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PLEISTOCENE SEDIMENTS OF THE NEW ORLEANS-LAKE PONTCHARTRAIN AREA

by

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PREFACE

This study was authorized in a first indorsement, dated 8 July 1969, to a letter from the Director, U. S. Army Engineer Waterways Experiment Station (WES), to the Division Engineer, U. S. Army Engineer Division, Lower Mississippi Valley (LMVD), dated 20 June 1969, subject: Status of Soils Division Projects for MRC and LMVD for FY 69 and Request for Funds for Projects for FY 70. The U. S. Army Engineer District, New Orleans, provided the funds for this project.

Special thanks are due to Mr. E. B. Kemp of the New Orleans District for soil samples, boring data, and general assistance on the study. Appreciation is extended to the many Federal and State agencies who made logs of soil borings available to us and to the many engineering, utility, and similarly oriented firms who furnished us with reports and other data from their files. A listing would include almost all such groups in the New Orleans area and some outside the area. We also gratefully acknowledge the help of those individuals who have, through their long experience and their publications on the New Orleans and other deltaic areas, gained enviable reputations on the geology of the study area. Many were consulted in the preparation of this report, and it is difficult to give them proper credit for their ideas. However, the list of references cited at the end of this text does mention some of those who contributed.

Compilation and analysis of data and the preparation of the various plates which form the basis for this report were accomplished by many individuals in the Engineering Geology and Rock Mechanics Division (EG&RMD) of the Soils and Pavements Laboratory (S&PL) at WES. Individuals directly or indirectly responsible for various inputs to the study include Dr. R. T. Saucier and Messrs. W. B. Steinriede, Jr., F. L. Smith, D. P. Russ, R. C. Silva, A. R. Fleetwood, J. R. Benham, and Wicks Covey.

Earlier phases of the study were under the direction of Dr. Saucier and later phases under the direction of Dr. C. R. Kolb, then Chief of the EG&RMD. Final preparation of the plates was accomplished principally by Messrs. Smith and Silva under the direction of Dr. Kolb. The text was written by Dr. Kolb. The report was prepared under the general supervision of Mr. J. P. Sale, Chief of S&PL, and final stages of its preparation were done under the general supervision of Mr. D. C. Banks, present Chief of EG&RMD.

The Directors of the WES during the conduct of this study and preparation of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
miles	1.609344	kilometers
pounds per square inch	0.070307	kilograms per square centimeter
pounds per cubic foot	16.0185	kilograms per cubic meter
tons per square foot	95,760.52	pascals
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

PLEISTOCENE SEDIMENTS OF THE NEW ORLEANS-LAKE PONTCHARTRAIN AREA

PART I: INTRODUCTION

1. The purpose of this folio of plates is to delineate the geology and summarize selected engineering parameters of the Pleistocene soils which underlie New Orleans and Lake Pontchartrain at shallow depth and reach the surface as terrace deposits to the north of Lake Pontchartrain. Although the Pleistocene soils are soils in every sense of the word, they are considerably stronger than the overlying Recent or Holocene deposits and form the stratum to which most pilings are sunk for adequate bearing capacity beneath the large buildings and other large structures in the area.

2. The term "Holocene" will be used throughout this report when referring to the soft, recently deposited soils which overlie the Pleistocene. This use is consistent with present geologic practice which at one time permitted the use of the capitalized term "Recent" when referring to these deposits. The term "Pleistocene" refers to those sediments deposited during glacial and interglacial times which lie beneath the Holocene or occur as terraces at elevations slightly higher than the Holocene.

3. Much is known concerning the disposition of the Holocene deposits in the study area; however, except for a brief discussion of these deposits in the text, the emphasis in this report is on the Pleistocene. The geology of the Holocene is inherently complex and, with the tremendous amount of boring data available, deserves separate comprehensive treatment. This report will concentrate on the Pleistocene sediments, the upper portion of which forms the most competent bearing stratum of the study area. It was found that beneath an irregular eroded contact between the Holocene and the Pleistocene, there is a zone of consistently strong oxidized soils, but that beneath this upper layer of the Pleistocene, strengths can be highly irregular. Some Pleistocene soils are as weak as the overlying Holocene. Furthermore, there is ample evidence that beneath the major depositional break between the Holocene and the Pleistocene, one or possibly more depositional breaks occur within the Pleistocene at relatively shallow (200 ft* or less) depth. These are referred to in the text as the First, the Second, and a possible Third Pleistocene Horizon.

4. The following descriptions are useful in examining the plates in this folio:

a. Plate 1 is an index of all the plates in the area which follow and outlines the area studied.

b. Plate 2 is a generalized geologic map.

c. Plates 3-8 show detailed contours of the Holocene-Pleistocene contact, or the First Pleistocene Horizon.

d. Plate 9 uses available data to contour the Second Pleistocene Horizon.

e. Plates 10-49 consist principally of subsurface sections or soils profiles illustrating the heterogeneity of soil stratification in the Pleistocene and indicating the Holocene-Pleistocene contact and the Second Pleistocene Horizon wherever these determinations could be made.

5. Several of these plates are special ones prepared to illustrate: (a) the variation in soil strengths and other engineering parameters; (b) the utility of acoustic subbottom (pinger) profiles in determining lithologic and structural conditions in the study area; and (c) the use of detailed petrographic and X-radiographic studies in distinguishing environments of deposition within the Pleistocene sediments. The index map (Plate 1) shows the locations of these special studies.

PART II: GENERAL GEOLOGY

6. Plate 2 depicts the general geology of the area. As is customary in stratigraphic description, the various geologic units which occur in the study area and which reach the surface will be discussed from the oldest to the youngest. The three Pleistocene units mapped, beginning with the oldest, are the Montgomery, the Prairie, and the Deweyville Terraces. The Holocene is considered as a single unit with relict beaches, abandoned distributaries, and point bar deposits shown in separate colors. Contours on the First Pleistocene Horizon which underlie the soft Holocene deposits are shown in red. Faults are designated by heavy red lines. It is useful in visualizing subsurface conditions to understand that there is essentially no dip on the Holocene and that each successively older geologic unit dips southward at a shallow but increasing angle, as shown in Figure 1. Thus, although the older units occupy higher elevations inland, they gradually dip beneath the younger units toward the south. Because of the controversy (see paragraphs 17-33) concerning the correlation of the Pleistocene units beneath Lake Pontchartrain with the terraces to the north, these units are shown simply as First, Second, and Third in the figure below. Structure of the area, e.g. the significance of the Baton Rouge and related faults, will also be described more fully later (paragraphs 45-51).

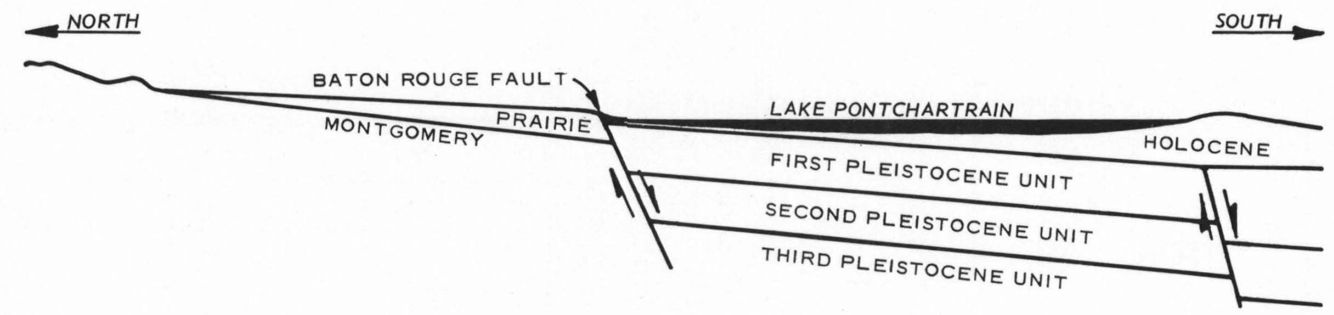


Figure 1. Generalized relationships between the Holocene and older deposits in the New Orleans area

PLEISTOCENE CHRONOLOGY

7. The geologic history of the various Pleistocene units which lie beneath the study area is closely interrelated with the history of continental glaciation to the north. Massive sheets of ice came as far south as the latitude of St. Louis and covered only the northern part of North America, but their effect on the remainder of the continent was almost as profound as it was on that portion overridden by the ice. This is particularly true of the study area where the worldwide drop in sea level, associated with glacier growth, caused the shoreline to retreat several hundred miles south of the present shoreline, subjecting what had formerly been shallow bay and sound bottoms and offshore Gulf areas to thousands of years of oxidation, desiccation, and erosion.

8. As more and more data are collected and analyzed, the original picture of an ice age or a Pleistocene age marked by four major ice advances in the past 1 to 2 million years has become more complex. Although the four major ice advances are still considered valid during this time period, it is now obvious that there were major fluctuations within each major advance and retreat. Moreover, worldwide cooling is now believed to have occurred during Early Pliocene times (10 million years ago), and dozens or even scores of ice advances and retreats may have occurred since that time. Not only were major ice advances and retreats more numerous and erratic than previously thought, but complex expansion and contraction of the continental ice sheet during a major period of advance or retreat appear to be the rule rather than the exception.

9. Oscillations in sea level may or may not have accompanied these fluctuations in the ice front. Data from a host of related but independent variables concerning the record of ice movement and sea level fluctuation often agree but data can also be contradictory. Such data include:

a. Temperature variations deduced from cores in the Greenland and Antarctic ice.

b. Temperatures based on cores of sea-floor sediment.

c. The spread of plants and animals with the advance and retreat of the ice.

d. The effect of glacial climates on lakes in arid regions (the growth and shrinkage of pluvial lakes).

e. Geomagnetic reversals.

f. C-14 and potassium-argon radiometric age determinations.

g. Mapping of the outer limits of permafrost in the geologic past.

10. In Figure 2 several curves are shown to illustrate the utility of such data in visualizing the events that have affected the Pleistocene soils which underlie Lake Pontchartrain and New Orleans. The top curve is based on Flint[1] and shows major ice advances and retreats in North America in the past 100,000 yr. The figure schematically represents the advance and retreat of the ice front between the Hudson Bay region and the Ohio River. In most cases, the part of the curve representing ice retreat is left open because there is little information about the extent of deglaciation between glacial expansions. The irregularities of ice advance and retreat since the major advance of the Tazewell, which culminated some 17,000 yr ago, reflect the vast amount of data available for analysis during this more recent period of time. Comparable data for the previous 80,000 yr would probably result in an equally complex history of erratic pulses during an individual advance and retreat.

11. Flint also suggests that Wisconsin glaciation be subdivided into the time spans, as shown in the top curve of Figure 2; the Early Wisconsin from 85,000 to 55,000 yr ago; the Middle Wisconsin from 55,000 to 25,000 yr ago; and the Late Wisconsin from 25,000 to 10,000 yr ago.

12. Some workers in the field have suggested that the Mid-Wisconsin was a period of major ice retreat and that the period between the Middle Winnebago and Upper Winnebago ice advances was sufficiently long to represent a major interglacial period. This view is partially substantiated by the second curve which illustrates the variation of the calculated solar heat received at 65°N latitude, expressed in degrees of equivalent latitude. It was mathematically derived from astronomical data and modified by Emiliani[2] in 1955. Although the curve has been criticized (Reference 1, pp 798-800)

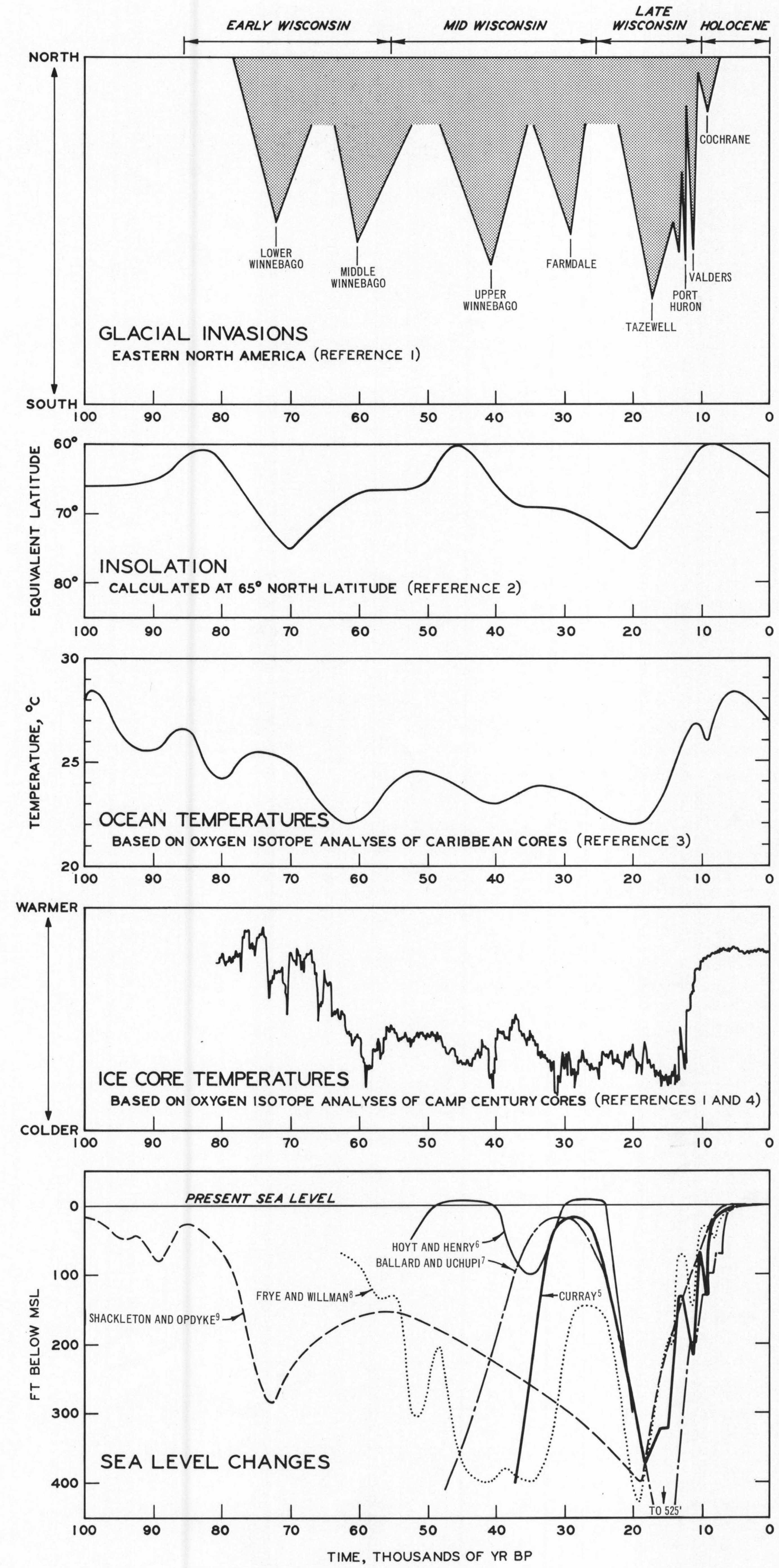


Figure 2. Selected Pleistocene events during last 100,000 yr

* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 1.

by astronomers and geologists alike, it coincides with a generally accepted conclusion that two major glacial advances, the Late and Early Wisconsin, were divided by a single, warm interglacial period which corresponds to the Mid-Wisconsin.

13. The third curve, adapted from a paper by Emiliani[3] in 1972, depicts mean temperatures of the ocean in the Caribbean versus time. Emiliani's work is based on oxygen isotope analyses of numerous deep-sea cores and suggests that in the Caribbean, at least, ocean temperatures did not warm to any great extent during the Mid-Wisconsin.

14. The fourth curve, based on ice cores from the Greenland ice cap at Camp Century,[1,4] shows even less of a temperature change during the Mid-Wisconsin. Beginning about 15,000 yr ago, however, the trend toward a warmer climate is well marked as is the drop in temperature during the Early Wisconsin around 70,000 yr BP (before present). It is possible, of course, that the ice sheets could have retreated and readvanced several times during the Wisconsin, as suggested in the first curve, and that temperatures at Camp Century could have stayed at relatively low levels until the end of the Late Wisconsin.

15. Finally, and this is particularly important to our discussion, five curves have been superposed to show various interpretations of data concerned with the eustatic change in sea level which occurred as the ice sheets waxed and waned. The curve by Curray,[5] which is generally accepted by workers in the Gulf coast, is designated by a heavy black line. Compare this curve with those by Hoyt and Henry[6] and by Ballard and Uchupi.[7] Ballard and Uchupi suggest a drop in sea level during Late Wisconsin more than 100 ft below that suggested by Curray. On the other hand, they agree with Curray that sea level rose to within 15 ft of its present level some 25,000 yr ago. Alternatively, Hoyt and Henry believe that about 25,000 yr ago sea level reached heights slightly more than those of the present. The latter researchers also suggest a long period of high sea level in Mid-Wisconsin with only a slight drop during the period 30,000 to 40,000 yr ago. It should be noted that the works of Curray and of Ballard and Uchupi were based on geomorphic studies and C-14 dates* in the Gulf coast area while Hoyt and Henry used samples from the east coast.

16. Two additional curves are shown which extend farther back in geologic time. The curve by Frye and Willman[8] is based chiefly on a correlation of the advances and retreats of the Wisconsin ice sheets in the Midwest with sea level changes. Their curve generally agrees with those previously discussed but suggests that 25,000 yr ago the sea reached only to within 150 ft of its present level. Corroborating this thesis is work by Shackleton and Opdyke[9] and others. Their work is based on oxygen isotope analyses and paleomagnetic stratigraphy of deep-sea cores and their correlation with ocean temperatures, ice volumes, and sea level change. As their data suggest, in the timespan 80,000-15,000 yr BP, sea level was consistently below 150 ft of its present stand. They state,

> The only significant limitation on the reliability of the curve is that imposed by sediment mixing and the limited stratigraphic resolution of the core. It is perfectly possible that a short episode of high sea level could be obscured in a record with a resolution of a few thousand years—but any supposed evidence for such an event must be read in conjunction with the curve of averaged sea level....There was clearly substantial ice accumulated in the Northern Hemisphere from...about 70,000 years ago until the rapid melting between 16,000 and 6000 years ago.

17. The previous discussion summarizes only a fraction of the findings of the many studies which relate to rise and fall of sea level during the past 100,000 yr, but it is apparent that there is little concensus concerning the interrelation of this phenomenon with climatic change and ice expansion and contraction. One trend is common to all the curves: Late Wisconsin ice reached its maximum advance, temperatures were coldest, and sea level was lowest in the period 15,000 to 18,000 yr ago. Another consistent trend shown by the curves is that Wisconsin glaciation began about 80,000 yr ago. Studies of sea level fluctuation also indicate that the sea level rose during the Mid-Wisconsin or the early part of the Late Wisconsin. Whether the sea rose to an elevation slightly above, the same as, to within 15 ft or so, or to only within 150 ft of its present level is highly controversial. A reasonable consensus is that the sea was at or may have been slightly above its present level about 100,000 yr ago. It dropped at the beginning of Early Wisconsin times, fluctuated intermittently, and then rose to nearly its present level between 25,000 and 35,000 yr ago. Then it dropped 400 ft or more 17,000 yr ago and rose rapidly thereafter to its present stand about 5,000 yr ago.

18. Just how these changes in sea level affect the Pleistocene deposits in the study area is important. Obviously, the time of deposition of each Pleistocene unit and the time during which the upper portions of each unit were subjected to subaerial oxidation were controlled by the changes in sea level. Three geologic units of controversial age occur at the surface in the study area. These are the Montgomery, the Prairie, and the Deweyville Terraces. Two, or possibly three, Pleistocene units occur at fairly shallow depths (200 ft) below Lake Pontchartrain and New Orleans. The uppermost of these is believed to be either (a) the equivalent of the Deweyville Terrace which borders the Pearl River or (b) the age equivalent of the coastwise Prairie Terrace north of Lake Pontchartrain, a terrace surface that is older and higher than the Deweyville. The geologic ages of the less well-defined Second and Third Pleistocene Units which underlie the study are even more speculative.

* A radiometric age expressed in years and calculated from the quantitative determination of the amount of carbon 14 remaining in an organic material.

19. To further complicate matters, the eustatic rise and fall in sea level is not the only factor affecting the various horizons which lie beneath the deltaic plain. Poag,[10] Coleman (personal communication), and others have pointed out that as deltas shifted during Holocene and Pleistocene times, the weight of deltaic deposits (the depocenters) caused the downwarping of various horizons to such an extent that effects of the rise and fall in sea level may be completely obscured. Add to this the offsets caused by faulting, and complications multiply.

MONTGOMERY TERRACE

20. One well preserved and one poorly preserved coastwise terrace flank the northern borders of the lowland basins occupied by Lakes Maurepas and Pontchartrain. These are the Prairie and Montgomery Terraces named by Fisk in the late 1930's.[11,12] Fisk postulated that each terrace represented deltaic and marine deposits laid down during Mid-Wisconsin or Peorian (Bradyan) time and during the Sangamon, respectively. Saucier[13] considers the Prairie Terrace to be Sangamon in age and the Montgomery to be pre-Sangamon. Following Saucier's correlation, this would date the Montgomery Terrace as having been deposited during the Yarmouth interglacial, or in the time span of about 400,000 to 800,000 yr ago. Cullinan[14] and Campbell[15] consider the Montgomery to be part of a single depositional unit, the Citronelle, which includes all the terrace sand and gravel deposits extending northward from the study area into southern Mississippi.

21. The Montgomery Terrace slopes toward the south. Along a line coinciding roughly with the 30° 30′N parallel, it dips beneath the younger Prairie Terrace and continues to dip toward the south beneath Lake Pontchartrain and New Orleans. Whether it corresponds with the Second or Third Pleistocene Horizons, as shown in Figure 1 and in the various plates accompanying this report, is conjectural.

22. Where the Montgomery Terrace is exposed in the study area, it consists of oxidized, tan and red silty and sandy clays which grade downward into sands and gravels. Gravel is absent beneath the study area, and even the sand is generally fine-grained. The thickness of the Montgomery has been cited as about 350 ft by Campbell and its dip southerly at about 6 ft per mile.

PRAIRIE TERRACE

23. The Prairie forms a low, almost featureless, flatland that slopes from an elevation of about 60 ft mean sea level (msl) where it joins the Montgomery Terrace, to near sea level along the northern border of the Lake Maurepas-Lake Pontchartrain Basin. The slope of the surface approximates 4 ft per mile. The contact between the Prairie and the Holocene, where the former is gradually buried by the latter, is irregular (Plate 2) with "islands" of Pleistocene Prairie standing slightly above the level of the surrounding deltaic plain. Soils at the surface consist of sands, silts, clays, and occasional organic deposits like those of the present deltaic plain but readily distinguished from them by their higher strengths and their tan, red, or brown color, a reflection of the many years during which the surface was subject to subaerial erosion and oxidation during and subsequent to Wisconsin glaciation.

24. Fisk and McFarlan[16] considered the Prairie to be a broad deltaic plain bordered by a continental shelf similar in width and slope to the modern one. They assigned it a Mid-Wisconsin age. Saucier[13] postulated that the surface was formed in Sangamon times (circa 80,000 to 110,000 yr ago) in the interglacial period prior to the start of Wisconsin glaciation.

25. The surface consists of both deltaic and marine deposits. Andersen and Murray[17] report an assemblage of Pleistocene microfauna of marine origin found in borings at Mandeville at depths of 15 to 30 ft. Saucier[18] postulates that much of the southern part of the Prairie Terrace mapped in Plate 2 consists of marine lagoonal deposits, the lagoon having been separated from the open Gulf by a system of massive barrier beaches which are now buried beneath Lake Ponchartrain. Furthermore, he believes they are correlative with a conspicuous, 30-mile-long barrier island complex that trends east-west on the Prairie Terrace surface, north and west of Lake Charles in southwestern Louisiana. As he suggests, subsidence and downwarping have probably buried this eastern equivalent of this barrier island system beneath the Holocene deltaic deposits of the study area. Plate 18 is an example of one of the subsurface sections which encounters these sand bodies, and Plate 9 shows the position of all major Pleistocene sand bodies located in the sections.

DEWEYVILLE TERRACE

26. Low terraces along the Pearl River on the eastern flank of the study area (Plate 2) have been described by Gagliano and Thom.[19] Meander scars on this surface with dimensions several times those of the present Pearl suggest a river with volumes more than five times larger than those of the present stream. The size of these meanders can be estimated in Plate 2 by the broad arcuate cusps, which indent the Prairie Terrace where this remnant terrace is mapped, and by comparing these with the present small meanders characteristic of the Pearl.

27. The Deweyville consists of material that is somewhat coarser than the Holocene alluvium of the Pearl River floodplain, and several gravel pits exploit these materials. The dip of the Deweyville surface is controversial. Gagliano and Thom state that 20 to 30 miles inland the Deweyville remnants merge with the Prairie, indicating that the dip of the Deweyville exceeds that of the Prairie. Cullinan,[14] on the other hand, cites a dip of about 4 ft per mile on the Prairie Terrace, about 2.5 ft per mile on the Deweyville surface, and about 2.0 ft per mile on the Holocene alluvium in the present Pearl floodplain. Regardless of the dip of the Deweyville, it plainly merges with and dips beneath the Holocene near the mouth of the Pearl.

28. The age of the Deweyville deposits is generally conceded to be between 17,000 and 30,000 yr. Its distribution, however, where it lies buried beneath the Holocene, is highly conjectural. It also poses a significant problem in the identification of the materials which lie beneath the Holocene, materials whose upper surface is identified in the plates which accompany this report as the First Pleistocene Horizon. Is this surface the submerged coastwise Deweyville Terrace, the downfaulted Prairie Terrace as is accepted in much of the geologic literature on the area, or something of some intermediate age? If oxidized material directly beneath the Holocene is not the equivalent of the Deweyville, where are the deltaic deposits of the ancient Pearl River which left such huge meanders at the surface during Deweyville time?

29. The question is significant enough in any discussion of the Pleistocene beneath New Orleans to warrant a short review here of the literature on the subject. The term "Deweyville" was first applied to terraces with large, outsized meanders on the Sabine River by Bernard;[20] since then, abnormally large meanders associated with low river terraces have been reported (a) on the Brazos, Trinity, and Pascagoula Rivers along the Gulf coast; (b) along the Arkansas, Big Black,[21] and the Ouachita[22] tributary to the Mississippi; and (c) along the Pee Dee and Waccamaw[19] on the South Carolina coast. No equivalent terraces have been found bordering the Mississippi. C-14 dates of materials from this terrace range generally between 17,000 and 30,000 yr, although it should be understood that no dates are available from the Deweyville terraces along the Pearl.

30. The consensus[13,19,23] is that the enlarged meanders indicate a pluvial period of increased precipitation during the Late Wisconsin. That a pluvial period occurred in the time span roughly equivalent to the suggested age of the Deweyville is documented by a number of studies, particularly of the many large lakes, such as Lake Bonneville and Lahontan, which once occupied vast areas in western United States. Only small remnants (e.g. Great Salt Lake) of these larger lakes exist at present. Lake Bonneville at its maximum covered an area equal to that of existing Lake Michigan and had an estimated depth of more than 1000 ft. A comprehensive study by G. I. Smith and others[24] of the fluctuation of ancient Searles Lake in California and C-14 dating of sediments in the lake indicates a distinct pluvial period in the time range of 10,000 to 24,000 yr ago.

31. Comparing these dates with those in Figure 2, particularly the bottom set of curves of sea level versus time, is instructive. The above dates indicate that a pluvial period, at least in western United States, lasted roughly from the beginning of the drop in sea level about 25,000 yr ago to a point in time when sea level had recovered from its low 17,000 yr ago to about 150 ft below its present level. No actual dates are available on the Deweyville bordering the Pearl, but its age should be correlative with ages determined on the Sabine and other rivers, i.e. 17,000 to 30,000 yr ago. Thus, the Deweyville was deposited both during a period of fairly high, standing sea level and during a period of rapidly falling sea level. This is contradictory to the generally accepted thesis that falling sea level was a period of extensive erosion and nondeposition and that depositional sequences only formed during rising sea level and a transgressive sea.

32. A comprehensive and statistically valid group of C-14 dates could probably resolve the controversy. At the outset, carbonaceous samples are needed from the exposed Prairie Terrace to confirm the age of this feature as being definitely beyond the limits of C-14 dating. Only a few such determinations are known to have been made, and all have proved to be radioactively inert. The topographic and stratigraphic position of the Deweyville places it at an age obviously younger than the Prairie, but likewise no definitive C-14 dates have been determined on the Deweyville Terrace materials along the Pearl. It is merely assumed that the age 17,000 to 30,000, characteristic of Deweyville materials in other areas, is valid for the Pearl. If this date is reliable, C-14 dates of the material beneath the Holocene in the study area should permit identification of the First Pleistocene Horizon as being Deweyville or Prairie.

33. Published[25] and unpublished C-14 data on material from this sequence are inconclusive and puzzling. Many samples tested from this horizon are indeed inert, i.e. greater than 35,000 yr in age, but some have yielded ages ranging from 17,000 to 27,000 yr. Such samples are generally classified as anomalous, i.e., material contaminated during the sampling process with younger materials. In fact, it may be the older sample determinations that are anomalous, the dates having been determined on old material unearthed by fluviatile processes and reburied at a later date. Even more puzzling are C-14 dates of samples of borings made south of New Orleans, which show what may be continuous deposition throughout the time span of C-14 dating. In several instances, there appears to be no evidence of a hiatus in deposition or subaerial oxidation and erosion, suggesting as indicated that deposition was more or less continuous throughout the last period of sea level drop which culminated some 17,000 yr ago.

34. Another point to consider is that the First Pleistocene Horizon is a well-marked surface that is oxidized in some instances to depths of 20 ft. It seems logical to assume that the surface underwent a lengthy period when it stood above sea level. Perhaps sea level never reached its present level during Deweyville times, as intimated in Figure 2 by Ballard and Uchupi, Curray, and more pointedly, Frye and Willman. Thus, Deweyville deltaic deposits would have been laid down further seaward than the area under study in a Gulf significantly lower than it is today. When subsidence under delta load and downward movement by faulting are also considered, it is possible that Deweyville deposits may be found only at depths which are presently 80 to 100 ft below sea level. If

this is true, the First Pleistocene Horizon would be definitely older than Deweyville and would correspond either to the Prairie Terrace in age or be of some intermediate age between Deweyville and Prairie.

35. Obviously, many more C-14 dates are needed, and much more boring data must be analyzed before these controversial issues are resolved. For this report, the oxidized zones of the Pleistocene detected in borings are labeled simply First, Second, and in a few instances, a possible Third Horizon.

HOLOCENE

36. Holocene (Recent) deposits in the New Orleans-Lake Pontchartrain area have been studied[16,23,25,32] more than any other such deposits in the Mississippi Deltaic Plain. Literally tens of thousands of cored and augered borings have been made, and a great deal is known concerning the various waves of marine, lacustrine, and deltaic sedimentation which have buried the Pleistocene with a wedge of soft Holocene soils, that is thinnest where it borders the Prairie Terrace and gradually thickens southward. Many of these borings are included in this study. However, because the emphasis in this report is on the Pleistocene soils underlying the Holocene, no attempt is made to identify environments of deposition and associated engineering properties of the soils of which the Holocene is composed. In many of the subsurface sections (Plates 10-45), only the lower portions of borings, i.e., those portions showing the nature of the Pleistocene, are shown. The upper soft Holocene soils should be studied separately and in the detail consistent with the vast amount of data available.

37. Three environments of Holocene age are delineated in Plate 2: relict sand beaches, abandoned courses and distributaries, and Mississippi River point bar deposits. These environments are relatively sandy. Intermingled with them are the finer marine sediments that carpeted the shallow sounds, bays, offshore Gulf areas, and extensive waves of deltaic sedimentation which invaded the area as the Mississippi River shifted its deltaic distributaries during the past 4500 yr.

Relict Sand Beaches

38. The most conspicuous relict sand beaches are the Miltons Island trend and the Pine Island trend described by Saucier.[26] Plate 2 shows the locations of these two sand units, the former forming an arc of sandy deposits along the north shore of Lake Pontchartrain westward beneath the lake and into the swamps south of Pontchatoula, and the latter trending northeastward through New Orleans to the Rigolets. The consensus is that both sand beaches began forming slightly before sea level reached its present stand, probably reaching their maximum development about 4500 yr ago. More recently, in an unpublished paper, Saucier[18] has suggested a Pleistocene age for the Miltons Island trend, but data are controversial and as yet undefinitive.

39. Figure 3 shows development of the area at stages from approximately 9000 yr ago to the present. Nine thousand years ago, sea level is believed to have been about 100 ft lower than at present. The 100-ft contour on the Pleistocene surface (Plate 2 and Reference 25), representative of the shoreline at that time, has been generalized on the first inset map. New Orleans and all of Lake Pontchartrain were at that time still above sea level. When the effect of subsidence of the area since that time is considered, the shoreline may have been miles seaward of the position shown 9000 yr ago.

40. As sea level continued to rise, the shoreline moved rapidly inland over the shallow Pleistocene shelf, now overlain by Lake Pontchartrain, and as early as 6000 yr ago the first sand spits, extending southeastward from the shoreline, began to form and grow. The Miltons Island trend consists of a fairly shallow (10 to 15 ft thick) sand body. The Pine Island trend beneath New Orleans reaches thicknesses of 40 ft or more (Plate 22). This latter sand body has been mapped and contoured[25,26,28] by various researchers. The Miltons Island relict beaches are described as consisting of very fine to medium quartz sand with few shell fragments. The Pine Island buried beach consists of well sorted, mostly fine sand with sizeable quantities of shell and shell fragments.

Abandoned Distributaries

41. The first introduction of Mississippi River Delta deposits into the area was about 4700 yr ago.[31] The first of a series of St. Bernard distributaries is thought by Frazier[31] to have extended eastward in roughly the position shown in Figure 3b. The shoreline about 4500 yr ago probably resembled that shown in the figure with the St. Bernard-Mississippi distributary practically closing off, and in effect, forming the Lake Maurepas-Lake Pontchartrain Basin. By 3000 yr ago (Figure 3c), the St. Bernard Delta had developed additional lobes and succeeded in entirely closing off the Lake Maurepas-Lake Pontchartrain Basin. Two thousand years ago (Figure 3d), most of the Miltons and the Pine Island beaches had subsided beneath the lake or beneath the deltaic plain, and the St. Bernard Delta extended large delta lobes to the east and south. Figure 3e shows the separation of Lake Maurepas and Pontchartrain and Lakes Pontchartrain and Borgne by the Bayou Sauvage Delta lobe between 1800 and 700 yr ago. Figure 3f carries development of the area to the present. A large number of C-14 dates together with a study of the sediments themselves permitted Frazier to develop this detailed picture. As more data are gathered, however, there is no doubt that considerable refinement of this postulated geologic history will be possible.

42. Abandoned distributaries in the study area are depicted in solid yellow in Plate 2. Sediments in them vary from clays to sand. Sand fills the lower portions of these abandoned water bodies, and overlying clays become progressively thicker downstream from the point where the abandoned distributary leaves the main channel.

Mississippi River Point Bar Deposits

43. Point bar deposits left in migrating bends of the Mississippi River are shown with a dotted yellow pattern in Plate 2. Kolb[32] and Kolb and Van Lopik[29] discuss these in some detail. Generally, these deposits consist of fine sands at a depth—consistent with the depth of scour of the river—grading into silts, sandy silts, and clay nearer the surface. Plate 19, Section E-E′ presents an example of the lithology, geometry, and thickness of Mississippi point bar deposits.

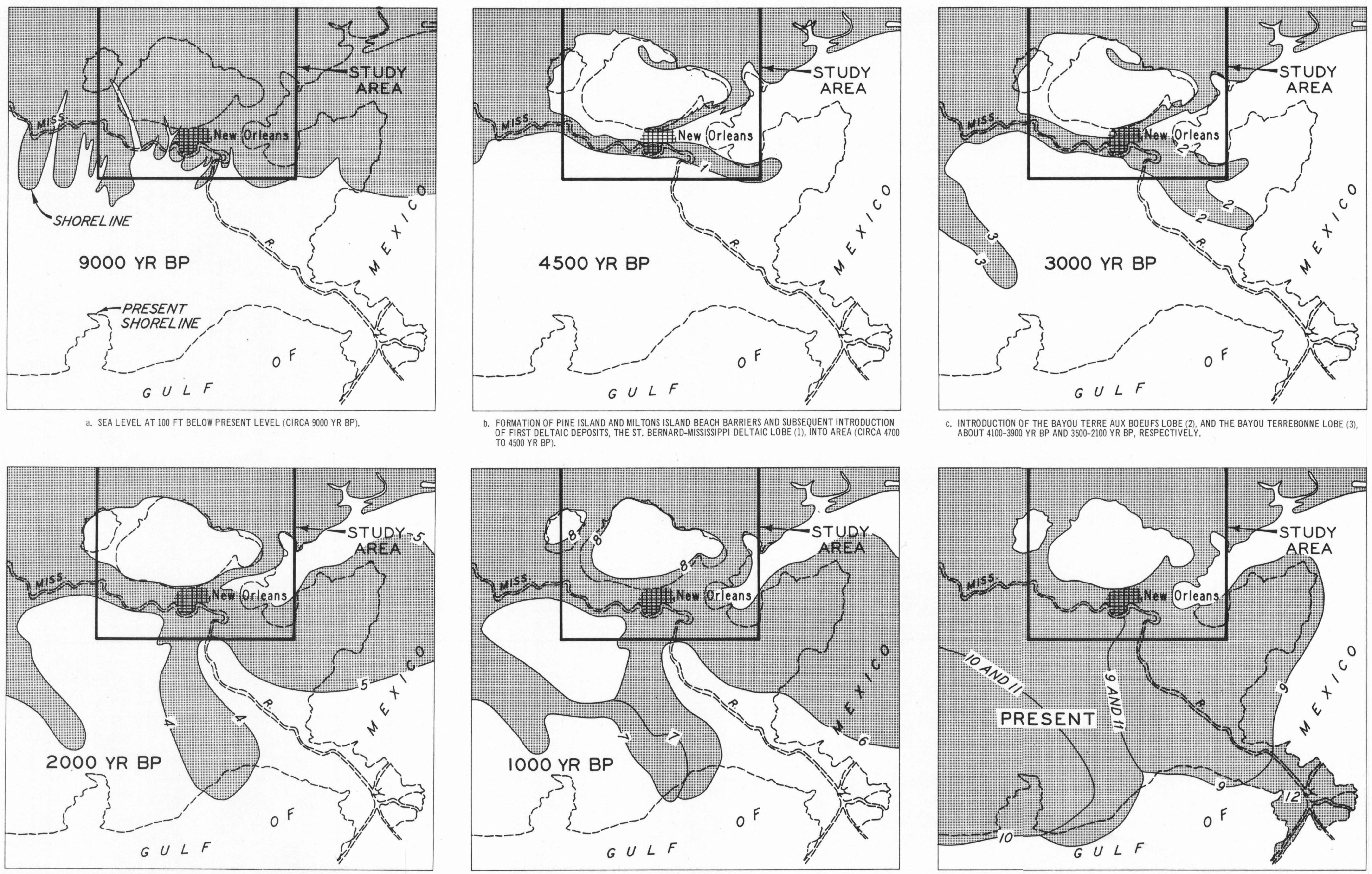
44. The sinuous nature of the Mississippi from Donaldsonville (where the river enters from the left in Figure 3) to English Turn, just downstream from New Orleans, is striking when compared with the rather straight Mississippi River downstream from English Turn. The reason for this change in sinuosity is indicated in Figure 3. The segment upstream from English Turn has been occupied since 4700 yr BP; the segment downstream from English Turn was first occupied by the Plaquemines lobe around 1000 yr BP and thus has not had time to develop significant meanders.

STRUCTURE

45. Faulting has long been recognized as an important factor in the New Orleans-Lake Pontchartrain area.[33] Faults are typically normal, trending generally west-east or northwest-southeast, and are downthrown toward the south. Storm[34] and others postulate that many of the faults are structural adjustments caused by the load of deltaic sediment, that is, many of the faults are massive slumps rather than deep-seated tectonic faults. That these phenomena may indeed be slumps is suggested by the fact that dips on many of the faults tend to get shallower with depth, suggesting huge arcuate wedges of sediment gradually subsiding and rotating slightly along a circular arc of failure. Intermittent activity on many of the faults is indicated by the fact that displacement of beds increases with depth.

46. Saucier[26] has pointed out the frequent difficulty in locating these faults in the field. The poorly consolidated Holocene deposits tend to warp rather than to shear. Minute displacement of beds may occur over a broad zone so that, though aggregate displacement across the zone may be large, any single displacement is too small to be visually significant. Thus, abnormal drainage patterns, lineaments, and the offset of a particular physiographic feature, or its disappearance beneath the marsh are vague clues that are used to identify the position of a fault.

47. The most significant structural feature which can be identified on the study area is the Baton Rouge fault which generally follows and is responsible for the relatively straight Prairie Terrace-Holocene contact north of Lake Pontchartrain. Plate 2 shows the location of the better defined offsets along this fault, but the Baton Rouge fault should be considered as a zone several miles wide of many such roughly parallel faults. Offset along this fault is speculative. Section M-M′ (Plate 38) crosses the fault between borings 22-19 and 193. Note the distinctive difference in the soils penetrated north and south of the fault. The Prairie Terrace lies north of the fault. If it correlates with the First Pleistocene Horizon south of the fault, the amount of displacement since Prairie time would be minimal, i.e. on the order of 5 ft. On the other hand, if the Second Pleistocene Horizon is



a. SEA LEVEL AT 100 FT BELOW PRESENT LEVEL (CIRCA 9000 YR BP).

b. FORMATION OF PINE ISLAND AND MILTONS ISLAND BEACH BARRIERS AND SUBSEQUENT INTRODUCTION OF FIRST DELTAIC DEPOSITS, THE ST. BERNARD-MISSISSIPPI DELTAIC LOBE (1), INTO AREA (CIRCA 4700 TO 4500 YR BP).

c. INTRODUCTION OF THE BAYOU TERRE AUX BOEUFS LOBE (2), AND THE BAYOU TERREBONNE LOBE (3), ABOUT 4100-3900 YR BP AND 3500-2100 YR BP, RESPECTIVELY.

d. INTRODUCTION OF THE BAYOU DES FAMILIES LOBE (4), ABOUT 3400-2000 YR BP, AND THE MISSISSIPPI-LA LOUTRE LOBE (5), ABOUT 3000-2300 YR BP.

e. INTRODUCTION OF THE BRETON SOUND LOBE (6), CIRCA 2500-1800 YR BP; THE BAYOU BLUE LOBE (7), CIRCA 2000-1900 YR BP; AND THE BAYOU SAUVAGE LOBE (8), CIRCA 1800-700 BP.

f. INTRODUCTION OF THE MISSISSIPPI-PLAQUEMINES LOBE (9), CIRCA 1000 YR BP TO PRESENT; THE LA FOURCHE-TERREBONNE LOBE (10), CIRCA 800 YR BP TO PRESENT; AND THE PLAQUEMINES LOBE (12), CIRCA 300 YR BP TO PRESENT.

Figure 3. Geological development of southeast Louisiana since 9000 yr BP (before present) (based principally on Reference 31)

equivalent to the Prairie, displacement since Prairie time would be on the order of 50 ft, a much more credible figure.

48. Although many faults other than those along the Baton Rouge fault zone have been postulated and mapped in the New Orleans-Lake Pontchartrain area,[12,26,35] only two are shown in Plate 2: (a) one short problematic cross fault near the Rigolets, and (b) one much longer feature trending east-west through Lake Pontchartrain. The positions of both faults are based on data developed in this study, and both affect the uppermost or youngest of the Pleistocene deposits.

49. The southernmost of these faults was detected on acoustic subbottom (pinger) profiles made parallel to Section B-B′ (Pontchartrain Causeway) and Section M-M′, Plates 13 and 39, respectively. As illustrated in Plate 13, there is a distinct break in the continuity of the bedding shown by the acoustic profile at the indicated fault. Bedding to the north is offset about 10 ft. Note that there is no offset of the erosional surface represented by the First Pleistocene Horizon or in the overlying Holocene deposits. In Plate 39, the Second Pleistocene Horizon is offset about 15 ft, and the offset in the bedding above this horizon is progressively less upward in the section. Again, there is no offset in the First Pleistocene Horizon. This implies that progressive movement occurred along the fault while material within the uppermost sequence of Pleistocene sediments was being deposited. Movement along the fault probably ceased entirely or was very minimal during the period when sea level withdrew from the area (about 23,000 to 7,000 yr ago, Figure 2), and the erosional surface delineated as the First Pleistocene Horizon was formed.

50. A third acoustic subbottom profile was obtained at a position roughly intermediate between the two profiles, Sections B-B′ and M-M′, and the fault was again detected. This permitted the refinement in the delineation of the fault, as shown in Plate 2. The position of the fault was further defined by projecting the positions of deep-seated faults to the surface. One such deep-seated fault, which has offset beds hundreds of feet at depths of several thousand feet, was projected to the surface and corresponded closely in position and strike to the fault, as mapped in Plate 2.

51. As previously mentioned, a cross fault trending in a northwest-southeast direction is thought to lie just south of the Rigolets. Its position in Plate 2 is based on a distinctive lithologic break at that point in Section D-D′, Plate 18. A massive sand unit appears to be offset at this point, reaching a thickness of more than 100 ft on the downthrown side of the fault. The sand body is thought by some investigators to represent relict beaches of Pleistocene age. A similar, thinner, and possibly correlative unit is found to the north of this feature. A fault at this point would help to explain the rather anomalous occurrence of two "islands" or outliers of Prairie Terrace on the upthrown side of the fault between it and the Baton Rouge fault extension. These outliers, Prevost Island and Apple Pie Ridge, are mapped as Prairie Terrace in Plate 2 and are identified in Plate 18. If they are indeed Prairie in age, the offset along the Baton Rouge fault extension to the north would be very moderate. The major offset would be along the cross fault.

PART III: PLEISTOCENE SOILS

52. Strengths materially greater than those of the Holocene soils characterize the Pleistocene soils. Unconfined compressive strengths (Q_u) of 1.5 tons/sq ft are common at and for several feet below the contact between these two geologic units, and strengths of more than 2 tons/sq ft are occasionally found. Strengths of cohesive soils in the Holocene, on the other hand, are almost always less than 0.5 ton/sq ft and are often less than 0.1 ton/sq ft. Such an important change in soil strength is, of course, of paramount importance, and the depth to and the variations in lithology and strength in the Pleistocene have long been recognized as critical factors in many engineering projects.

FIRST PLEISTOCENE UNIT

Topography of Buried Surface

53. Plates 3-8 show detailed contours on the First Pleistocene Horizon on six quadrangle maps covering the heart of the study area. All control borings are plotted. These contours have been generalized and transferred to Plate 2 where additional contours have been added for the rest of the study area. Control borings for these additional contours are shown in Plate 2.

54. It should be remembered that the buried Pleistocene surface once stood several hundred feet above sea level and was subjected to thousands of years of erosion. A drainage network developed on the surface consisting of relatively flat expanses dissected by fairly deep entrenched streams, which have since been backfilled with soft Holocene deposits, a topography not unlike that of the presently exposed Prairie Terrace. The contours in Plates 2-8 attempt to reproduce this topography. Earlier contours on this surface[16,25,26,32] were revised during this study with the help of at least 1000 new control points. The revised contours are also guided by the concept that two, rather than one, eroded and oxidized Pleistocene surfaces exist within 200 ft of the surface, the lower horizon sometimes having been confused with the upper on earlier contour maps.

55. One major entrenchment of the Pleistocene surface occurred at a later date in its geologic history—when the first Mississippi distributary trended across and cut into this surface some 4500 yr BP (Figure 3). This small channel eventually developed into the present full-flow course of the Mississippi, a Mississippi that has scoured deeply (as much as 200 ft below msl) and built sizeable segments of point bar deposits along its banks (Plate 2). Because of the scale of mapping used, the rather abrupt borders of this entrenchment could not be properly contoured in Plates 2-8. Contours, thus, have been halted at the edges of this entrenchment, and depths to Pleistocene beneath the Mississippi River and its bordering point bar deposits should be estimated as averaging 130-170 ft below msl. Plates 10 and 19 illustrate these relationships in profile.

56. The series of contour maps presented in this report are considerably more accurate than earlier maps; nevertheless, there are broad areas where there is little control, and the depth to Pleistocene is largely conjectural. This should be considered when these maps are used to estimate depths to Pleistocene for planning purposes or for specific engineering sites.

Lithology

57. Since the Pleistocene was a former deltaic plain of the Mississippi River, its lithology is similar to that of the overlying Holocene, the materials consisting of intricately interfingered soils of deltaic and marine origin. The sequence of soils in the study area is illustrated by subsurface Sections A-A′ through N-N′ (Plates 10-45). Locations of the sections are shown in Plate 1, and each plate contains the detailed location of the borings used in preparing the corresponding section. Soils have been grouped into four units, as designated in the legends accompanying each plate. Details of the soils and engineering properties of a small number of the many borings used in preparing the subsurface sections are illustrated in Plates 12a, 12b, and 40-43.

58. Generally, sands and silty sands appear to be more common in the Pleistocene than in the Holocene. As is the case in the Holocene, the principal environments of deposition characterized by granular soil are ancient beaches, abandoned distributaries, abandoned courses, and their associated point bar deposits. Such sand units in the Holocene have been delineated in Plate 2. Information is too sparse to attempt a similar delineation of sand units in the Pleistocene. However, Plate 9 shows the approximate positions of significant granular units within the Pleistocene as determined in Sections A-A′ through N-N′.

Recognizing the Holocene-Pleistocene Contact

59. Recognizing the contact between the Holocene and the Pleistocene deposits in borings is of importance in engineering studies and is usually a simple matter. The Holocene deposits are typically dark gray or blue-gray to fairly black. The upper portion of the Pleistocene is tan, yellow, or buff-colored. Kolb and Van Lopik[25] point out that where the contact is deeper than 50 ft, the color of the Pleistocene is often mottled tan to orange or greenish gray, a reflection of the shorter period of time during which the deeper deposits were above sea level and subject to oxidation. They also cite other characteristics of Pleistocene deposits distinguishing them from overlying Holocene deposits as (a) a marked decrease in water content, (b) a distinctive stiffening of soil consistency, (c) a decrease in rate of penetration of sampling devices, (d) an increase in soil strength,and (e) the occurrence of calcareous concretions.

SECOND PLEISTOCENE UNIT

60. What is believed to be a second eroded and oxidized surface underlies the first in the New Orleans-Lake Pontchartrain area at depths ranging from 50 to 100 ft. Plate 9 attempts to contour this second horizon based on control points wherever this horizon was identified. Although the contours should be considered a first approximation, they permit a rough estimate of the depth to this surface. For important, heavy structures such an estimate could be useful, particularly when the overlying younger Pleistocene unit contains critically weak soils.

61. Saucier[18] suggested the existence of this second erosion surface in a recent (1973) unpublished report. He pointed out that previous researchers had failed to recognize this second horizon or had sometimes misinterpreted it as being the upper erosion surface. This misinterpretation resulted in the contouring of anomalous entrenchments in the upper surface and the placing of the First Pleistocene Horizon at a depth significantly greater than is actually the case mainly in the area south of New Orleans.

62. Kolb[32] and others[25] have previously noted the occurrence of anomalously weak soils beneath the generally stiff crust which characterizes the First Pleistocene Horizon, weak soils which were in turn underlain by very stiff materials. However, they had failed to recognize the lower, stiffer soils as part of a depositional hiatus beneath a second oxidized surface. That such a surface or such surfaces must exist had been suggested as early as 1939 by Fisk[11] who had hypothesized that the downdip equivalents of the coastwise terraces must be burried beneath one another in the New Orleans-Lake Pontchartrain area. Nevertheless, the depth to such surfaces was conjectural.

63. The present study substantiates Saucier's contention. Careful logging of core borings with special attention being given to soil colors, soil consistencies, and the occurrence of concretions and other signs of an oxidixed, eroded surface permits the delineation of a Second Pleistocene Horizon. One series of borings made parallel to the New Orleans Causeway proved to be particularly useful in this respect. A few of these borings have been reproduced in Plates 12a and 12b. Soft, gray soils invariably characterize the uppermost Holocene deposits, and almost invariably the First Horizon consists of stiff tan (oxidized) soils. Tan colors persist to varying depths below the First Horizon. Gray colors again appear in the First Pleistocene Unit with depth. The second erosion surface is marked by distinctively stiff soils and by tan colors. In some instances, the tan colors are replaced by greenish gray colors, suggesting a reversal of the oxidation process, a possible reduction of former tan-colored soils with time. Many of the subsurface sections in this report, delineating the Second Pleistocene Horizon, have been prepared using such criteria. Depths of these points have been used to prepare the contour map in Plate 9.

64. Although Pleistocene soils are generally considerably stronger than the young Holocene soils above them, the erratic nature of the soil strengths are indicated in Plates 12a and b. Soil strengths (Q_u values) have been color coded in Plate 12, using data from this series of borings. Notice that occasional weak pockets of soil occur within the First Pleistocene Unit, that is, soils with Q_u values of less than 0.5 ton/sq ft. Few such pockets are found within the Second Pleistocene Unit; in fact, soil strengths in this unit are usually in excess of 1.0 ton/sq ft. Where data on soil colors, oxidation, etc., are less meticulously recorded, unconfined compressive strengths and lithologic breaks can sometimes be used to pick the break at the Second Pleistocene Horizon. Numerous Q_u determinations were available for the borings shown in Plate 38, and color coding of soil strengths was of considerable value in delineating the Second Horizon in this plate.

65. Another useful method for determining the depth to the Pleistocene horizons is through the use of acoustic subbottom (pinger) profiles. The erosional surfaces, distinctively stiffer than the overlying soils, are frequently well delineated on such profiles. Plate 39 illustrates this particularly well. Both the First Horizon and the Second Horizon, in this case offset by a fault, are prominently displayed. One important caution is that other horizons or strata may also be displayed, and these often mask the soil strata below. This condition is illustrated in Plate 13, where a sand unit effectively masks the Second Pleistocene Horizon which lies some 15 to 20 ft below. Thus, proper geologic interpretation of 100- to 200-ft-deep borings made in the New Orleans-Lake Pontchartrain area often involves delineation of not one but two Pleistocene erosional surfaces.

66. Soils are strongest at the top of a given Pleistocene horizon and for 10 ft or more below it, but unusually weak soil with Q_u's of less than 0.5 ton/sq ft can be found in small pockets to depths of more than 200 ft. An understanding of the various Pleistocene geologic units in the study area, their age, their structure, and their recognition in samples from core borings is important in correlating between borings and in evaluating the results of laboratory tests on soil samples for engineering purposes.

ENVIRONMENTS OF DEPOSITION

67. Determining the environments of deposition within an individual Pleistocene unit is complicated and time-consuming, but such studies can be useful on many engineering projects. Many of these studies have been made within the Holocene deposits of the present deltaic plain. Because the Pleistocene units are simply former deltaic plains now buried beneath the Holocene, an attempt was made to duplicate such studies within the Pleistocene. Plates 46-49 show the results of this study. Samples from two cored borings in east New Orleans were examined in considerable detail. Radiographs were made; mineral content and macrofossil (large fossil) content were examined; and microscopic analyses were made of washed residues of the samples. The results of this study indicated that, just as in the overlying Holocene deposits, valid determinations of environments of deposition can be made within the Pleistocene.

68. Plate 46 shows logs of the two borings and identifies the depositional environments which they penetrated. Photos and comparative radiographs of cores, illustrative of most of the environments, are shown in Plates 47 and 48. These plates also contain basic information concerning each environment and a listing of those microforms that are characteristically associated with one environment or occur abundantly within that environment. No attempt is made to reproduce the mass of data developed from the microscopic examination of the many washed samples used in preparing the basic information. Such data are available in the files of the Engineering Geology and Rock Mechanics Division, Soils and Pavements Laboratory, Waterways Experiment Station.

69. Plate 49 summarizes some of the results of the microscopic studies in graphic form. Percentages of glauconite, iron pyrite, organic matter, and fragments of macroforms in each sample are plotted opposite the sample depths in each boring. The absolute numbers of foraminifera in each washed sample are also plotted. Comparison of these graphs with the environments of deposition delineated in Plate 46 indicate certain features common to individual environments. Such relationships are invaluable in subsurface correlation.

70. Perhaps the most important factor in the correlation of strata in the buried Pleistocene units is a knowledge of the geologic processes responsible for the deltaic environments of deposition and an understanding of the geologic history of the area. Much has been published concerning the geologic history and development of the present Mississippi deltaic plain. In time, as additional borings are made and as the many available borings are more fully analyzed, the broad outlines of delta development during Pleistocene time should be possible in the New Orleans-Lake Pontchartrain area.

SOIL STRENGTHS

71. As previously mentioned, unusually weak soils, some with unconfined compressive strengths of less than 0.5 ton/sq ft, occasionally occur in the Pleistocene. The occurrence of the weak pockets of soil are of concern to those planning the engineering structures. In the following

paragraphs, the discussion should by no means be considered an in-depth study of the strength of Pleistocene soils. Such a study involves the analysis of strength parameters more sophisticated than unconfined compressive strengths and the relationship of these parameters (as well as other engineering parameters) to a degree of consolidation. These considerations are beyond the scope of the present study. Instead, the purpose of this discussion is twofold: (a) summarize just how weak occasional low-strength strata within the Pleistocene soils are, where they tend to be found in the Pleistocene sequence, and where they might be expected; and (b) weigh the possibility that cementation—or in this case, lack of cementation—may be an important reason for the occurrence of occasional low-strength strata within the Pleistocene.

72. Illustrative data are compiled in Plates 12, 12a, 12b, 38, and 40-43. The color code in Plates 12 and 38 is based on Q_u values taken at 10- to 20-ft intervals, but color differentiation in Plate 38 used a much larger number of borings than were available for Plate 12 and a correspondingly larger number of Q_u values. Both sets of data show essentially the same thing, i.e., unusually low strengths are more-or-less randomly distributed below the 10 to 20 ft of oxidized Pleistocene soils which mark the upper portion of the First Pleistocene Unit.

73. Kolb and Van Lopik[25] have assembled similar data on Pleistocene soils that graphically illustrate the erratic spread of soil strengths with depth below the First Pleistocene Horizon. Figure 4 is based on these data. The strengths in the upper 10-ft "crust" range from 0.5 to slightly more than 2.0 tons/sq ft, but strengths as low as 0.4 ton/sq ft are found at a depth of 82 ft below this horizon.

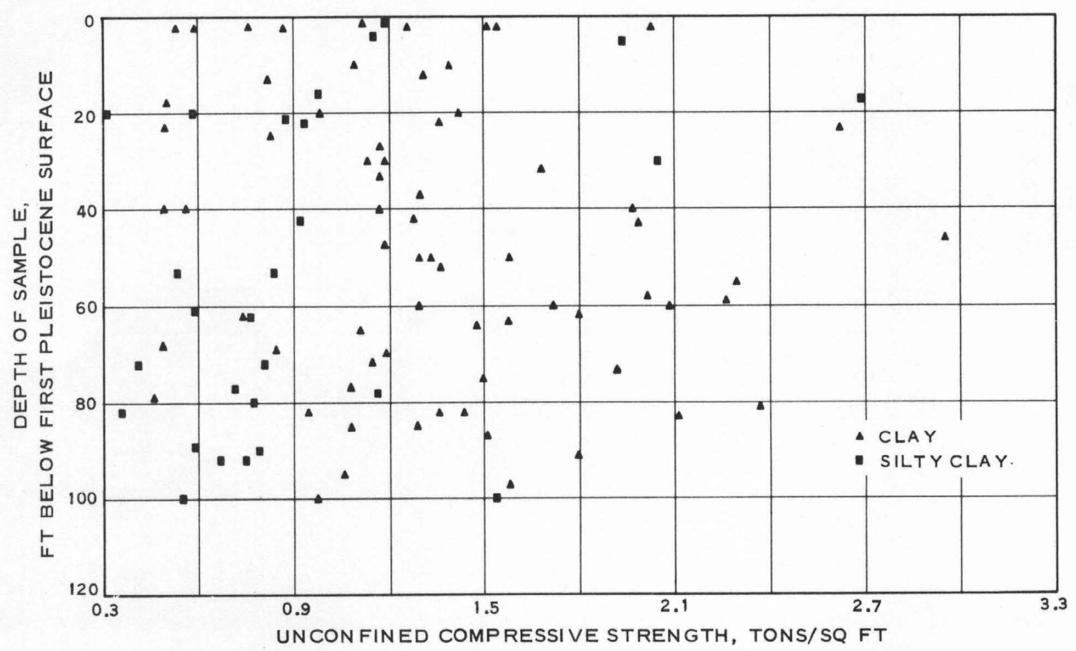


Figure 4. Depth versus strength relationships (Reference 25)

74. The high strengths of the topmost Pleistocene strata can be attributed to the geologic history which these soils have undergone. They were subjected to a long interval of oxidation, desiccation, and erosion. High strengths of geologically old soils are often caused by their overconsolidation by former overlying strata. In this instance, however, there is little evidence that the amount of erosion was substantial in terms of the removal of overlying strata. It is doubtful if as much as 10 ft of the originally deposited Pleistocene soils were eroded away except where deep drainageways entrenched the surface. The high strengths are instead partially caused by oxidation, desiccation, and preconsolidation down to a general level reached by the water table during the time of lowered sea level.

75. The detailed data in Plates 12a, 12b, and 40-43 indicate that although strengths drop off below the upper oxidized zone, they generally increase again with depth. However, the increase in strength is erratic and unpredictable with the same soil types, showing high variations in strength in samples within a few feet of each other. Ho and Coleman[36] working with Holocene samples in the Atchafalaya Basin have found that such minerals as hydrous iron oxides, calcium carbonate, siderite, and manganese carbonate play major roles in cementing the soils and increasing compressive strength. An obvious conclusion is that erratic cementation processes perform a similar or even greater role in imparting irregular strength characteristics to Pleistocene soils. Strength values accompanying the graphic log of boring 1AU in Plate 46 are cases in point. Unconfined compressive strengths of 6.75 and 3.8 tons/sq ft occur at depths of 185 and 212 ft, respectively, in this boring, a situation entirely inconsistent with strength increase due to normal consolidation under load.

76. Alternatively, soils with low strengths within the Pleistocene are equally erratic in their distribution. Bjerrum[37] has pointed out that fine-grained marine clays of glacial age in Norway are sometimes conspicuously lacking in strength. They are also highly sensitive, often quick, i.e., exhibiting a complete loss of strength on remolding. The Norwegian clays, originally deposited in a marine environment, have subsequently been lifted above sea level, resulting in the gradual drainage from the clays of saline waters and its replacement by fresh water. Loss of strength of the clays has been correlated by Norwegian investigators with this loss of salinity. In addition, they found that a change in salt content is accompanied by an appreciable change in plasticity in such a way that the liquid limit and the plasticity index are lowered with decreasing salt concentration in the pore water.

77. Such drainage undoubtedly occurred during the Pleistocene drop in sea level in the study area. However, this should have affected only the upper portions of the Pleistocene geologic units, and it is in these very upper portions where the higher strengths usually are found. Studies of the salinity of the pore water of Pleistocene clays—particularly those that are weak—might be informative.

78. Possible correlations were explored of low strengths in the Pleistocene soils with organic content, soil type, environment of deposition, and the distance to permeable strata where pore pressures could be dissipated. However, no meaningful correlations could be made.

79. It was anticipated that weak Pleistocene strata would have significantly higher water content values than high strength strata. This is not true. Similar soils, with identical Atterberg limits, often have highly variable unconfined compressive strengths despite essentially similar water contents and similar depths of burial. For example, analogous CH soils at depths of 195 and 212 ft in boring 1AU (Plate 46) have Q_u values of 1.5 and 3.8 tons/sq ft, respectively. A curve, developed from work by Weller,[38] was superimposed on the water content-Atterberg limits data which accompany boring 1AU. This curve equates water content with overburden pressure. It is based on the reaction of a homogeneous marine clay to load, and thus water contents shown opposite any but CH soils should be disregarded. Water contents of the CH soil samples are reasonably close to this hypothetical curve, suggesting normal consolidation under the given overburden pressure.

80. Skempton's[39] relationship of the unconfined compressive strength of the normally consolidated clays to their plasticity index was used to construct the dashed-line curve to the far right of boring 1AU. This relationship can be expressed as

$$Q_u = P(0.11 + 0.0037\ PI)$$

where Q_u is the unconfined compressive strength, P is the effective overburden pressure, and PI is the plasticity index. As can be readily seen, the actual Q_u values for the Pleistocene soils are erratic but usually much higher than the calculated values for normally consolidated clays. The conclusion then is that Pleistocene soils are close to being normally consolidated under their present overburden pressures and that strengths greater than those attributable to consolidation are probably degrees of cementation of the soil particles. In Plate 46, the curve based on Skempton's data shows that in the Second, or Lower, Pleistocene Unit only two actual values closely approach the calculated value. Similarly, water contents in the Second Pleistocene Unit are generally higher than those based on Weller's curve. This suggests that the clays in the Second Pleistocene Unit are approaching but have not quite reached full consolidation under their imposed loads—a reflection of the time necessary to transmit the consolidating effect of the more recently deposited Holocene load to these lower levels.

81. Skempton's relationship was also applied (where data were available) to the weaker soils graphically portrayed in Plates 12a, 12b, and 40-43. These are the weaker Pleistocene soils shown in red in Plates 12 and 38. Almost all of the soils in this weakest category proved to have strengths slightly to moderately higher than would have been the case for normally consolidated soils. Borings 63 and 69 in Plates 40-43 illustrate the only two instances in this series of borings where the data indicated the soils had not reached normal consolidation.

82. To summarize, it is concluded that the Pleistocene soils are close to being normally consolidated under present overburden conditions but that only the lowest strengths, about 0.5 ton/sq ft, are due entirely to consolidation. Higher strengths, averaging 1.5 tons/sq ft and reaching 6.75 tons/sq ft in one instance (Plate 46), are caused by desiccation and cementation. Because water tables probably never reached depths of more than 20 ft below the First and Second Pleistocene Horizons, desiccation must be ruled out as a major contributing factor. The high soil strengths of the great majority of Pleistocene soils are thought to be caused chiefly by cementation, a process that is only poorly and partially understood.

PART IV: SUMMARY

83. Pleistocene soils of significantly greater strength than overlying Holocene soils underlie the New Orleans-Lake Pontchartrain area. Deposition and age of these soils are related to the eustatic rise and fall in sea level which accompanied the expansion and contraction of the continental ice sheets during the Pleistocene or Glacial Epoch.

84. There is much controversy among geologists concerning the last 100,000 yr of sea level fluctuation. A reasonable consensus is that sea level was at or may have been slightly above its present level about 100,000 yr ago. It dropped at the beginning of Early Wisconsin time, about 80,000 yr ago, and fluctuated intermittently between then and about 45,000 yr ago, possibly reaching and again retreating from its present level during this interval. Between 35,000 and 25,000 yr ago, it rose to within at least 150 ft of its present level. Then, it dropped 400 ft or more, by 17,000 yr ago, but rose rapidly thereafter to its present level, about 5,000 yr ago.

85. The Prairie Terrace, exposed to the north of Lake Pontchartrain, is believed to have been formed during the interglacial high stand in sea level between 110,000 and 80,000 yr ago. The Deweyville Terrace, which forms low flats along the Pearl River in the study area, is dated between 30,000 and 17,000 yr ago. Ages are based largely on geomorphic correlations with other regions. Few radiometric dates are available on the Prairie and none on the Deweyville of the study area.

86. The well-defined oxidized Pleistocene horizon which lies directly beneath the Holocene (Recent) deposits is believed to be the downdip and downfaulted equivalent of either the Deweyville or the Prairie. There is a remote possibility that it is of some intermediate age. Available, but controversial, C-14 dates of this uppermost Pleistocene unit range from 17,000 yr to inert, i.e. greater than 35,000 yr.

87. Major faulting in the area occurs in a broad zone called the Baton Rouge Fault. The surface contact between the Pleistocene and the Holocene is largely controlled by offset along this east-west fault zone. A generally parallel fault lies to the south beneath Lake Pontchartrain. Offset along this fault is confined to the First Pleistocene and older units. There is no offset in the overlying Holocene which ranges in age from about 7000 yr to the present.

88. A second eroded and oxidized surface underlies the first at depths ranging from 50 to 100 ft. The age of the second unit is also conjectural. Pleistocene soils are markedly stronger than the overlying Holocene soils. Unconfined compressive strengths (Q_u values) of 1.5 tons/sq ft are common at and for 10 to 20 ft below the contact, and strengths of more than 2 tons/sq ft are not uncommon. On the other hand, strengths of Holocene clays, are almost always less than 0.5 ton/sq ft and often less than 0.1 ton/sq ft.

89. Unusually weak soils, some with Q_u values of less than 0.5 ton/sq ft, occasionally occur in the Upper Pleistocene Unit. These soft strata were found to be more or less randomly distributed below the top 10 to 20 ft of the oxidized Pleistocene soils. Possible correlations were explored of low strength with organic content, soil type, environment of deposition, and the distance to permeable strata where pore pressures could be dissipated. However, no meaningful correlations were possible.

90. High strengths of Pleistocene soils are not caused by their overconsolidation by former overlying strata. It is doubtful if as much as 10 ft of the originally deposited Pleistocene soils were removed by erosion except where deep drainageways entrenched the surface. The high strengths of the "crust" (the upper 10 to 20 ft) are instead partially caused by oxidation and desiccation to a general level reached by the water table during the time of lowered sea level.

91. Using a relationship among the plasticity index, the effective overburden pressures, and the compressive strength, it was determined that Pleistocene clays generally have much higher compressive strengths than can be accounted for by normal consolidation under load. The lowest strengths, about 0.5 ton/sq ft, could be due entirely to consolidation. Higher strengths, averaging 1.5 tons/sq ft and reaching 6.75 tons/sq ft at a depth of less than 200 ft in one instance, are caused by desiccation and cementation. Because water tables probably never reached depths of more than 20 ft below the First and Second Pleistocene Horizons, desiccation must be ruled out as a major contributing factor. The high soil strengths of the great majority of Pleistocene soils are thought to be due to cementation by such minerals as hydrous iron oxides, calcium carbonate, siderite, and manganese carbonate.

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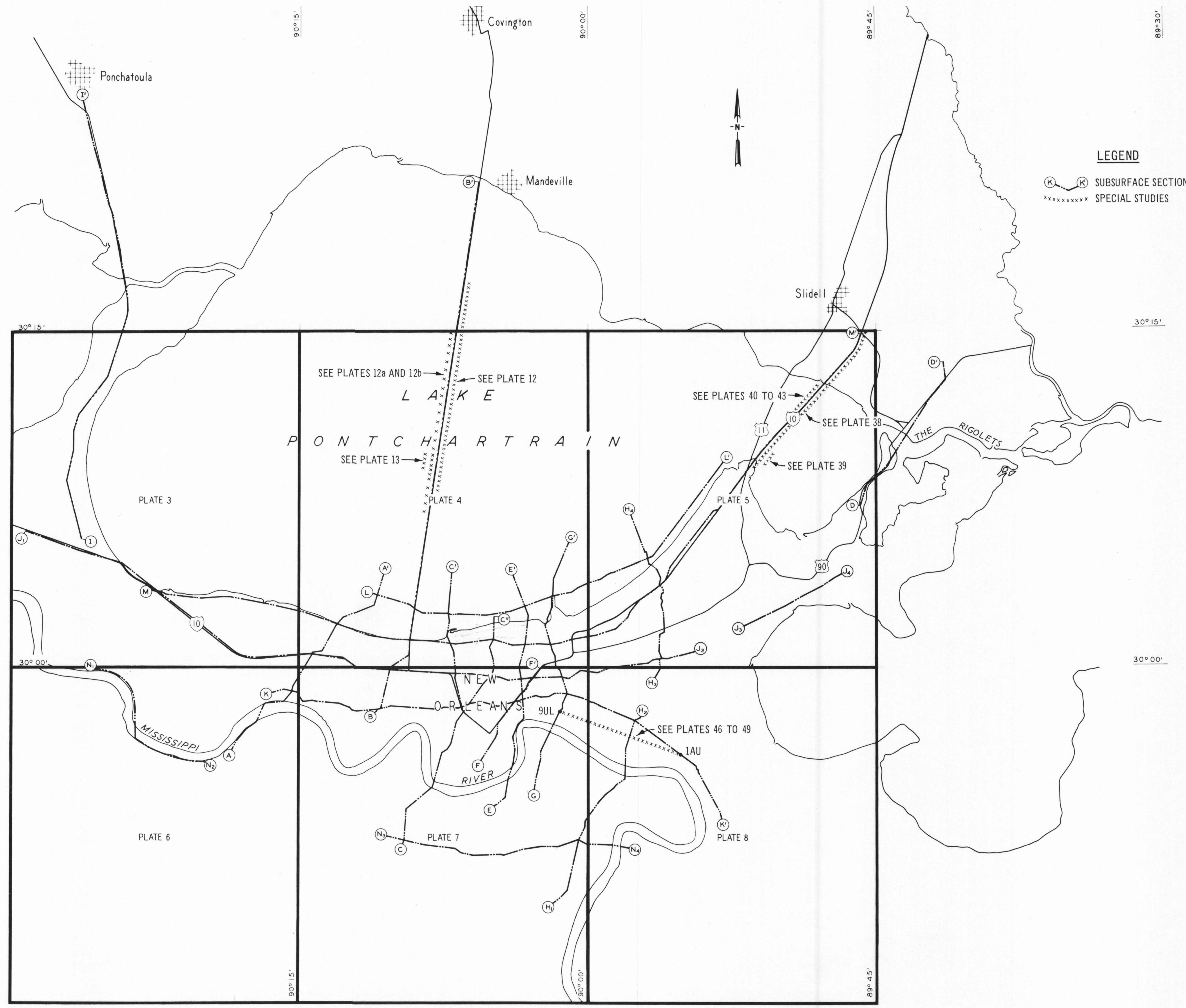

PLEISTOCENE SEDIMENTS
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