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GEOLOGICAL, GEOMORPHOLOGICAL, AND GEOTECHNICAL ASPECTS OF THE MARCHAND LEVEE FAILURE, MARCHAND, LOUISIANA

by

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13. ABSTRACT *(Maximum 200 words)*

This report examines the factors leading to and the mechanisms involved in the levee failure at Marchand, Louisiana. The report addresses the (a) geology within the pertinent river reach, (b) Holocene chronology of the study area and historic meander of the river, (c) characteristics of the channel geometry in the study reach, and (d) mechanisms of the failure.

The failure reach exhibits a clay topstratum about 90 ft in thickness underlain by fine sands. The river incises into the sand to a depth well below the base of the clay topstratum. A three-stage failure mechanism is suggested. The first stage was a retrogressive mechanism in the deep sands which undercut the cohesive overburden. The second stage of failure involved intermittent loss of riverward pieces of the overburden by shear failure, perhaps occurring over considerable time. Following sufficient loss of neutral block shear strength along the critical failure surface, the final failure stage was a massive wedge-type failure along the clay topstratum/sand substratum interface with the levee embankment as part of the active wedge.

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PREFACE

This document represents a task associated with the US Army Engineer Division, Lower Mississippi Valley (LMVD) study, "Evaluation of Potentially Unstable Riverbank Sites Below Baton Rouge, Louisiana, and Selection of Measures to Prevent Failure." The work has been under the immediate purview of Mr. Frank J. Weaver, Chief, LMVD Geology, Soils and Materials Branch. The Principal Investigator conducting the study is Dr. Victor H. Torrey III, Soil Mechanics Branch, Soil and Rock Mechanics Division (S&RMD), Geotechnical Laboratory (GL), US Army Engineer Waterways Experiment Station (WES).

This report was prepared by Mr. Joseph B. Dunbar, Geologic Environments Analysis Section, Engineering Geology Branch, Earthquake Engineering and Geosciences Division (EE&GD), GL, WES, and Dr. V. H. Torrey III. Personnel assisting in this study included Messrs. Bennie Washington, John May (retired), and Tom Harmon all of EE&GD. Mrs. Joyce Walker of the Visual Production Center, Information Technology Laboratory, WES, edited the report.

The technical suggestions and contributions as well as the unfailing support and interest of the key personnel of the Geotechnical and Materials, Water Control, and Project Management Branches, LMVD have been appreciated and instrumental in success of the work. Special thanks should be given to Mr. Jay Joseph of the US Army Engineer District, New Orleans, who has always willingly contributed to the work in any manner he could despite the impositional nature of special requests for assistance and information.

The work was performed under the general supervision of Mr. Clifford L. McAnear, former Chief, Soil Mechanics Division, GL, and Dr. Don C. Banks, Chief, S&RMD, Dr. Arley G. Franklin, Chief EE&GD, and Dr. William F. Marcuson III, Chief, GL.

COL Larry B. Fulton, EN, is Commander and Director of WES. Dr. Robert W. Whalin is Technical Director.

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.8564	square metres
cubic feet	0.02831685	cubic metres
feet	0.3048	metres
inches	2.54	centimetres
miles (US statute)	1.60934	kilometres
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.880267	pascals
pounds-mass	0.4535924	kilograms
pounds-mass per cubic foot	16.01846	kilograms per cubic metre
square feet	0.09290304	square metres

GEOLOGICAL, GEOMORPHOLOGICAL, AND GEOTECHNICAL ASPECTS OF THE MARCHAND LEVEE FAILURE, MARCHAND, LOUISIANA

PART I: INTRODUCTION

Background

1. On 23 August 1983, a major failure occurred in the east bank (left descending) of the Mississippi River between river miles 180.2 and 181.1 in the Pontchartrain Levee District and approximately 6 miles* upstream of Donaldsonville, Louisiana. The slide involved some 700 ft of the mainline levee embankment whose riverward toe was located about 150 ft from the top of the river bank along the failure reach. Because the levee failure location corresponded to the articulated concrete bank revetment reach known as the Marchand Revetment, it was dubbed the Marchand levee failure. Since the slide occurred during the low water season of the river, there was no eminent threat of flooding. Levee setback operations were undertaken by the US Army Engineer District, New Orleans, which involved the construction of 5,400 ft of new levee, relocation of adjacent Louisiana State Highway 75 for about 7,500 ft at the landside toe of the new levee, and placement of over 2 million square feet of new articulated concrete revetment within the setback limits to replace the lost mattress and reinforce the remaining revetment. An examination of past records from the Marchand area has shown that river attack on the bank has been historically severe as evidenced by the fact that the levee alignment at the time of failure was the result of previous setbacks which were the US Gem Setback of 1908 and the Willow Grove Emergency Loop of 1929.

2. The Marchand failure represents an enlargement of the scope of the on-going major effort by the US Army Engineer Division, Lower Mississippi Valley (LMVD), directed at understanding the mechanisms of and preventing retrogressive failures in sand deposits of the Mississippi River from Baton Rouge, Louisiana, at about river mile 230 above head of passes (AHP), downstream to Head of Passes at river mile zero. This particular type of bank failure has been traditionally referred to as a "flow slide" and has been

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* A table of factors for converting non-SI to SI (metric) units of measurement is presented on page 4.

empirically associated exclusively with point bar deposits consisting of relatively thin cohesive overburden overlying thicker fine sand strata. Such failures have threatened the integrity of the mainline levee below Baton Rouge at several locations necessitating emergency setbacks and have actually resulted in levee failure at Wilkinson Point (opposite Baton Rouge) in 1949 and at Celotex (opposite Audubon Park, New Orleans, Louisiana) in 1985. The current findings of the major LMVD investigations of these retrogressive failures are presented in the reports by Torrey, Dunbar, and Peterson (1988) and Torrey (1988). However, the Marchand failure did not occur in a point bar deposit but, instead, was apparently wholly contained within surficial natural levee and underlying thick cohesive backswamp deposits. The key to its significance in studies of retrogressive failure in sands lies in the fact that the thick backswamp clays overlie substratum sands which are exposed to the river's attack. In studies of historic river migration, Torrey (1988) showed that the river has very successfully altered its alignment along banks in very thick, cohesive and erosion resistant deposits if its thalweg depth significantly exposed underlying sand substrata. So arises the concept that the Marchand failure, although itself a different mechanism of classic nature in clays, was the more surficial finale of a continuing bank caving process which began deep in the river's scour pool in the substratum sands.

Purpose and Scope

3. The purpose of this engineering-geological study is to examine the factors leading to and the mechanisms involved in the levee failure at Marchand, Louisiana. Consequently, this report will address (a) the surface and subsurface geology within the pertinent river reach, (b) the general Holocene chronology of the study area and the historic movement of the river, (c) the general characteristics of the channel geometry in the study reach, and (d) the mechanism of the failure itself.

Study Area

4. In addition to the Marchand reach, two river bendways known as Smoke Bend and Aben, immediately upstream and downstream, respectively, of

Donaldsonville have also required considerable revetment maintenance activities. Therefore, it is considered appropriate and advantageous to include a total reach of river in the studies which will provide a broader sense of river behavior through the failure reach than can be obtained by only examining a relatively limited area containing the failure location. The study reach selected is shown in Figure 1 and ranges from White Hall, Louisiana, at about Mississippi River mile 166.0 AHP to Carville, Louisiana, at about river mile 189.0 AHP. This 23 mile river stretch includes the New River Bend (left bank), Philadelphia Point (right bank), Marchand (left bank), Smoke Bend (right bank), St. Elmo (left bank), Aben (right bank), and Burnside (left bank) revetments. The study area is depicted on portions of the Carville, Gonzales, Donaldsonville, and Belle Rose 1:24000, 7-1/2 min, USGS topographic quadrangle maps. Included are portions of Ascension, Assumption, Iberville, and St. James Parishes. The largest community within the area is Donaldsonville.

PART II: GEOLOGY

Physiography

5. The study area is located in the extreme southern portion of the lower Mississippi Valley and is a part of the Gulf Coastal Plain. The most prominent physiographic features in this area are the broad natural levees associated with the Mississippi River and Bayou Lafourche. Bayou Lafourche originates at Donaldsonville and traces an ancient Mississippi River course southward. The surface topography is generally of low relief with surface elevations ranging from approximately 40 ft* along the natural levee crests to 5 ft several miles away from the river in the southeastern and southwestern portions of the study area.

6. The Mississippi River within the study area ranges in width from 1,700 to 3,400 ft. Its thalweg through the reach ranges from about elevation -50 ft to about -170 ft which corresponds to a range in bankfull depths of about 75 to 195 ft. The depth profile is typical and is characterized by deep "permanent" scour pools in the bendways which are linked by shallower crossings. The revetments at New River Bend, Marchand, Smoke Bend, St. Elmo, Aben, and Burnside (see Figure 1) reflect the river's attack upon its banks at the locations of the deeper scour pools. The meander pattern of the river is somewhat anomalous through the study reach (see Figure 1) in that the channel makes a strong eastward turn (see Figure 2) out of its north-northwest to south-southeast flow direction. The river continues in a roughly due eastward direction for about 35 miles to New Orleans, Louisiana (mile 100 AHP). Just east of New Orleans, between Gouldsboro and English Turn bends, it again redirects itself to the southeast. Interestingly, the meander configuration from Gouldsboro Bend to English Turn Bend is similar to that of the study reach except for being a mirror image and larger in scale.

Geologic Setting and History

7. To understand the geology of the area it is first necessary to briefly review the geologic history of coastal Louisiana during the late

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* Elevations are in feet referred to the National Geodetic Vertical Datum (NGVD).

Pleistocene age (100,000 to 10,000 years ago) and Holocene age (10,000 years to present). The Holocene chronology of the Deltaic Plain (synonymous with Gulf Coastal Plain) is based upon an analysis of several thousand detailed engineering and geologic borings that have been drilled during the past fifty years and from hundreds of radiocarbon dating determinations. Information obtained from these borings identifies a diverse subsurface that is related to the different periods of Mississippi River and deltaic deposition during the Holocene age.

8. The history of coastal Louisiana began approximately 18,000 to 20,000 years before the present during the late Pleistocene age. The land surface at this time was very different from what it is today. Glaciers covered much of the North American continent, and sea level was at a lower level than at present. Radiocarbon dating of primarily marine fossil organisms from deep borings indicates that sea level was approximately 300 ft below the present level 15,000 to 20,000 years ago (Flint 1971). Consequently, the gulf shoreline was further seaward than at present.

9. The ancestral Mississippi River and its tributaries were entrenched into the Pleistocene surface. This surface was deposited during the previous interglacial cycle, the Sangamonian period, which lasted from approximately 70,000 to 125,000 years before the present. The upper Pleistocene surface is a combination fluvial and deltaic deposit which Fisk (1944) called the Prairie Formation. The ancestral Mississippi River had scoured a broad drainage valley into this surface, measuring approximately 10 to 25 miles in width (Kolb and VanLopik 1958). The ancestral river valley extended in a general southeasterly direction beneath the present deltaic plain as defined by boring information. The approximate axis of the valley entrenchment occurs near Houma, Louisiana. The western valley wall of the entrenchment at this general latitude is located near St. Martinville, and the eastern valley wall is located at Donaldsonville, Louisiana (May et al. 1984).

10. Sea level began rising approximately 17,000 to 20,000 years ago because of glacial melting. It began stabilizing approximately 12,000 years ago at the close of the Pleistocene with sea level approximately 200 ft below its present level (Fairbridge 1968). The time interval between sea level rise and the beginning of the Holocene corresponds to a period of massive deposition of sediments in the ancestral drainage valley of the Mississippi River.

Coarse grained sediments (sand and gravel) were deposited in the valley as large quantities of sediment were released by the melting glaciers. These sediments overloaded the ancient drainage system and reduced it to a network of numerous, shallow and swiftly flowing, braided stream courses.

11. Beginning approximately 10,000 to 12,000 years ago, the ancestral Mississippi River changed from a braided to a meandering system (Saucier 1969, 1974). The change brought with it a change in the type of Mississippi River floodplain deposits, from mainly coarse grained to predominantly fine-grained sediments.

12. Sea level eventually reached its present level approximately 4,000 to 6,000 years ago. The advent of the modern sea level marks the beginning of the present land surface and the creation of the Deltaic Plain. The present land surface is the product of numerous but generally short lived, seaward prograding delta systems. Five major deltaic lobes or systems have been built seaward during the past 6,000 to 8,000 years, as shown by Figure 2 (after Saucier 1974).

13. The earliest delta lobe, the Maringouin, was along the western valley margin approximately coincident with the present course of Bayou Teche. This delta was active when sea level was at a lower base level. Subsidence and later deposition by younger delta systems have covered any surface expression of this early delta. The Teche delta complex soon followed and was active approximately 5,800 years before the present (Smith, Dunbar, and Britsch 1986). The Teche system extended in a southeasterly direction from the western valley margin towards Houma, Louisiana. The Teche system was abandoned approximately 3,500 years ago for the St. Bernard delta system. This delta built seaward from the eastern valley margin near Donaldsonville and extended due east. The Lafourche delta followed and was active approximately 2,000 years ago. Abandonment of the Lafourche course for the Modern system occurred approximately 500 years ago. However, the Lafourche course continued to receive partial flow until 1904 when this former Mississippi River channel was closed by construction of the mainline levee at Donaldsonville.

14. The study area has received sedimentation from three delta systems. The first advance of a major system into the area under study occurred with the St. Bernard system. The Mississippi River was roughly within its current channel alignment between Carville and Donaldsonville through the duration of

the St. Bernard system. During the active Lafourche system, the major channel flow turned southward at Donaldsonville through what is now called Bayou Lafourche. The primary Mississippi River flow returned to the modern course after abandonment of the Lafourche system, approximately 500 years ago.

Geologic Structure

Darrow Salt Dome

15. Located within the study area is the Darrow or Belle Hellene Salt Dome. The dome is centered beneath the Marchand failure site. A contour map of the dome is presented in Figure 3 (from New Orleans Geological Society 1963). The top of the dome is approximately 4,600 ft below ground surface. The dome is generally circular in plan shape and extends radially for several miles. The vertical relief on the dome is approximately 1 mile.

16. The Darrow Salt Dome is an intrusive or piercement type dome. It was first discovered in 1927 by the first reflection seismic work done in Louisiana. The first oil production from the dome began in 1929 and reached its peak by the late 50's and early 60's. In recent times, oil production has declined, but brine recovery or solution mining has become an important chemical industry in the study area.

Pleistocene and Holocene faulting

17. The relationship between intrusion of the salt dome, uplift, and faulting in the overlying stratigraphy is not well documented. There is no doubt that faulting must be significant near the cap. However, at ground surface, measurable relief or visible displacement caused by the Darrow dome is not evident on topographic maps or from aerial photography. Recent Mississippi River deposition has covered much of the Pleistocene deposits where evidence of faulting could probably be defined. Faulting is not evident in the Holocene age deposits because these sediments are unconsolidated (in geologic terms) and are highly variable.

18. Halbouty (1967) indicates that the oldest formations affected by the dome are of Miocene age (10-25 million years ago). Howe (1938) suggests with considerable uncertainty that there is the possibility of faulting within the upper Pleistocene age sediments at depths between 300 and 1,000 ft below the ground surface. He saw the implications in correlations of near-surface gravel horizons across the Darrow Salt Dome derived from numerous petroleum

borings which exhibited lack of detail and inconsistencies (see Figure 3 for boring locations).

19. Sufficient boring information is not available to determine detailed Pleistocene stratigraphy to correlate for the presence of faults over the salt dome. Nothing is actually known about shallow faulting which may relate to the Darrow Salt Dome. Waterborne geophysical techniques conducted through the study reach during this investigation did not successfully penetrate into the Pleistocene age sediments and, thus, provided no insight regarding the presence of faulting.

20. There is no evidence that any vertical movements are associated with the presence of the dome or due to fluid extraction on the dome by the petroleum and chemical industries which caused or contributed to the levee failure at the Marchand site. If vertical movements have been occurring over the dome in the last 100 years, they should have been detected by elevation changes in recent topographic data.

Geology and Environments of Deposition

Surface geology

21. The first objective of this investigation was to define and map the surface geology of the study area. Definition of the geology was accomplished by examination and interpretation of various vintages of aerial photography, subsurface data consisting of engineering borings and electrical logs, various ages of hydrographic surveys, historic maps, and a review of the available geologic literature. In addition, waterborne geophysical surveys were conducted at Marchand, Smoke Bend, and Aben. The surface geology of the area is presented in Figure 4. It is based on the data described above and work by Kolb (1962) and Saucier (1969).

22. The geology of the study area is directly related to present and past courses of the Mississippi River. The surface geology consists of unconsolidated Pleistocene and Holocene age deposits. The Pleistocene age deposits rise to the surface northeast of the Marchand failure site at a distance of about 2 miles (Figure 4) and north-northeastward of Donaldsonville at a distance of about 3 miles. Holocene age deposits occur at the surface at the Marchand failure site and west of the river.

23. The Holocene deposits or environments of deposition include natural levee, point bar, backswamp, and an abandoned Mississippi River course. The abandoned course is now Bayou Lafourche, the Mississippi River course that was active between 2,000 and 500 years ago. Natural levee, point bar, and backswamp deposits occur with both the present and the former Mississippi River course.

24. The surface geology of the Marchand failure area, Smoke Bend, and Aben is composed of backswamp deposits. Detailed descriptions of the geologic environments that are present in the study area are contained in Appendix A. The description of each environment includes how it formed and associated major soil types.

Subsurface geology

25. Six detailed geologic cross-sections were constructed from borings and geophysical logs collected during this study. The locations of the cross-sections are shown in Figure 4. Sections A through F are presented in Figures 5a through 5f, respectively (see Figure 5g for legend). Sections were constructed such that Marchand, Smoke Bend, and Aben each have a section that is parallel to and perpendicular to the bank. Included in the geologic cross-sections are the Unified Soil Classification System (USCS) soil types. Those borings not using the USCS are shown with the textural soil type identified.

26. The geologic sections define the vertical distribution for each of the various depositional environments as well as characterize their primary soil types. The topstratum is composed of fine-grained soils representing the combined thicknesses of natural levee and backswamp deposits. At Marchand the topstratum is between 120 to 130 ft thick (see Figures 5a and 5d), at Smoke Bend it is between 130 to 140 ft thick (see Figure 5e), and at Aben it is about 120 ft thick (see Figure 5f).

27. Underlying the topstratum deposits are substratum deposits which extend to the Pleistocene surface below. The general characteristics of the substratum are described in detail in Appendix A. Substratum deposits are generally coarse grained, primarily composed of sand with traces of gravel. The substratum deposits at Marchand are over 100 ft thick, at Smoke Bend they are about 150 ft thick, and at Aben they are 40 to 60 ft thick.

28. The position of the Pleistocene surface shown in the cross-sections is based on the Pleistocene contour map of Figure 6. The contour map contains data points that are shown as a solid circle (boring drilled to Pleistocene)

or a triangle (deep boring not reaching Pleistocene but used as a control point). The Pleistocene surface in the study area dips to the southwest and south. The Pleistocene surface is 220 to 230 ft below the ground surface beneath the Marchand area. The Pleistocene surface at Smoke Bend is approximately 280 ft below ground surface and at Aben is 170 to 190 ft below ground surface. In the vicinity of the upstream end of the Burnside Revetment reach, the Pleistocene outcrops at surface and the river actually incises into those deposits. The Pleistocene deposits are generally characterized by a considerable increase in stiffness and shear strength as compared with the overlying Holocene sediments (see Appendix A). Therefore, these very erosion-resistant soils in the riverbank and riverbed represent an exceptionally "hard point" (as compared with very resistant backswamp clays) which restrains the river's migration in that direction. The thick backswamp clays at Smoke Bend extend below the thalweg and exert a significant influence on the meander pattern through this river reach. It will be seen later in this report from historical erosion/deposition maps that the river channel along the Burnside reach has remained stationary in its position over the period of record which is about the last 93 years.

PART III: HISTORIC MISSISSIPPI RIVER MIGRATION

Bankline Migration

Introduction

29. Historic Mississippi River migration is examined in this section. Migration of the channel will be addressed in two ways. First, the entire study reach from about Carville to Whitehall, Louisiana, will be treated and then a subreach from Marchand to Smoke Bend to Aben which has seen the greatest channel movement within the total study reach will be treated separately. Hydrographic surveys from six different time periods were compared. The surveys compared were those conducted along the study reach within the period 1880 to 1894 (Mississippi River Commission 1877-1880), 1921 (Mississippi River Commission 1921), 1937 (US Army Engineer District, New Orleans 1938), 1951 (US Army Engineer District, New Orleans 1952), 1961 (US Army Engineer District, New Orleans 1965) and 1974 (US Army Engineer District, New Orleans 1976). While the hydrographic surveys after 1921 spanned a two to three year period (i.e., period required for survey completion from above Baton Rouge, Louisiana, to Head of Passes), the survey years cited above are the years within those two to three year periods in which the study reach was actually surveyed. Overlays containing bankline configurations were prepared for each of the hydrographic survey periods and the overlays then were registered to a common datum (North American Datum) at a scale of 1:20,000. Areal changes, i.e., area of deposition or erosion, were calculated using a computerized planimeter program. Hydrographic survey comparisons were made with both the 1974 and 1880-1894 surveys as the base, as well as making comparisons between succeeding surveys.

30. Hydrographic survey data from 1983-1985 (US Army Engineer District, New Orleans 1988) has recently become available. They were not included in the general analyses presented in this report because cursory examination of those sections revealed no major changes from the 1973-1975 survey and because their inclusion would have significantly delayed completion of this report. However, 1983-1985 survey data have been selectively included in the illustrations and discussions concerning specific survey reaches.

31. Characteristics of the hydrographic survey data used in this study are presented in Table 1 which includes survey year, reference datum, actual

water surface elevation at Donaldsonville, and the map datum for the survey period. Some error is inherent in the survey comparisons presented in this report since the 1880-1894 survey represents a compendium of individual range surveys which spanned the 14-year period. That is to say that, although all ranges are shown on one chart together and are the best data available, one range may have been surveyed in 1880; whereas another in the study reach was surveyed in 1894.

32. Other possible sources of error that need to be identified are those dealing with the elevation of the water surface at Donaldsonville. The elevation of this surface is the basis for the bankline comparisons. Bankline surveys from 1880-1894 and 1921 are based on the 1877 US Coast Land Survey and are independent of river soundings or depths shown on the hydrographs for those periods. It was assumed, although not stated on the early bankline surveys, that the banklines are referenced to a low water datum since those surveys were made during the winter months. In any event, the contours from the hydrographic surveys generally confirm that the 1877 banklines were acceptably correct for use in the comparative studies.

33. Low water datum for all the surveys compared are also identified in Table 1. Water surface elevations for surveys prior to 1937 are based on Mean Gulf Level and are calibrated to the Donaldsonville staff gage at the time the survey was conducted. The actual water surface elevation at Donaldsonville on the days the 1880-1894 and 1921 surveys were conducted has been referenced to a common datum. Banklines derived from hydrographic surveys after 1921 are referenced to either the Mean Low Water, Average Low Water Plane, or Low Water Reference Plane which are the same between survey periods (see Table 1). However, the bankline comparisons are based on a water surface elevation which varies only from el 0 to el 4.18. Channel width variations associated with such a small vertical interval tend to be negligible in the apparent absence of any major flat, shallow bars along the reach during any of the survey periods.

Historic migration, entire study reach

34. Mississippi River migration for the entire study reach, i.e., from about Whitehall to Carville, Louisiana, is compared with the 1974 survey for the times identified in Figures 7a through 7e. The general trend has been a steady migration of the river to the north at New River Bend (see Figure 1, area map), to the southeast at Marchand, to the south-southwest at Smoke Bend,

to the north at St. Elmo, and to the southeast at Aben. The Burnside reach around Houma Point has seen practically no movement of the channel over the period of record.

Historic migration Marchand, Smoke Bend and Aben subreach

35. Although Figures 7a through 7e show the changes throughout the 23 mile study reach, more detailed hydrographic survey comparisons given in Table 2 were made for the Marchand, Smoke Bend, and Aben subreach which is approximately 12.5 river miles in length (river mile 170 to 182.5). Comparisons were made using both the 1974 and 1880-1894 surveys as the base in addition to comparisons between succeeding survey periods. The comparisons are expressed in acres. The results for each of these sites are compared with the total measured subreach changes. A ratio factor was calculated at each location and represents the major process as compared with the minor process. A positive ratio indicates deposition was dominant for the specified period; whereas a negative ratio indicates that erosion was dominant. Values for Marchand, Smoke Bend, and Aben are site specific. They are for those particular bends only.

36. The comparisons for the Marchand to Aben subreach indicate channel migration is not in equilibrium (i.e., deposition does not equal erosion). The dominant process for the 1974 based comparison, ranges from -1.7 to 1.4. For the 1880-1894 based comparisons the range is from 1.4 to 2.0. Overall, the dominant process has been deposition which has exceeded erosion by a multiple of 1.4. The comparisons between succeeding surveys indicate constant land gain until 1937 followed by erosion after 1937 with a net depositional effect over the entire period of record.

37. <u>Marchand.</u> The river stretch containing the Marchand site constitutes the major land loss and gain for the Marchand to Aben survey reach. Approximately 50 to 60 percent of land loss (left bank at Marchand) and land gain (right bank at Marchand) in the reach has occurred there. The major bank losses at Marchand extend well downstream of the revetted bank into the point bar deposits of Eighty-One Mile Point despite the fact that the deep Marchand scour pool does not. The observed trend, i.e., bank loss rates versus accretion rate (opposite Smoke Bend revetment) since 1880-1894, indicates that the river has been attempting to cut off Eighty-One-Mile Point. Continuance of this trend is very undesirable since river attack upon the opposite bank will

shift downstream toward Donaldsonville. The LMV Master Plan (for channel stabilization) recognizes the situation and includes future revetment to maintain the present channel alignment. Deposition on the right bank in the Marchand bendway is the major fluvial process as determined using both the 1880-1894 and 1974 based survey comparisons, exceeding erosion by a factor between 1.3 to 1.8. Comparisons between succeeding surveys identify erosion as the dominant fluvial process from 1937 to 1951 and from 1961 to 1974. An examination of land gain (acres) since 1937 defines a nearly constant rate (60 to 70 acres per 10 to 14 years). In contrast, land loss (acres) was more variable with a negligible amount occurring during 1951 to 1961.

38. The most significant observation relative to the Marchand site is the amount of southeastward movement of the channel over the period of record. Figure 7e shows that movement to have been almost 2,000 ft toward the Marchand failure site. The severity of historic river attack is apparent and the occurrence of the major bank failure in 1983 tends to confirm its continuation. It must also be observed from Figures 1 and 7e that the bank reaches corresponding to the New River Bend and St. Elmo revetments have also seen considerable bank losses over the period of record. The continuing attack along these banks is apparent and has resulted in the recent (within the last 20 years) placement of the revetment protection. Some sections of the mainline levee have very little protective batture along New River Bend and St. Elmo so that it will be necessary to include these reaches along with Smoke Bend and Aben in assessing the risk of additional Marchand-type failures after discussions of the hypothesized Marchand failure mechanism.

39. Smoke Bend. The contribution that Smoke Bend provides to land loss and gain for the Marchand to Aben reach is approximately 15 percent. Overall, deposition on the left bank has been the dominant process. However erosion of the right bank was the major process between 1937 and 1961. Movement of the river channel to the south over the period of record has resulted in an average loss of less than 500 ft of batture transverse to the direction of flow. The reasons for the reduced bank loss at Smoke Bend as compared with Marchand will be discussed later.

40. Aben. Aben contributes approximately 15 percent land loss and gain to the survey sub-reach. Deposition on the left bank at Aben was the major process for both the 1880-1894 and the 1973-1975 based survey comparisons and exceeded erosion by a factor of 1.2 to 1.6. Bank losses transverse to stream

flow over the period of record have amounted to about 1,000 ft with the channel migration in a due east direction.

41. Summary. Deposition as defined by surface measurements has been the major fluvial process. This is in keeping with findings by Torrey (1988) that, from Baton Rouge (mile 230 AHP) to Bonnet Carre Spillway (about mile 120 AHP), the low water widths shown in the 1973-1975 survey are narrower than those shown on the 1880-1894 survey, while thalweg depths are shallower (see Figures 8 and 9).

Marchand Scour Pool Historic Migration

42. Apparent Marchand scour pool migration for the different survey periods is shown in Figure 10 (including the 1983 data). The low water banklines for the 1880-1894, 1973-1975 and 1983-1985 surveys are included in Figure 10. The scour pool outline corresponds to the el -120-ft contour. This contour was selected because it was consistently present as a scour pool delineator between survey periods and encompassed a large enough area to characterize the failure reach. Scour pool dimensions can be significantly affected by the discharge at the time of survey. Therefore, each pool outline shown in Figure 10 is a "snapshot" in time. Conclusions drawn regarding trends with time are then subject to some uncertainty and should be taken in that light. The Marchand scour pool during the period of record has apparently steadily moved in a southeasterly direction. Pool width decreased from approximately 1,000 ft at the widest point in the 1880-1894 survey to approximately 800 ft in the 1973-1975 survey, but shows an increase in maximum width to about 1,000 ft in the 1983-1985 survey.

43. Profiles of the Marchand pool contrasting pool length and maximum depth for the various time periods are shown in Figure 11. Note that in Figure 11, the length of the scour pool is not associated with the el -120-ft contour. For comparative purposes, the profiles were constructed so that the upstream end of each survey period's scour pool was at the origin. The vertical scale exaggeration in Figure 11 is 100 times. The distance scale of Figure 11 does not represent a straight-lined distance but rather the cumulative distance connecting the deepest points recorded on each range line survey. This thalweg point-to-thalweg point method shouldn't have introduced significant length errors. In order to show lengths (Figure 11) which

correspond to widths (Figure 10) on the same basis, it is necessary to pick off pool lengths corresponding to the el -120-ft contour. On that basis, scour pool length has apparently steadily declined from a maximum of approximately 9,500 ft in the 1880-1894 survey to approximately 4,000 ft in the 1983-1985 survey. The pool was deepest during the period of record in 1880-1894 with a maximum depth at approximately el -180 ft (about 205 ft of water depth at bankfull). The depth decreased to approximately el -150 ft in the 1973-1975 survey and increased again to about el -165 ft in the 1983-1985 survey. The thalweg is seen to be at about el -150 ft (175 ft of water at bankfull) in the 1973-175 survey as compared with approximately el -160 ft (about 185 ft in depth at bankfull) in the 1983-1985 survey. Since the 1973-1975 survey the pool has continued to migrate southeastwardly, has decreased in length, but has widened and deepened.

PART IV: MISSISSIPPI RIVER CHANNEL MORPHOLOGY

Entire Study Reach

Procedure

44. Width to depth (W:D) ratios represent a simple and convenient method to describe and compare the channel shape or morphology. These ratios were calculated for the study reach from the 1880-1894 and the 1973-1975 hydrographic surveys. W:D ratios represent the width of the river divided by the maximum depth of the river at a given survey location (both based on low water reference plane or its equivalent). W:D ratios were calculated for each survey period for every second range line from Range 189.04 to Range 166.0 or approximately from Carville to White Hall.

45. Statistical sorting and classification were conducted on the W:D ratios for each hydrographic survey period. Statistical results for each survey were then compared with each other to identify basic channel characteristics and to define changes that have occurred between the two surveys.

Morphology

46. The W:D results are presented statistically as frequency histograms in Figures 12 and 13 for the comparisons between the 1880-1894 and 1973-1975 surveys. Figure 12 presents the data for the two surveys compiled into identical class intervals permitting direct comparison of the two distributions. Figure 13 presents the data such that the class intervals for each survey are equal to their respective standard deviations. Several observations are pertinent for the revetment reaches (see Figure 1) of New River Bend (Range 187.7 to 183.6), Philadelphia Point (Range 182.9 to 181.5), Marchand (Range 181.5 to 180.0), Smoke Bend (Range 178.2 to 175.4), St. Elmo (Range 175.4 to 173.0), Aben (Range 173.2 to 172.1), and Burnside (Range 171.3 to 167.9).

- *a*. There is only a slight increase in the mean value of W:D ratio for the 1973-1975 survey as compared with the 1880-1894 survey. However, the dispersion of the data has increased more significantly as evidenced by an increase in the range and standard deviation.
- *b*. The shape of the distribution (see Figure 12) has undergone a strong transformation from a more uniform appearance in the 1880-1894 survey to a more normal distribution, although skewed, shape in the 1973-1975 survey.
- *c*. From Figure 13 it is seen that Marchand and Aben which have seen the larger bank losses of record are within the second

standard deviation left from the sample mean, i.e., exhibit generally lower values of W:D for both survey periods. Smoke Bend and Burnside also reside in the comparatively lower domain of W:D values but, as will be discussed later, these bank reaches exhibit thick strata of very erosion-resistant soils and the river does not scour into the underlying sands. The mean value of W:D at New River Bend has shifted from its position to the right of the mean in the 1880-1894 survey to left of the mean in the 1973-1975. The mean value of W:D at St. Elmo has moved further to the right of the mean in the 1973-1975 survey. The St. Elmo reach seems to be entering a depositional trend after the 1973-1975 survey as will be further described later in this report.

d. The following changes are seen in average values of W:D for the individual revetment reaches identified below:

(1) New River Bend. Average W:D declined from about 34 in 1880-1894 to about 25 in 1973-1975.

(2) Philadelphia Point. Average W:D increased from about 42 in 1880-1894 to about 53 in 1973-1975.

(3) Marchand. Average W:D decreased from about 18 in 1880-1894 to about 15 in 1973-1975.

(4) Smoke Bend. Average W:D remained about the same at 25.

(5) St. Elmo. Average W:D increased from about 39 in 1880-1894 to about 47 in 1973-1975.

(6) Aben. Average W:D declined from about 19 in 1880-1894 to about 16 in 1973-1975.

(7) Burnside. Average W:D increased from about 20 in 1880-1894 to about 22 in 1973-1975.

47. In summary, as seen from Figures 8, 9, and 13 and Table 3, there have been some strong changes in channel geometry through the study reach over the period of record. The changes in W:D are such that increasing ratio usually corresponds to a channel which is wider and more shallow and decreasing ratio corresponds to a channel which is more narrow and deeper.

Morphology of the Marchand Reach

48. Since this report is specifically directed at the Marchand failure, hydrographic cross sections were constructed at six locations in that reach (see Figure 14) to examine its general characteristics. Ranges 182 and 181.3 are upstream 5,900 ft and 2,600 ft, respectively, from the failure location; range 180.7 lies within the failure location; range 180.4 is about 2,000 ft downstream; range 180.2 about 3,500 ft downstream; and range 179.6 about

6,500 ft downstream. Ranges 180.7 to 180.2 correspond to the Marchand scour pool location. A factor to be considered in the selection of cross-section locations was the relative correspondence of range positions among succeeding survey periods in order that they be located as near together as possible. The survey ranges from the oldest survey (1880-1894) matched relative locations with the 1973-1975 survey and intermittent surveys so that 1880-1894 survey cross sections are acceptable, but they are not exact comparisons. The individual cross sections are compared in two formats in Figures 15a through 15f and Figures 16a through 6c, respectively, beginning with the upstream cross section and extending downstream. Note that the 1983-1985 hydrographic survey data are included among these profiles. The cross sections in Figures 15 and 16 are presented looking in a downstream direction, so that the right bank is to the right of the plot. The origins of these cross sections are at the intersection of the low water reference plane (or equivalent) with the right (west) bank. The purpose of this format is to allow easy comparison of changes in channel configuration over the period of record. It is emphasized that Figures 15a through 15f do not indicate bank loss or deposition but only serve to compare the geometries of the channel over the period of record. Figures 16a through 16c show the cross sections on a relative horizontal scale which reveals the migration of the channel at each range. Each individual profile was constructed with its origin at the intersection of the low water reference plane or its equivalent beginning with the west (right descending) bank for the given survey period. The distance scale in Figures 16a through 16c is referenced to the 1880-1894 survey so that a positive distance infers the riverbank has moved eastward and a negative distance infers the bank has moved westward with respect to the position of the 1880-1894 banklines.

Channel Characteristics of the Marchand Reach

49. In the channel crossing between the New River Bend scour pool and the Marchand pool represented by Range 182.0 (Figure 15a), a general decrease in channel depth with little change in channel width over the period of record is clearly evident. Moving downstream through Ranges 181.3 (Figure 15b), 180.7 (Figure 15c), 180.4 (Figure 15d) and 180.2 (Figure 15d) the migration of the scour pool into the left bank and the consequent steepening of that bank

is seen. Figures 16a through 16c show that this trend also produced a steady loss of the left bank as the channel migrated eastward.

50. Channel cross-sectional areas beneath low water reference plane or its equivalent at each range were calculated. Assuming the survey data to be correct, the accuracy of those calculations is limited to the accuracy of measuring distances with a scale from the hydrographic plan sheets and the accuracy of estimating the position of a recorded elevation on the survey range. The practice employed was consistent and it is reasoned that perhaps errors were systematic such that implied trends have some merit. However, one could not reasonably argue that calculated changes in area of perhaps as much as 10,000 to 20,000 sq ft are significant. The results of those calculations are presented in Table 4 and plotted in Figure 17. It is seen from Figure 17 that all ranges indicate a decline in channel area from 1880-1894 until 1937. The period 1921 to 1937 stands out as a time of significant perturbation of the prevailing regime with most of the ranges seeing an accelerated decline in area. In correspondence with this period, it was previously mentioned that the levee alignment at the time of the 1983 Marchand failure was the result of the Willow Grove Emergency Loop setback of 1929. It may or may not be pertinent to this period of accelerated decline in channel area that major floods occurred in the years 1929 and 1937. It is also of interest that a major upriver meander loop cutoff program was begun in 1933. By 1940, 16 such cutoffs had been constructed, the most southerly of which was about 20 miles downriver of Natchez, Mississippi (about mile 363 AHP). It is documented that this cutoff program resulted in accelerated bank caving problems upriver and consequent passing of greater sediment volumes into the lower river. An attempt to establish the effects, if any, of the floods and the cutoffs on the area changes during the period 1921 to 1937 would be a major study in itself and beyond the scope of this work. From 1937 until 1962, all ranges indicate essentially stable conditions. Since 1962, it is suggested that the reach from range 180.7 (at the Marchand failure location) downstream to range 179.6 has been tending toward increasing area. Since the survey of 1961, the channel areas at ranges 180.7 and 180.2 have increased the most (by about 20 percent). From a soil mechanics point of view, the significance of the increase in the channel area lies in how it occurred. Figure 16b, showing ranges 180.7 and 180.4 nearest the Marchand failure location (range 180.7 lies within the failure limits), indicates that the area increase was not as much by deepening

of the channel as it was by steepening of the bank, particularly on the Marchand side. Figure 16c showing range 180.2, which is downstream of the failure and corresponding to the deepest portion of the scour pool, shows more significant deepening since 1961 and less significant steepening of the left bank. Channel areas for range 182.0 and 181.3 upstream of the Marchand failure site seem to be continuing in a slowly declining trend begun in 1937, although range 182.0 exhibited a distinct scour trench against the right bank in 1961 as compared with a more U-shaped channel in the earlier and later years.

51. As pointed out in previous reports relative to flow slides, this type of failure has been regularly observed in revetted banks and, often as not, within the limits of the mattress. The Marchand failure also occurred in a revetted bank. For want of proven better methods, previous practice for establishing the riverward limit of the articulated concrete mattress was to go at least to, and preferably beyond, the "toe" of the underwater bank slope. In some cases, high stages and swift currents during construction in a given year, resulted in it not being feasible to attain the design limit. If significant toe deepening after construction was detected by annual monitoring surveys, additional mattress was laid to reinforce the scoured area. This procedure was usually successful, but the exceptions were cause for concern. In recent years, two factors have combined to lead to an increasingly conservative engineering philosophy regarding riverward limits:

a. Increasing concern over the detrimental effects of toe scour, a concern which was accentuated as this study progressed and the mechanisms of failure became better understood.

b. The completion of new revetments at many of the remaining high priority locations, thus reducing the need to stretch available funds over as many locations as possible.

The current practice for establishing the riverward limit of the articulated concrete mattress for riverbanks below Baton Rouge is to use the most conservative of the following two approaches:

a. Assume that 20 ft of vertical scour will occur at the riverward end of the mat after placement and that retrogression in the underlying sand will occur back toward the bank on a 1V:5H slope in the sand strata. The riverward mat limit is then selected to ensure that this assumed retrogression will not reach up to the sand-overburden interface, but will instead "breakout" on the lower bank slope.

b. Assume that if the riverward end of the mat after 20 ft of vertical scour is at or above a line drawn downward on a 1V:4H slope from the intersection of the sand-overburden interface with the existing bank slope, then retrogression in the sand will not reach the sand-overburden interface. This is a preliminary empirical approach based on toe scour and bank movement shown by high water surveys of selected study reaches.

This approach accepts toe scour and retrogression in the sands as inevitable, but seeks to prevent subsequent shear failures of the upper bank. The practice usually results in the mat limit being well riverward of the thalweg. While the logic behind the above practice is very solid, its success dictates that several necessary conditions be met. Unfortunately, most of those necessary conditions either have not been proved conclusively to exist or there is evidence that they probably do not. The LMV is fully cognizant of the uncertainties. These conditions are:

a. The mat is not only placed such that it is a continuous blanket in every direction but its riverward extent is as planned. In the placement operation the mat is cut loose from the placement barge at its riverward extent and falls through deep, moving water to its resting place on the bottom.

b. A single layer of mattress must be strong enough to remain intact if it is significantly undercut in a relatively localized manner.

c. A single layer of mat is durable enough to remain intact and in place across deep scour pools even if there is no undercutting.

d. The critical point of protection is at the riverward end of the mat and sufficient sand to initiate retrogression is not removed through the openings of the mat at some point closer to the toe of the riverbank. Condition b. above is also pertinent in this case.

e. The riverbank slope is stable under all reasonably expectable conditions of loading in the first place.

f. The riverbank slope is not so steep and/or exhibits no surficial "muck" or very soft cohesive soils such that minor river attack may cause shifting/sliding of the mat so that it tears itself apart or develops nonconformities to the slope surface which permit eddies/current forces to breach it.

g. Other unknown conditions, such as actual maximum scour depth.

It is too early to determine whether the conservative methods described above will be fully effective. In the meantime, the possibility of even one exception to the generally successful performance of articulated concrete mattress is a cause for continued concern and study, since there are many levee locations where a single failure could threaten integrity of the levee system. Suspicion exists that a single mat layer may not be adequate, or that some form of extra weighing of the mat toe may be needed, or that some system of filter is needed under the mat within the sand, or that some other heavier form of scour pool/bank armor may be required, or so forth. The LMV is currently conducting very limited tests with double-laid mat and mat laid over filter cloth. The whole matter is greatly complicated by the lack of practical methods for confirming the actual presence of the relatively thin mat through deep, turbid water and/or under sediment, much less determining its subacqueous areal condition. It is also complicated by the lack of dependable methods for estimating maximum scour depths that will occur during the life of a revetment. The latter complication is not unique to the design of revetments on the Mississippi River, but is universally recognized as one of the major problems in design of flood control channels and bank stabilization work in general. Solving it just for the specialized case of maximum effectiveness and economy of revetment construction below Baton Rouge will require a major cooperative effort involving the disciplines of both mobile-bed hydraulics and geotechnics.

PART V: MARCHAND BANK FAILURE

General

52. Specific information on the Marchand failure and several statements made in the following paragraphs were taken directly from the New Orleans District unpublished routine internal report, "Mississippi River Levees, Item M-181.1 to 180.2-L, Marchand Levee Setback," Final Report, October 1984.

Before Failure Conditions

Survey implications

53. True-to-scale bank cross sections for two locations in the Marchand reach are shown in Figure 18. The cross sections present results of the revetment surveys made between 1971 and 1983. Included in Figure 18 are two surveys made just prior to and immediately after the 23 August 1983 failure (i.e., 12 August 1983 and 24 August 1983). The sections shown in the lower portion of Figure 18 pertain to the Marchand revetment range U-14 which was situated within the failure scar but about 200 ft downstream of the failure centerline. The sections shown in the upper portion of Figure 18 pertain to Marchand revetment range U-10 which was situated about 330 ft downstream of the downstream limit of the failed bank. These two sections compare the bank reach that failed against one that did not suffer mass instability. It is likely that the underwater configuration of the bank before the Marchand failure is indicated by the 12 August 1983 survey which was 11 days prior to surface manifestation of the slide and collapse of a portion of the levee. The 12 August section shows a relatively smooth bank slope at an average slope of about 1 on 3. However, earlier surveys suggest the regular presence of small and relatively shallow circular arc slip surfaces at various positions on the lower to upper bank. There are even some suggestions of slide debris immediately at the riverward end of some of these small arcs. The bank cross section of October 1973 may show the damage exacted by the exceptionally lengthy great Mississippi River flood during spring and early summer of that same year. A comparison of the October 1973 cross section with the 1971 cross section reveals an average downcutting of the lower bank by about 80 ft horizontally and some 40 ft vertically. Three shallow arcuate slip surfaces are

distinctly evident in the 1973 cross section from the upper bank and extending into the substratum sands. The survey of 1979 indicates a major bank failure at range U-14 which also apparently involved to a lesser degree range U-10 some 340 ft downstream. It cannot be said that this major failure occurred during 1978-79 because the routine revetment surveys between that of 1973 and 1979 were not readily available in a form suitable for inclusion in the New Orleans report on the Marchand setback. Considering the severity of the bank loss indicated by the October 1973 survey, particularly noting the loss of substratum sands (movement of the scour pool into the bank), it would seem logical that the bank movement seen in the 1979 survey occurred relatively shortly after the 1973 survey. The elevation of the batture (foreshore between top of the riverbank and toe of the levee) at range U-14 had dropped as much as 40 ft. Comparing the 1979 section with that of 1971, it appears that failure intersected the ground surface landward somewhere within 200 ft of the riverward levee toe. Obviously, this slide reduced the overall factor of safety against bank failure by reducing the shear strength along its failure surface to a remolded value. Subsequent to this occurrence there is no way to tell whether the clay slide debris remained in the scour pool or was removed and replaced with sand. The 1979 survey does show the filling of the pool as much as 30 ft over the 1973 cross section. It is true that, with rare exception, after-failure surveys of flow slides have shown no evidences of remains of clayey overburden pieces either within the failure scars or the scour trench or pool even though logically there would have been some intact masses of considerable size generated during failure.

River conditions

54. During the 1983 high water season which constituted a major flood period, the maximum river stage at Marchand was el 33.7. The design levee grade at this location is el 38.5. The ground surface landward of the levee was at about el 16 and the riverward batture was at about el 26 due to deposition. Therefore, during the maximum stage there existed about 8 ft of water depth over the batture and against the approximately 12 ft high riverward levee slope. At this same time the river stage at New orleans was at about el 17 which statistically represents a probability (since 1871) of being equaled or exceeded on any given day or during any given period of less than 10 percent. Bankfull or greater river stages had existed at Marchand since before the first of the year and continued through the month of June. From

31 May to 23 August, the river stage at Marchand fell 29 ft to el 4.6. This was the most rapid fall from a great flood ever recorded (since 1871). In addition to these river conditions, heavy rainfall occurred during the months of July and August. In light of these environmental factors, it is reasonable to assume that at the time of the failure the backswamp clays of the riverbank were essentially saturated. Since water had also been on the levee and heavy rainfalls had occurred in the two months immediately before the failure, it is also likely that the levee too was near a saturated state.

After Failure Conditions

Surveys

55. Underwater bank surveys were taken on 24 August 1983, 1 day after the bank movements at Marchand were first reported to the New Orleans District. These cross sections are also shown in Figure 18. The limits of the failure were determined to be levee sta 2501+00 (upstream) to sta 2508+00 (downstream) which correspond to Marchand revetment ranges U-20 to U-13. The major batture movement appears to have been centered near levee sta 2505+00. In plan view, the failure exhibited the typical U-shape of a shear type failure (as opposed to flow-type failure) after the terminology used in the old LMVD Potamology Report series titled, "Verification of Empirical Criteria for Determining Riverbank Stability" (Gann 1978).

The failure

56. The movements reported on the morning of 23 August 1983 were naturally those manifest in the above-water bank. Representatives of the Foundations and Materials and Design Branches of the New Orleans District proceeded immediately to inspect the site and arrived in time to witness the collapse of the levee section. Six hours after the District office had first been notified of batture movements, a photo (not suitable for reproduction herein) was taken from the crown of the levee, looking downstream from a position near the upstream end of the failure. That photo reveals the following (dimension estimates are crude):

a. The failed riverward batture segment was submerged except for a small mound of material about 3 ft above water near the failure centerline and about aligned with the old top of bank line (see 1979 cross section, Figure 17). Batture vegetation was visible on the mound. A near-vertical scarp in excess of 20 ft in height existed from original batture ground surface (el 26) to water surface (el 4.6) and encroached on the levee toe at its most landward point.

b. The levee crown had displaced downward about 4 to 5 ft and translated 6 to 8 ft riverward producing a graben about 10 ft down the landward levee slope from the crown and also 6 to 8 ft wide.

The photos in Figures 19 and 20 indicate the continuation of the failure after the above described photo was taken. The riverward mound of material described above is seen in Figure 19a. The levee section continued to move riverward and downward with the landward graben described above growing into a wide, deep crack (Figure 19b). Approximately, the middle third of the 700-ft section eventually failed completely into the river (Figure 20). At the upstream and downstream ends of the failed section intact pieces of riverward slope wedges about 200 ft in length moved downward and rotated riverward as if hinged at their unfailed levee ends but remained on the bank (Figure 20).

57. Since the river stage on that day was at el 4.6 ft, there was some 100 ft of clay topstratum under water. There is, of course, no way to determine whether the visible surface movements of the batture were the result of one very large single mass movement or represented the final stage that was preceded by a series of subaqueous slides. It has already been pointed out that earlier bank cross sections had regularly implied the presence of small rotational slip surfaces from lower to upper bank.

58. The 24 August cross section through the failure at revetment range U-14 (see Figure 18) exhibits a "hummocky" appearance often seen after the failure of natural slopes. The upper portion of the 24 August cross section gives the impression that the batture surface had dropped and rotated in a clockwise manner as compared with the 12 August section. It would have been convenient in considerations of a safe setback distance for the new levee section if the failure of the levee embankment geometry of the failure left no reasonable doubt as to the location of the shear surface or surfaces. However, because of the lengthy time frame of bank movements and because significant batture mass was lost into the scour pool before the survey of 24 August was made, it was decided to be imprudent to establish setback distance by guessing failure surface(s) location. Therefore, the determination of a satisfactorily safe location for the setback levee reach was predicated on a wedge-type stability analysis of the riverbank utilizing the before failure survey for range U-14 and incorporating the existing levee embankment in the

active wedge. From those analyses, the failure plane resulting in the greatest setback distance (which was adopted) for the new embankment fell at el -96 at the clay/sand interface where the factor of safety was calculated to be 1.37. The authors will subsequently use the after-failure bank cross section to conjecture the failure mode. That conjecture supports the contention that the failure surface occurred at the interface between the topstratum and substratum sands (el -96).

59. It is certainly a moot issue, but the photographic indications presented above lead the authors to suspect that the batture failure may have proceeded independently of the driving forces represented by the levee embankment. The presence of the major scarp at the levee toe with the large movement of a large portion of the batture toward the river while the levee apparently lagged along with much smaller deformation and movement gives this impression. The cross sections of November 1979, 12 August 1983, and 24 August 1983 are redrawn in Figure 21. The 24 August cross section is augmented by the authors' conjectures of the deformed levee, batture scarp, and landward portion of the batture not surveyed on 24 August. In addition, conjectured slip surfaces are also indicated. In the authors' judgment, the survey of 24 August does offer a suggestion of the location of the failure plane when coupled with the conjectured failure surfaces indicated in Figure 21. That picture is one of successive block movements along the interface between the topstratum backswamp clay substratum sands. The successive blocks inferred for the cross section of 24 August also include an explanation of the narrow ridge of material remaining above the water and approximately aligned with the old top of bank line. That section also suggests an intact piece of perhaps the first and most riverward block within the apparent failure debris. The authors also depict in Figure 21 the conjectured presence of an old slip surface of 1979 (or prior, but after 1973) which is also indicated to have moved along the topstratum/substratum interface. Wedge-type pre-failure stability analyses were performed by the New Orleans District using the 12 August bank cross section for revetment range U-10. That analyses showed a factor of safety of only 1.02 for a failure surface along the clay topstratum/sand substratum interface and an active wedge breaking out about 40 ft riverward of the levee toe. A similar wedge with the active wedge breaking out about 30 ft landward of the levee centerline had a factor of safety only slightly higher at 1.08. These were the lowest

calculated values for 14 different failure surfaces at various elevations and landward-riverward positions. These analyses tend to support the idea that the bank failed riverward of the levee first followed by a block movement involving the levee itself which is the sequence surmised above from the photographs.

The hypothesized failure mechanism

60. In simple terms, Turnbull, Krinitzsky, and Weaver (1966) described the basic mechanics by which the river has probably been successfully attacking the Marchand bank since 1880-1894. Figure 22 is taken from that paper (also included in Krinitsky (1965) where the "1-2-3" step mechanism is illustrated. Figure 22 schematically applies the concept to the Marchand case in an oversimplified manner. The first step of the process begins with scour at the toe of the riverbank which erodes or produces instability in the substratum sands. Loss of the sand by erosion or from failure by shear or flow leads to instability and failure of the overlying and undercut upper bank soils.

61. In reality, while the process is simple to describe as above, the actual progression of failure beginning deep in the scour pool within the substratum sands and progressing up through a very thick and cohesive deposit such as that existing at Marchand is surely complex. Other factors such as overall steepness of the bank within the topstratum clays and the magnitude of undercutting by loss of the substratum sands are involved. In the work by Padfield reported by Torrey, Dunbar, and Peterson (1988) it was shown that a cohesive topstratum possesses an ability to arch and span a cavity which reflects its shear strength and thickness. While Figure 22 shows a mass slip through the depth of the topstratum for simplicity's sake, its available shear strength and its great thickness (more than 100 ft) would permit it to easily bridge a very large cavity while perhaps exhibiting relatively minor vertical deformation at the ground surface. It is deemed most logical that the failure of the topstratum proceeds in a "chipping away" manner with smaller shear failures first occurring locally into the void created at depth by the loss of substratum sands. This in turn results in a local net oversteepening of the base of the topstratum which leads to additional, but still moderate in size, local shear failure. With time, the process works its way up the bank. Of course, over that period of time it is possible that the loss of substratum sands continues with the next seasonal river attack so that there may be new shear failures of the topstratum developing at depth as the previous spawning

of moderate sized failures reaches the surface. In any event, for such thick deposits as that present at Marchand, it appears that some time would transpire before upper bank losses would occur. At Marchand, this "chipping away" at the topstratum finally reached the point where sufficient soil had been lost along a critical failure path, the bank was so steepened and the situation aggravated by probable saturation of the above-water soils that mass shearing involving the entire thickness (speculative) of the topstratum occurred.

62. It is irrelevant to the failure of the topstratum whether the substratum sands are removed by erosion, shear failure or retrogression in the dilatant material (flow). The hypothesized retrogression mechanism believed to explain flow slides in point bar deposits (Torrey, Dunbar, and Peterson 1988) would seem to represent a most severe case with respect to degree of topstratum undercutting although brute erosion cannot be casually dismissed. It is speculation whether the channel fill seen in Figure 18 above the 1973 cross section was sand as opposed to clayey slide debris from the failure which occurred between the 1973 and 1979 survey dates. There is no way to know why a very large "runout" of sand did not occur and cause that failure to be larger. There is the distinct possibility that the 1973 cross section reflects river attack deep in the scour pool during the great flood of 1973; whereas, the 1983 failure event took place during the low water season. There is some evidence (Torrey 1988) that it is during low water periods that some scour pools are deepened most severely. This is inconsistent with the generally accepted hypothesis and with findings of other studies by LMV that pools scour and crossings fill during high water. The authors believe that there is an issue here worthy of closer study below Baton Rouge. Of course, additive evidence is perhaps represented by the 30 July 1985, flow slide at Celotex, Louisiana (Torrey 1988), which also occurred during low water. Surveys associated with that failure rather clearly indicated that the permanent scour pool in the Greenville bendway had deepened and extended further downstream.

63. If the authors are permitted the considerable license of assuming that only sand existed in the Marchand scour pool on the day of failure, a retrogressive failure in the substratum sands can be postulated as shown in Figure 23. The reader is referred to Torrey, Dunbar and Peterson (1988) and Torrey (1988) for explanation of the concept of retrogression in dilatant sand including the definitions of "runout" angle α and after failure slope in the

sands β . It is to be noted that the survey of 12 August shows a deepening of the scour pool toward the 1973 thalweg and a steepened landward slope in the pool. If the currently empirically established value of the "runout" angle of 10 deg (Torrey 1988) is applied from the thalweg (point A, Figure 23) and projected to intersection with the base of the topstratum (point B, Figure 23), the degree to which a retrogressive flow of the sands would undercut the topstratum clays is implied (assuming that revetment does not prevent the occurrence). Furthermore, if the after-retrogression slope in the sands, β is assumed at half of the "runout" angle α , or 5 deg, it can be back-projected from point B to point C, Figure 23, to imply the after-retrogression profile in the sand. The procedure shown can only be used to indicate a feasibility of failure by retrogression in the substratum sands.

Implications for Other Reaches in the Study Area

General

64. It has been shown by Torrey (1988) and supported by the evidence relative to Marchand, that the river may freely shift its channel alignment with time by first removing the "weak link" sands and silty sands underlying cohesive, erosion resistant topstratum soils of its banks. Subsequently, gravity does its work in removing the unsupported overlying resistant materials. Whether the cohesive topstratum is relatively thin as is the case where flow slides have been observed or very thick as is the case at Marchand, the results are ultimately the same with perhaps only a difference in time until batture loss occurs. Flow slides remove so much sand from beneath the thin topstratum that batture loss proceeds with runout of the sand and all is over in a matter of hours. With increasing thickness of topstratum, the time delay between loss of underlying sand and batture probably also increases. In assessing the magnitude of the threat to other bank reaches in the study area, i.e., from New River Bend revetment to Burnside revetment, two factors should be considered as follows:

a. The historic migration of the channel along the reach of interest, i.e., the historic attack factor.

b. The soil profile of the bank compared with the thalweg elevation of the river. Specifically, does the thalweg penetrate into substratum sands?

If the scour pool is against the bank in question and is working the deep sands, upper bank losses should be considered as inevitable at least until recent changes in bank revetment practices are proven effective. Potential magnitude of bank losses is probably related to the relative depth of penetration of the thalweg into the substratum sands, particularly if the retrogression mechanism is occurring. The greater the potential for undercutting of the topstratum in the landward direction, the greater the potential for mass losses of batture. The actual performance of current revetment practices which are intended to prevent undercutting of the topstratum has been previously addressed.

65. Boring data pertaining to the study reach are reproduced from Torrey (1988) as Figure 24a through 24c. Note that these figures also show the 1974 thalweg, the position of the thalweg (on the right bank, left bank, or at mid-channel), and the depth of the topstratum/sand substratum interface. Boring data evaluated in this study (see Figures 4 through 6) in addition to those presented in Figures 24a through 24c indicate that the thalweg of the Mississippi River throughout the study area is in the substratum sands except for the Burnside Revetment reach. The river along the Burnside Revetment is incising into the Pleistocene age deposits. The paragraphs that follow discuss each revetment subreach's bank loss over the period of record (see Figure 7e) in light of the two factors presented above.

New River Bend, left bank

66. From Figure 7e it is seen that bank losses over the period of record have occurred from approximately river mile 188 AHP to mile 184 AHP. In Figure 24a this reach corresponds to about 1974 hydrographic survey range 187.5 to range 183.9. The scour pool, although moderate in depth, lies along the left bank. The 1974 thalweg did not penetrate the substratum sands at the upstream end of this reach from range 188.5 to 186.8. From range 186.8 to range 183.9 the 1974 thalweg does penetrate into the sands. It is seen from the geologic section of Figure 5a that point bar deposits exist from about range 186.4 to range 181.7 and consist largely of silts and clays with interbedded sands. Bank losses since 1951 (Figures 7a and 7b) have been confined to that reach where the thalweg is located in the deep sands and the bank is composed of point bar deposits which are less erosion resistant. The earlier surveys (Figures 7c through 7e) show considerable bank losses from range 188.5 to 186.8 where the 1974 thalweg does not penetrate into the

substratum sands. Unfortunately, the borings shown in Figure 24a were not deep enough to reach the topstratum/substratum interface at this location. However, other borings used to establish the geological section of Figure 5a show the substratum sands to lie at about el -100. It has been shown by Torrey (1988) that the river has become more shallow over the period of record. It is possible that the deeper channel of earlier times did penetrate the sands between Range 188.5 and Range 186.8 and caused the bank losses between 1880-1894 and 1937 (Figures 7c through 7e).

Philadelphia Point, right bank

67. Philadelphia Point is a point bar deposit with thin topstratum as seen in Figures 5c and 24b. The thalweg of the 1973-1975 survey typically penetrates the substratum sands along this reach from about Range 184 to Range 181.7. Figures 7a through 7e show very little movement along this bank over the period of record although some bank losses are seen along the upstream portion of the reach. The thalweg in the 1973-1975 survey is very shallow and the survey does not show a well defined scour pool or trench. It is obvious that this bank which is susceptible to flow slides because of the thin topstratum is not being subjected to much pressure because it lies in the crossing between the New River Bend and Marchand pools. However, the small bank losses identified in Figure 7 may be significant with respect to the potential for a future flow slide during high river stages if the current tends to "cut the corner" from about hydrographic Range 183.0 to Range 181.7.

Marchand, left bank

68. The Marchand case has been treated amply but it is reiterated from Figure 24a that the 1973-1975 thalweg is well into the substratum sands and against the left bank. River migration trends over the period of record imply that this bank reach will continue to see severe movement in the future unless revetment prevents scouring of the substratum sands.

Smoke Bend, right bank

69. Figures 7a through 7e indicate that Smoke Bend has experienced only minor movement with most of it occurring when the river was deeper between 1880-1894 and 1921. Figure 24b shows that there is only one small reach that may be a problem area. This reach extends from river mile 178.2 AHP to mile 177.5 AHP, is in the deepest portion of the 1973-1975 scour pool, is against the right bank, and the thalweg is in the substratum cohesionless materials. There appears from the boring information to be relatively little thickness of

fine sands or silty sands before the substratum soils become very gravelly. Runout is possible in the very gravelly soils but, according to theoretical analyses of the failure mechanism (Torrey, Dunbar, and Peterson 1988), the runout angle for such very highly permeable soils would be considerably greater than the 10 deg empirically indicated for fine sands/silty sands. This analyses would infer a much reduced potential for undercutting of topstratum soils which are seen to be mostly clays from the geologic sections (Figures 5b, 5d and 5e, about Range 178.2 to 176.5) and which encompass the limits of the scour pool. The historic migration of the Smoke Bend scour pool is to be included in a comprehensive study of all "permanent" scour pools from Baton Rouge to Head of Passes which is in progress at the writing of this report. If the Smoke Bend pool migrates downstream, it will begin to encroach on point bar deposits (Range 176.1 to Rnge 174.5) containing a mix of cohesive and cohesionless soils but with considerable sand strata. This would eventually spell flow slide trouble in that reach. The pool is of such great depth (el -170, 1983-1985 survey) that the approximately 400 ft of batture may be insufficient to protect the levee only a mile upstream of Donaldsonville.

St. Elmo, left bank

70. The 1973-1975 thalweg penetrates the substratum sands along the St. Elmo revetment as seen in Figure 24a. The scour pool is very localized (around 1,500 ft in length based on the el -60 contour), against the left bank and centered about Range 174.1. However, Figures 7a through 7e show that bank losses have occurred from about Range 176.5 to Range 173.3. Banklines from the 1973-1975 comprehensive surveys (Black Hawk, Louisiana, to Head of Passes) show a large scallop with only about 150 ft of batture to the levee toe centered at Range 174.1 where the localized scour pool is evident in Figure 24a. However, the 1983-1985 comprehensive survey indicates that scallop has since been mostly filled, some 350 ft of batture exists, and the deepest point of the scour pool at about el -80 remains in the same position as in the 1973-1975 survey. The small east-west oriented St. Elmo scour pool and the gigantic (in excess of 6,000 ft in length) north-south oriented Aben pool immediately downstream are only about 6,000 ft apart and in a direct line with one another. It would seem that the possibility exists for some exceptionally turbulent conditions to exist between these two closely spaced pools during high discharges. The history of localized bank loss at St. Elmo probably

merits concern for future levee stability at Range 174.1 should the apparent depositional conditions of recent times appear to be reverting to erosion.

Aben, right bank

71. The Aben bank has suffered considerable losses over the period of record. The loss has occurred from about hydrographic Range 173.0 to Range 171.9 which corresponds to the length of the very large, flat bottomed scour pool against the right bank in that very tight bendway. Figure 24b reveals that this reach also corresponds to the location where the thalweg penetrates into the substratum sands. The topstratum is a thick backswamp clay deposit, some 100 ft thick (Figure 5b). Levee alignment seen from the comprehensive hydrographic survey indicates a past setback from about Range 172.9 to Range 172.5. This setback falls within the limits of the deepest portion of the scour pool (Figure 24b). The scenario here bears a strong resemblance to that at Marchand. It was also shown in paragraph 45 that the W:D characteristics of the Aben reach are also very similar to those along the Marchand reach. The 500 ft of batture existing here is of little consolation in consideration of the about 600 ft of batture involved at Marchand. In addition, the presence of a riverward borrow pit at Aben represents a shorter potential failure plane passing through it.

Burnside, left bank

72. The Burnside scour pool is centered about Range 170.6 and against the left bank where the river incises the relatively tough Pleistocene age deposits (see Appendix A). There are no significant sand strata present in the bank. Therefore, as identified in Figures 7a through 7e, this bank reach has been an exceptional "hard point" which essentially hasn't budged over the period of record. The river enters substratum sands well downstream at about Range 168.0 but the thalweg then crosses to the right bank and there is no evidence of left bank attack over the period of record. The Burnside reach is probably one of the most stable major scour pools anywhere along the lower river.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Historic river migration and morphology

73. The conclusions given below are based on a period of record of 1880-1894 to 1973-1975. The 1983-1985 survey data have not been included.

a. There is no evidence to suggest that the Darrow Salt Dome, almost centered at depth beneath the Marchand area, has produced faulting in the overlying Holocene deposits to the ground surface. It is concluded that this major geologic subsurface structure in no way contributed to conditions leading to the Marchand bank and levee failure of 23 August 1983.

b. There is no evidence to suggest that fluid extraction by the petroleum and chemical industries on the Darrow Salt Dome contributed to conditions leading to the Marchand bank and levee failure.

c. Over the period of record from 1880-1894 to 1973-1975, the Mississippi River channel from about Carville, Louisiana, to White Hall, Louisiana, has persistently migrated northward in the New River Bend Revetment reach, southeastward in the Marchand Revetment reach, south to southwestward in the Smoke Bend Revetment reach, northward in the St. Elmo Revetment reach and southeastward along the Aben Revetment. The Burnside Revetment reach has seen essentially no movement of the channel over the period of record.

d. Within the study reaches, the most severe losses of batture over the period of record have occurred along New River Bend, Marchand, and Aben reaches. New River Bend has seen a maximum of about 1,500 ft, Marchand has experienced over 2,000 ft, and Aben about 1,000 ft. Smoke Bend and St. Elmo reaches have suffered bank losses of about 500 ft each. The rates of bank losses along all reaches under attack appear to be roughly constant with time. New River bend, Marchand, and Aben have experienced declining average W:D ratios over the period of record while Smoke Bend, St. Elmo, and Burnside have experienced increases.

e. Channel cross-sectional areas throughout the study reach declined an average of about 30 percent from 1880-1894 to 1937. Between 1937 and 1961 little change occurred. Since 1961, the river has been increasing its channel area on the average.

f. Both average channel width and channel depth decreased between 1880-1894 and 1973-1975 from Carville to White Hall, Louisiana.

g. The river has been severely attacking the bank along 81-Mile Point downstream from the extent of the Marchand Revetment and the deep Marchand scour pool. The bank losses on the northwest side of Eighty-One-Mile Point have been outstripping the accretion on the south side opposite Smoke Bend Revetment. These are point bar deposits exhibiting thin topstratum over fine sands.

The Marchand failure

74. The following conclusions are drawn relative to the Marchand failure mechanism:

- a. The Marchand failure occurred as a result of the initial loss of deep substratum sands from beneath the thick topstratum of backswamp clays followed by progressive failure of the topstratum over a period of time which eventually manifested itself in the upper bank. This process has also produced the bank losses of record along New River Bend, Smoke Bend, St. Elmo, and Aben reaches.
- b. The mechanism by which substratum sands beneath the thick Marchand topstratum were removed is not known. Any of or a combination of scour, shear failure, or retrogression (flow) may have initiated the failure.
- c. The ultimate major dimensions of the Marchand failure of August 1983 reflected a weakening of the bank by a lesser, but significant, failure which occurred sometime between October 1973 and November 1979.

Implications for other reaches

75. The following conclusions relate to bank reaches in the study area other than Marchand reach:

- a. The geology of the Aben reach bears a strong resemblance to the Marchand reach with thick topstratum backswamp clay over substratum sands and a very deep scour pool at the bank toe which penetrates into the sands. The significant difference between the two reaches may only lie in the relative degree of river attack which has been less severe over the period of record at Aben. However, the Aben bank is deemed highly susceptible to failure by the process believed to account for that at Marchand.
- b. The New River Bend reach, while susceptible to erosion of its silty/clayey point bar deposit, may be less susceptible to a massive Marchand type failure because of relative shallowness of the scour pool, perhaps suggesting less turbulence and the gradual removal in small masses of substratum sands beneath the topstratum.
- c. Migration of the deep scour pool along the Smoke Bend reach is an important issue for future consideration. Downstream drift of that pool into the point bar deposits with thin topstratum would eventually bring the threat of a major flow slide which might imperil the levee at Donaldsonville particularly at range 175.6 where there is very little batture.

Recommendations

76. The following recommendations are made in light of the findings of this study.

- a. Update the data base containing historic changes in channel alignment and channel geometry over the period 1880-1894 to 1973-1975 to incorporate the 1983-1985 hydrographic survey information.
- b. Complete the study of historic migration and morphology of all the "permanent" scour pools from Baton Rouge, Louisiana, to Head of Passes to complement the study of historic channel migration by Torrey (1988). A knowledge of the direction and relative rate of movement of the individual pools and changes in size and depth will be of fundamental value in developing bank stability defensive measures and prioritizing the application of those measures.
- c. Employ the above general scour pool study along with the channel migration information to select at least two very active scour pools below Baton Rouge which are in substratum sands to be subjected to detailed study. These detailed scour pool studies should be by means of closely controlled hydrographic surveys conducted several times during the year to "see" the pool during low stage, rising stage, high stage, and falling stage. It is deemed particularly important to survey those pools during a very low and a very high stage, however long it takes to do so. It is imperative that the surveys be conducted with utmost care for accuracy and replicate horizontal positioning. Only by means of such "viewing" of the pools will an understanding of the flow slide and Marchand-type failure mechanisms (if different) be obtained.

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Table 1

Hydrographic Survey Reference Data

Hydrographic Survey Year	Reference Datum	Actual Water Surface Elev*	Map Datum
1880	Mean gulf level** (Mean water surface)	-0.8	US Coast 1877 Survey†
1894	Mean gulf level** (Mean water surface)	-1.41	US Coast 1877 Survey†
1921	Mean gulf level (Mean water surface)	2.77	US Coast 1877 Survey Modified 1921†
1937	Mean gulf level (Mean low water)	1.27	Gulf Coast or Memphis Datum
1951	Mean sea level (Mean low water)	1.33	Gulf Coast or Memphis Datum
1961	Mean sea level (Average low water plane)	1.33	North American Datum
1974	Mean Sea Level (Low water reference plane)	1.33	North American Datum

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* The water surface is referenced to Donaldsonville, Louisiana, and is corrected to mean sea level for all hydrographic survey periods. The water surface elevations for 1880 through 1921 surveys are for day of survey only.

** Mean gulf Level prior to 1899 was referenced at 8.13 ft instead of the current 6.083 ft on the Biloxi, Mississippi, staff gage.

† Banklines were surveyed for each hydrographic survey period independently of river depth soundings.

Table 2

Marchand to Aben Subreach Hydrographic Survey Comparison Results

Entire Subreach

Hydrographic Survey	Time Years	Gain Acres	Loss Acres	Ratio Factor
1974-1961	13	142	248	-1.7
1974-1951	23	215	268	-1.2
1974-1937	37	292	418	-1.4
1974-1921	53	681	493	1.4
1974-1880/94	87	1244	889	1.4
1880/94-1921	34	633	406	1.6
1880/94-1937	50	991	496	2.0
1880/94-1951	64	1076	655	1.6
1880/94-1961	74	1228	783	1.6
1880/94-1974	87	1244	889	1.4
1880/94-1921	34	633	406	1.6
1921-1937	16	454	169	2.7
1937-1951	14	152	224	-1.5
1951-1961	10	160	150	1.0
1961-1974	13	142	248	-1.7

Marchand

Hydrographic Survey	Gain Acres	Percent Total	Loss Acres	Percent Total	Ratio Factor
1974-1961	60	42	76	31	-1.3
1974-1951	114	53	91	34	1.3
1974-1937	177	61	169	40	1.0
1974-1921	395	58	268	54	1.5
1974-1880/94	759	61	489	55	1.6
1880/94-1921	398	63	223	55	1.8
1880/94-1937	588	59	322	65	1.8
1880/94-1951	647	60	397	61	1.6
1880/94-1961	712	58	426	54	1.7
1880/94-1974	759	61	489	55	1.6
1880/94-1921	398	62	223	55	1.8
1921-1937	190	42	106	63	1.8
1937-1951	70	46	86	38	-1.2
1951-1961	68	43	15	10	4.5
1961-1974	60	42	76	31	-1.3

(Continued)

Table 2 (Concluded)

Hydrographic Survey	Gain Acres	Percent Total	Loss Acres	Percent Total	Ratio Factor
		Smoke Bend			
1974-1961	11	7	4	1	2.8
1974-1951	33	6	45	17	-1.4
1974-1937	12	4	56	13	-4.6
1974-1921	68	10	44	9	1.5
1974-1880/94	154	12	122	14	1.3
1880/94-1921	94	15	53	13	1.8
1880/94-1937	150	15	71	14	2.1
1880/94-1951	133	12	89	14	1.5
1880/94-1961	180	15	132	17	1.4
1880/94-1974	154	12	122	14	1.3
1880/94-1921	94	15	53	13	1.8
1921-1937	71	16	18	11	3.9
1937-1951	4	3	11	5	-2.8
1951-1961	55	34	57	38	-1.0
1961-1974	11	8	4	2	2.8
		Aben			
1974-1961	8	5	33	13	-4.1
1974-1951	35	16	41	15	1.2
1974-1937	52	18	64	15	-1.2
1974-1921	111	16	92	19	1.2
1974-1880/94	161	13	138	16	1.2
1880/94-1921	61	10	38	9	1.6
1880/94-1937	104	10	65	13	1.6
1880/94-1951	120	11	88	13	1.4
1880/94-1961	157	13	113	14	1.4
1880/94-1974	161	13	138	16	1.2
1880/94-1921	61	10	38	9	1.6
1921-1937	46	10	23	14	2.0
1937-1951	22	14	13	6	1.7
1951-1961	22	14	14	9	1.6
1961-1974	8	6	33	13	-4.1

Table 3

General Width and Depth Characteristics for the Marchand Reach

	Hydrographic Survey	
	1974	1880/94
Average width, ft	2448	2741
Range, ft	1,700-3,800	2,025-3,800
Average depth, ft	91	100
Range, ft	49-165	55-163
Number of survey ranges included	80	80

Table 4

Area Measurements for Selected Channel Location in the Marchand Reach, values in square feet

Range	1880/94	1921	1937	1961	1974	1983	Average
R182.0	154,634	151,467	102,325	98,876	90,621	101,490	116,569
R181.3	214,262	140,132	111,292	103,140	100,113	98,515	127,909
R180.7	229,665	141,138	130,130	125,736	155,710	150,800	155,530
R180.4	179,094	164,308	141,844	142,287	149,773	156,500	155,634
R180.2	210,185	194,813	150,535	151,720	154,617	181,805	173,946
R179.6	189,034	150,960	120,314	112,870	120,641	124,625	136,407
Average	196,162	157,136	126,073	122,438	128,580	135,622	

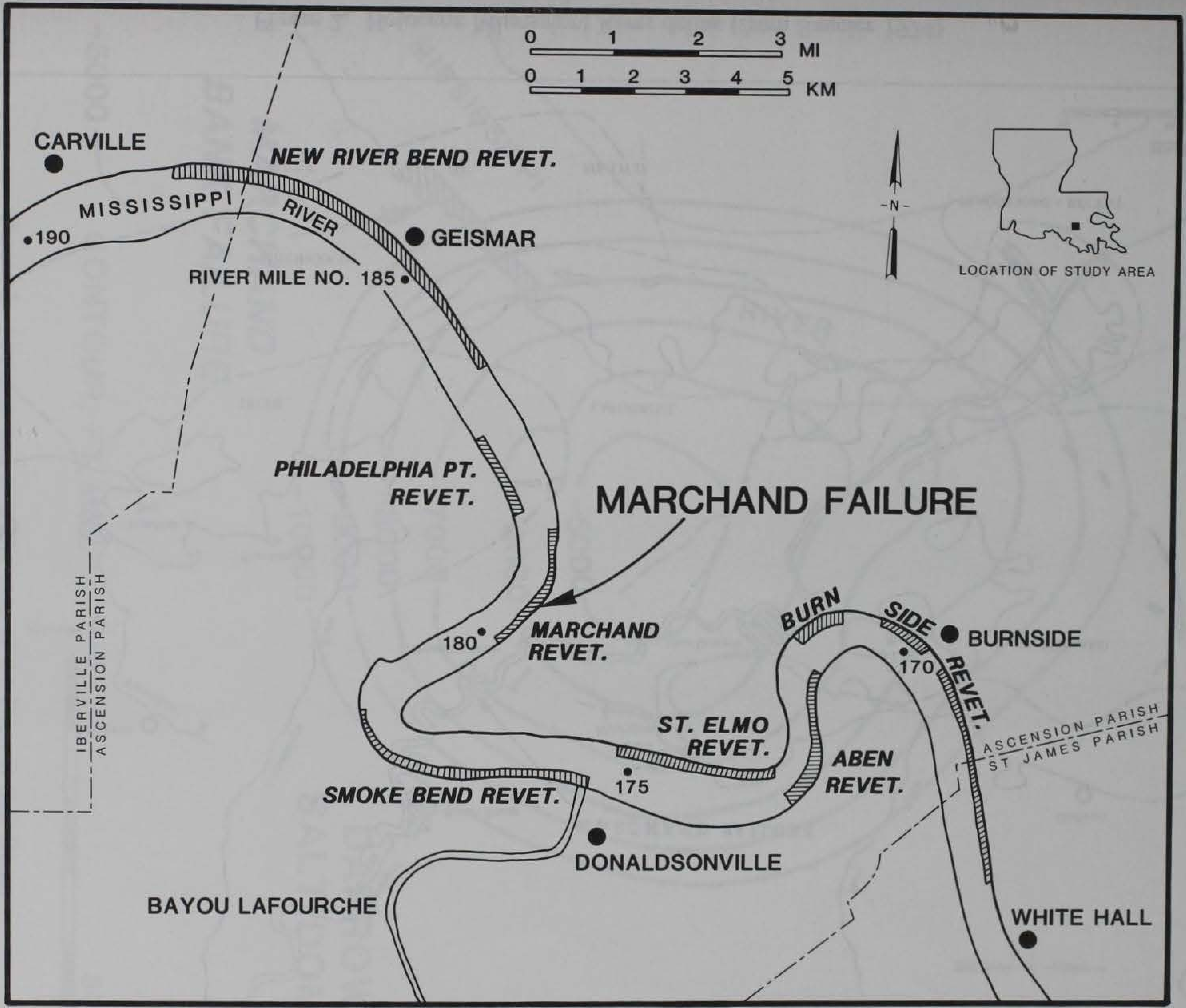


Figure 1. The Mississippi River study reach

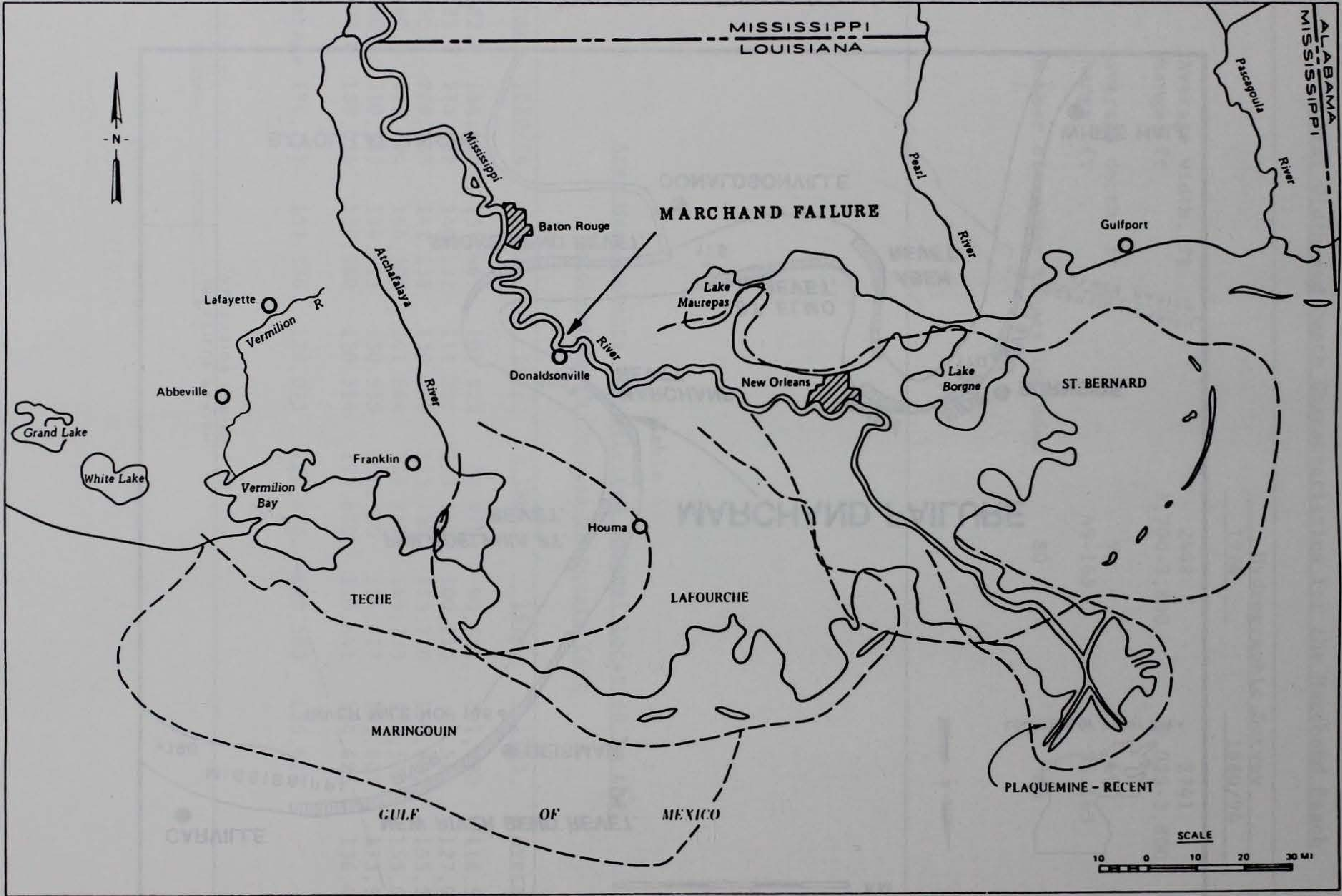


Figure 2. Holocene Mississippi River deltas (from Saucier 1974)

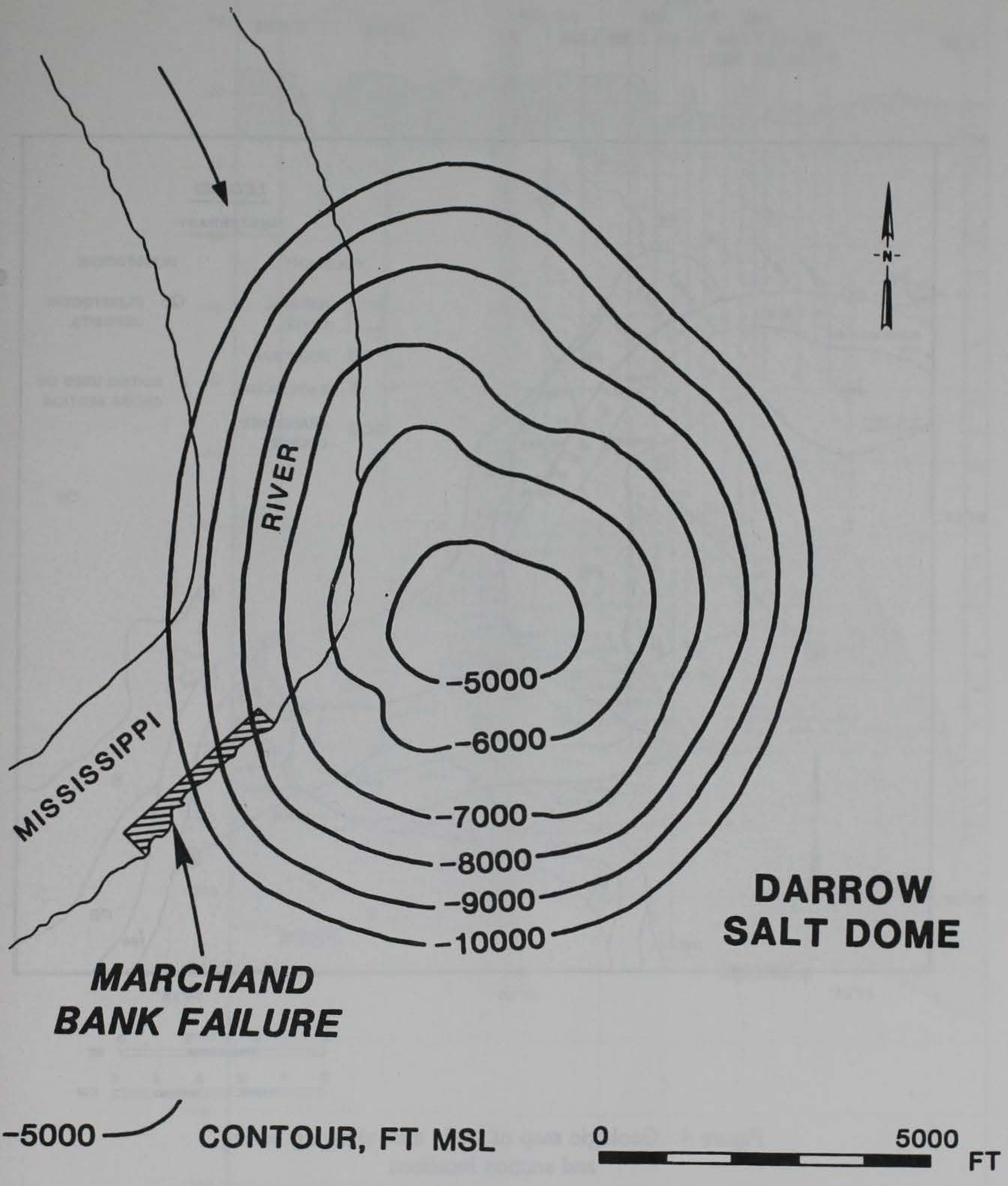


Figure 3. Location and structure map of the Darrow Salt Dome (from New Orleans Geological Society 1963)

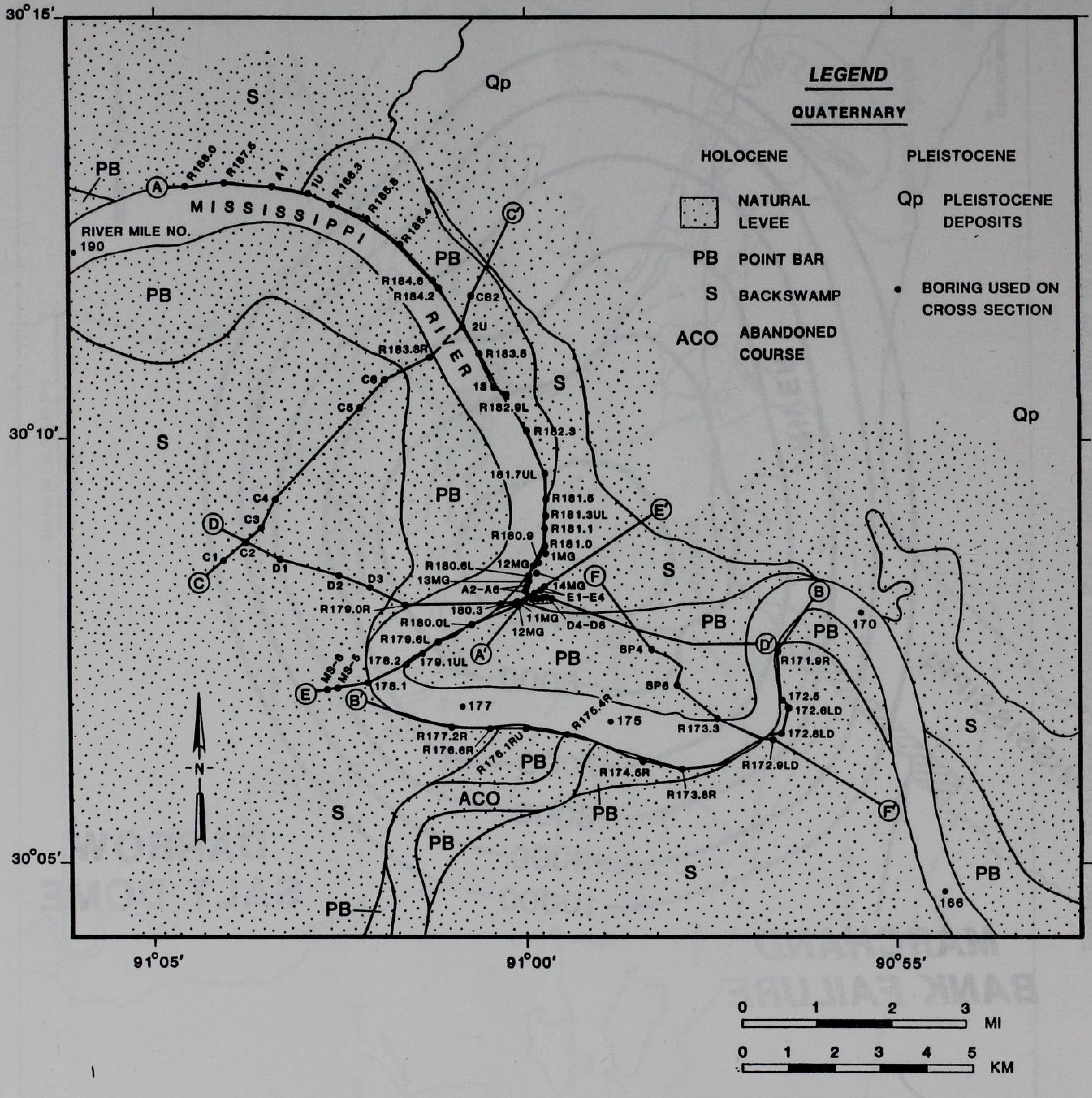


Figure 4. Geologic map of study area showing boring and section locations

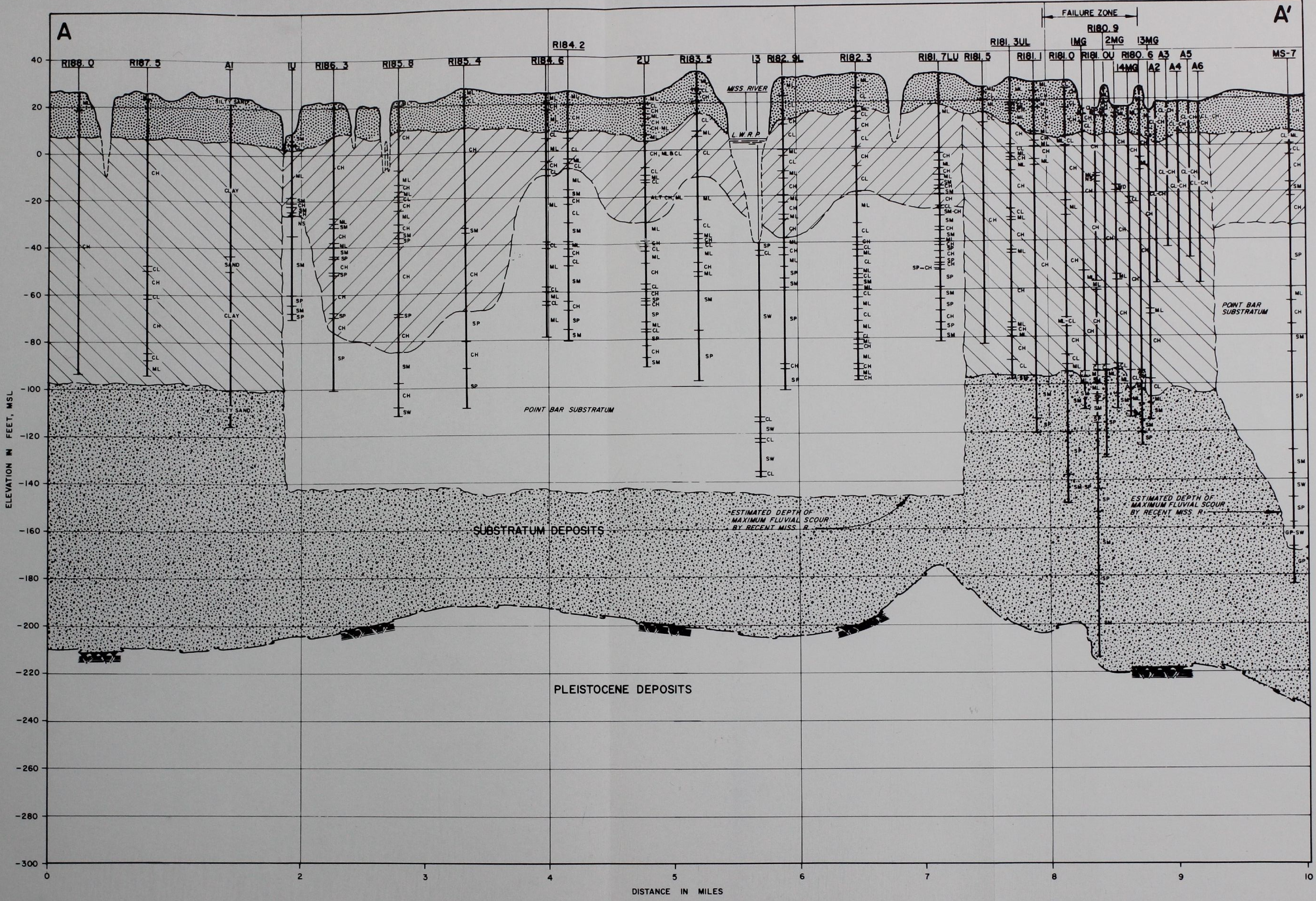


Figure 5a. Geologic cross-section A-A′ (see Figure 5g for legend)

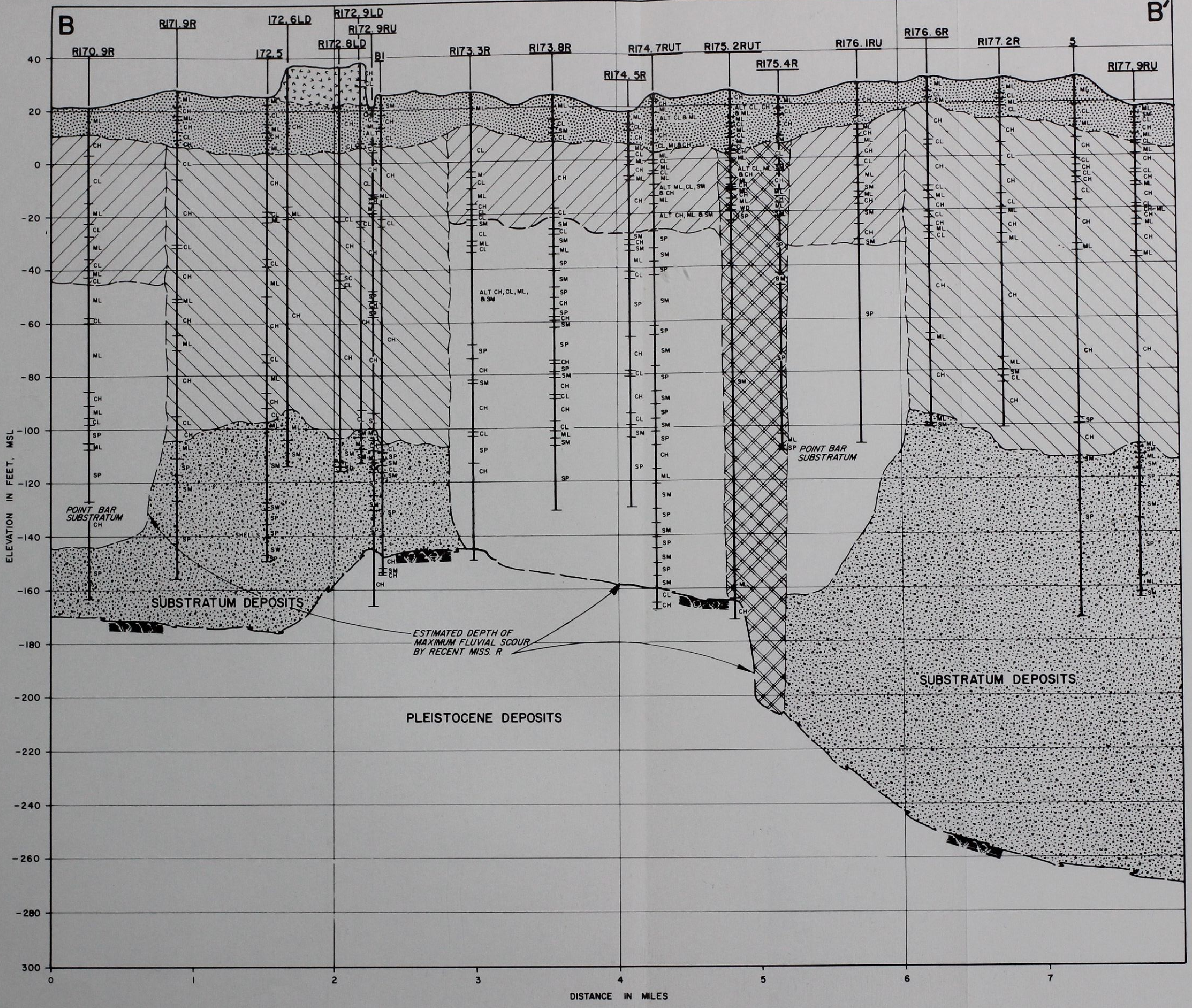


Figure 5b. Geologic cross-section B-B′ (see Figure 5g for legend)

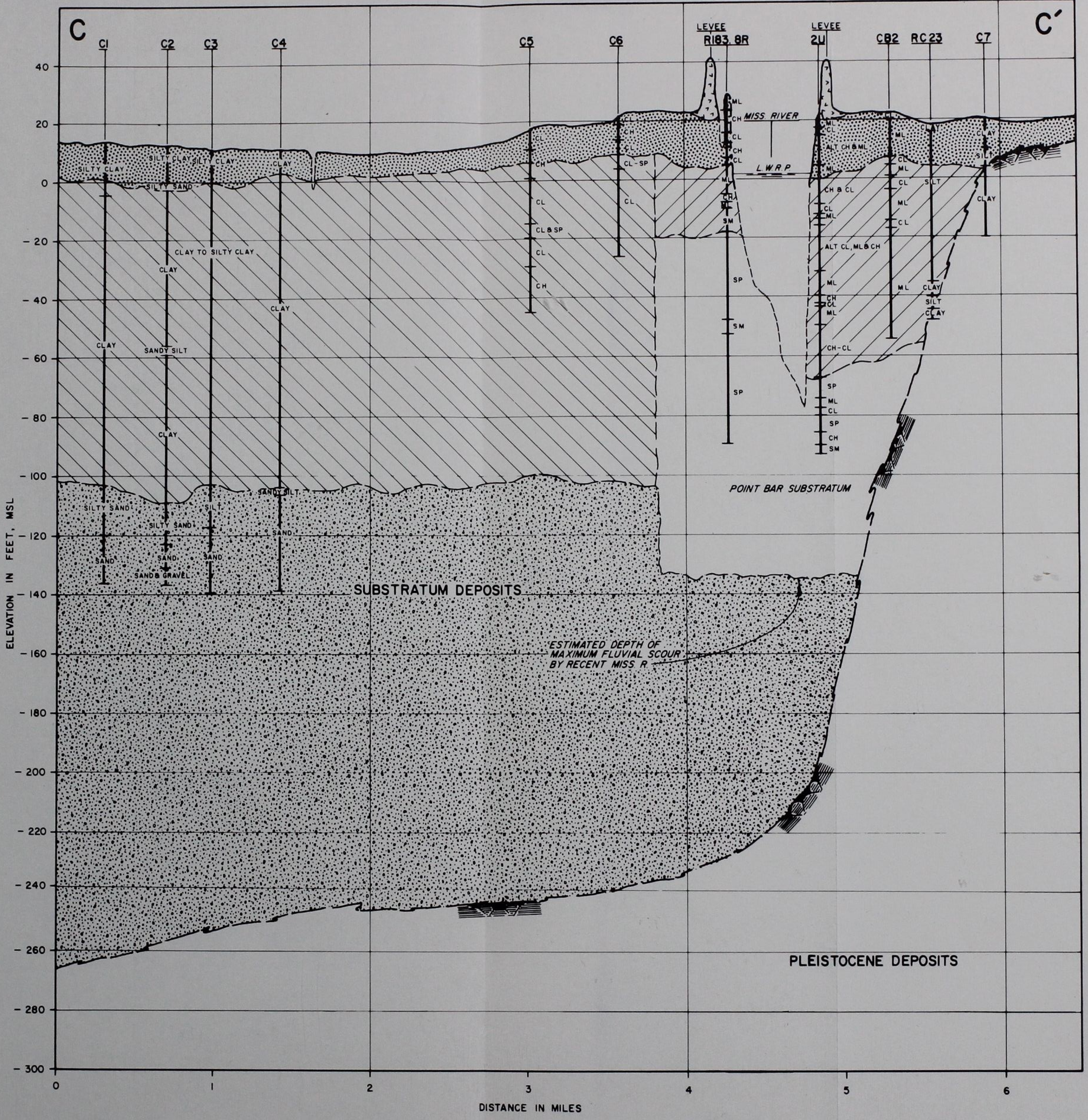


Figure 5c. Geologic cross-section C-C′ (see Figure 5g for legend)

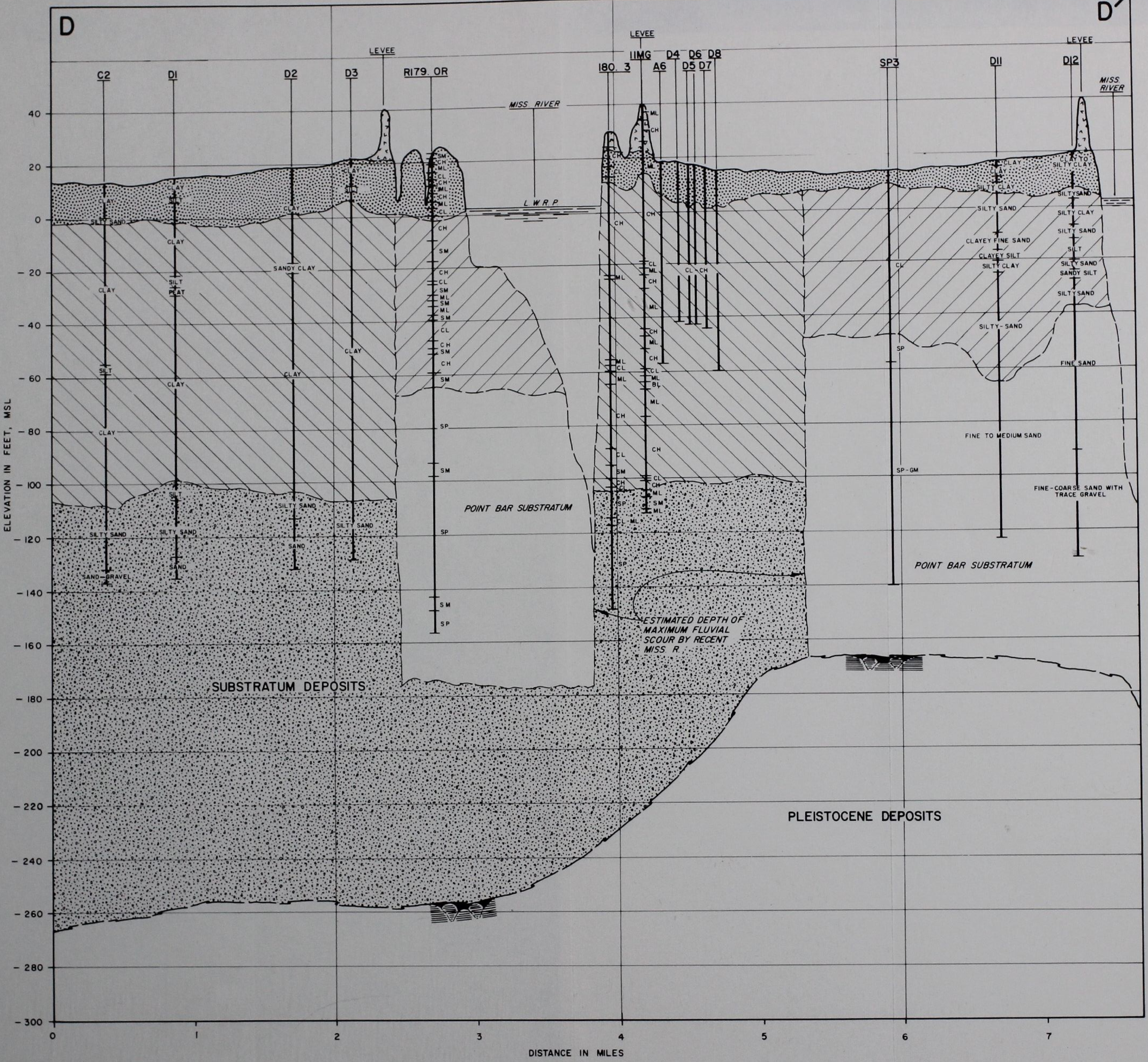


Figure 5d. Geologic cross-section D-D′ (see Figure 5g for legend)

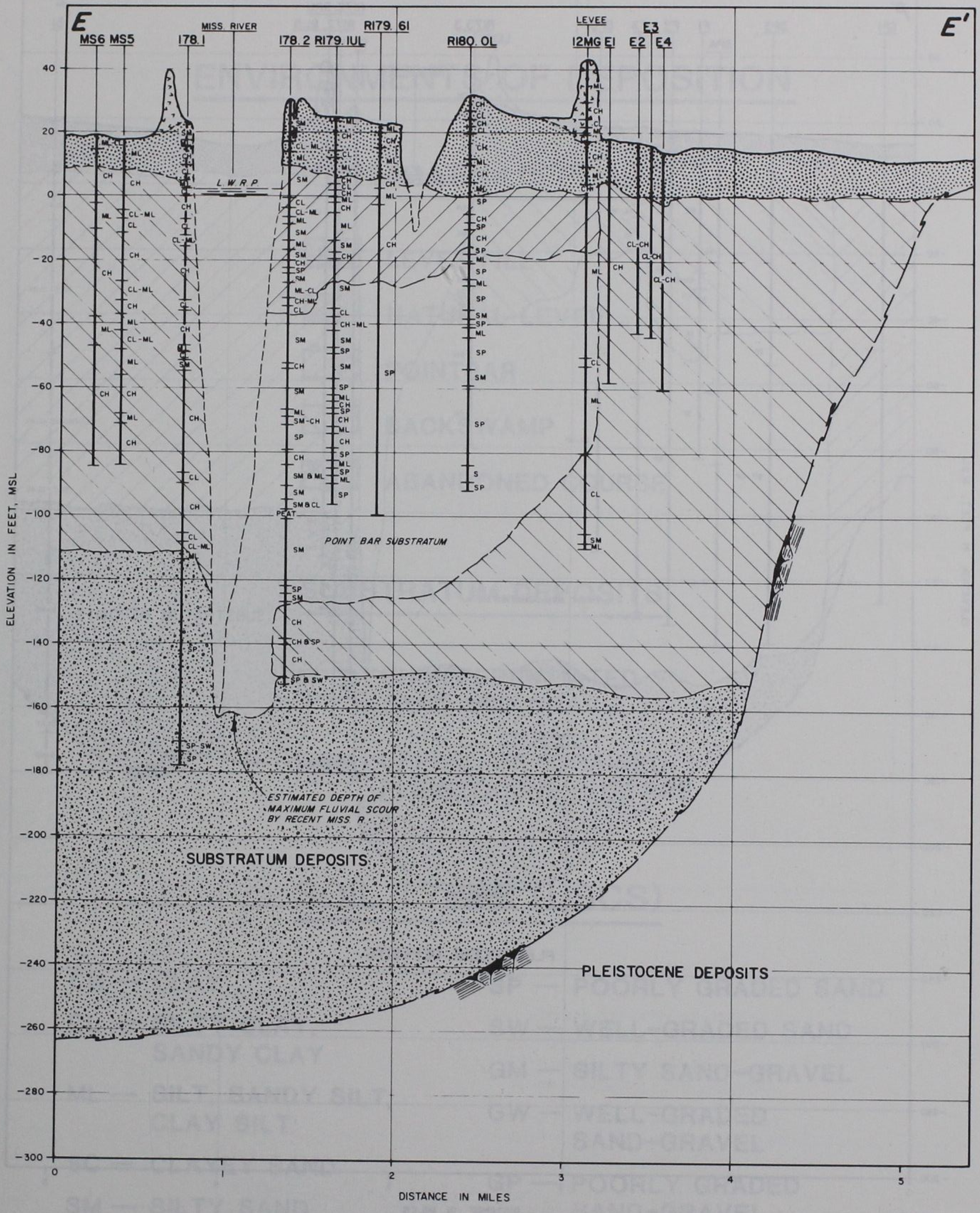


Figure 5e. Geologic cross-section E-E′ (see Figure 5g for legend)

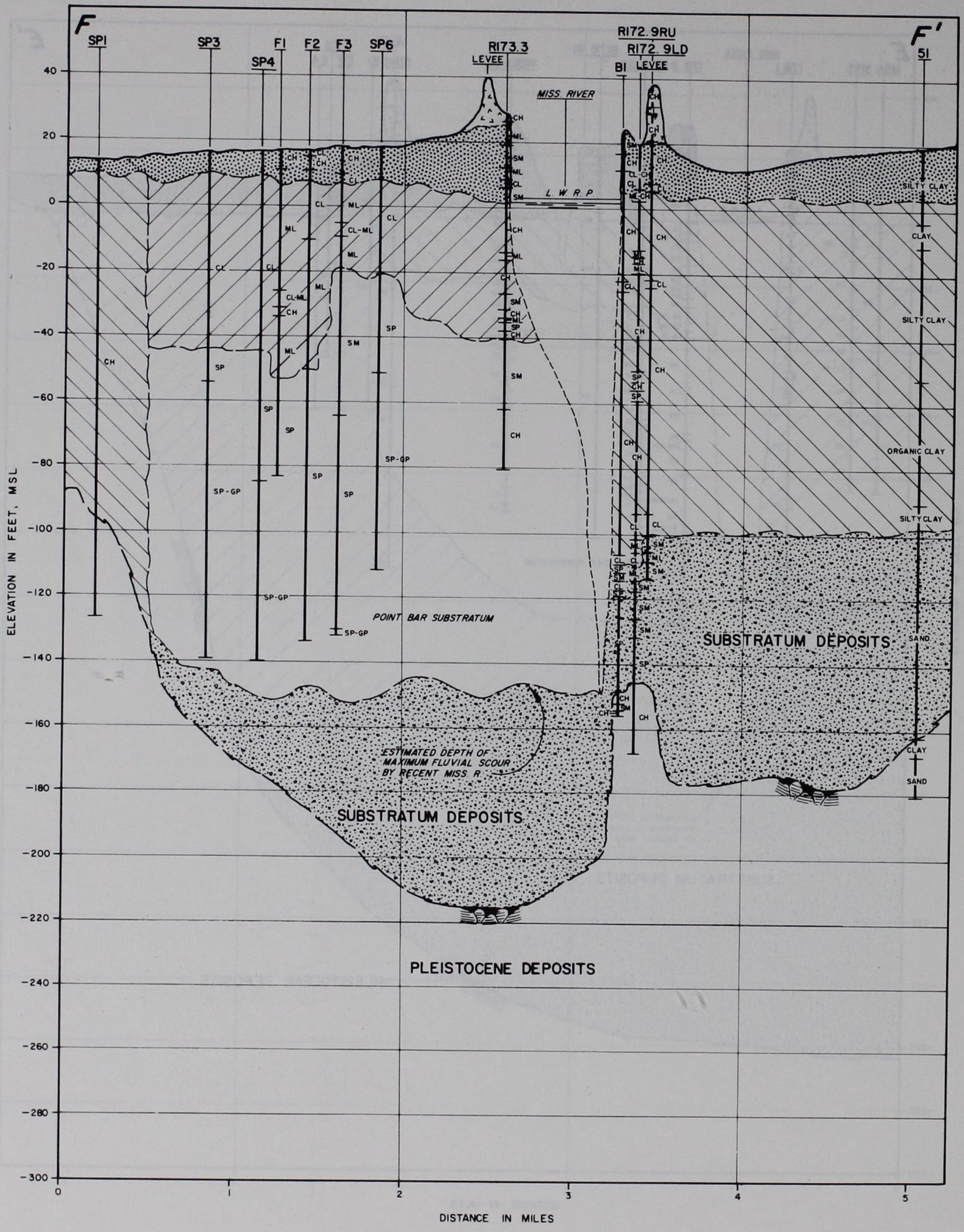


Figure 5f. Geologic cross-section F-F′ (see Figure 5g for legend)

LEGEND

ENVIRONMENTS OF DEPOSITION

TOPSTRATUM DEPOSITS

- ░ LEVEE FILL
- ▒ NATURAL LEVEE
- ▨ POINTBAR
- ▧ BACKSWAMP
- ▩ ABANDONED COURSE

SUBSTRATUM DEPOSITS

- ░ UNDIFFERENTIATED SAND AND GRAVEL
- ▓ UPPER FINE-GRAINED PLEISTOCENE SURFACE

SOIL TYPES (USCS)

CH — CLAY

CL — SILTY CLAY, SANDY CLAY

ML — SILT, SANDY SILT, CLAY SILT

SC — CLAYEY SAND

SM — SILTY SAND

SP — POORLY GRADED SAND

SW — WELL-GRADED SAND

GM — SILTY SAND-GRAVEL

GW — WELL-GRADED SAND-GRAVEL

GP — POORLY GRADED SAND-GRAVEL

Figure 5g. Legend for the geologic cross-sections

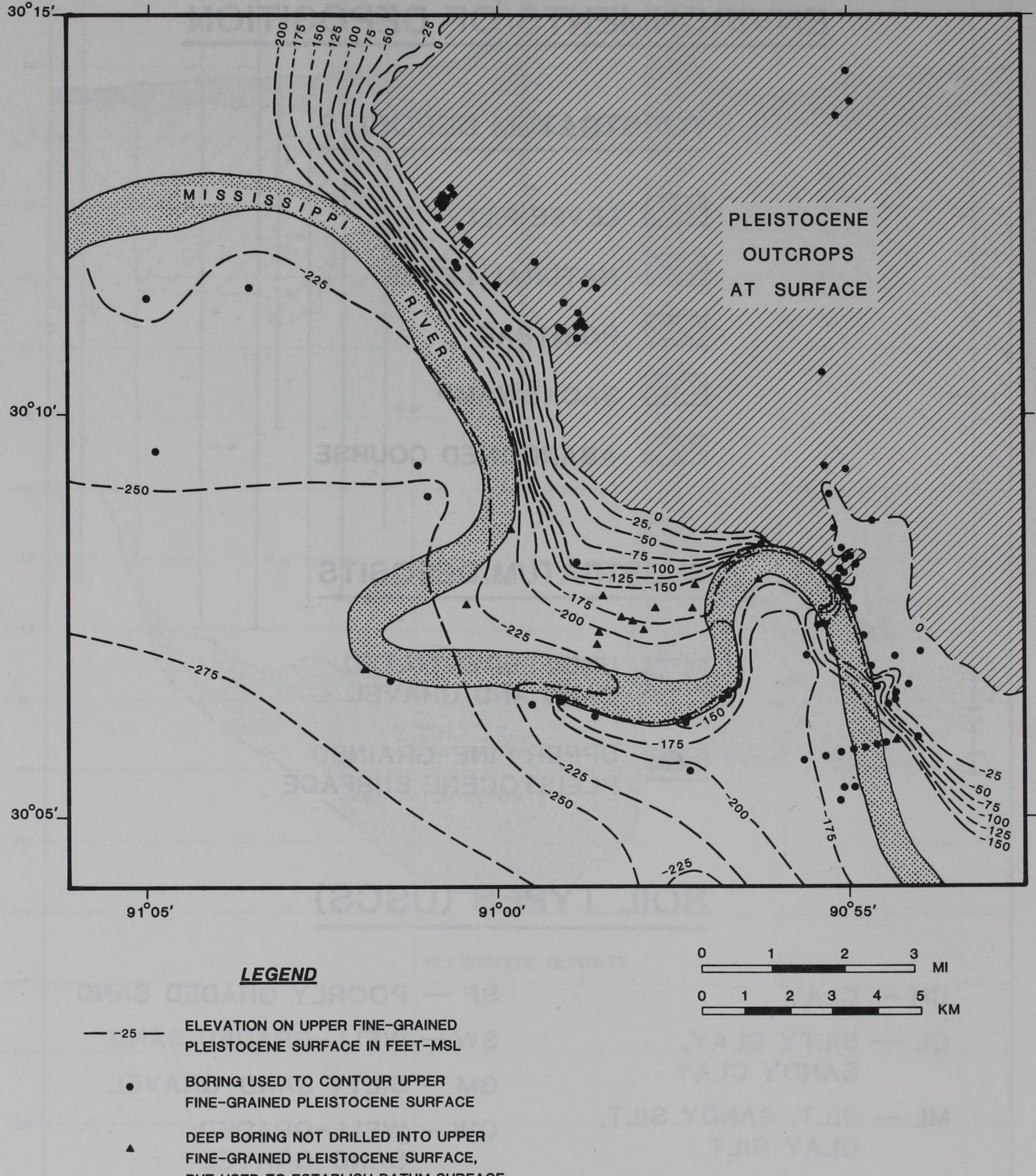


Figure 6. General contour map of the Pleistocene surface

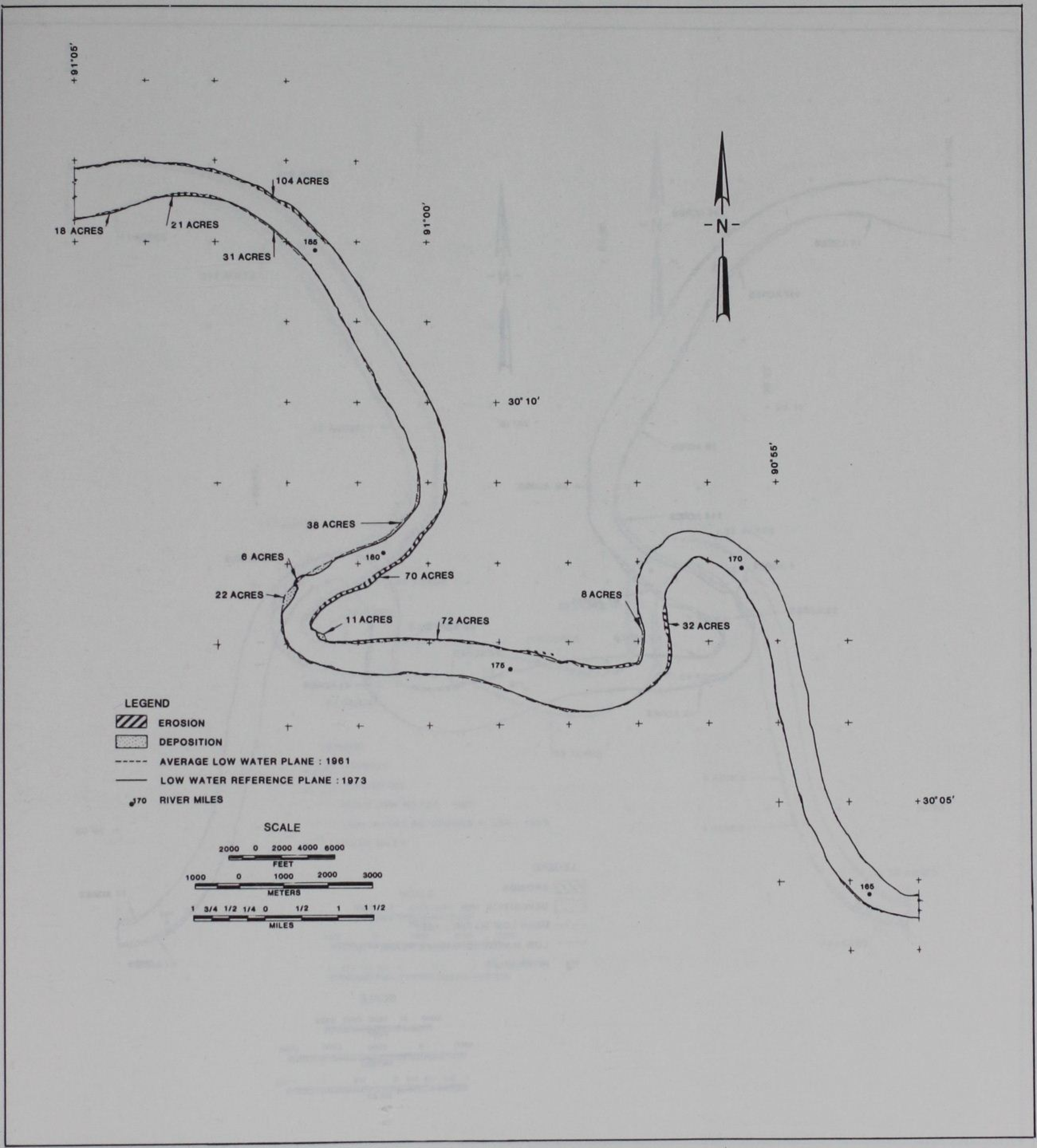


Figure 7a. River migration between 1961 and 1974

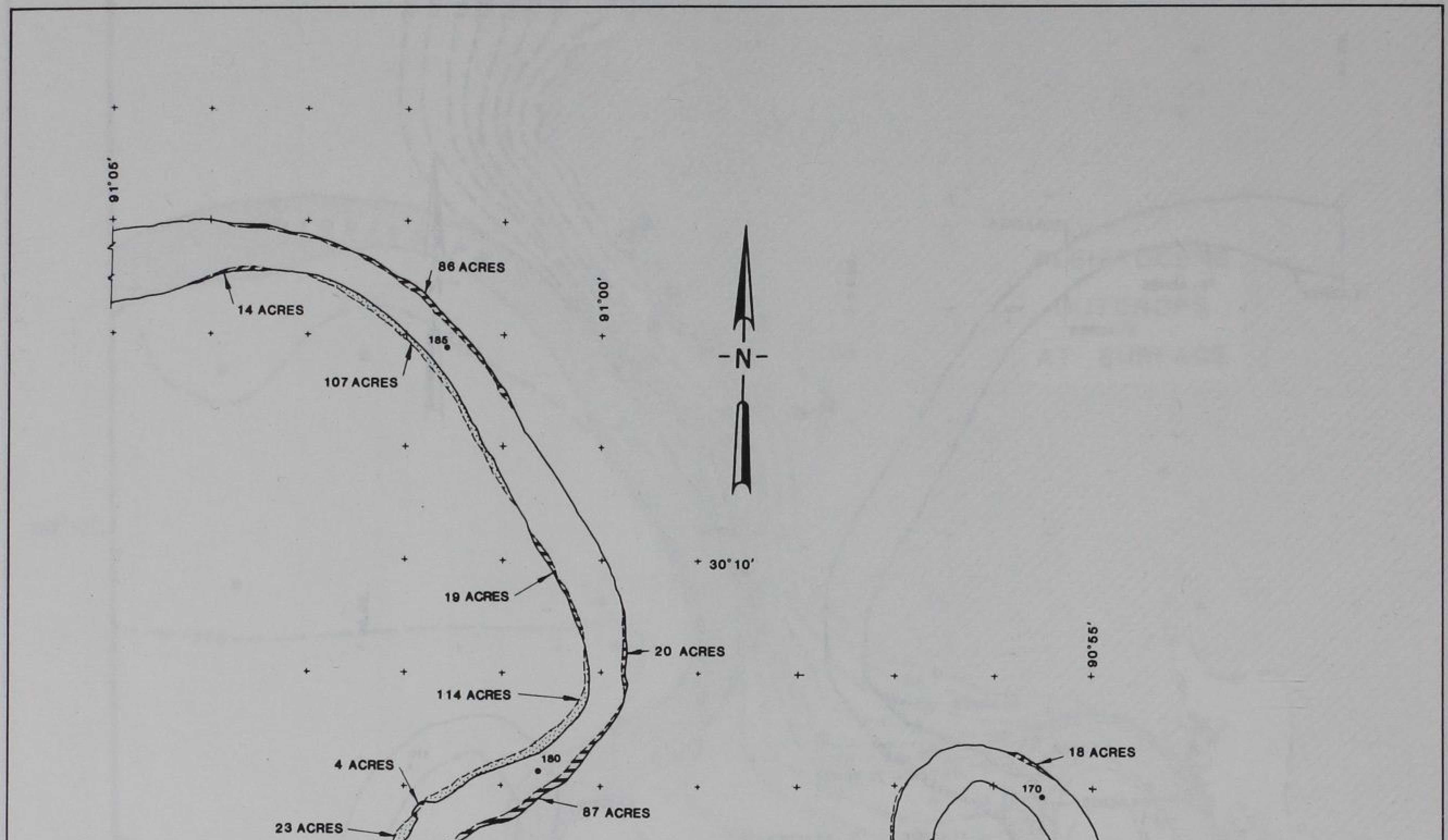


Figure 7b. River migration between 1951 and 1974

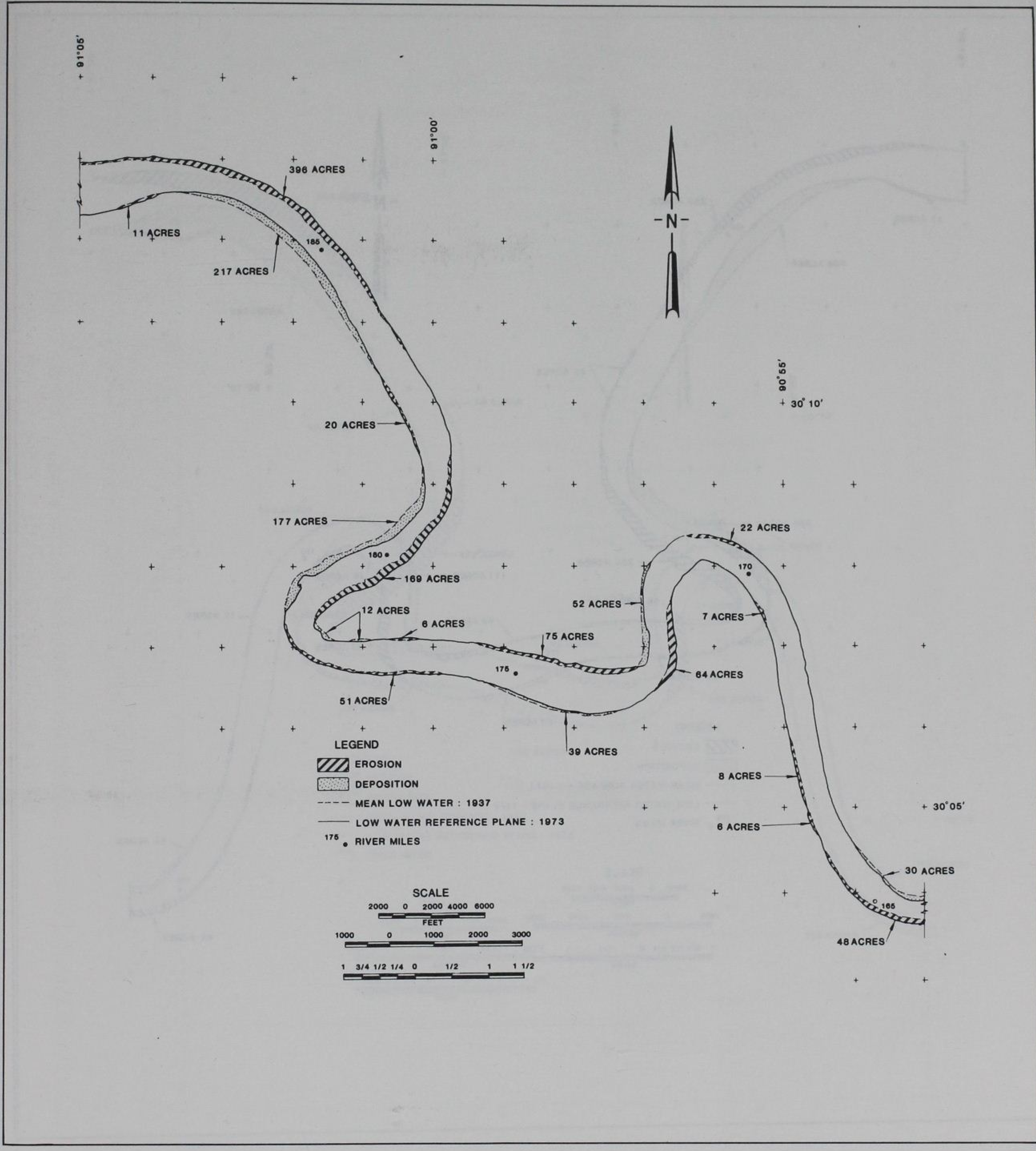


Figure 7c. River migration between 1937 and 1974

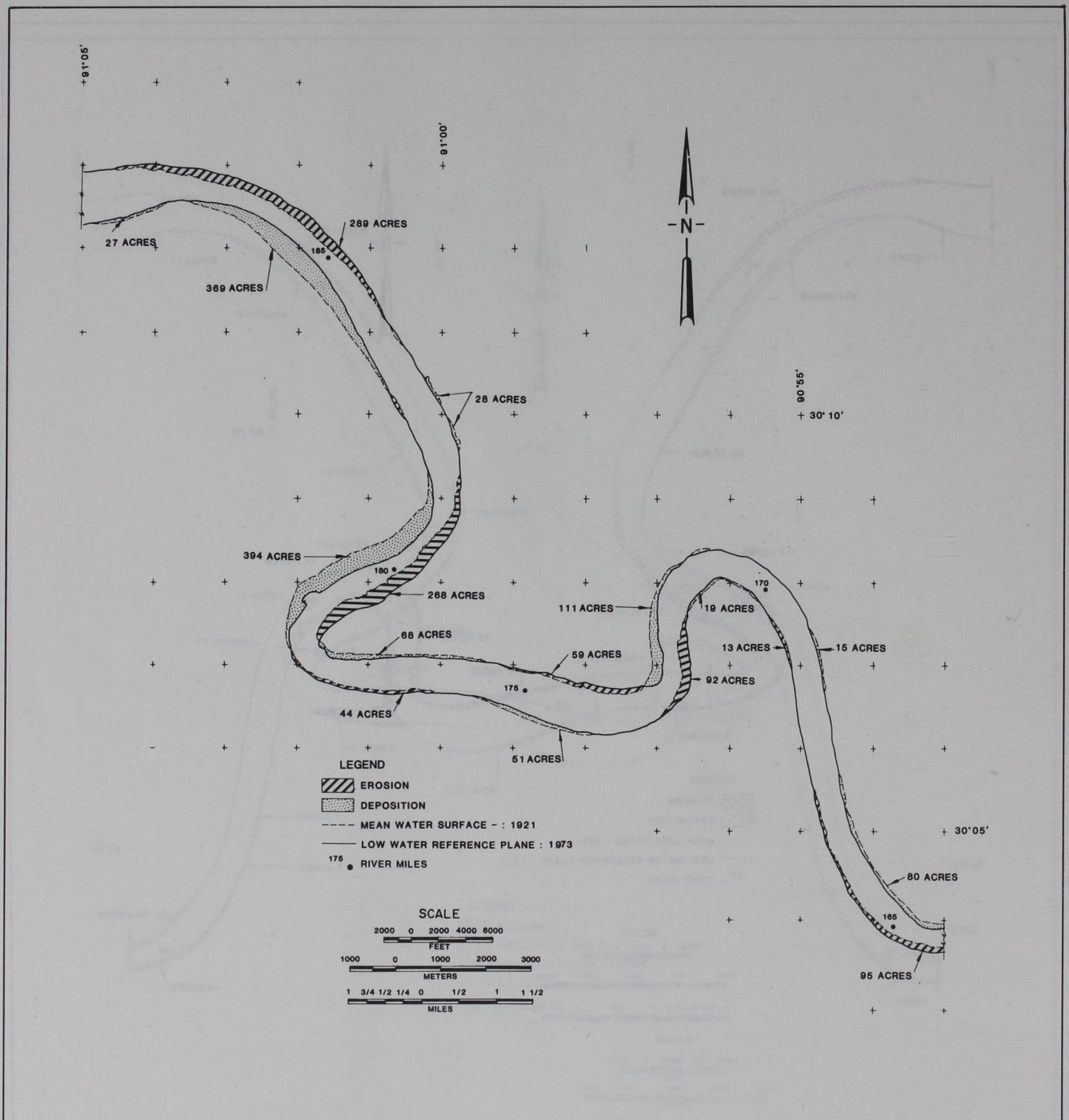


Figure 7d. River migration between 1921 and 1974

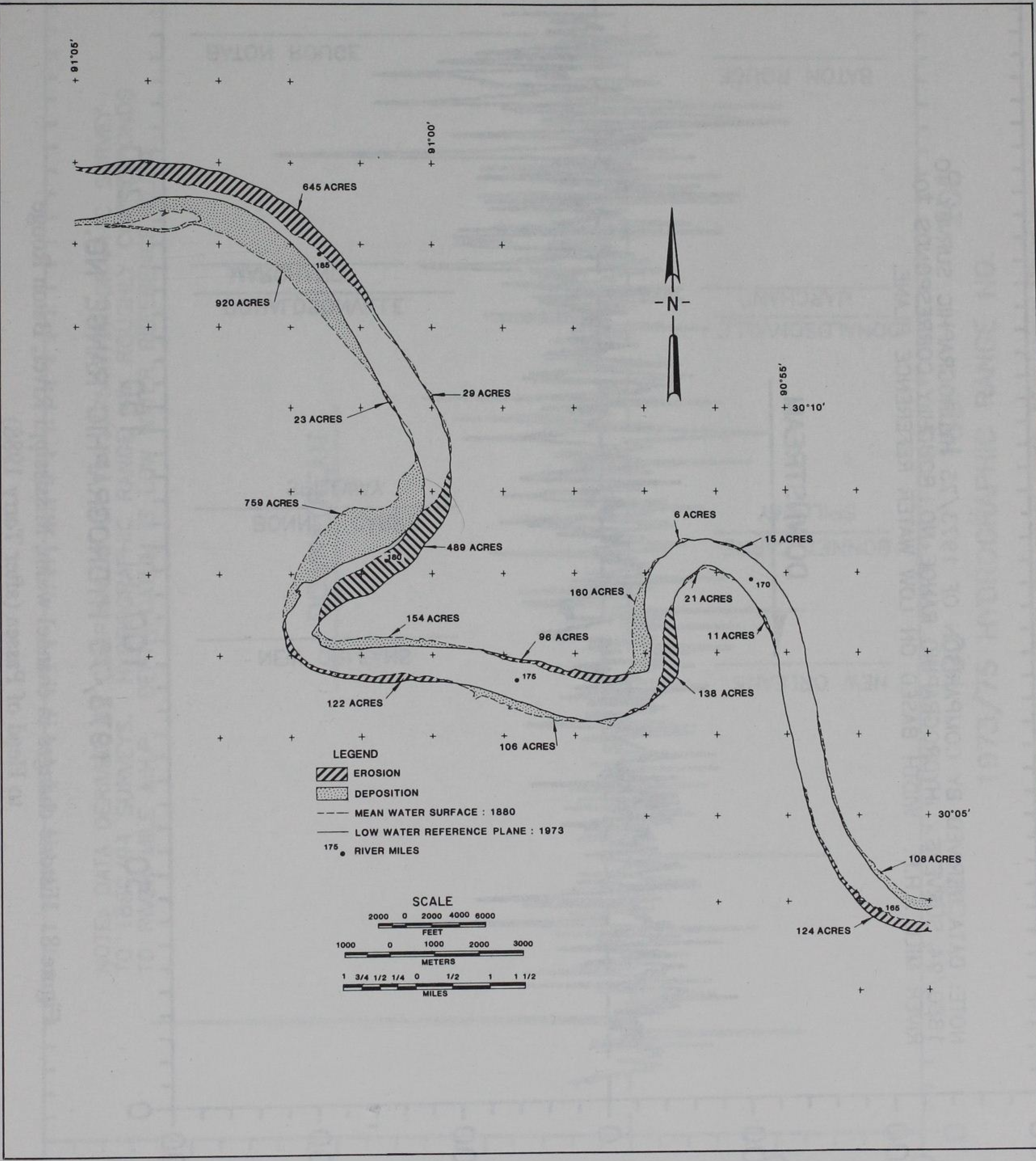
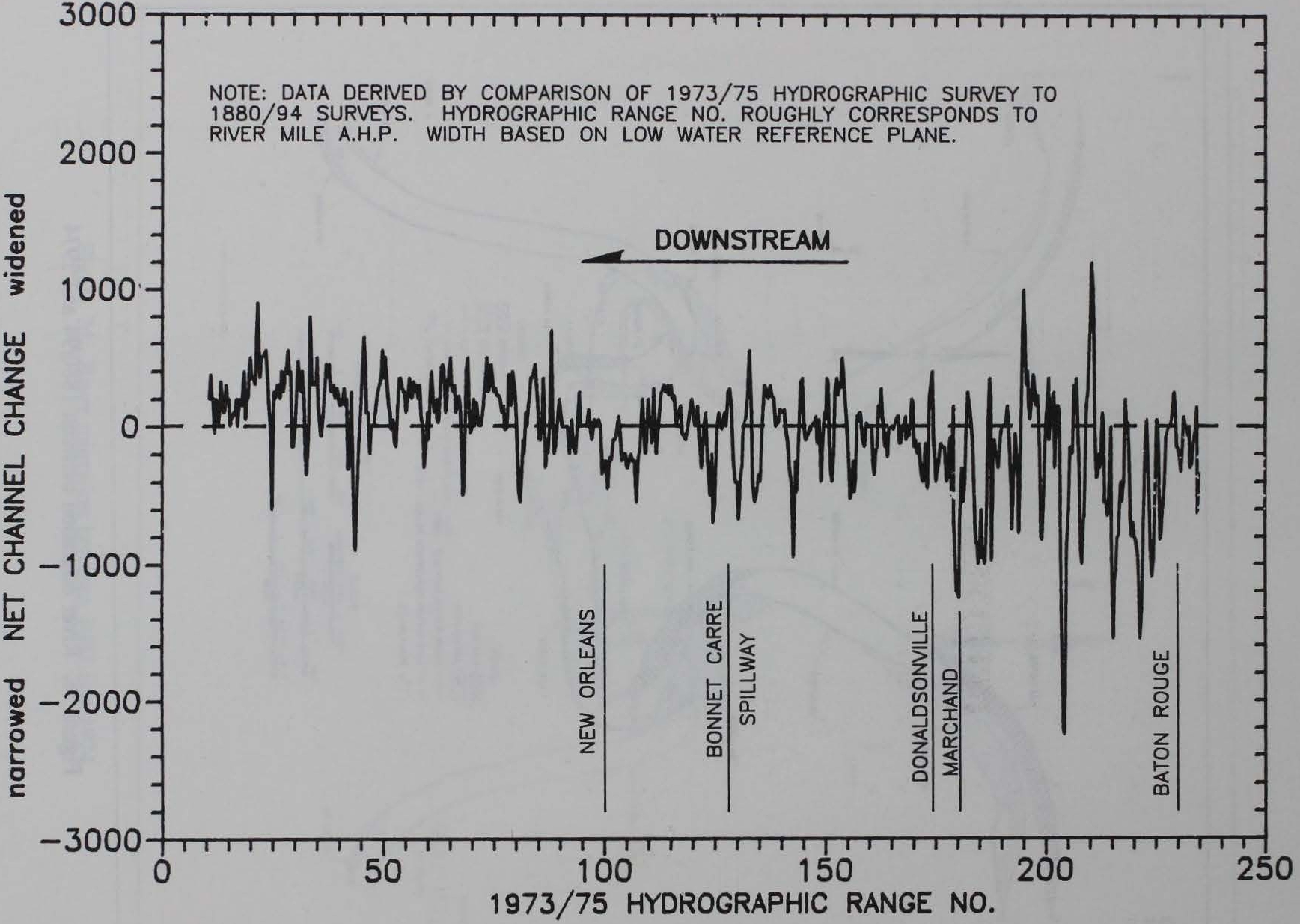


Figure 7e. River migration between 1880/94 and 1974



NOTE: DATA DERIVED BY COMPARISON OF 1973/75 HYDROGRAPHIC SURVEY TO 1880/94 SURVEYS. HYDROGRAPHIC RANGE NO. ROUGHLY CORRESPONDS TO RIVER MILE A.H.P. WIDTH BASED ON LOW WATER REFERENCE PLANE.

Figure 8. Historic changes in channel width, Mississippi River, Baton Rouge to Head of Passes (after Torry 1988)

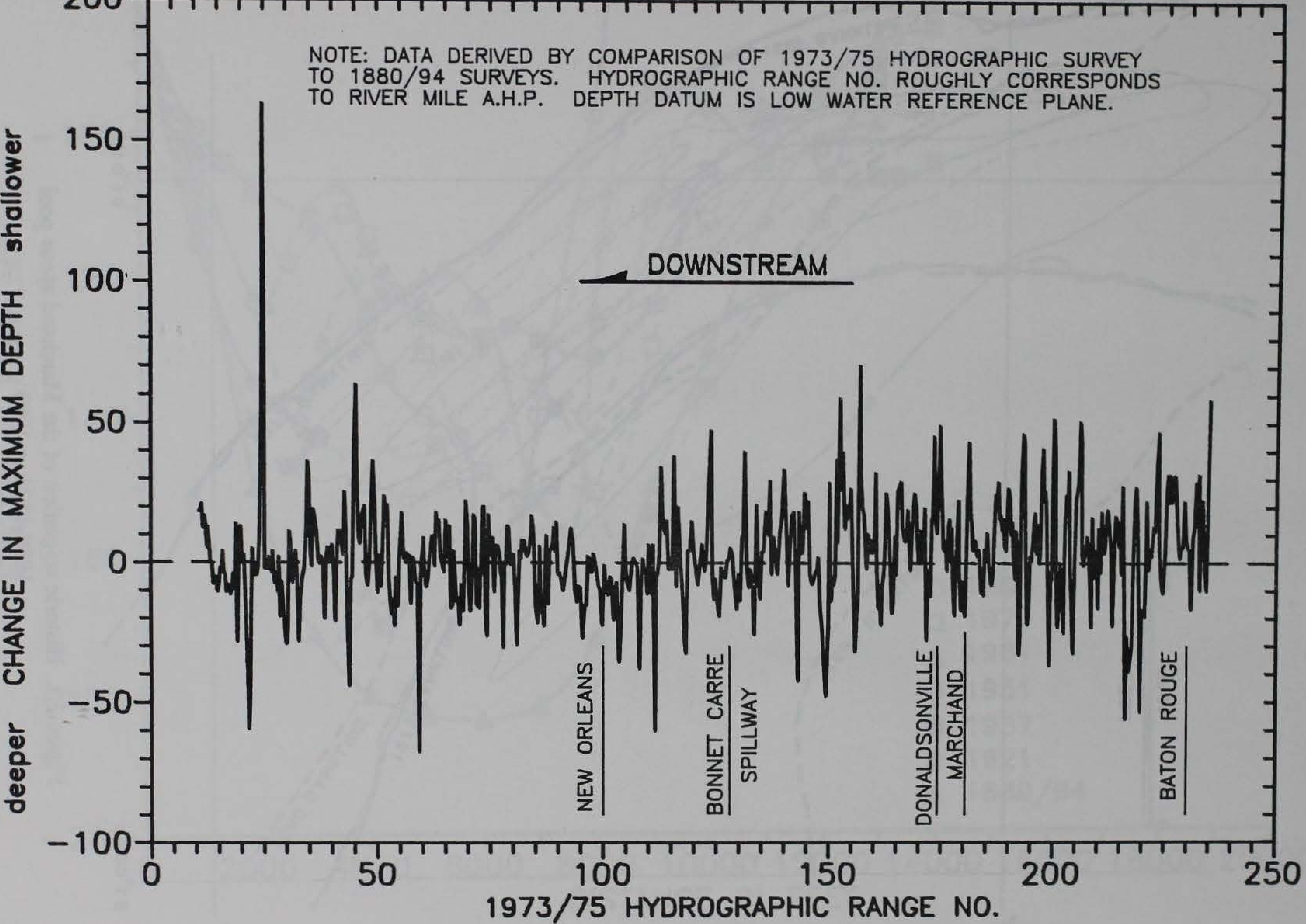


Figure 9. Historic changes in channel maximum depth, Mississippi River, Baton Rouge to Head of Passes (after Torry 1988)

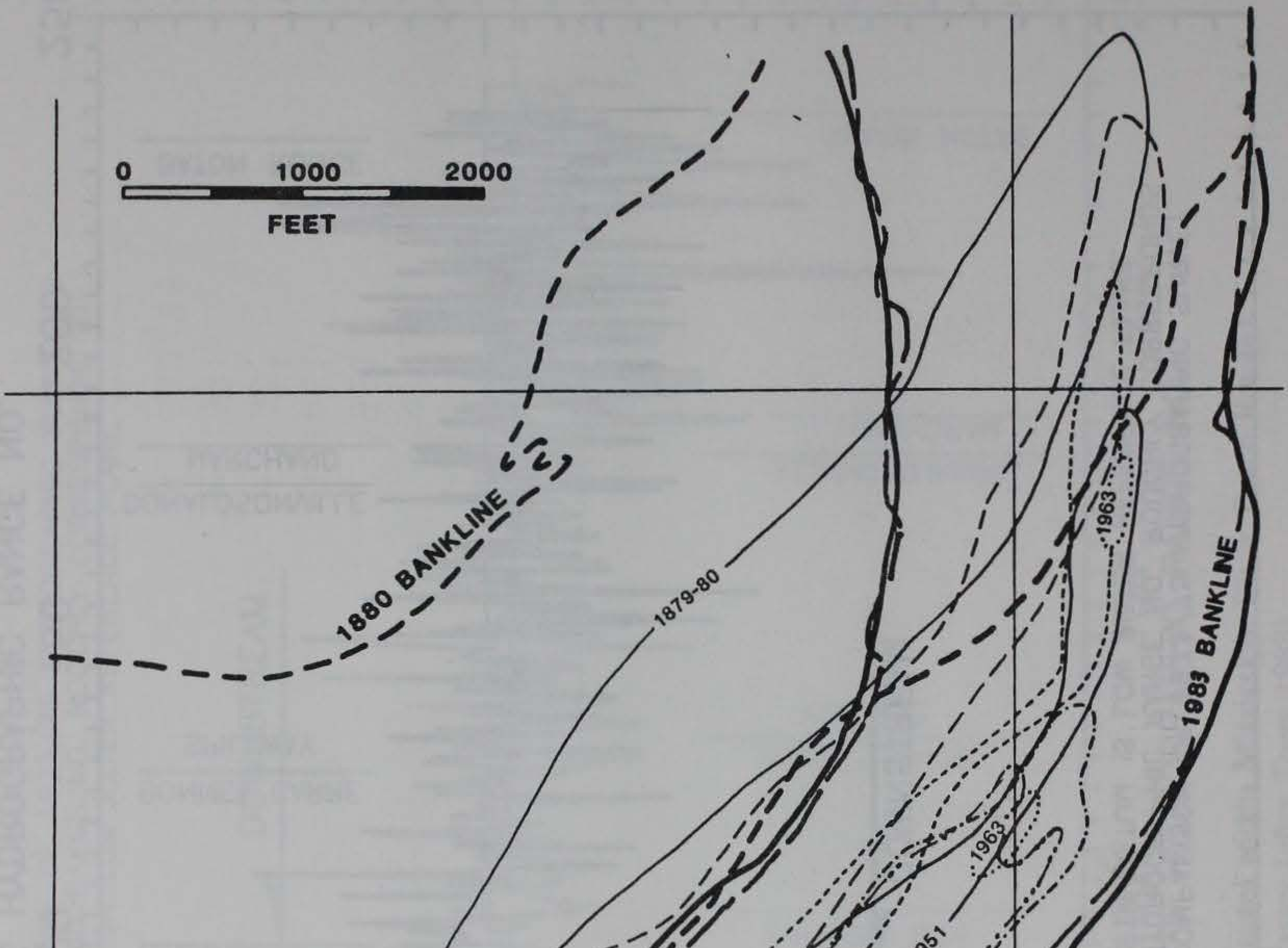


Figure 10. Historic migration of the Marchand scour pool
1880-1894 to 1983

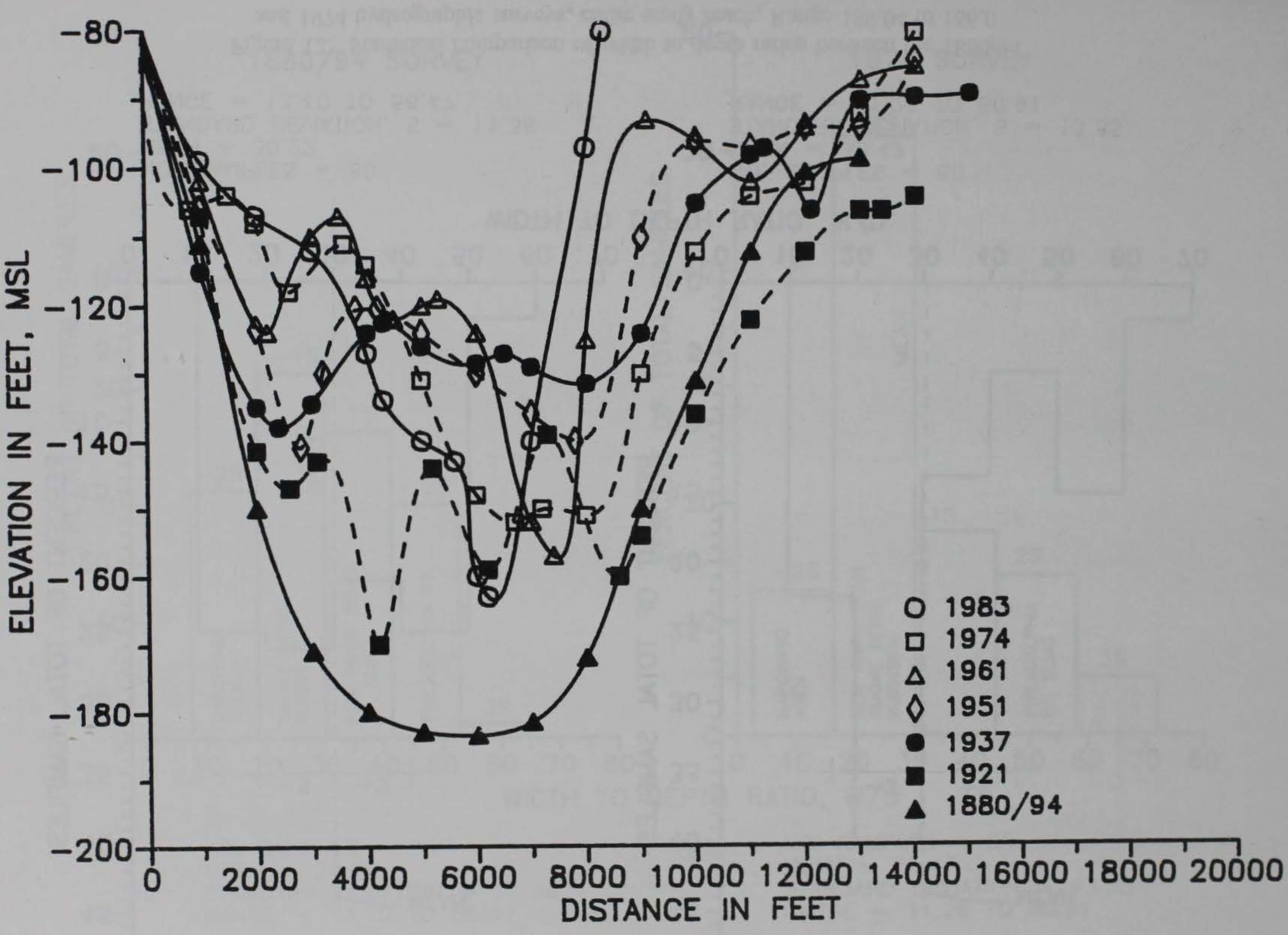
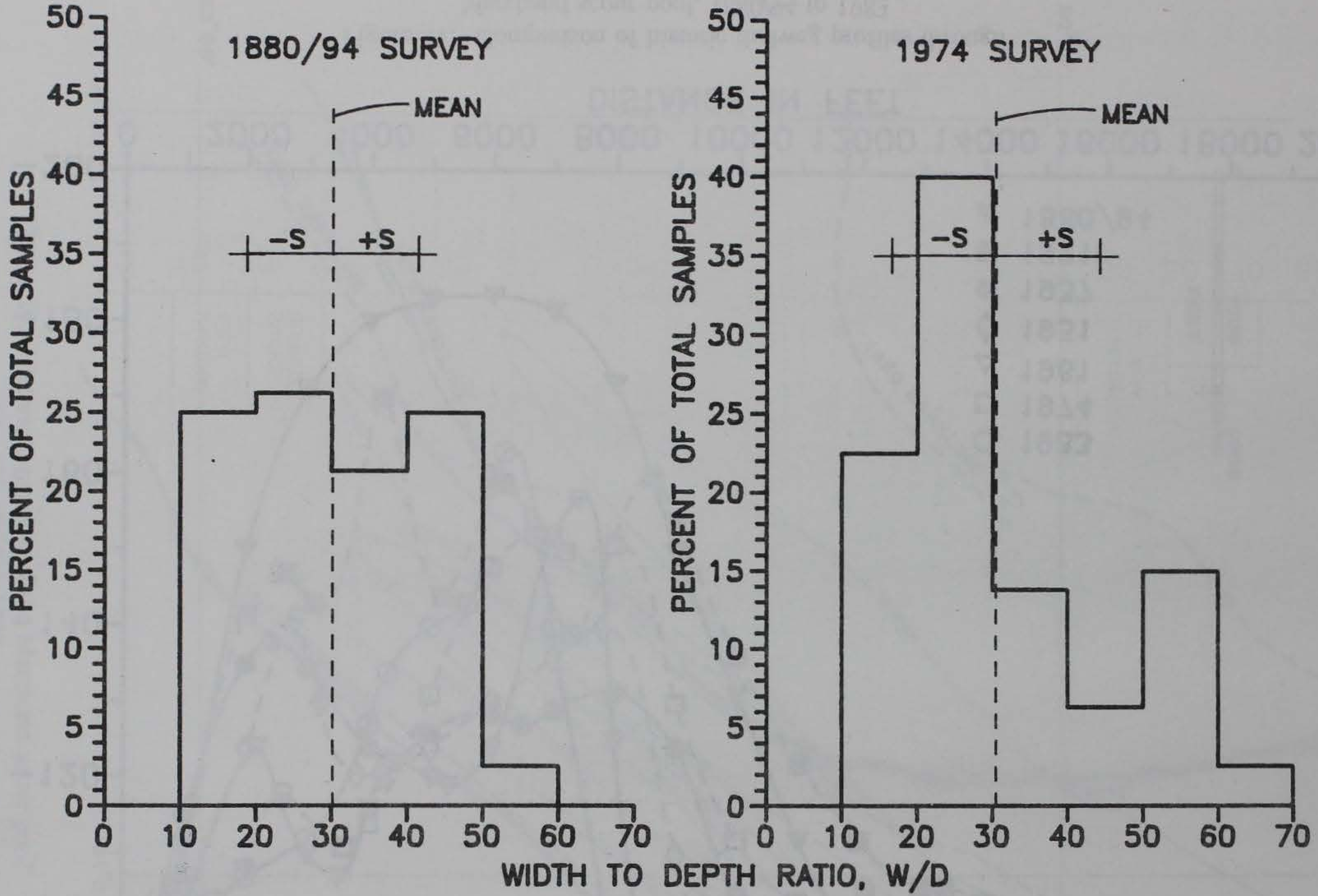


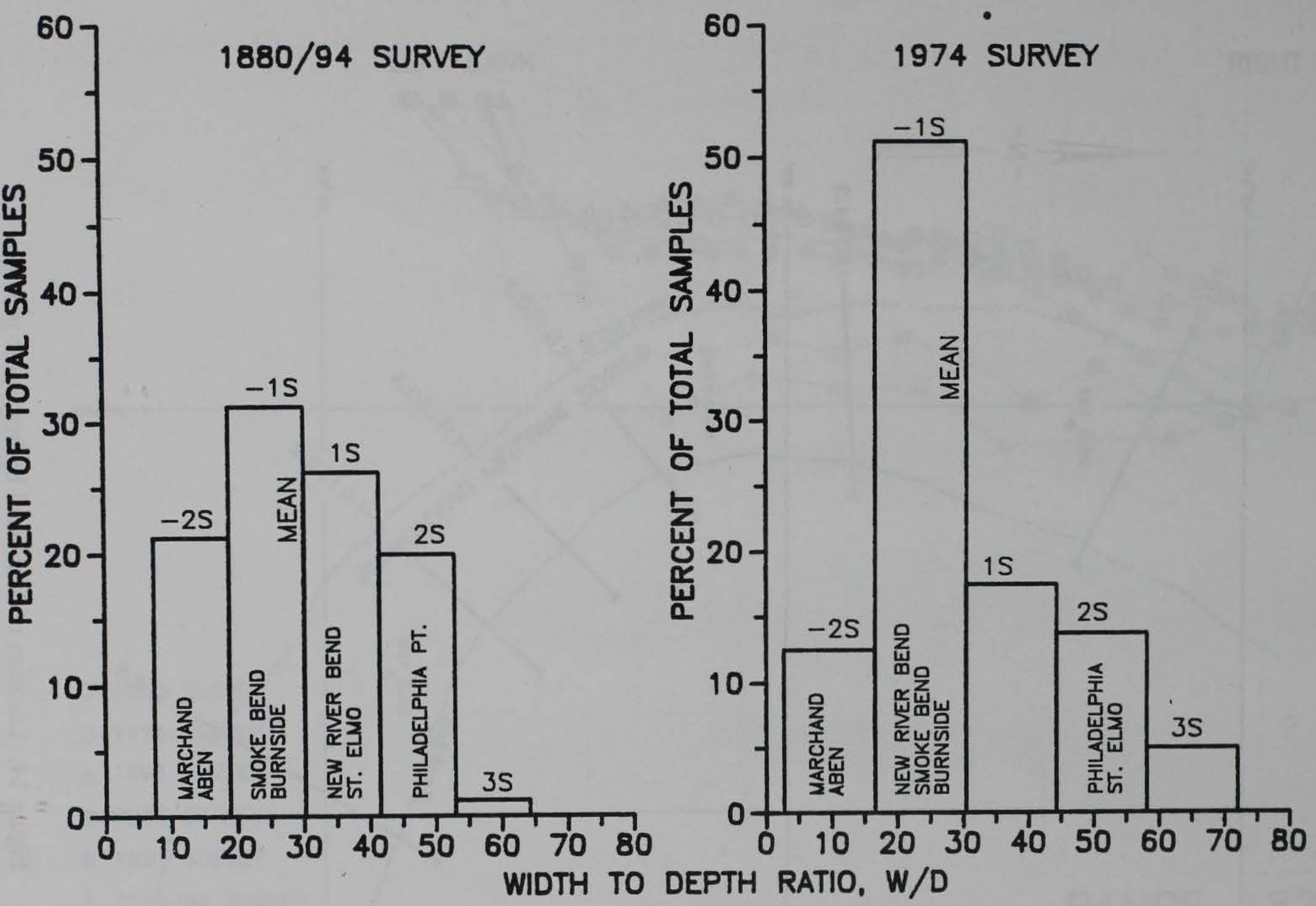
Figure 11. Comparison of historic thalweg profiles through Marchand scour pool, 1880/94 to 1983



NO. SAMPLES = 80
MEAN = 30.22
STANDARD DEVIATION, S = 11.36
RANGE = 13.10 TO 56.47

NO. SAMPLES = 80
MEAN = 30.47
STANDARD DEVIATION, S = 13.85
RANGE = 11.26 TO 60.91

Figure 12. Statistical comparison of width to depth ratios between the 1880/94 and 1974 hydrographic surveys, entire study reach, Range 189.04 to 166.0



NO. SAMPLES = 80
MEAN = 30.22
STANDARD DEVIATION = 11.36
RANGE = 13.10 TO 56.47

NO. SAMPLES = 80
MEAN = 30.47
STANDARD DEVIATION = 13.85
RANGE = 11.26 TO 60.91

Figure 13. Relative statistical positions of revetment reaches by average value of W/D. 1880/94 and 1974 hydrographic surveys

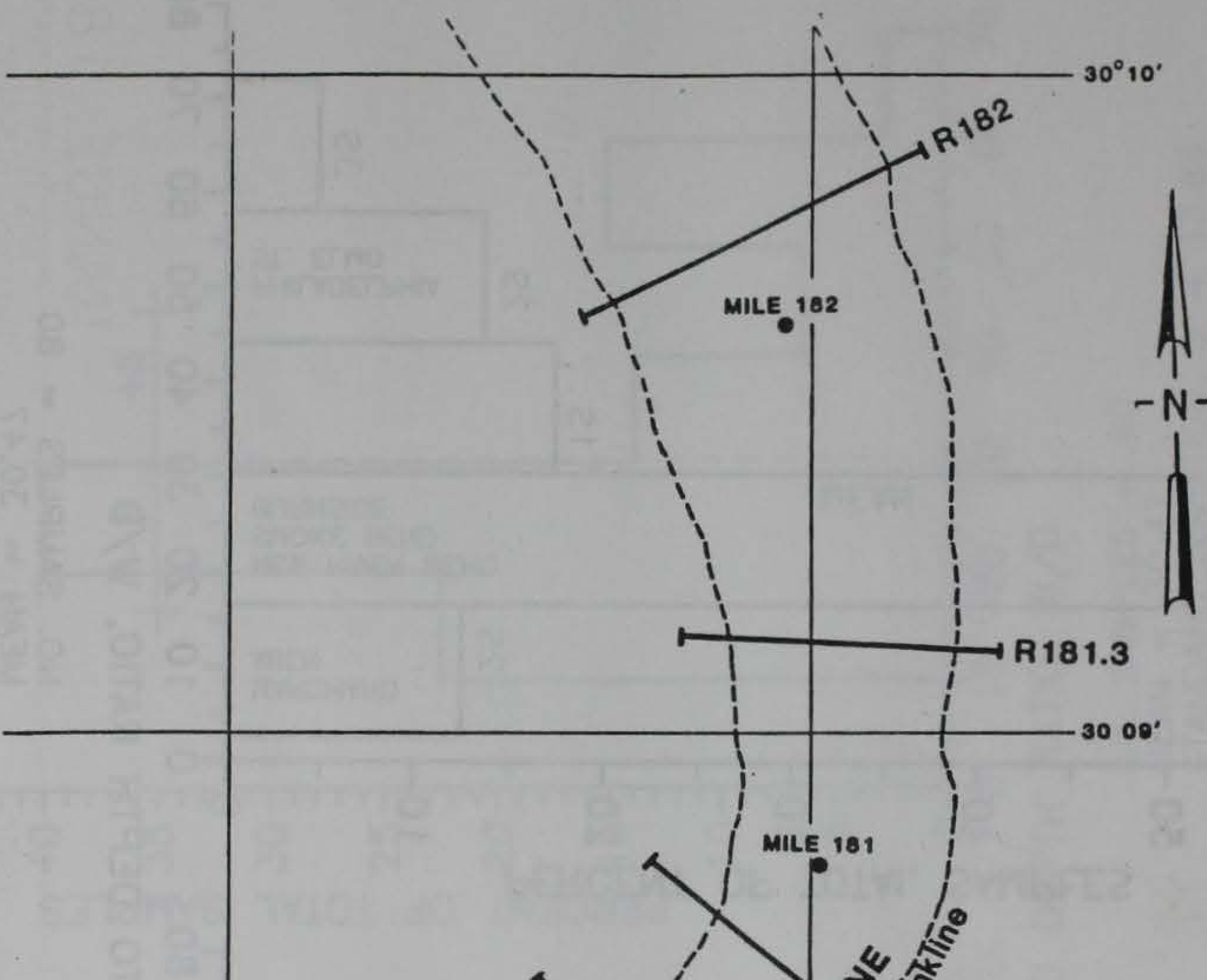


Figure 14. Location of Marchand hydrographic profiles

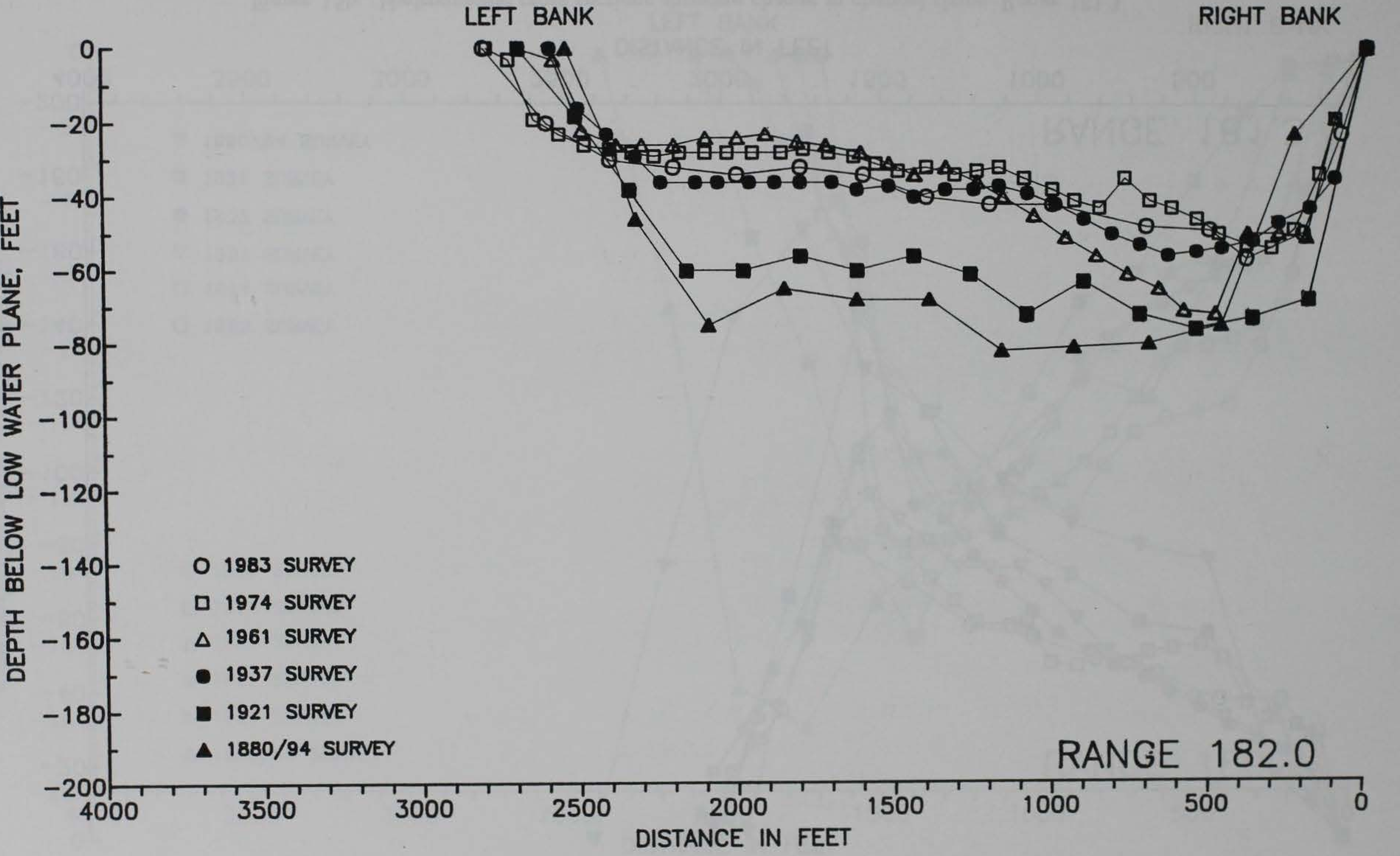


Figure 15a. Hydrographic cross sections showing change in channel shape, Range 182.0

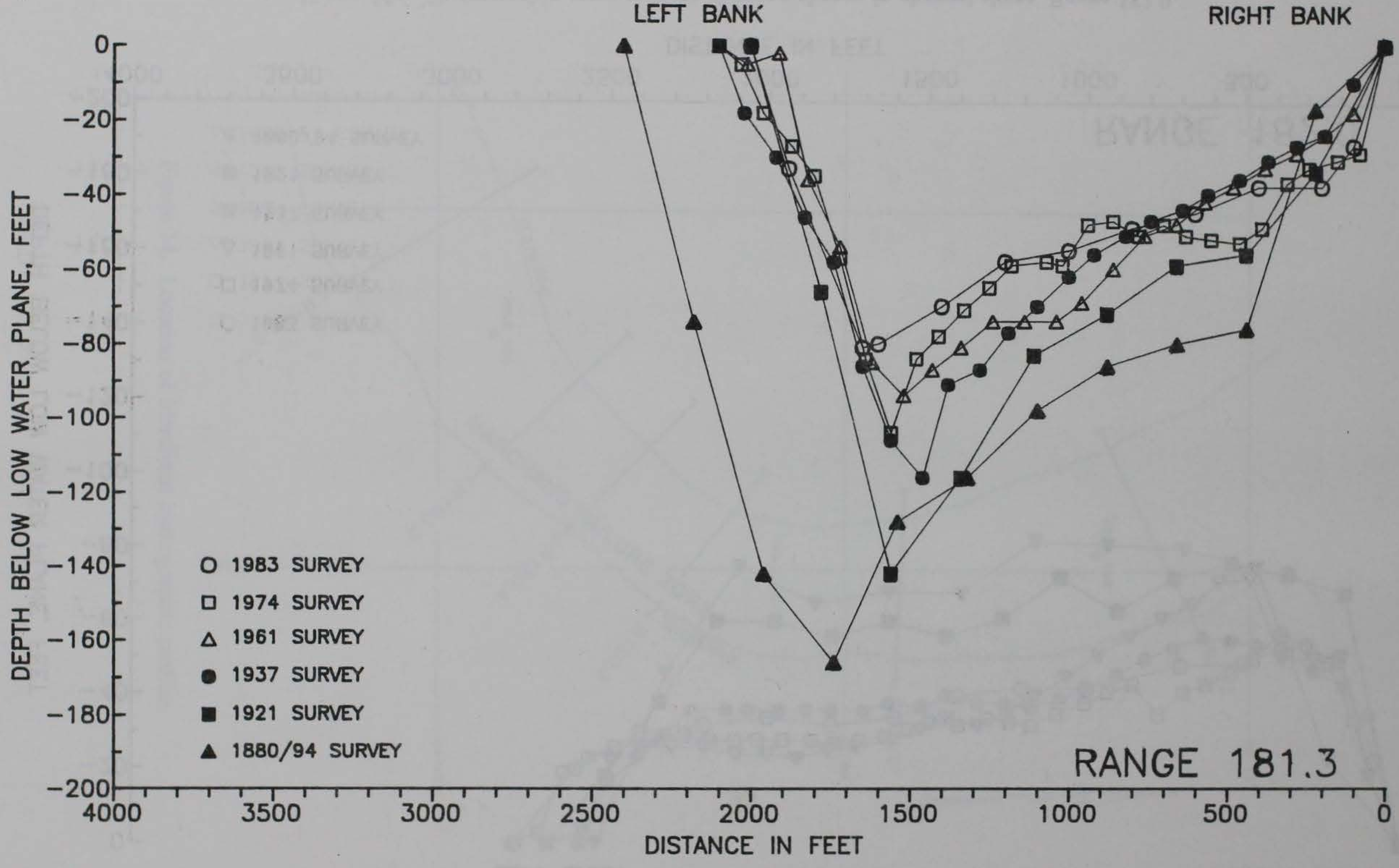


Figure 15b. Hydrographic cross sections showing change in channel shape, Range 181.3

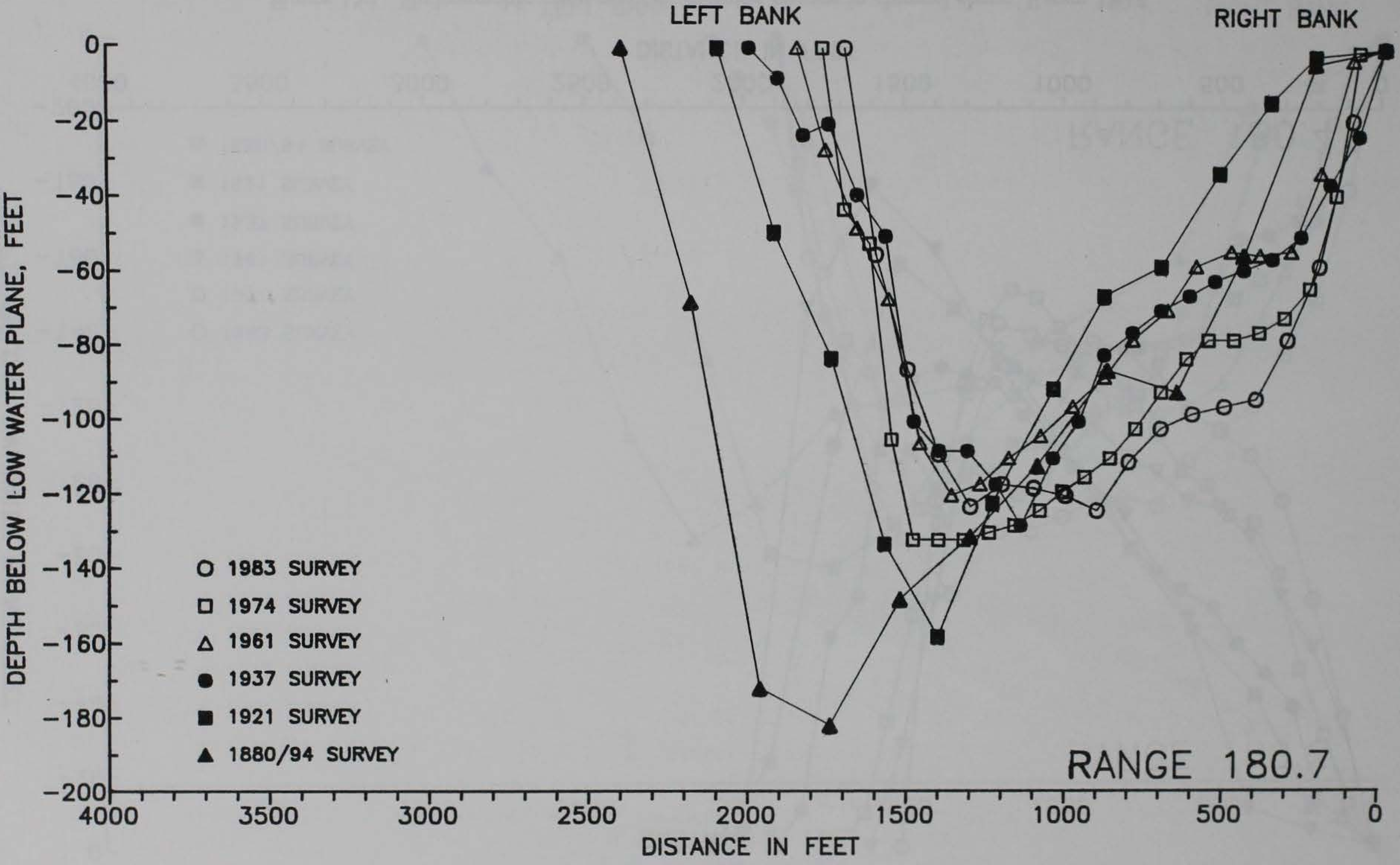


Figure 15c. Hydrographic cross sections showing change in channel shape, Range 180.7

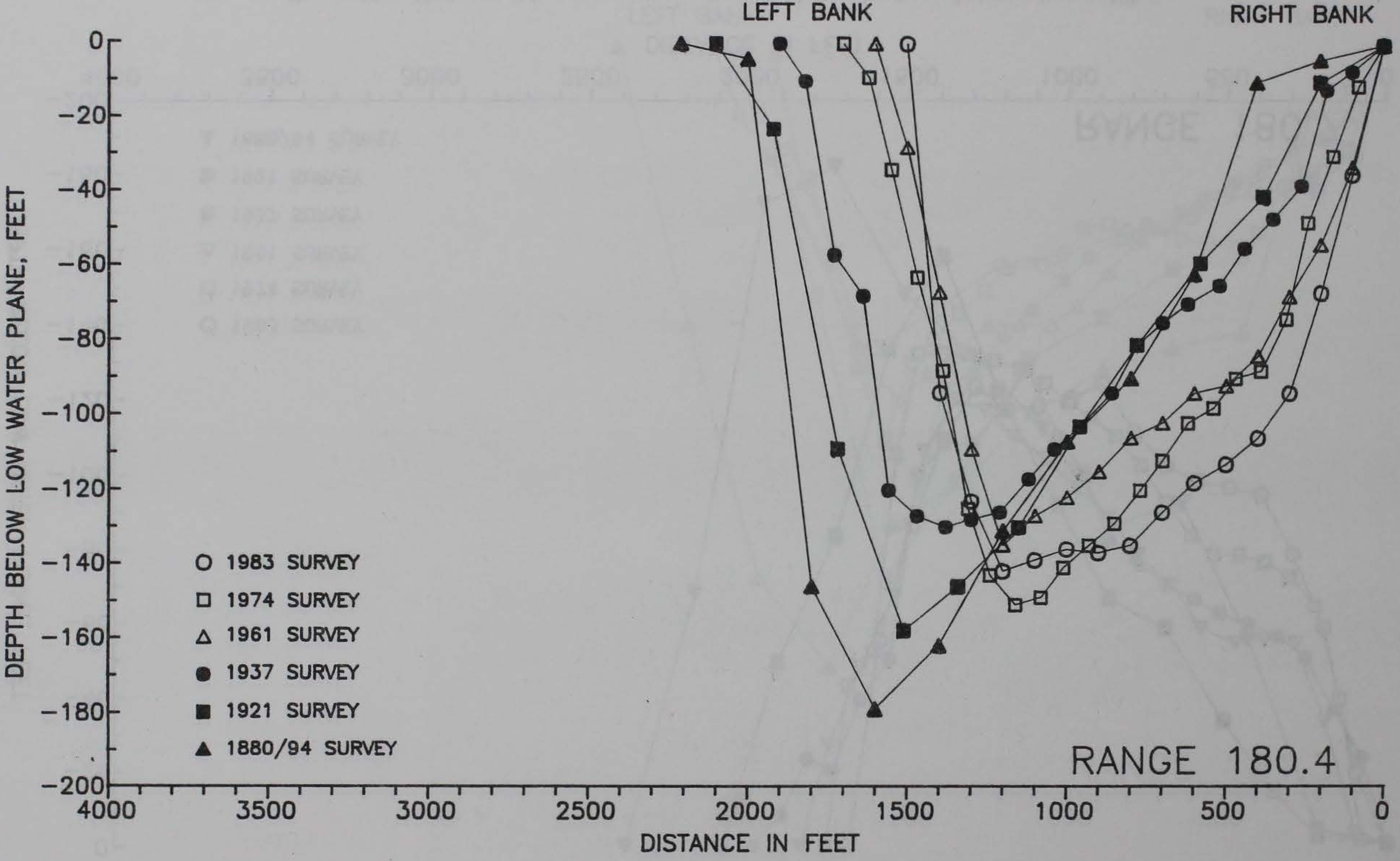


Figure 15d. Hydrographic cross sections showing change in channel shape, Range 180.4

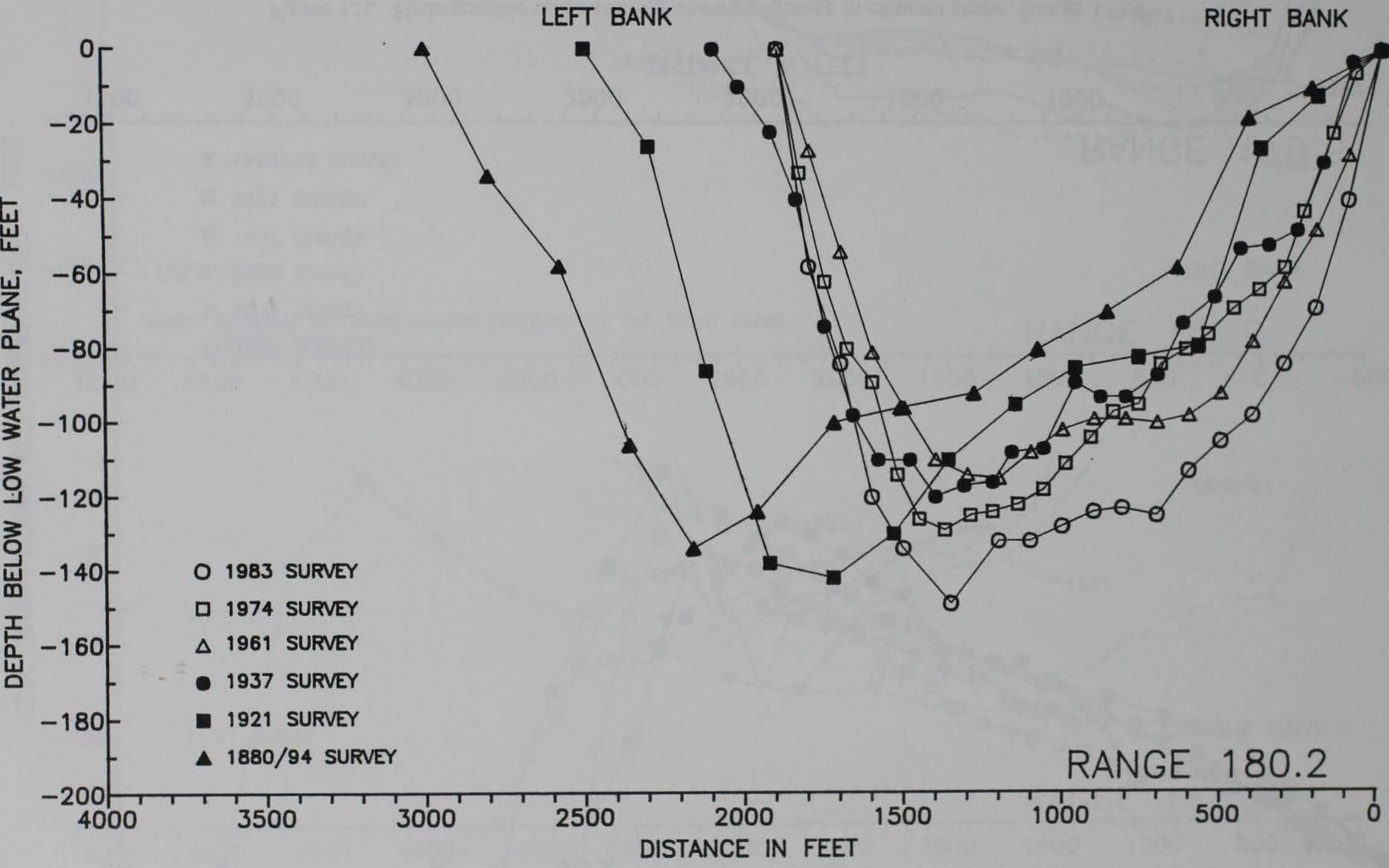


Figure 15e. Hydrographic cross sections showing change in channel shape, Range 180.2

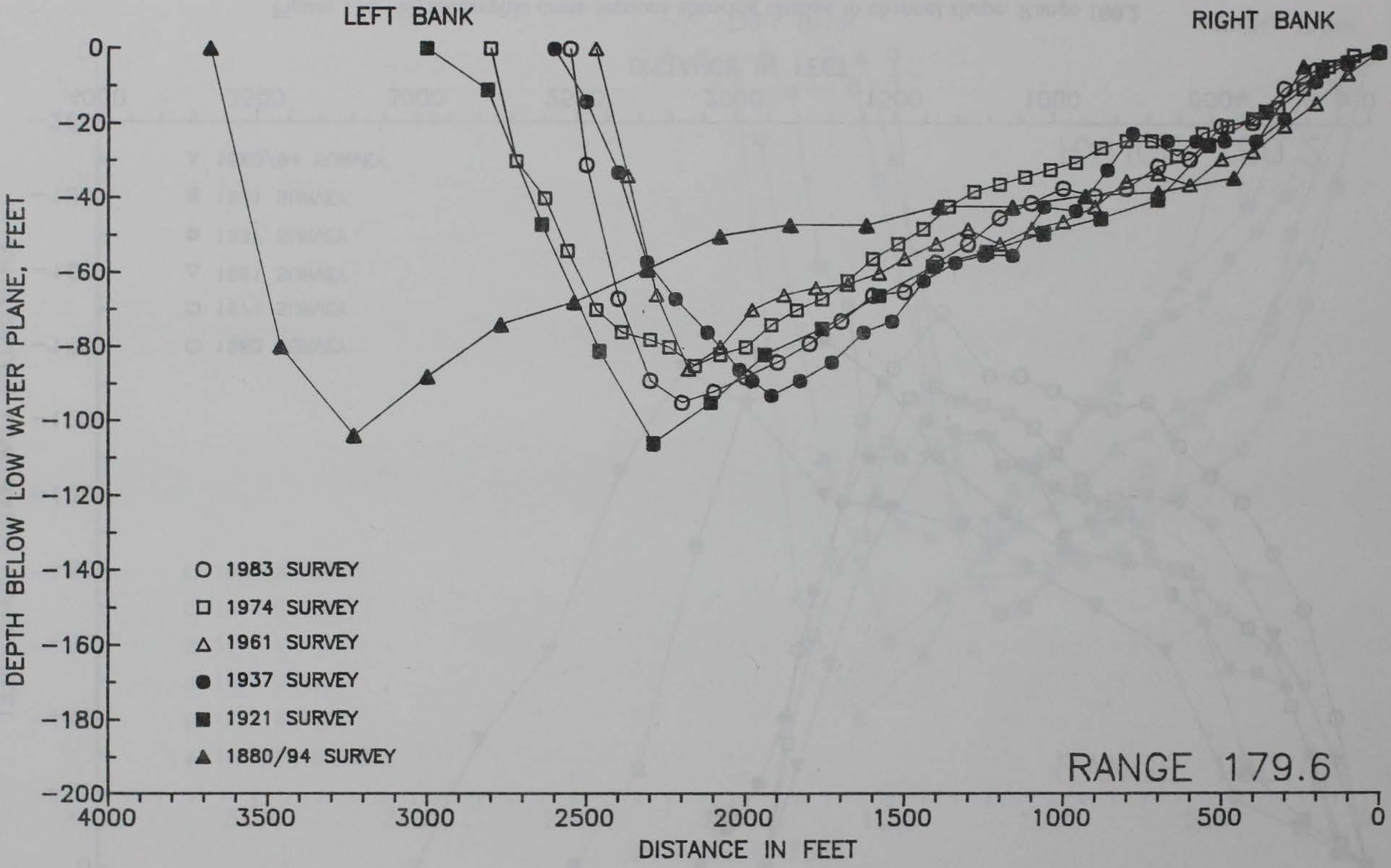


Figure 15f. Hydrographic cross sections showing change in channel shape, Range 179.6

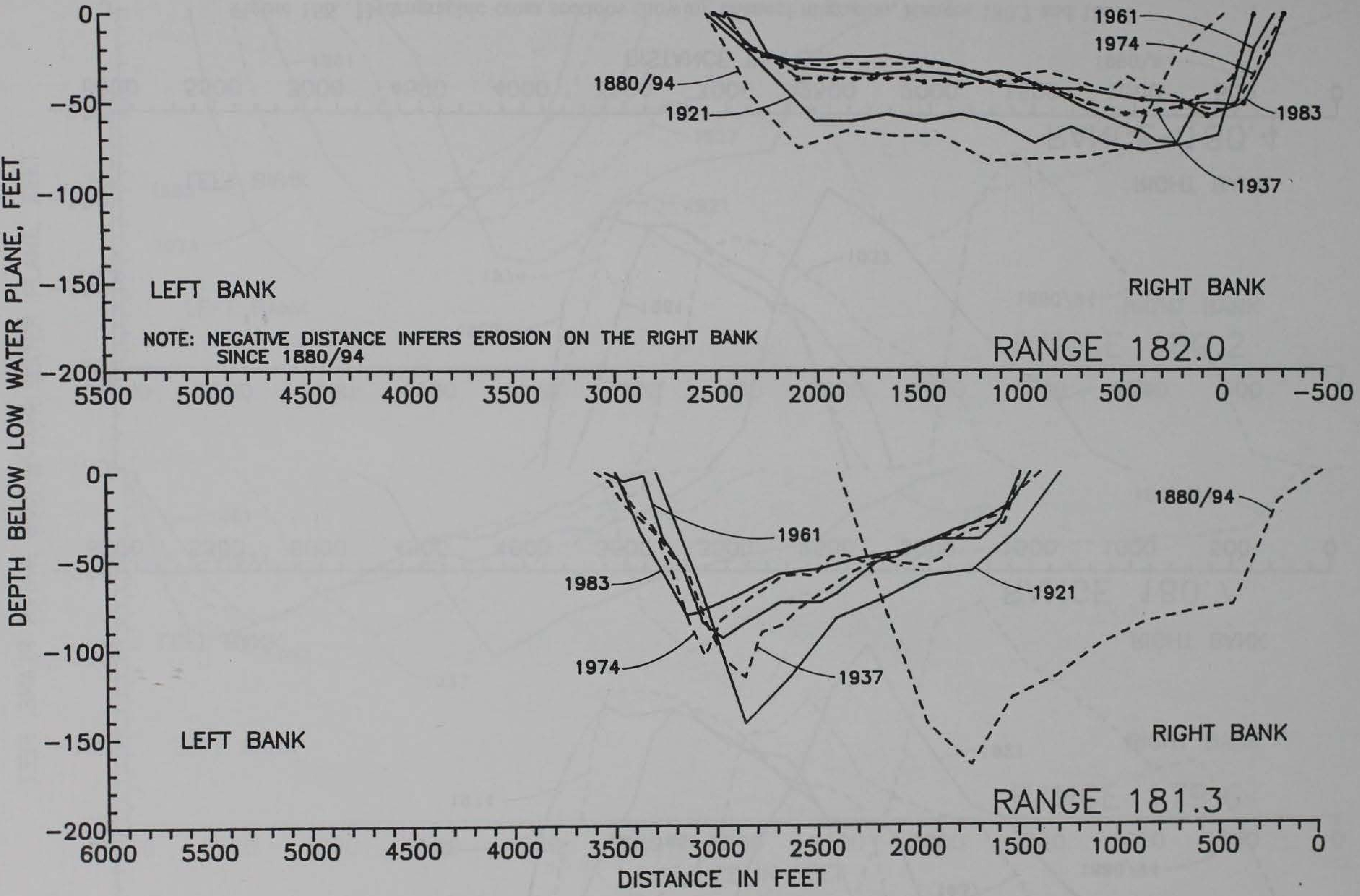


Figure 16a. Hydrographic cross sections showing channel migration, Ranges 182.0 and 181.3

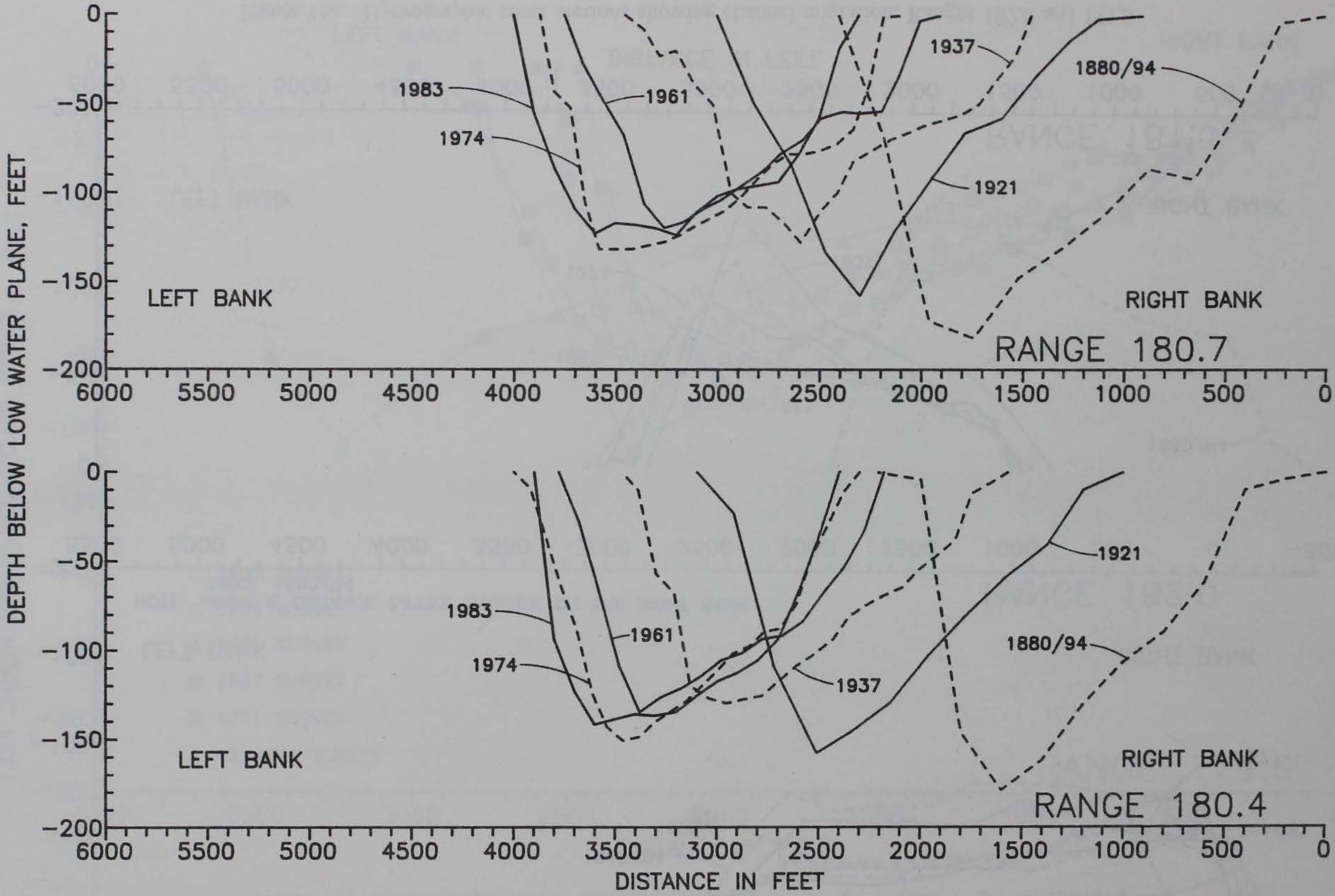


Figure 16b. Hydrographic cross sections showing channel migration, Ranges 180.7 and 180.4

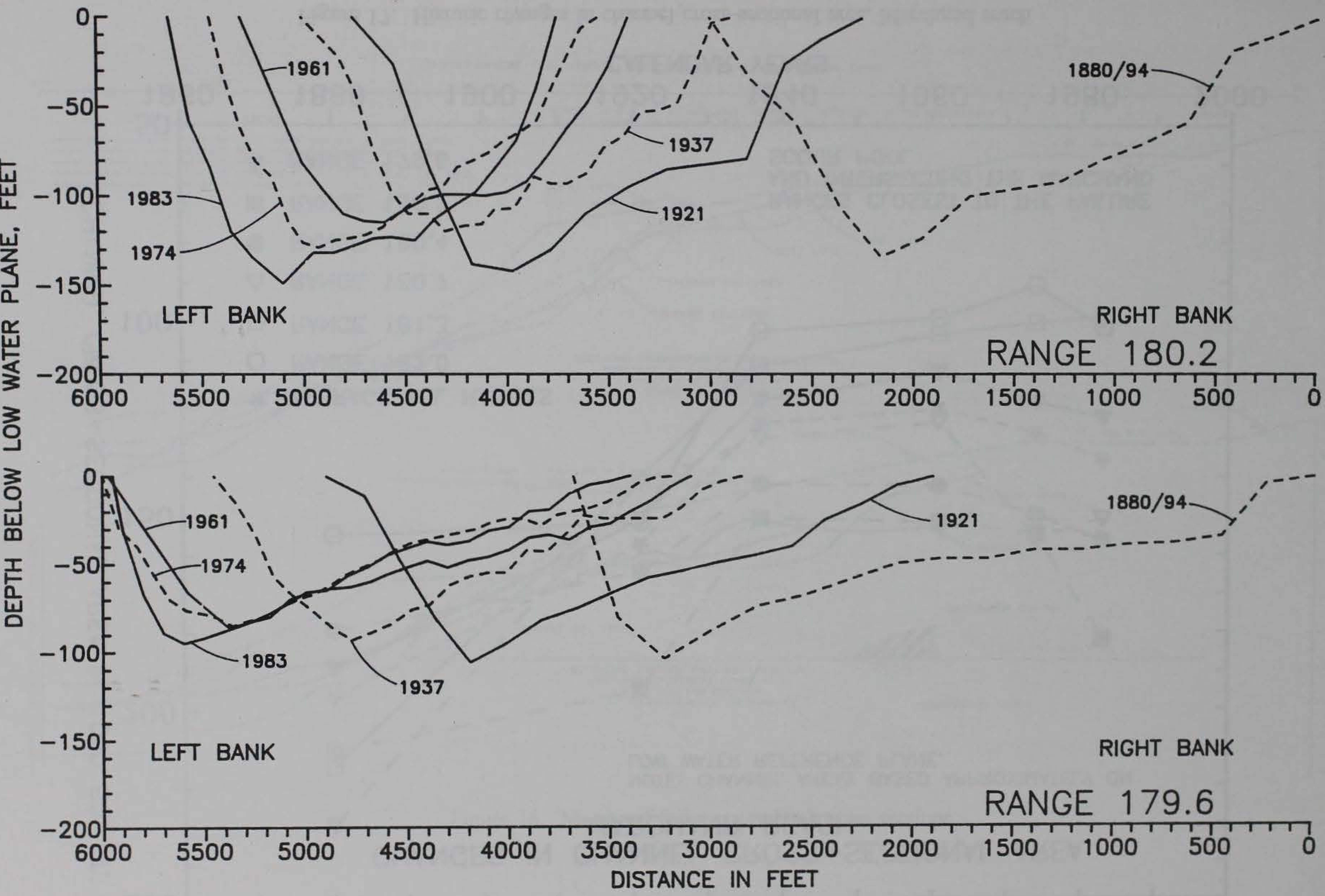


Figure 16c. Hydrographic cross sections showing channel migration, Ranges 180.2 and 179.6

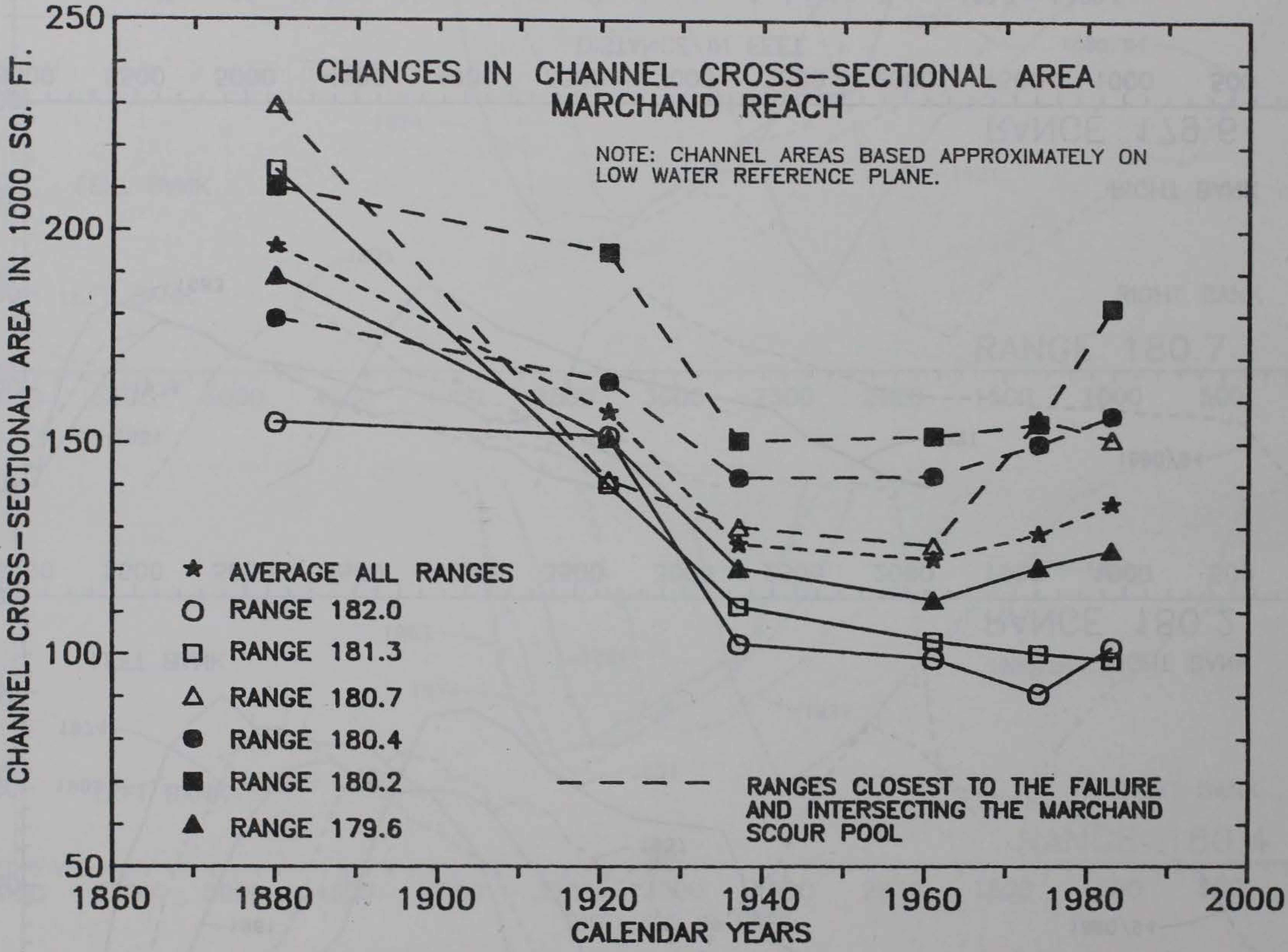


Figure 17. Historic changes in channel cross-sectional area, Marchand reach

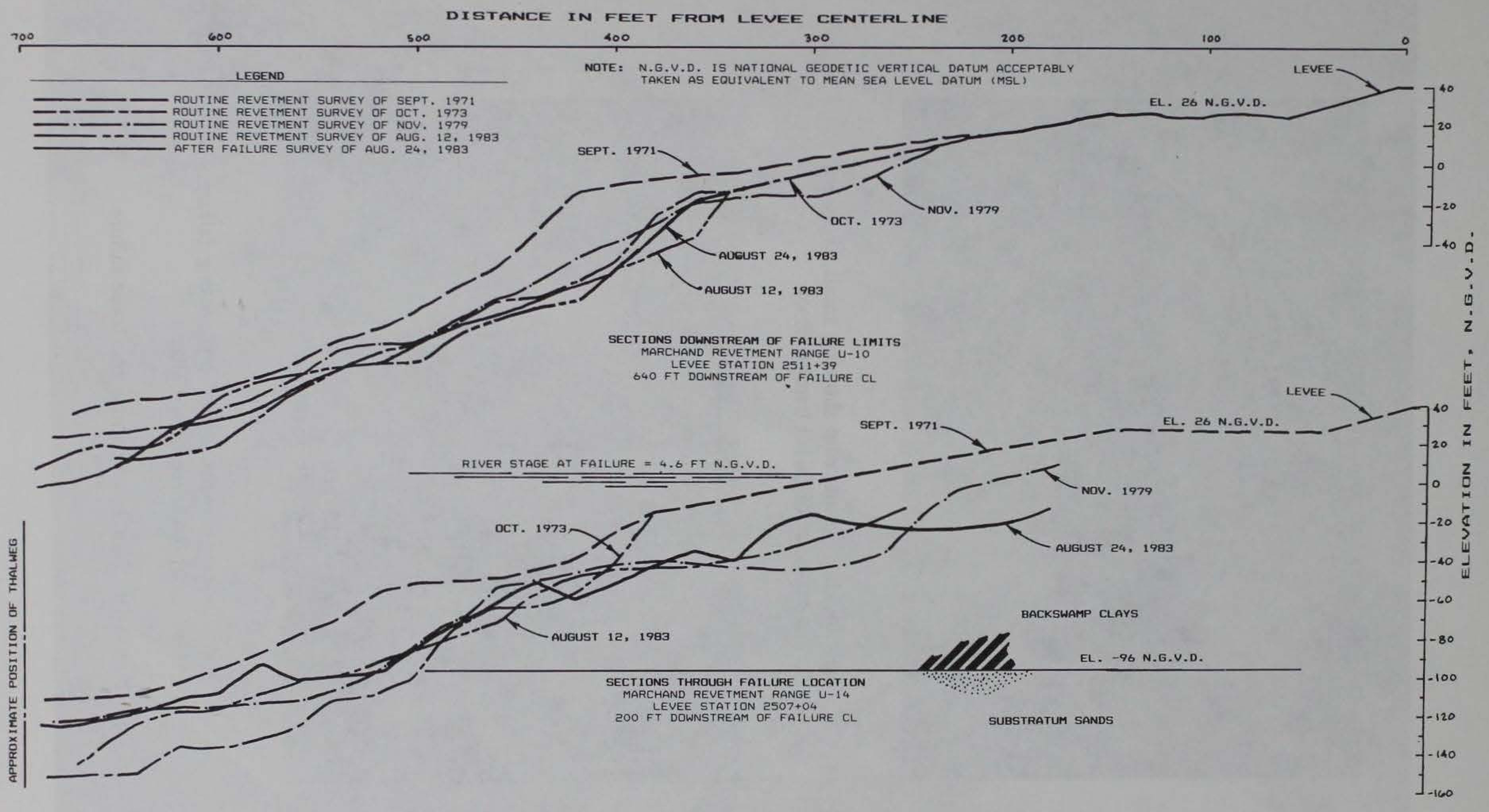
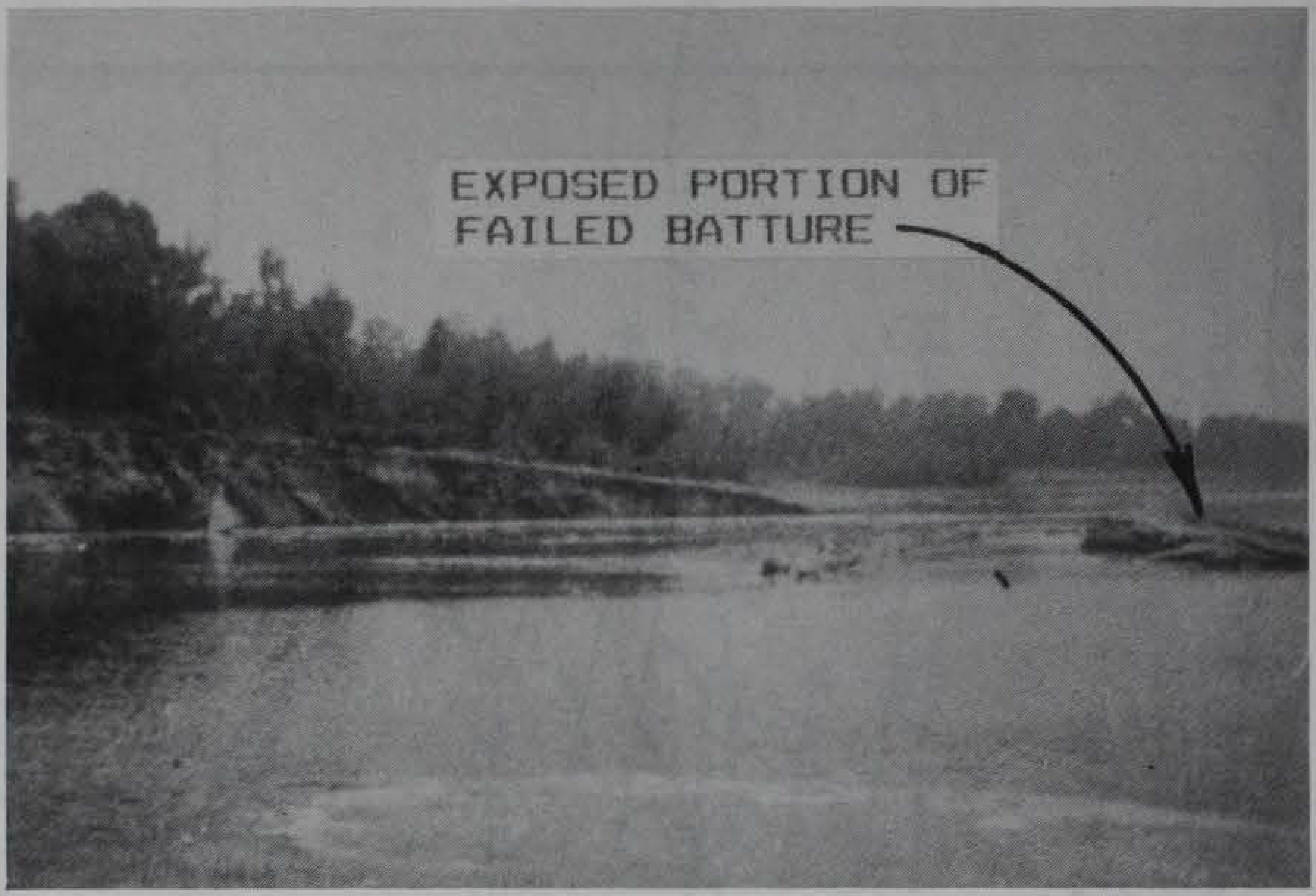


Figure 18. Marchand failure, riverbank cross sections

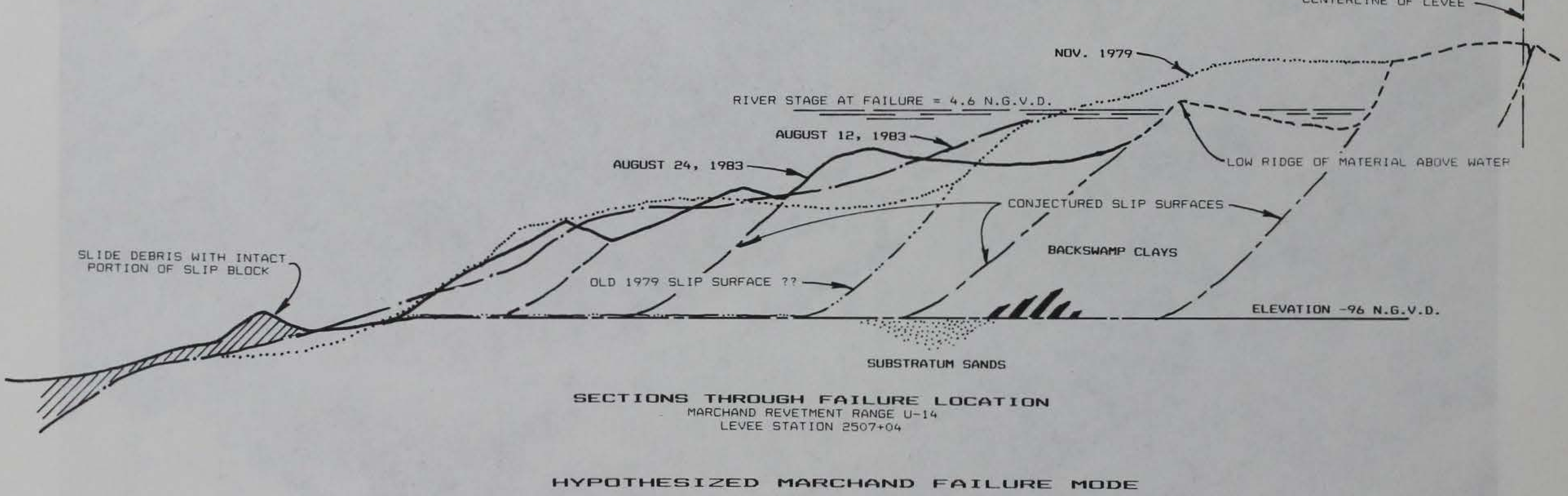


a. View looking downstream showing small riverward exposure of failed batture block

b. View looking downstream of progressing failure of the levee embankment

Figure 19. Marchand batture and levee failure

Figure 20. Aerial view looking upstream of the Marchand batture and levee failure



SECTIONS THROUGH FAILURE LOCATION
MARCHAND REVETMENT RANGE U-14
LEVEE STATION 2507+04

HYPOTHESIZED MARCHAND FAILURE MODE

Figure 21. Conjectured mode of failure, Marchand batture and levee

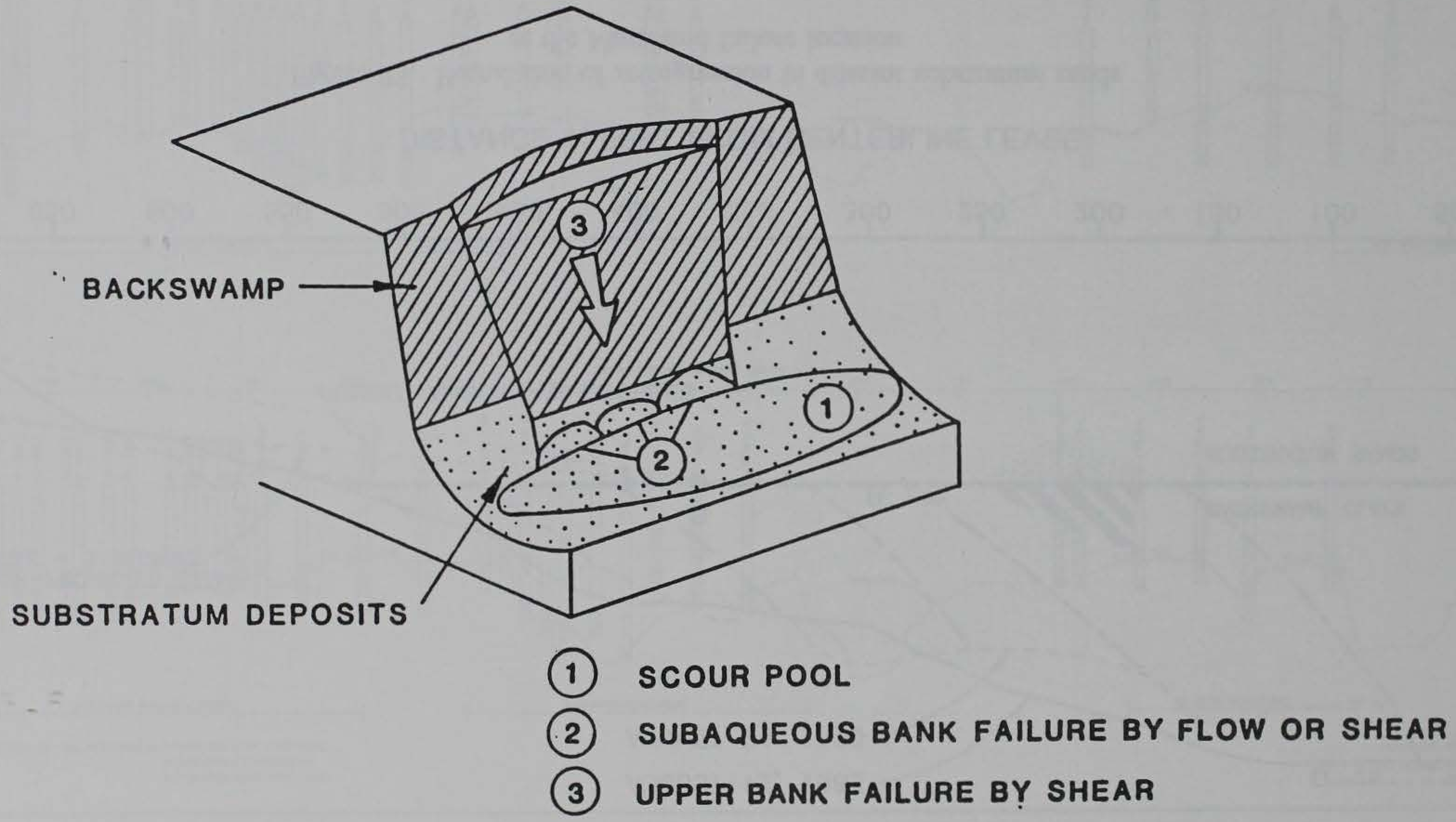


Figure 22. General mechanics of bank failure (after Turnbull, Krinitzsky, and Weaver 1966)

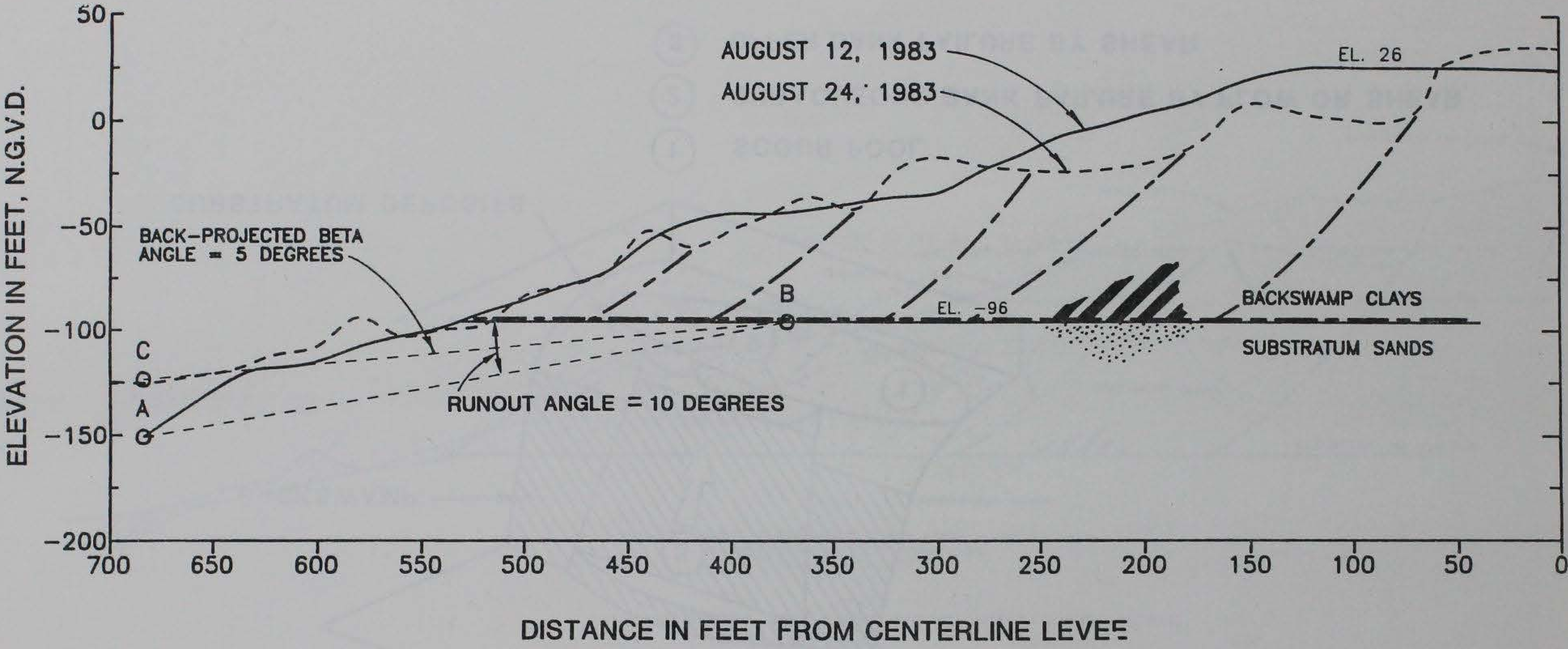


Figure 23. Postulation of retrogression in dilatant substratum sands at the Marchand failure location

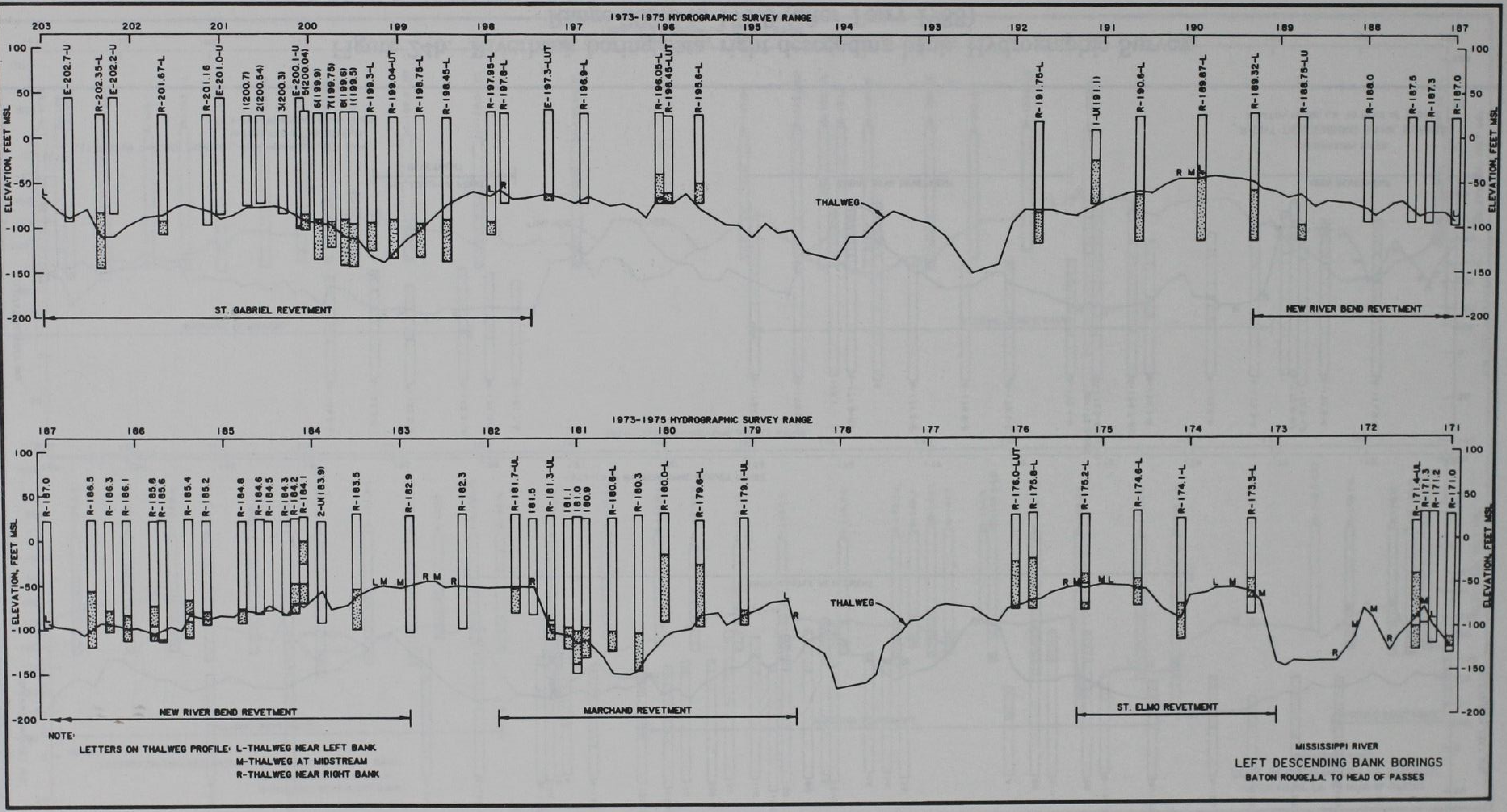


Figure 24a. Riverbank boring data, left descending bank, Hydrographic Survey Range 203.0 to 171.0 (after Torry 1988)

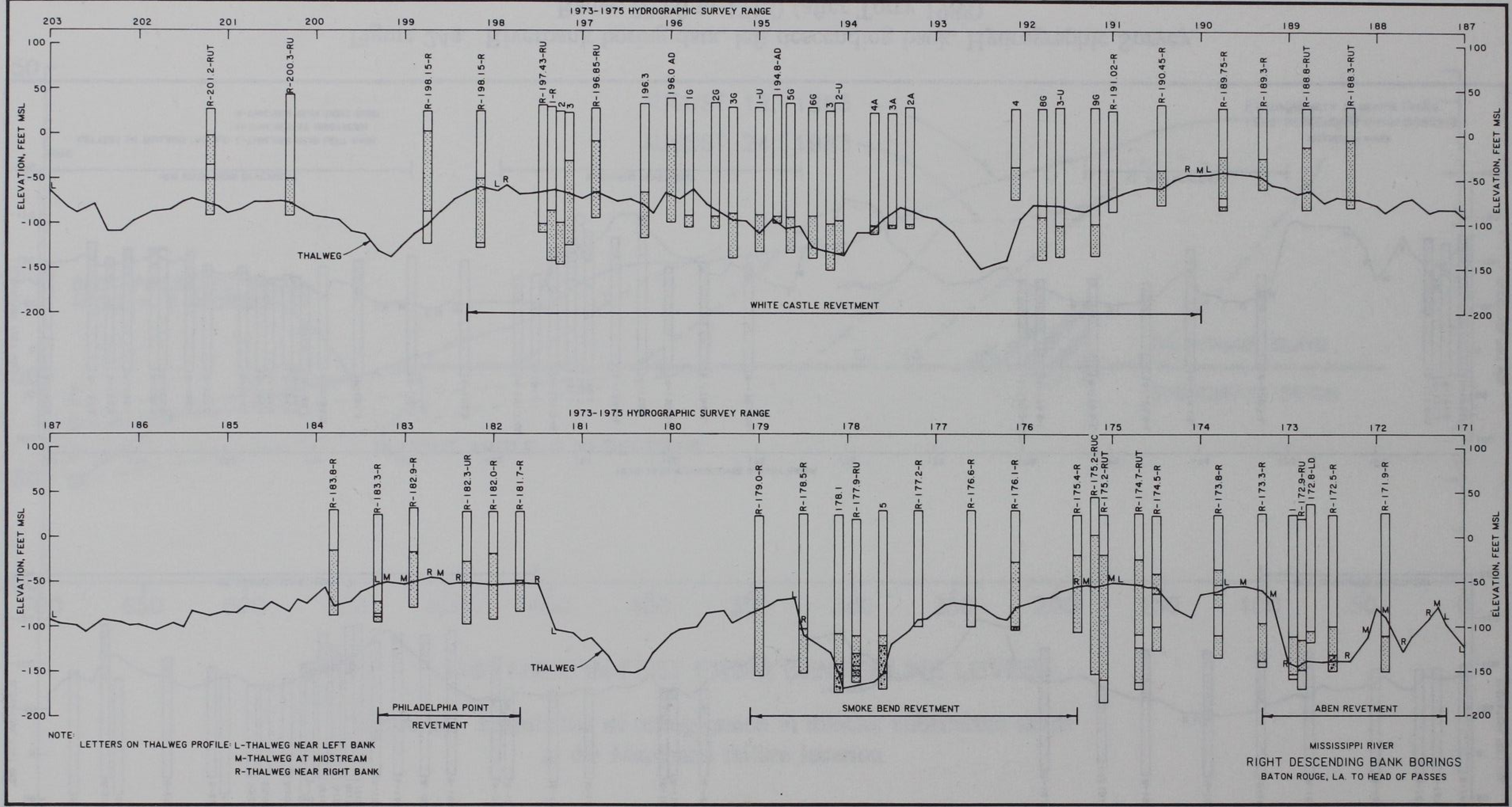


Figure 24b. Riverbank boring data, right descending bank, Hydrographic Survey Range 203.0 to 171.0 (after Torry 1988)

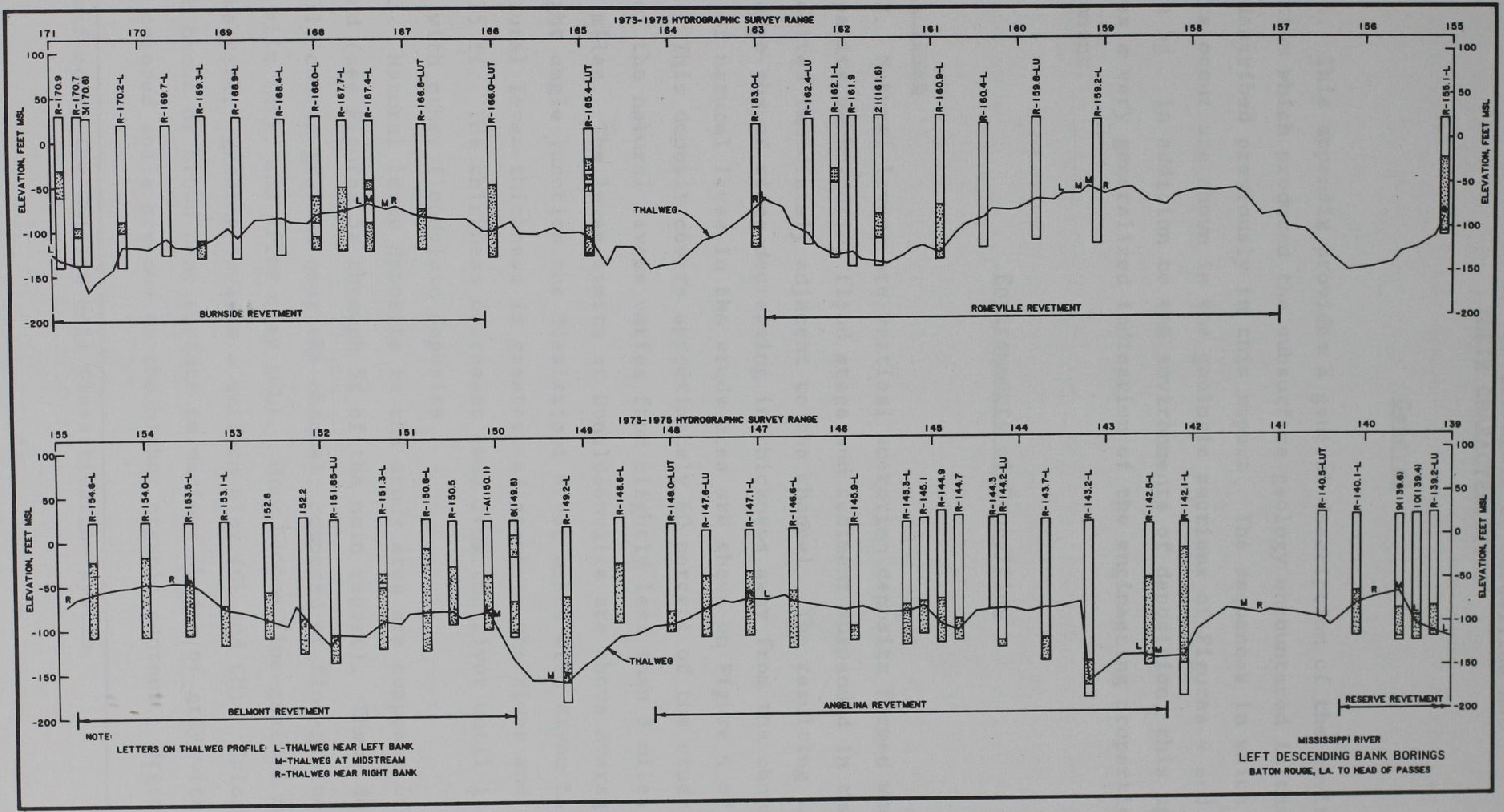


Figure 24c. Riverbank boring data, left descending bank, Hydrographic Survey Range 171.0 to 139.0 (after Torry 1988)

APPENDIX A: ENVIRONMENTS OF DEPOSITION AND THEIR CHARACTERISTICS

General

1. This appendix provides a general description of the environments of deposition which produced the subsurface geology encountered in the study reach described previously in this report. The sequences in which the deposits occur are shown in the geologic sections of Figures 4 and 5a through 5g. In addition to the environments of deposition, this appendix also provides a very generalized indication of the engineering properties of each environment.

Environments of Deposition

Natural levee

2. Natural levees are vertical accretion deposits formed when the river overtops its banks during flood stage and sediment suspended in the flood flow is deposited immediately adjacent to the channel. The resulting landform is a low, wedge-shaped ridge decreasing in thickness away from the channel. The limits of natural levee in the study area are shown on Figure 4 of the main report. This deposit covers approximately 60 percent of the study area. The width of the natural levees varies from slightly less than 3 miles to greater than 7 miles. The levee limits at Donaldsonville are above average because of the right angle junction the Mississippi River makes with Bayou LaFourche. The natural levee thickness is greatest adjacent to the river and ranges from 20 to 25 ft. The thickness decreases away from the river until it eventually merges with other floodplain deposits.

3. Natural levee deposits in the study area are composed of clay, silt, and sand (see Figures 5a through 5f of the main report). These deposits are generally coarse grained near the channel, composed of fine-grained sand (SM),[*] silt (ML), and silty clay (CL). They become fine-grained further away from the river, grading towards a uniform clay (CL and CH). Color varies from reddish brown or brown near surface to various shades of gray with depth. The darker colored soils are due to the higher organic content. Organic content

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[*] Classified by the Unified Soil Classification System.

is generally low and is in the form of small roots and occasionally disseminated wood fragments. Larger wood fragments are uncommon as oxidation has reduced organic materials to a highly decomposed state. Frequently associated with natural levee deposits are small calcareous nodules, formed as a result of ground water percolating through the permeable soils. The nodules are precipitated from solution. Natural levee soils are well drained, have low water contents, and generally have a stiff to very stiff consistency.

Backswamp

4. Backswamps are vertical accretion deposits that receive sediment during times of high water flow, when the natural levees are crested and suspended sediment in the flood waters is deposited in areas well removed from the main channel. Backswamp environments are low, often poorly drained, tree-covered areas flanking the main channel. Backswamps are areas bordered either by uplands or present and former Mississippi river courses. They are low areas that are settling basins for flood flow and sediment.

5. Backswamps overlain by natural levee are the dominant geologic deposit in the study area. Backswamp deposits comprise approximately 50 percent of the Holocene deposits in the study area. The top of the backswamp surface begins at about the el 5 contour. These deposits are approximately 100 to 140 ft thick. The base of the backswamp sequence is generally at approximately the el -100 contour. A backswamp sequence is identified in Figure 5f of the main report that occurs well below this elevation. In borings 178.2 and 12MG (from Kolb 1962) backswamp deposits are found at el -160. These deposits underlie point bar deposits and directly overlie the Pleistocene surface along the eastern valley wall. The age of this lower backswamp deposit may be late Pleistocene.

6. Backswamps deposits are composed of uniform, very fine-grained sediments. They are composed primarily of silty clay (CL) and clay (CH). Sand (SM and SP) and silt (ML) soils may occur but are considered a minor constituent of the total depositional sequence (see Figures 5a through 5f of the main report). These deposits typically contain moderate to high organic contents in the form of decayed roots, leaves, and wood. Disseminated pyrite is a common but a very minor constituent of these soils. Pyrite is commonly found in poorly drained areas which promote reducing conditions. These soils often become well drained during times of low water and undergo short periods of oxidation, lending a mottled appearance to the soil. Backswamp soils are

gray, dark gray, or occasional black. Backswamp soils have generally high water contents, between 30 and 60 percent.

Point bar

7. Point bar deposits are lateral accretion deposits formed as a river migrates across its floodplain. River channels migrate across their floodplain by eroding the outside or concave bank and depositing a sandbar on the inside or convex bank. With time the convex bar grows in size and the point bar is developed. Associated with the point bar are a series of arcuate ridges and swales. The ridges are formed by lateral channel movement and represent relic lateral bars separated by low lying swales. The swales are locations for fine-grained sediments to accumulate. Point bar deposits are as thick as the total depth of the river that formed them. These deposits become finer upward from the maximum size of the river's bedload (coarse sand and fine gravel) to very fine-grained soils (clay) at the surface. The basal or coarse grained portion of the point bar sequence is deposited by lateral accretion while the fine-grained or upper portion of the point bar sequence is deposited by vertical accretion.

8. Mississippi River point bar deposits in the study area are generally less than 2,500 years old. They began forming when the St. Bernard delta system was active. The Mississippi River has occupied the same reach of river between Geismer and Donaldsonville for the past 2,500 years. However, point bar deposits at Geismer, Louisiana, were identified by Fisk (1952) and Kolb (1962) as being older than 2,500 years. The grain size of these deposits and their meander geometry indicate deposition by a smaller system than a full-flow Mississippi River course. The deposits at Geismer (see Figure 5a of the main report) are finer-grained than the normal deltaic plain point bar sequence identified by Kolb (1962). The fine-grained character of the Geismer point bar coupled with its meander direction and geometry suggest the origin of this deposit may be related to a fluvial system other than the present Mississippi River. Fisk (1952) and Kolb (1962) indicated that these point bar deposits were possibly related to an earlier and smaller "Yazoo" sized river system that emptied into the gulf in the vicinity of Donaldsonville. The Yazoo River supposedly flowed along the eastern valley margin during the active Mississippi-Teche stage. Point bar deposits overlain by natural levee compose approximately 20 percent of the area covered by this study (see

Figure 4). The lateral extent of these deposits on the floodplain is variable and is related to the different Mississippi River courses.

9. Point bars associated with the Bayou Lafourche course are less developed than the present Mississippi River course. This is due to the length of time during which the Mississippi River actively flowed through Bayou Lafourche, approximately 600 years. Point bars formed by the Bayou Lafourche course were mapped according to their meander geometry (see Figure 4 of the main report). The Bayou Lafourche point bars range in width from approximately one-half mile to a little less than one mile.

10. Mississippi River point bars range in width from approximately one-half mile to slightly more than two miles. Mississippi River point bars are approximately 120 to 160 ft thick with the surface generally between the 5 and 10 ft msl contour. Their thickness as indicated earlier is a function of the maximum depth to which the river scours. The base of the point bar deposits depicted on the detailed geologic cross-sections was estimated and is based on the hydrographic survey data.

11. Soil types in a point bar sequence grade upward from coarse-grained sands and fine gravels near the base to clays near the surface. These deposits are variable but, in the deltaic plain, are generally composed of at least 50 percent poorly graded fine sand (Kolb 1962). Point bar deposits are separated into two distinct units, a predominantly fine-grained upper sequence or point bar topstratum, and a coarse grained lower sequence or point bar substratum. Soil types are identified in the geologic sections in Figures 5a through 5f of the main report.

Abandoned course

12. An abandoned course as the name implies is a relic fluvial course that is abandoned in favor of a more hydraulically efficient course. An abandoned course contains a minimum of two meander loops and forms when the river's flow path is diverted to a new position on the river's floodplain. This event usually is a gradual process and begins by a break or a crevasse in the river's natural levee during flood stage. The crevasse forms a temporary channel that may, over time, develop into a more permanent channel. Eventually, the new channel diverts the majority of flow and the old channel progressively fills. Final abandonment begins as coarse sediment fills the abandoned channel segment immediately down stream from the point of diversion. Complete filling of the abandoned course is a slow processes that occurs by overbank

deposition. The complete filling process may take several hundred years to complete.

13. The Bayou Lafourche abandoned course is a prominent physiographic feature that extends due south from Donaldsonville. It contains broadly developed natural levees which are easily identified on aerial photography and topographic maps. Well developed natural levees and a meandering planform distinguish the abandoned course from its short lived counterpart, the crevasse channel.

14. Boring information from the Donaldsonville area indicates a channel fill consisting of primarily thick, sand deposits capped by a thin layer of finer grained soils. The coarse grained channel fill extends well beyond the limits of the Donaldsonville area (Fisk 1952). Detailed boring information through the abandoned channel at Donaldsonville is presented in Figure 5b of the main report.

Substratum deposits

15. Substratum deposits are coarse grained unconsolidated sediments that were deposited during sea level rise. These Pleistocene and early Holocene age deposits are believed to have formed under a braided stream environment, a depositional environment characterized by numerous shallow, branching or anastomosing streams. These streams were created when large volumes of glacial-derived sediment overloaded the drainage system.

16. Substratum deposits in the study area are found only in the subsurface, beginning at approximately the -100 ft msl. These deposits directly overlie the older Pleistocene surface and thicken to the south and southwest. Substratum deposits are composed of poorly graded fine sand and generally become coarser-grained with depth. Grain size characteristic of substratum deposits in the Donaldsonville area are summarized in Figure A1 (from Kolb 1962). Grain sizes are typically lacking in the medium and coarse sand size particles (1-6 mm). Kolb (1962) indicated that this was probably a function of the ability of the drainage system to continually transport this specific particle size.

17. Depth to the substratum at numerous locations along the river is shown in Figures 5a through 5f of the main report. It is worth mention that there is a difference between substratum deposits and basal point bar substratum. As shown by the cross sections, the line separating the two is an

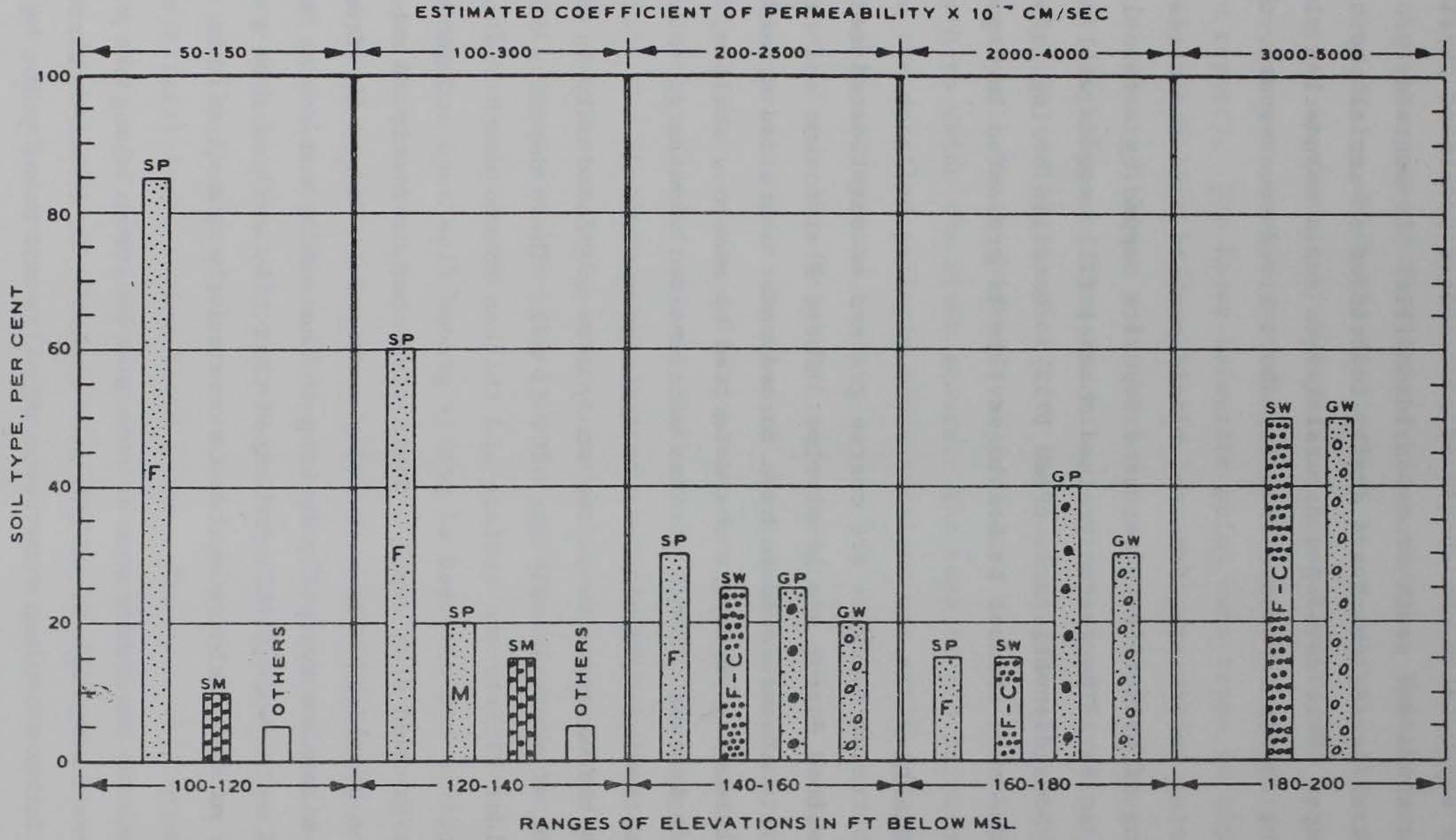

Figure A1. Grain size characteristics of substratum deposits at Donaldsonville, Louisiana (after Kolb 1962) imaginary line which denotes a time boundary rather than a major difference in grain size characteristics. The oldest point bar deposit in the study area is less than 10,000 years old while, as stated above, the substratum deposits are between 18,000 and 10,000 years old.

General Engineering Properties

18. The correlation of general engineering properties to environments of deposition has been attempted only to a limited degree. The best current references containing such information are Kolb (1962), Montgomery (1974) and Kolb, Smith and Silva (1975). Figure A2, taken from Kolb (1962), is perhaps the best available summary for the purposes of this report. The most pertinent item in Figure A2 is the comparison between Pleistocene and Holocene deposits. Basement Pleistocene deposits are generally stiffer and stronger as compared with overlying clays of Holocene age, whatever the environment of deposition. Obviously, silty and sandy soils of Holocene age are even less resistant to fluvial scouring and bank migration.

Pleistocene deposits

19. Pleistocene deposits outcropping at surface and extending into the subsurface are correlative with the Prairie Formation. The Prairie Formation is the youngest of Fisk's (1944) four major interglacial fluvial and deltaic sequences deposited during Sangamonian time, approximately 70,000 to 125,000 ago.

20. The Prairie Formation and in general Holocene age deposits overlying the Prairie are similar in origin and general physical characteristics. They are both products of deposition following the melting and retreat of continental glaciation. They were both envisioned by Fisk (1944) as fining upward from a coarse grained substratum to a fine grained topstratum. However, detailed analysis of glacial chronology from the midwest combined with detailed geologic mapping from the Lower Mississippi Valley in recent years indicates that the four cycle model of Pleistocene glaciation and the accompanying interglacial deposition is very oversimplified. The recent data indicates that the geology of the Prairie Formation is more complex (Kolb, Smith, and Silva 1975). The base of the Prairie Formation in the study area is unknown. Detailed borings defining lithologic and stratigraphic data on the Prairie Formation are lacking. No attempt was made to separate the

	DEPOSITIONAL TYPES	LITHOLOGY PER CENT 0 25 50 75 100	PREDOMINANT SOIL TEXTURES(1)	NATURAL WATER CONTENT PER CENT DRY WEIGHT 0 50 100 150 200	UNIT WEIGHT LB/CU FT 60 80 100 120 140	SHEAR STRENGTH (2) COHESIVE STRENGTH LB/SQ FT 0 200 400 600 800	SHEAR STRENGTH (2) ANGLE OF INTERNAL FRICTION IN DEGREES	REMARKS
RECENT ENVIRONMENTS	NATURAL LEVEES		CH, CL, ML & SM			VALUES RANGE TO APPROXIMATELY 2600 CHARACTERISTIC RANGE 800-1200	ML 20-35	Disposed in narrow bands flanking the Mississippi River and its abandoned courses and distributaries. Consists of interfingering layers of fat and lean clays and sandy silt along the Mississippi River and its abandoned courses. Natural levee materials along abandoned distributaries usually much finer. Thickness varies from 25 ft near Baton Rouge to 0 at sea level. Thickness along distributaries usually on the order of 5 ft or less.
	POINT BAR SANDY		ML, SM & SP	FINE FRACTION ONLY	INSUFFICIENT DATA	INSUFFICIENT DATA	SP 25-35	Usually found flanking the more prominent bends of the present and abandoned courses to a depth of more than 100 ft. Consists of a bedded topstratum 25 to 75 ft thick of silty sand, sandy silt, and sand coarsening with depth. The substratum consists of essentially clean sand.
	POINT BAR SILTY		CL & ML		INSUFFICIENT DATA	———	ML 20-30	An unusually fine-grained point-bar deposit consisting almost entirely of silt. Identified just upstream from Donaldsonville and at Laplace.
	PRODELTA CLAYS		CH				0	A homogeneous fat clay in offshore areas and at depth. Contains increasing amounts of lean clay disposed in thin layers near the mouths of active distributaries. Thickness normally varies with depth to Pleistocene. Thicknesses range between 50 and 600 ft.
	INTRADELTA		CH, ML & SM		INSUFFICIENT DATA	INSUFFICIENT DATA	———	Relatively coarse sediments bottoming bays and sounds. Thickness ranges from 3 to 20 ft and averages 15 ft. Because of the reworking of bottom sediments by burrowing marine organisms soils have a mottled appearance due to the inclusion of lumps or pockets of coarse material in a fine matrix or fine material in a coarse matrix.
	INTERDISTRIBUTARY		CH				0	Forms clay wedges between major distributaries. Clay sequence interrupted by silty or sandy materials associated with myriad small distributaries. Minor amounts of silts and fine sands typically occur in very thin but distinct layers between clay strata giving deposit a "varved" appearance. Thickness similar to intradelta above.
	ABANDONED DISTRIBUTARY		CH & CL	INSUFFICIENT DATA	INSUFFICIENT DATA	INSUFFICIENT DATA	———	Forming belts of clayey sediments from a few feet to more than 1,000 ft in width and from less than 10 to more than 50 ft in depth. A wedge of coarser material is normally found at the upstream end, this wedge of material may range from fine sand for the larger distributaries to silty clays for the smaller.
	ABANDONED COURSE		CH & SP	INSUFFICIENT DATA	INSUFFICIENT DATA	INSUFFICIENT DATA	———	Forming belts of fairly coarse sediment in abandoned Mississippi River courses. Average width 2,500 ft. Depth may be 75 to 150 ft. Lower portion of course filled with sandy material which thickens in an upstream direction. Upper portion filled with silts and clays.
	SWAMP		CH			INSUFFICIENT DATA	———	Tree-covered organic deposits flanking the inner borders of the marsh and subject to fresh-water inundation; also mangrove-choked areas found landward of the barrier beaches and fringing the mainland. Deposits average 3 to 10 ft thick.
	MARSH		PT	VALUES RANGE TO APPROXIMATELY 800	INSUFFICIENT DATA	VERY LOW	———	Forms 90 per cent of the land surface in the deltaic plain. Ranges from watery organic oozes to fairly firm organic silts and clays. Maximum thicknesses (30 ft or more) normally associated with areas of greatest subsidence. Average thickness 10 ft.
	SAND BEACH		SP	SATURATED	INSUFFICIENT DATA	0	30-35	Border the open gulf except in areas of active deltaic advance. May be a mile or more in width and more than 10 miles in length. Beach sand may pile as high as 30 ft above gulf level and subside to depths of 30 ft below gulf level. Buried sand beaches reach a thickness of 35 ft in New Orleans area.
	BAY-SOUND		ML & SM				15-30	Relatively coarse portion of subaqueous delta. Intricately interfingered deposits. Disposed in broad wedges about abandoned courses and major distributaries. Thickness of intradelta associated with present Mississippi on order of 200 ft. Thickness of intradelta associated with abandoned courses much less, averaging between 25 to 100 ft.
	NEARSHORE GULF		SP	SATURATED	INSUFFICIENT DATA	0	25-35	Found at the borders of the open ocean seaward of the sand or barrier beaches. Thickness appears to increase with distance from shore--maximum thickness believed to be on order of 25 ft. Discontinuous blanket of this material occurs directly above Pleistocene.
	ESTUARINE		SP	SATURATED	INSUFFICIENT DATA	0	30-40	Sandy facies correlative with nearshore gulf deposits but filling minor valleys entrenched into underlying Pleistocene surface.
	BACKSWAMP		CH & CL			VALUES RANGE TO APPROXIMATELY 1745 CHARACTERISTIC RANGE 450-1450	0	Thick clays overlying substratum sands upstream from College Point. Occasional lenses of shell are found indicating interfingering fluvial-marine deposits.
	SUBSTRATUM		SP	SATURATED	INSUFFICIENT DATA	0	30-40	Massive sand and gravel deposits filling entrenched valley and grading laterally into nearshore gulf deposits. Material becomes coarser with depth. Maximum thickness on the order of 300 ft in deepest portion of entrenched valley.
PRE-RECENT	PLEISTOCENE		CH & CL			VALUES RANGE TO APPROXIMATELY 3500 CHARACTERISTIC RANGE 900-1700	0	Ancient former deltaic plain of Mississippi River. Consists of environments of deposition and associated lithologies similar to those found in recent deltaic plain. Depth to this ancient, eroded surface increases in a southerly and westerly direction in southeastern Louisiana.

LEGEND

GRAVEL (>2.0 MM)

SAND (2.0-0.05 MM)

SILT (0.05-0.005 MM)

CLAY (<0.005 MM)

ORGANIC MATERIAL

SHELL

TYPICAL RANGE OF VALUES INDICATED BY LENGTH OF BAR. BAR WIDTH INDICATES RELATIVE DISTRIBUTION OF VALUES.

(1) SYMBOLS BASED ON UNIFIED SOIL CLASSIFICATION SYSTEM.

(2) SHEARING STRENGTHS OF CLAYS BASED ON UNCONFINED COMPRESSION TESTS.

Figure A2. Typical properties of depositional types--Donaldsonville, Louisiana, to the Gulf of Mexico (after Kolb 1962)

Pleistocene deposits into more specific formational of time-stratigraphic units.

21. Pleistocene age soils outcrop at surface in the northeast corner of the study area. The soils are predominately fine-grained. Numerous engineering borings drilled into the upper Pleistocene identify it as composed primarily of clay and silty clay. These soils have the following characteristics (from Kolb and VanLopik (1958) and Kolb (1962)): (a) oxidized tan, yellow, or greenish gray color, (b) a marked decrease in water content, (c) distinctive stiffening in soil consistency and a general increase in shear strength, and (d) the presence of concretions. The Pleistocene age soils are usually easily distinguished from Holocene age soils. The engineering properties (water content and shear strength) between the two are very different.

22. The Pleistocene surface dips steeply to the southwest and south beneath the Mississippi River (see Figures 4 and 6 of the main report). Elevations on the Pleistocene surface range from approximately el 5 to 10 where it outcrops to approximately el -350 in the southwest corner. The Pleistocene forms a steep escarpment north and east of the river. There is more than 200 ft of vertical relief between the valley floor and the upper edge of the valley wall. The Pleistocene surface is an irregular surface that dips seaward at approximately 3 ft per mile (Kolb 1962, and May and others 1984). The irregular Pleistocene surface was produced from erosion and scouring by the ancestral Mississippi River and its tributaries during lowered sea level.