---	---	80.7	-101.1	---
73	---	---	-155.2	---	---	---	110.6	-106.5	---
74	---	---	-53.9	---	161.8	-195.4	76.4	-11.2	---
75	---	---	17.6	---	129.2	-143.7	52.1	55.2	---
76	---	---	-54.3	---	146.5	-124.4	82.4	50.3	---
77	---	---	55.0	---	62.9	-96.7	156.1	177.4	---
78	---	---	64.1	---	99.7	-87.5	112.8	189.1	---
79	---	---	85.4	---	66.1	-40.7	69.4	180.3	---
80	---	---	-37.0	---	7.2	-12.0	36.5	-5.3	---
81	---	---	-135.6	---	27.3	-54.9	63.3	-99.9	---
82	---	---	-76.8	---	16.8	-12.1	70.1	-2.1	---
83	---	---	-117.3	---	-4.6	-30.6	107.3	-45.2	---
84	---	---	-96.7	---	64.2	-20.7	80.1	26.9	---
85	---	---	11.3	---	45.8	33.6	36.8	127.6	---
86	---	---	261.5	---	-29.5	45.5	-76.2	201.3	---
87									
88									
89									
90	-788.4	---	735.9	---	18.0	56.7	39.1	849.7	61.4
91	-274.4	---	-169.1	---	86.5	-118.8	-24.8	-226.1	-500.5
92	-157.1	---	-255.9	---	24.2	-261.7	-5.8	-499.1	-656.3
93	-247.1	---	-430.5	---	30.2	-256.7	17.3	-639.7	-886.8
94	-169.1	---	-364.3	---	-28.8	-202.5	-37.0	-632.6	-801.7
95	-372.6	---	-321.4	---	-42.5	-199.7	-71.6	-635.3	-1007.9
96	-218.9	---	-521.6	---	-5.8	-164.7	-44.4	-736.6	-955.5
97	-248.2	---	-499.9	---	-42.1	-181.2	-45.8	-768.9	-1017.1
98	-330.1	---	-435.5	---	-41.8	-181.5	-52.9	-711.7	-1041.7
99	-210.5	---	-522.1	---	-16.2	-247.3	-55.9	-841.4	-1051.9
100	-212.1	---	-454.2	---	-52.1	-288.8	-43.6	-838.7	-1050.9
101	-222.3	---	-356.6	---	-38.4	-315.1	45.1	-665.0	-887.3
102	-281.8	---	-353.4	---	-40.4	-265.0	-10.5	-669.3	-951.1
103	-416.5	---	-328.9	---	-41.4	-148.5	-42.5	-561.3	-977.8
104	-394.4	---	-379.5	---	-29.3	-118.3	-33.6	-560.7	-955.1
105	-275.3	---	-415.0	---	-9.2	-98.8	-24.1	-547.0	-822.4
106	-186.4	---	-385.1	---	2.1	-82.7	4.3	-461.4	-647.7
107	-122.8	---	-350.0	---	-4.8	-64.7	12.9	-406.5	-529.4
108	-79.7	---	-332.7	---	8.8	-65.3	32.6	-356.6	-436.3
109	-142.3	---	-273.3	---	13.5	-49.8	4.4	-305.2	-447.4
110	-128.0	---	-354.2	---	21.4	-40.6	-7.9	-381.3	-509.3
111	-222.9	---	-352.0	---	3.0	-1.2	-35.9	-386.0	-608.9

112	-147.5	-48.6	-343.1	-294.5	13.7	2.8	-23.3	-349.9	-497.4
113	-81.7	-83.7	-343.5	-259.7	33.7	-36.7	3.1	-343.3	-425.0
114	94.8	-192.2	-456.1	-263.9	71.7	-38.1	-4.9	-427.5	-332.6
115	-60.3	-169.6	-427.7	-258.1	44.4	-59.8	5.5	-437.6	-497.9
116	-234.9	-120.2	-348.3	-228.2	34.2	-62.6	-20.3	-397.1	-632.0
117	-121.9	-81.3	-317.2	-235.9	13.9	-60.5	-14.3	-378.1	-500.0
118	8.4	-115.3	-366.5	-251.2	-18.9	-53.4	-16.7	-455.5	-447.2
119	-23.9	-129.8	-366.9	-237.1	-18.0	-56.2	-19.5	-460.6	-484.5
120	-51.3	-152.0	-390.5	-238.5	17.2	-73.1	-12.4	-458.8	-510.1
121	-13.9	-161.1	-412.4	-251.3	17.0	-121.4	-29.5	-546.3	-560.2
122	92.8	-202.3	-522.9	-320.6	9.2	-86.3	-41.4	-641.4	-548.5
123	116.9	-228.2	-566.1	-337.9	7.0	-147.2	-33.4	-739.7	-622.8
124	99.7	-212.2	-557.5	-345.3	34.4	-168.4	-47.8	-739.3	-639.7
125	37.9	-272.5	-559.6	-287.1	-24.6	-175.0	-24.7	-783.9	-746.0
126	-118.1	-261.0	-658.1	-397.0	78.2	-178.9	-42.9	-801.7	-919.8
127	199.5	-337.8	-491.4	-153.5	9.2	-170.9	-54.6	-707.6	-508.1
128	195.2	-141.8	-245.6	-103.8	-9.1	-122.2	-64.6	-441.5	-246.4
129	171.6	-115.4	-247.4	-132.0	41.7	-97.6	-83.3	-386.5	-214.9
130	-85.3	-123.0	-281.5	-158.5	132.2	-115.0	-70.3	-334.6	-419.8
131	-89.8	-76.9	-191.5	-114.6	41.1	-112.2	---	---	---
132	-156.5	-123.5	-285.6	-162.1	36.1	-94.4	-29.2	-373.1	-529.6
133	-211.2	-180.9	-476.7	-295.8	94.2	-222.2	-66.2	-670.8	-882.0
134	-296.3	-80.7	-347.8	-267.1	32.5	-209.4	-33.6	-558.3	-854.6
135	---	-182.8	-439.6	-256.8	-52.4	-160.8	-45.3	-698.1	---
136	-32.3	-276.0	-520.8	-244.8	-9.9	-149.8	-34.4	-714.9	-747.2
137	167.7	-137.7	-384.1	-246.5	-14.5	-161.9	-31.4	-592.0	-424.3
138	286.4	-149.8	-514.1	-364.4	5.0	-95.0	-76.5	-680.7	-394.3
139	-55.0	-134.2	-268.0	-133.8	18.3	-43.2	102.1	-190.9	-245.8
140									
141	-58.8	-175.4	-317.3	-141.9	7.3	-87.8	57.2	-340.7	-399.5
142	-252.9	-37.4	-177.2	-139.8	12.4	-111.4	47.7	-228.5	-481.3
143	-94.3			-95.6	-19.8	-107.2	252.1	-652.9	-747.3
144	-116.8	0.4	-110.4	-110.8	60.3	-121.7	-60.2	-232.0	-348.8
145	-149.4	-181.8	-246.2	-64.4	53.5	-64.2	-10.3	-267.2	-416.6
146	-66.9	-125.2	-260.1	-134.9	52.4	-17.2	-39.3	-264.3	-331.2
147	-109.1	-98.1	-271.5	-173.5	60.4	-133.0	-59.3	-403.4	-512.5
148	-407.3	-152.9	-338.7	-185.8	32.3	-106.2	-35.7	-448.3	-855.5
149	-286.4	-147.0	-382.2	-235.2	-9.0	-106.4	-7.8	-505.4	-791.8
150	-128.1	-153.9	-399.7	-245.9	-12.3	-100.3	-20.8	-533.2	-661.3
151	-75.2	-178.9	-326.2	-147.3	-1.5	-81.6	-3.1	-412.4	-487.6
152	-86.2	-141.3	-317.1	-175.8	16.5	-62.6	-1.6	-364.8	-451.0
153	-118.1	-154.6	-287.6	-133.0	24.5	-50.6	-28.2	-342.0	-460.1
154	-162.2	-168.6	-232.0	-63.4	10.6	-71.8	22.6	-270.7	-432.9
155	-165.7	-224.3	-319.9	-95.5	-2.6	-21.6	75.6	-268.5	-434.2
156	-264.9	-274.3	-306.9	-32.6	3.3	6.4	54.7	-242.6	-507.5
157	-419.0	-151.4	-189.5	-38.2	4.6	41.4	-13.3	-156.8	-575.8
158	-497.0	-177.4	-177.9	-0.5	29.1	2.3	-5.3	-151.8	-648.8
159	-583.8	-165.5	-191.3	-25.8	---	---	-30.0	-191.8	-775.6
160	-658.0	-82.7	-154.9	-72.2	---	---	-6.7	-176.1	-834.1
161	-407.8	-88.1	-77.9	10.1	---	---	-87.9	-204.7	-612.5
162	-265.3	-181.3	-175.9	5.5	-82.0	37.6	-42.6	-262.8	-528.2
163	-260.8	-175.7	-246.5	-70.8	20.1	22.4	-37.7	-241.6	-502.4
164	-318.5	-199.1	-221.4	-22.3	58.6	20.9	-6.8	-148.7	-467.1
165	-151.4	-44.1	-132.8	-88.7	-107.7	-90.3	17.4	-313.3	-464.8
166	-119.3	-126.9	-295.0	-168.1	199.8	-108.9	-142.1	-346.1	-465.4
167	-372.1	-183.6	-322.9	-139.3	163.8	-139.0	-67.3	-365.3	-737.4
168	-467.9	-248.7	-381.5	-132.8	145.4	-62.3	-19.7	-318.1	-786.0
169	-471.4	-237.9	-338.4	-100.6	157.5	-79.1	-0.8	-260.9	-732.3
170	-445.5	-294.5	-424.3	-129.8	165.2	-103.7	33.4	-329.3	-774.8
171	-504.1	-60.8	-137.6	-76.9	70.6	-151.7	-72.9	-291.6	-795.7
172	-458.1	-260.6	-201.2	59.4	36.9	-137.2	-87.3	-388.8	-847.0

173	-739.3	-389.0	-404.5	-15.4	23.4	-92.6	-87.1	-560.8	-1300.1
174	---	---	---	31.1	-29.7	-173.7	-77.8	---	-1480.5
175	---	---	---	-73.3	-56.1	-65.5	-167.1	---	-1363.2
176	-880.6	328.5	276.4	-52.1	15.8	-65.6	-478.1	-251.5	-1132.1
177	-861.2	-122.1	-442.1	-320.0	43.7	-550.4	-201.0	-1149.9	-2011.1
178	-839.7	-399.3	-824.4	-425.2	-24.8	-258.4	-361.9	-1469.5	-2309.2
179	-884.6	-839.8	-1386.0	-546.2	-16.8	-198.6	-126.9	-1728.3	-2612.9
180	-1349.4	-521.3	-1180.2	-658.9	-133.2	-283.4	-132.8	-1729.5	-3078.9
181	-792.1	-611.4	-1370.6	-759.2	-52.0	-435.0	-139.1	-1996.8	-2788.9
182	-2050.9	-425.1	-1272.9	-847.8	-168.7	-478.0	-8.2	-1927.7	-3978.6
183	-2035.4	-665.1	-1343.0	-677.9	-271.3	-246.1	-166.0	-2026.4	-4061.8
184	-1006.2	-1131.7	-1986.7	-855.0	-246.5	-415.8	-19.8	-2668.8	-3675.0
185	-680.1	-1062.5	-1823.3	-760.8	-210.2	-387.9	-18.4	-2439.8	-3120.0
186	-600.6	-382.7	-1194.7	-811.9	-202.4	-426.1	-386.7	-2209.8	-2810.4
187	-429.4	-578.8	-1029.1	-450.3	-262.3	-204.3		-2416.2	-2845.6
188	-683.0	-321.9	-453.9	-132.0	30.6	-175.8	-149.6	-748.8	-1431.8
189	-905.4	-496.8	-559.6	-62.8	-63.0	-196.1	-126.2	-944.9	-1850.3
190	-929.4	-587.1	-739.4	-152.4	-95.1	-384.5	-107.7	-1326.8	-2256.2
191	-1169.1	-559.5	-849.9	-290.4	-34.1	-225.2	-174.1	-1283.2	-2452.3
192	-794.1	-474.8	-688.1	-213.3	-91.0	-212.4	-165.3	-1156.8	-1950.9
192	-794.1	-474.8	-688.1	-213.3	-91.0	-212.4	-165.3	-1156.8	-1950.9
192	-794.1	-474.8	-688.1	-213.3	-91.0	-212.4	-165.3	-1156.8	-1950.9
MEAN:	-338.3	-244.7	-300.6	-225.7	+3.1	-116.0	-15.0	-427.2	-998.0

APPENDIX 4

Data Accuracy Assessment

The shoreline change maps (Appendix 1) graphically illustrate the historic changes (erosion and accretion) which have taken place along the western shore of Delaware Bay from 1845 to 1977. There are several gaps in the shoreline plot lines due to data unreliability or unavailability. The largest gap occurred in the 1842 data due to excessive stretch along both axes of T151 (2.5%). This sheet was eliminated so there are no reliable data available for the southern half of the study area for this year and, therefore, no line has been plotted from the approximate location of the Mispillion River jetties southward. In addition, a small segment of the available 1842 shoreline data was deleted due to a tear in the original "T" sheet (see map 38, Appendix 1). No 1910 data were plotted for the same approximate southern half of the study area as the unusable 1842 data. This was due to the unavailability of data for that area within that time frame. A segment of shoreline was deleted from the 1883 plot due to tears in the edge of the original "T" sheet (T1547B) which resulted in an unacceptable degree of error in that small area (see map 15). Sheet TP00063 (1970) was also rejected in its entirety due to excessive stretch, resulting in no plot line for that year group along the easternmost 1.2 miles of shoreline.

The largest air photo data gap is apparent in the 1954 plot. This is the result of the removal of aerial photograph ANH-4N-119 due to an excessive eastward displacement beyond the ability of the resection program to reliably correct (maps 12-14, Appendix 1). A smaller gap in the same 1954 plot is the result of the removal of a small line segment from near the edge of the frame due to excessive distortion (see maps 21-21).

Several apparent displacements will be noted along certain year group shoreline plots (e.g., 1940's year group; Figure 36). These displacements are due to adjacent maps within the year group being one or more years apart. Since dramatic changes can occur from one year to the next, no attempt was made to tie them together.

The most dramatic evidence of landward displacement of the shoreline was in the northernmost area of study. At first inspection, the 1842 plot on maps 52-58 appear to be anomalously displaced eastward of the other shorelines. Therefore, the inferred erosion rate from 1842 to 1883 appears disproportionately high as compared to subsequent years.

The map of 1842 was checked against polyconic tables, and no significant media distortion (<1%) was found to have taken place. In addition, the resection and transformation programs produced no inherent errors

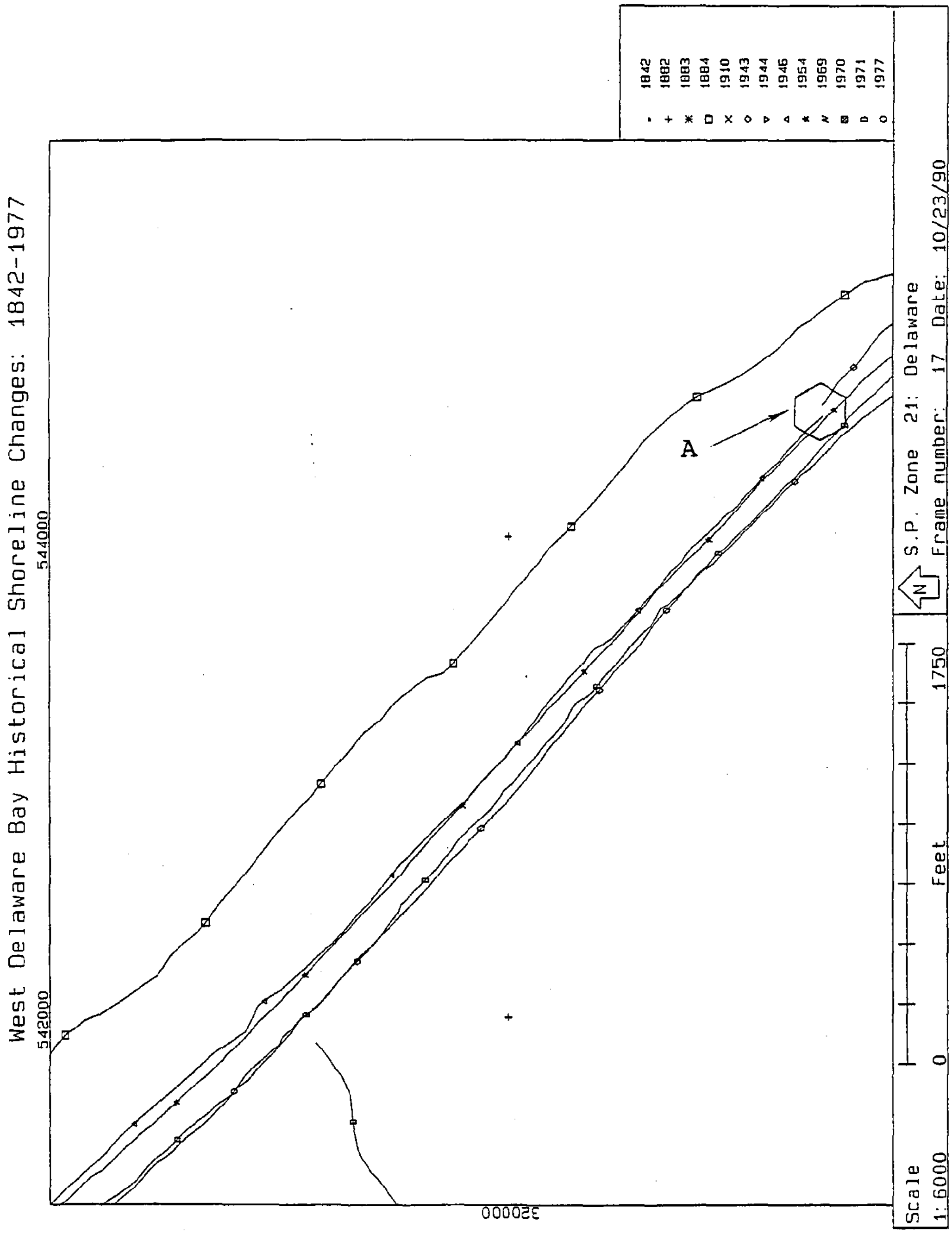


Figure 36. Map frame 17 showing the sequential year displacement (A) in the 1940's group shoreline plot.

in the map sheet itself. The coordinate system of T150 (1842) was updated to 1927 NAD using the LEFTI program. The resection was verified using four triangulation stations. This resection and transformation produced a total error of 14.8 feet which is well within the maximum acceptable error of 20 feet for a 1:20,000 scale map. Therefore, the 1842 data is as good as any other set and remains included in the study.

Numerical rates of shoreline changes were calculated using the TRANSECT sub-routine of the Metric Mapping process. Careful analysis of the tabulated results revealed that six of the transects provided spurious, or partially spurious, data. The extreme accretion which appears to have occurred along transects #87-89 (map frame 25) is incorrect because the computer calculated the distance between the intersection of those transect lines with the north jetty of the Mispillion River Inlet, rather than the actual shoreline. Therefore, all figures associated with those three transects are to be disregarded. However, the relatively high accretion which occurred along the adjacent transect line #90 (net +849 feet, 1882g-1977) is legitimate and is believed to be due to the effects of the jetties.

A similar situation occurred along transect line #28 (map 9) in that the line intersects the tip of the north Broadkill inlet jetty on the 1969g shoreline.

However, in this case, the only invalid figures are those which compare the 1969g data with other years along that line. This, therefore, invalidates only the 1969g-1977 -6.4 foot net change and -1.1 rate of change figures for transect line #28.

All data from transect line #140 (map 40) are invalid because the line first crosses the Bay shoreline, then passes up the Murderkill River before intersecting the up-river shoreline. Finally, on transect line #143 (map 41), the 1882g-1910 -682.3 foot net change and -25.3 foot rate of change figures are invalid for a similar reason.

These are problems which can arise with virtually any data set due to the techniques employed by the computer. When instructed to project transect lines at a given interval, the computer does so without regard for the specific point where that line may cross the shorelines. If it happens that a particular line is coincident with, for example, an inlet, then change rates will reflect a calculated value between where the line first encountered a user-chosen plotted line and where it encounters the next user-chosen line. This may result in the first encounter being with the tip of the jetty and the second with the shoreline some distance up-river. Thus, careful examination and quality control of the data are necessary so that the analyst can recognize and discount such values if appropriate.