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J. H. AUVIL, JR., DIRECTOR

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by

James W. Furlow

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STRATIGRAPHY AND ECONOMIC GEOLOGY OF THE EASTERN CHATHAM COUNTY PHOSPHATE DEPOSIT

LETTER OF TRANSMITTAL

Department of Mines, Mining and Geology

July 22, 1969

His Excellency, Lester G. Maddox
Governor of Georgia and
Commissioner Ex-Officio
State Division of Conservation
Atlanta, Georgia 30334

Dear Governor Maddox:

I have the honor to submit herewith Bulletin 82 of the Department of Mines, Mining and Geology, "Stratigraphy and Economic Geology of the Eastern Chatham County Phosphate Deposit," by James W. Furlow.

This report covers the relation between the economic phosphate zone, the fresh water aquifer, and the intervening impermeable sediments. In addition, the report shows the vast amount of phosphate which is present in eastern Chatham County. The report also shows that a properly conducted mining venture is technically and geologically feasible without further damage to the fresh water supply of the area.

Very respectfully yours,

JHAuvil, Jr

J. H. Auvil, Jr.
Director

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STRATIGRAPHY AND ECONOMIC GEOLOGY OF THE EASTERN CHATHAM COUNTY PHOSPHATE DEPOSIT

by James W. Furlow

ABSTRACT

This report is prepared by the Georgia Department of Mines, Mining and Geology with two main objectives: 1) to determine whether mining phosphate in eastern Chatham County would endanger the principal artesian aquifer which supplies the city of Savannah with fresh water, and 2) to determine the extent, depth, grade, volume, and value of the phosphate matrix.

The study indicates that the confining layer above the artesian aquifer is thick enough and impermeable enough to allow the phosphate ore zone to be removed and still prevent significant salt water infiltration into the acquifer. Therefore, mining the phosphate under supervision of established State and Federal agencies will not damage the aquifer nor adversely affect the quality of Savannah's fresh-water supplies.

In an area of Chatham County south of the South Carolina line, north of Ossabaw Sound, east of most residential development and within the oceanic three-mile limit, mining could be accomplished presently or in the near future. Evaluation of this delineated area shows that the overburden thickness varies from a minimum of 70 feet under Savannah Beach to 130 feet under Ossabaw Sound. In the same area the phosphate matrix thickness varies from 15 feet under the mouth of the Savannah River up to 50 or 60 feet under Skidaway Island. Where present consideration is being given to mining in the vicinity of Wilmington, Cabbage, and Little Tybee Islands the matrix is 20-30 feet thick.

Volumetric studies of phosphate recoverable both presently and in the near future show that there is within the delineated area approximately 4,800,000,000 cubic yards of matrix, containing an average of 22.5% Bone Phosphate of Lime, or BPL. At an approximate weight of 1.5 tons per cubic yard and a concentration of 22.5% BPL, there are about 1.6 billion tons of

100% BPL concentrate present. Assuming a not unreasonable recovery factor of 50%, at least 800,000,000 tons of 100% BPL concentrate could be recovered for market sale. At a present-day price of about $10 per ton, the value of this phosphate is approximately eight billion dollars.

In addition to the area considered above, evidence indicates that the phosphate matrix may extend continuously out to sea for at least ten miles, and probably beyond. Thus the coastal and offshore phosphate resources of Georgia may prove to be extremely valuable as the demand for this mineral commodity increases.

INTRODUCTION

General Statement

Phosphate production in the United States, mainly for agricultural fertilizer, was until very recently confined to Florida, several western states, and Tennessee. Florida is today, and has been for many years, the leading domestic producer of phosphate with about 75% of the total in 1965. The western states of Utah, Wyoming, Idaho, and Montana account for some 14% of the U.S. total, while Tennessee produces about 11% of the total.

Although it was common knowledge for many years that extensive phosphate-bearing sediments exist in the subsurface of the eastern seaboard, these deposits for the most part had been considered marginal or even uneconomic. About seven or eight years ago, however, numerous mining companies interested in developing new deposits, as well as established phosphate producers looking for future reserves, began extensive exploration programs on the Atlantic Coastal Plain. The results of this work are retained in the files of the organizations involved as confidential information, not available for public dissemination.

Nevertheless, as the demand for phosphate increased and mining technology improved, it became apparent that the eastern seaboard might become a source of major phosphate reserves. This possibility was borne out in 1966 by the Texas Gulf Sulfur Company, which pioneered a large phosphate mine at Lee Creek, North Carolina. Development of this deposit required the most modern mining concepts and equipment. Many of the techniques used in the Lee Creek mine would be applicable to phosphate mining in Georgia.

Concurrent with the development of the Lee Creek mine, the minerals industry in general began to concentrate exploration for phosphate in the Coastal Plain of Georgia. The Kerr-McGee Corporation, International Minerals and Chemical Corporation, and several other large corporations did detailed studies on the phosphate potential of southeast Georgia. At the same time, the Georgia Department of Mines, Mining and Geology began a special phosphate exploration program to assist industry and to evaluate the phosphate potential for the State of Georgia.

In 1966, after evaluation of its own exploration results, the Kerr-McGee Corporation began acquiring options on land in eastern Chatham County which International Minerals and Chemical Corporation had held but let lapse. By May of 1968 Kerr-McGee considered its holdings on Little Tybee, Wilmington, and Cabbage Islands to be sufficient for a large-scale mining operation if State-owned waterbottoms which wind through the marshes could be leased. Accordingly, Kerr-McGee through its subsidiary, Franjo, Inc., made application for a lease on State-owned waterbottoms and off-shore ocean floor.

Immediately following some initial discussion among the members of the State Mineral Leasing Commission, Governor Lester Maddox announced that the Commission would hold public hearings on the lease application at which all interested parties would be given a chance to have their say. Although the public hearings brought out a number of interesting points, they tended to cloud the issue rather than resolve it. Thus the Mineral Leasing Commission delayed action on Kerr-McGee's bid and allowed the deadline to pass without accepting or rejecting the bid. Kerr-McGee then withdrew its bid and the issue was settled for the present.

Purpose of this Investigation

Prior to the public hearings the Director of the Department of Mines, Mining and Geology suggested to the Governor the desirability of a study by an impartial group of specialists on all aspects of mining the marshlands. Immediately thereafter Governor Maddox directed the Board of Regents of the University System of Georgia to make a study of the effects mining would have on tourism, industry, marsh ecology, contamination of fresh water supplies, and other facets of the operation. This study was intended to provide the State Mineral Leasing Commission with sufficient information to enable it to formulate a fair and impartial decision (Cheatum and others, 1968).

The Georgia Department of Mines, Mining and Geology cooperated in this study by providing information and drill rigs to acquire detailed geologic knowledge of the area. Drilling and mineral analyses were done by Georgia Tech under the Georgia Minerals Program as sponsored by the Department of Mines, Mining and Geology.

The Kerr-McGee Corporation also willingly cooperated in the Board of Regents study by providing geologic information and by drilling strategic holes for the study in the relatively inaccessible marshes. Their drilling was followed closely by geologists of the Department of Mines, Mining and Geology, Georgia Tech, and the U. S. Geological Survey. The Department of Mines, Mining and Geology studied the core samples and had permeability tests made at strategic intervals.

The Department of Mines, Mining and Geology, realizing the importance of the investigation, undertook special independent studies to gain better knowledge of the subsurface geology of eastern Chatham County, especially regarding the relationships of overburden to matrix to aquiclude to aquifer. The great volume of geologic information accumulated during the course of these studies has resulted in a much clearer picture of the subsurface of eastern Chatham County.

In this study, the Department of Mines, Mining and Geology was concerned primarily with the effects of mining on the artesian aquifer system of eastern Chatham County. Therefore, only the upper aquifer zones just below the phosphate matrix were involved. For this reason, drilling was done only into the uppermost aquifers at the base of the Oligocene sediments and top of the Eocene sediments, where conditions permitted. There was no need to do a study on the whole aquifer system, as this has been thoroughly studied and described in previous publications.

Previous Work

McCallie (1898) was the first to publish a description of subsurface water in the Savannah area, followed by Veatch and Stephenson (1911) who described the geology of the Coastal Plain of Georgia county by county, including Chatham.

Collins, Lamar, and Lohr (1932) and Lamar (1940) described the water supplies and quality of water for the city of Savannah. Through a continuously-cooperative program between the Department of Mines, Mining and Geology and the Water Resources Division of the U. S. Geological Survey, artesian water composition and water levels in the Savannah area have been checked for many years. Also, artesian water systems of southeastern Georgia were described by Warren (1944a and 1944b) and Cooper and Warren (1945). Warren in 1955 published on artesian water in the Savannah area, while Herrick and Wait (1955 and 1956) described the subsurface geology and hydrology of Savannah. Siple (1957) reported on the geology and hydrology of nearby Parris Island, South Carolina, followed by Counts' (1958) report on the quality of water of Hilton Head Island, South Carolina.

The most useful and comprehensive reports on the geology and hydrology of the Savannah area, with special emphasis on salt-water encroachment, were published by Counts and Donsky (1963) and McCollum and Counts (1964). Thus there is a great deal of information available for the preparation of this report.

Acknowledgments

The author is indebted to Dr. S. M. Herrick of the U. S. Geological Survey for a great deal of freely given unpublished information on the subsurface geology and stratigraphy of Chatham County. Special thanks are also due Mr. Jesse H. Auvil, Jr., Director of the Georgia Department of Mines, Mining and Geology, for assistance on engineering and mining problems and to Mr. William E. Marsalis, Jr., geologist, Georgia Department of Mines, Mining and Geology, for assistance in lithologic logging and micropaleontological analysis of well cores for geologic contacts.

PHOSPHATE

Origin and occurrences

At this point, a brief discussion of the origin, transportation, and deposition of phosphate is desirable. In this case, however, only phosphate concentrations deposited in marine environments will be considered, as this is the type deposit found in eastern Chatham County. The other two types of phosphate deposits are igneous apatites and guano (McKelvey and others, 1953), not found in this area in commercial quantity.

Although there are some 200 minerals that contain more than 1% P_2O_5, most phosphorus occurs in the apatite group with a general formula of Ca_{10} $(PO_4, CO_3)_6$ $(F, CL, OH)_2$ (Palache and others, 1951, p. 877). The mineral structure of apatite allows a wide variety of atomic substitution for PO_4; the chemical composition of phosphate deposits may therefore be changed by substitution to something quite different from the original sediment.

The mineral apatite, common in most igneous rocks, is slowly soluble in neutral to alkaline water solutions and increasingly soluble in waters of increasing acidity, decreasing hardness, and decreasing temperature (McKelvey, 1967, p. D4). Most phosphorus is transported to the ocean as various phosphate minerals or adsorbed on iron, aluminum hydroxides, or clay. Some, however, is carried in particulate or dissolved organic compounds and about one-sixth of the total is carried in solution (Ibid, p. D4).

Since the oceans, as a whole, are almost saturated with respect to phosphate, an amount of phosphate equal to that brought in by the rivers is being continuously precipitated. The phosphate content of the oceans is not uniform, however; deep cold oceanic water can contain nearly 0.3 ppm PO_4, whereas warm surface water contains 0.01 ppm or less (Ibid, p. D5).

Oceanic circulation and overturn will eventually bring the cold phosphate-rich waters to the surface in four types of situations:

1) Where a current diverges from a coast or where two currents diverge from each other, deep cold water will rise up to replace the surface water.

2) Where two currents meet and produce considerable turbulence, deep cold water will rise.

3) Along the western edge of northward-moving currents (in the northern hemisphere), dynamic upwelling of cold water may occur.

4) In higher latitudes, very saline and dense water from the tropics sinks as it is cooled and cold water rises in replacement. (Ibid, p. D5).

In any event, where cold waters rich in phosphate and other nutrients are brought to the surface, the solubility of phosphate decreases as temperature and pH increase. As the solubility decreases, phosphate (as apatite) is precipitated out by organic and inorganic processes.

This upwelling of cold, nutrient-rich water with resulting changes in physical, chemical, and biological processes is one environment in which phosphate may be precipitated and deposited in the oceans.

Emigh (1958, p. 10) defines a phosphate deposit as a phosphorite if it is of sufficient size and grade to be of economic interest. Used in this sense, a phosphorite is a sediment or sedimentary rock of considerable volume which contains a high percentage of phosphate in the rock. This definition will be used in this text, so that phosphate refers to the mineralogical term and phosphorite refers to the body of sediments as a whole.

Of the phosphate consumed in the United States, most is used in agriculture as one of the main ingredients of fertilizer. "Superphosphate" (an industrial term for P_2O_5) is the principal ingredient of fertilizer, taking precedence over nitrogen (N) and potash (K_2O). Within the industry the phosphate content of a sample is commonly reported as $Ca_3(PO_4)_2$, which is known as Bone Phosphate of Lime (BPL). BPL percentage may be obtained by multiplying P_2O_5 percentage by a constant, 2.185. Dried phosphate rock, sold by the long ton, normally ranges in grade from 55 to 77% BPL (Barr, 1960, p. 650).

GEOLOGY

The Georgia Coastal Plain

The Coastal Plain Province of Georgia is a key segment of the Atlantic Coastal Plain which extends from New York southward to Guatemala. In southeast Georgia the Coastal Plain Province consists of Lower Cretaceous to Recent sediments overlying much older igneous and metamorphic "basement" rocks (Milton and Hurst, 1965) and (Herrick and Vorhis, 1963).

In early Cretaceous time the igneous and metamorphic rocks of the continental margin underwent subsidence, allowing the sea to encroach over much of Georgia; during this time sediments were deposited in an ever-thickening sequence above the "basement rocks." Since deposition began in early Cretaceous time, the seas have retreated and advanced over south Georgia repeatedly, leaving layers of sediments each time. Generally, the sediments are thickest in extreme southern Georgia and along the Atlantic Coast, then thin northward to wedge out near the Fall Line.

Cretaceous to Middle Eocene

Sediments of Lower Cretaceous to Lower Eocene age, although present in Chatham County, do not contribute significantly to the fresh-water aquifer system and therefore were not considered in this study. Sediments of Middle Eocene age do contribute water to the system, but mining would not affect this zone in any way, and since this sequence was described thoroughly by McCollum and Counts (1964) and Counts and Donsky (1963) there was no need to include the Middle Eocene in this study.

Upper Eocene

Ocala Limestone:

The Upper Eocene Ocala Limestone of the Jackson Group, first described by Dall and Harris (1892), extends over northern Florida, southern Alabama, southernmost South Carolina, and much of southern Georgia. Herrick (1961) has positively identified the Ocala in the subsurface of Chatham County by extensive lithologic and micropaleontological studies of well samples.

In the Savannah area, the Ocala has in practice been divided into a lower unit and an upper unit (Counts and Donsky, 1963, p. 25). The lower unit consists mainly of a buff, granular calcitized limestone with thin layers of dense, pale-blue limestone and sandy, silty marl (Ibid, p. 25). The average thickness of the lower unit in eastern Chatham County, according to Counts and Donsky (1963, p. 25), is about 230 feet.

The upper unit of the Ocala of Chatham County is a gray to cream, dense, highly fossiliferous limestone. Fossils identified in cores of the upper unit include echinoids, pelecypods, foraminifera, ostracods, and abundant bryozoans. The great profusion of certain fossils in the limestone indicates a reef type environment of deposition in this area in late Eocene time. The upper unit of the Ocala in the Savannah area varies from 80 to 155 feet thick, with an average thickness of about 100 feet (Ibid, p. 25).

Both lower and upper units of the Ocala contain numerous cavities and solution channels throughout; caverns are not uncommon in many zones of the Ocala. These interconnecting solution channels and caverns undoubtedly account for the very high transmissibility of water through the rock and therefore for the high yield of water wells drilled into the Ocala. In Chatham County the Ocala Limestone comprises about 75% of the principal artesian aquifer; the remainder is divided between Middle Eocene and Lower Oligocene sediments. The fresh-water resources of the Ocala Limestone, therefore, are vital to the city of Savannah and should be protected as long as possible against additional salt-water contamination other than that caused by present heavy pumping of the aquifer (McCollum and Counts, 1964, p. D15-D20).

The Ocala Limestone dips to the southwest at a gradient of about 12 feet per mile (Fig. no. 2). For the most part, the southwest-dipping trend is fairly uniform, except for the area underlying the mouth of the Savannah River and McQueens, Long, Tybee, and Little Tybee Islands. Here subsurface studies show a structural high elongated in a northwest-southeast direction with the axis of the easternmost portion of the structural high doubly plunging to the north and south (Fig. no. 2). Inasmuch as this structural high has not been previously recognized or described in the literature, the author has taken the liberty of naming it the Tybee High. There is no doubt that the high exists, for it persists upward into geologically younger sediments (Figs. 3 and 4). Delineation of the Tybee High in sediments below the Ocala Limestone is presently not possible, due to lack of accurate geological control.

Oligocene

The Oligocene section in the Savannah area has been for some time, and still is, a complicated problem in stratigraphic nomenclature. Dr. S. M. Herrick of the U. S. Geological Survey (personal communication, 1969) is of the opinion that stratigraphic and micropaleontologic correlations have not been sufficiently worked out to warrant the use of formational names on any portion of the Oligocene of Chatham County. The author concurs with this opinion and will consider all Oligocene sediments as undifferentiated Oligocene.

The Oligocene of Chatham County varies lithologically from a calcareous sand to a sandy marl to a sandy or clean limestone (Plates 1 and 2). Basal Oligocene sediments are lithologically indistinguishable from Upper Eocene sediments in the Savannah area; both consist of gray to cream dense fossiliferous limestone, with no transition or geologic hiatus apparent. Locating the Eocene-Oligocene contact in this area on any lithologic basis without use of microfossil assemblages is difficult and in most instances inaccurate. Examination of microfossils in well cuttings, however, will quickly and accurately pinpoint the depth of this contact. For the purpose of this study, all wells which penetrated the Eocene-Oligocene contact were examined for microfossils either by Dr. S. M. Herrick of the U. S. Geological Survey or by Mr. William E. Marsalis, Jr., of the Georgia Department of Mines, Mining and Geology. There is, therefore, a high degree of accuracy in the placing of the Eocene-Oligocene contact in the wells which were drilled into the Eocene.

In eastern Chatham County the Oligocene section varies in thickness from 55 feet under Tybee Island to 130 feet under the Vernon River to the west.

Structurally, the Oligocene sediments dip to the southwest at a gradient of 10 feet per mile (Fig. no. 3). This gradient, as in the underlying Eocene, is maintained with only minor variations from a monoclinal slope. Again, however, the Tybee High shows up as a prominent northwest-southeast trending structure (Fig. no. 3).

Miocene

The Miocene section of eastern Chatham County encompasses three formations: the Lower Miocene Tampa Limestone equivalent, the Middle Miocene Hawthorn Formation, and the Upper Miocene Duplin Marl. Contacts between these formations are frequently subject to individual interpretation due to the gradational nature of the sediments.

Tampa Limestone Equivalent:

Although Counts and Donsky (1963, p. 27-29) described the Tampa Limestone of the Savannah area in some detail, the author believes that in eastern Chatham County at least, it would be a misnomer to call basal Miocene sediments Tampa Limestone. There are two reasons for this: first, the Oligocene-Miocene contact was picked in this study partly on the basis of lithology and partly on the basis of gamma-ray logs. BPL analyses of cores studied in this report show only minor amounts of phosphate present in the Oligocene sediments. At the base of the Miocene, however, the phosphate content increases markedly, with a resulting distinctive peak on the gamma-ray log (Plates 1 and 2). The base of this peak was found to correspond quite well with the Oligocene-Miocene contact, allowing good correlation between wells where lithology alone is insufficient. It should be noted that this type of correlation by gamma-ray log requires the assumption that the amount of phosphate in the sediments follows time lines, with a drastic increase at the beginning of Miocene time. This, however, is not an unreasonable assumption, since the Oligocene-Miocene contact is an unconformity, thus implying a period of interrupted deposition or erosion in late Oligocene or early Miocene time. Therefore lithologic determination of basal Miocene sediments in eastern Chatham County is probably not as reliable as mechanical determination, and sediments previously described as Tampa Limestone might instead be Oligocene in age.

The second reason the term "Tampa Limestone" is a misnomer in eastern Chatham County is that the basal Miocene sediments are rarely limestone. More often they are sand, sandy clay, or marl. Thus the "limestone" part of the name is frequently incorrect terminology and should not be used. However, since the sediments are probably equivalent in age and, to some extent, in lithology to the Tampa Limestone of Florida, an acceptable compromise for the Savannah area would be to call this zone "Tampa Limestone equivalent."

The thickness of the Tampa Limestone equivalent in this area is probably no more than 5 to 15 feet, although a detailed study of the Lower Miocene would be necessary to establish an accurate top. In general there is rarely an abrupt change in lithology from Tampa equivalent to well into the Middle Miocene Hawthorn Formation.

Hawthorn Formation:

The Hawthorn Formation of the Savannah area consists mostly of marl, sandy clay, and clayey sand. In general, the lower portion of the Hawthorn is more calcareous, while the upper portion is mostly intermixed sand and clay. The sands and clays of the Hawthorn, as well as the calcareous portions, are typically olive-green in color and often contain appreciable amounts of phosphate.

The thickness of the Hawthorn in this area varies from a minimum of 20 feet under Wilmington Island to a maximum of 55 feet under the marshes to the east. In the area that the Kerr-McGee Corporation considered to be most favorable for mining (Cheatum and others, 1968, Fig. 3, p. 23), the Hawthorn Formation locally has a minimum thickness of 25 feet and a maximum thickness of 55 feet. However, throughout most of this area the Hawthorn is at least 40 feet thick. The sediments in this area are mostly tough clays and tough sandy clays of very low permeability. Over a portion of the area the Hawthorn Formation is capped by a dense dolomitic limestone stringer about one foot thick (Plates 1 and 2). Where the dense limestone stringer exists it would in effect be the bottom limit for any dredge mining type of operation.

Duplin Marl:

According to Counts and Donsky (1963, p. 31) the Hawthorn Formation is unconformably overlain by the Upper Miocene Duplin Marl in the Savannah area. In eastern Chatham County the Duplin Marl consists mostly of olive-green sand, sandy clay, and clayey sand. It is frequently difficult to distinguish visually between sediments of the upper Hawthorn Formation and basal Duplin Marl. There is, however, one lithologic characteristic that readily differentiates between the two: phosphate content. The Hawthorn Formation contains an average of two to three percent BPL and nowhere contains more than about five percent BPL (Plates 1 and 2). At the base of the Duplin Marl the phosphate content increases abruptly to 13 to 30 percent BPL and generally maintains a high level upwards. This increase in phosphate content can be explained by assuming that phosphate was being deposited in minor amounts at least until the end of Hawthorn time, when there was an interval of erosion. With the resumption of deposition in late Miocene time, conditions were favorable for precipitation and concentration of large amounts of phosphate in the Duplin Marl. Therefore the marked increase in phosphate content is probably a time line that coincides with the Hawthorn-Duplin contact in eastern Chatham County.

At this point it should be noted that the theory of phosphate precipitation and deposition from upwelling cold water as previously described does not fit with the known facts in this particular deposit. Lithologic evidence indicates that the sediments were deposited in a shallow-water, near-shore environment not associated with cold water upwelling. Pevear (1966, p. 251-256) has postulated a theory whereby phosphate may form in estuarine waters distant from cold water upwelling by the replacement of limestone. In this case the concentration of phosphorus is supplied by decaying marsh grass and benthic algae. Pevear (Ibid, p. 252) estimates that over a period of one million years a typical Georgia estuary of less than twenty square miles in area could produce one-half billion tons of phosphorite, providing that all the inorganic phosphorus from the Altamaha River and the tidal exchange were precipitated. Since this is not likely to occur, Pevear estimates that some 200 million tons of phosphorite is more realistic.

Briefly, Pevear's theory is as follows: Assuming that the estuarine waters are favorable for carbonate deposition, calcareous muds and silty marls would cover the floor of the estuaries. If a climatic cooling trend developed, the cooler sea water would hold more $CaCO_3$ in solution, and carbonate deposition would cease. At the same time, the cooler water would cause a substantial increase in nutrients and productivity of the estuarine waters. If the phosphorus concentration were to rise above a certain level (1 mg-atom/m^3), the existing calcareous muds would be converted to phosphorite (Ibid, p. 253). This theory fits into the known facts of the Chatham County deposit much better than a theory employing cold water upwelling but still does not answer all questions regarding environment of deposition. McKelvey (1967, p. D12), for example, states that only where this type of deposit has been subjected to extensive reworking by submarine currents or weathering is it rich enough to be mined. In this case part of the phosphate in the Duplin Marl could conceivably have originated from reworked and concentrated sediments of the Hawthorn Formation. Indeed, with such a great similarity between Duplin and Hawthorn sediments in this area, it is quite possible that the marked increase in phosphate content of the Duplin Marl could be attributed to some reworking of Hawthorn sediments with resulting concentration of phosphate. Microfossil studies might clear the problem up, but unfortunately microfossils are extremely rare in the Hawthorn Formation.

For this reason, then, the author believes that Pevear's theory is the best explanation advanced yet for the formation of the Chatham County phosphate deposit, but some modifications of his hypothesis might become necessary as this type of deposit is studied in more detail.

The phosphate found in the Miocene of Chatham County occurs as small grains, nodules, and phosphatized fish remains. The grains and nodules, black, brown, and reddish in color, range from very fine sand size up to about 2 cm. in length. They are commonly smooth, rounded, oval in shape, and relatively flat. Phosphatized shells up to 3 cm. long occur sparsely in the matrix along with phosphatized fish teeth and vertebra, which are more common. The phosphate in high concentration was in all cases associated with the olive green sandy clay and clayey sand of the Duplin Marl. Phosphate does occur in some of the marls and limestones of the Hawthorn Formation and even in Oligocene marls and limestones, but not to any degree of economic concentration. In eastern Chatham County the olive green color seems to be diagnostic for phosphate, and to a limited extent, for phosphate of economic grade.

The phosphate ore zone is overlain by up to 50 feet of additional sediments of the Duplin Marl, similar in lithology to the ore zone, but containing appreciably less phosphate. In the vicinity of the mouth of the Savannah River the Duplin Marl appears to have been scoured and subjected to erosion (Plates 1 and 2). Here the uneconomic portion of the Duplin is very thin or not present, and locally Pleistocene sediments rest directly on the ore zone of the Duplin.

Pleistocene to Recent

Although Counts and Donsky (1963, p. 31-32) described questionable Pliocene sediments of the Waccamaw (?) Formation, Herrick (1965, p. 7 and personal communication, 1969) believes that the Miocene Duplin Marl is directly overlain by Pleistocene sediments in eastern Chatham County. The author, after examination of cores from eastern Chatham County, could find no reliable evidence of Pliocene sediments and therefore must agree with Herrick.

Although the Miocene-Pleistocene contact is an erosional unconformity (Herrick, 1965, p. 7), it is frequently difficult to locate, since some basal Pleistocene sediments contain moderate to large amounts of reworked olive-green clay from the Duplin Marl. In making this study, it was found that the best way to pick the contact is by use of lithologic and gamma-ray logs. For example, a lithologic study would narrow the possible contact to a zone of some 20 feet which is transitional from definite Miocene to definite Pleistocene. A gamma-ray log of the hole shows a prominent peak just below the contact, and a certain amount of geologic interpretation will then produce a fairly accurate determination of the contact.

As stated previously, basal Pleistocene sediments contain reworked Miocene sediments and also very minor amounts of phosphate. It is not known whether phosphate present in Pleistocene sediments is also Pleistocene in age, although climatic conditions were probably favorable for phosphate precipitation then. Above this basal few feet of olive-green sandy clay the sediments become sandier. In some areas of Chatham County there is a zone of coarse sand and clay just above the base of the Pleistocene (Herrick, 1965, p. 1) which frequently contains subangular to rounded quartz pebbles averaging 1 to 2 cm. in length and 1 cm. in diameter. Overlying the coarse sand and gravel are tongues of bluish-gray to black clay with sand and many shell fragments. In all test holes the clay seams interfinger with layers of tan to gray sand and clayey sand. The black clay mentioned above is a dark brown to black lignitic clay with abundant plant remains; it appears to be a brackish-water peat bog deposit. The bluish-gray clay with abundant sand and shell fragments is almost identical in appearance to sediments being deposited in the present-day marshes of Chatham County, thus indicating the probability that such a marsh environment existed in the area through much of Pleistocene time.

The Pleistocene Epoch, as is well known, was a time interval of extensive glacial advances and retreats, with resulting rise and fall of ocean levels as water was melted and frozen. Sea levels have oscillated vertically several hundred feet along the Georgia coast during the Pleistocene, leaving recognizable marine terraces (Cooke, 1943). With the melting and retreat of the last glacial system the sea level rose to approximately its present level, flooding the coastal areas of Georgia about 4,000 years ago (Hoyt, Henry, and Howard, 1966). Following the submergence of the lower Georgia coastal area, the present marshes and coastal islands developed from the processes of erosion and sedimentation that are still going on today, constantly reshaping the coastline.

GROUND-WATER GEOLOGY

One of the main objectives of this study was to determine whether or not mining the phosphate ore zone would have detrimental effects on the principal artesian aquifer that supplies the city of Savannah with fresh water. Since Counts and Donsky (1963) and McCollum and Counts (1964) have done a thorough study of the hydrology of the principal artesian aquifer, such an undertaking by the Georgia Department of Mines, Mining and Geology would only be repetitive. Therefore, all that was necessary was a re-evaluation of the situation from a different viewpoint, using new geologic information to obtain an accurate and unbiased interpretation.

To properly understand the situation that exists in Chatham County today, it is necessary to know the past history of groundwater in the area. To begin with, the sediments of the Coastal Plain are in the shape of a wedge, thickest along the coast and to the south, thinnest along the Fall Line. These sediments dip gently towards the sea and the Gulf of Mexico or in the direction of the greater thickness. Older sediments are exposed at the surface near the Fall Line but dip deeper underground towards the Atlantic Ocean and the Gulf of Mexico. Certain geologic formations are more porous than others so that rain or surface water enters these pores and moves in a seaward or downdip direction through the rock. In the case of the aquifers supplying Savannah, water enters Tertiary limestones that crop out on the land surface some 60 to 100 miles northwest of the city. Overlying many of the limestones that serve as aquifers are layers of relatively impermeable sediments, called aquicludes. The aquicludes tend to confine the water within the limestones and prevent its loss upwards. Since the water in the recharge area northwest of Savannah is at a higher elevation than the water in the seaward-dipping aquifer, the confined water is under pressure and will rise to a certain level in wells that penetrate the aquifer. Water that rises above the level of the aquifer is called artesian water. The level to which the artesian water rises in a number of wells forms a theoretical water surface called the piezometric surface.

Before deep wells were drilled and large volumes of water were pumped from the aquifer under Savannah, the subsurface water moved in the direction of Port Royal Sound, South Carolina, where it discharged through thin spots in the overlying Hawthorn Formation into the sea (McCollum and Counts, 1964, p. D15).

The city of Savannah relies on ground water from the principal artesian aquifer for approximately one-third of its fresh-water supply. However, soon after heavy pumping of the aquifer began at Savannah, a cone of depression developed under the city, causing subsurface water to flow towards Savannah from all directions. With the flow of water thus interrupted, fresh water no longer discharged from the aquifer in Port Royal Sound. Instead, the flow reversed and sea water entered the aquifer in Port Royal Sound, moving towards the cone of depression at Savannah. At the present heavy rate of pumping (more than 63 million gallons per day) McCollum and Counts (1964, p. D2) estimate that salt water will reach Savannah through the upper zones of the aquifer in about 400 years. In the lower zones of the aquifer, however, unflushed salt water of an older geologic age is also moving towards Savannah. This salt water could reach Savannah in about 90 years, rendering a significant portion of the principal artesian aquifer useless.

In addition, where the piezometric surface of the artesian aquifer once stood 30 to 40 feet above sea level in the Savannah area, pumping has now caused it to decline to more than 120 feet below sea level under the city and 10 to 15 feet below sea level under the marshes of eastern Chatham County (McCollum and Counts, 1964, Plate 3). Wherever the piezometric surface stands below sea level, any breach in the confining layer or aquiclude that is not plugged could result in additional salt water flowing into the aquifer. It is obvious, therefore, that all practical measures should be taken to prevent any additional salt water from entering the aquifer and shortening the life span of Savannah's fresh-water supply.

In a mining operation for phosphate as conceived by the Kerr-McGee Corporation, the uppermost zones of the aquifer system and the overlying confining layer assume great importance. Before mining begins it is imperative to know just what effects, if any, such an operation would have on this portion of the principal artesian aquifer.

Although Counts and Donsky (1963, p. 27) considered the whole Oligocene section to be part of the principal artesian aquifer, they show (Ibid, Plate 2) only a basal zone of the Oligocene to be a producer of important water supplies. This apparent discrepancy may be better understood in terms of permeability, or the amount of water that will flow through the sediments in a given period of time. Basal Oligocene sediments have a very high permeability and therefore yield moderately large volumes of water to pumping. Overlying Oligocene sediments have a lesser permeability and will not yield water as readily. The Oligocene section above the basal aquifer, however, has a permeability high enough to allow water to infiltrate downward into the principal artesian aquifer. Therefore, if salt water enters the top of the Oligocene in any large quantity, it will eventually contaminate the fresh water in the principal artesian aquifer.

The only barrier to salt water contamination of the subsurface of Chatham County is the confining layer above the Oligocene. This confining layer consists of sediments of the Hawthorn Formation and Duplin Marl. Permeability of the confining layer is extremely low (Plates 1 and 2), so that for all practical purposes it is nearly impermeable.

If the phosphorite in eastern Chatham County were mined, part of the confining layer would be removed. Generally speaking, the phosphate ore zone extends to the base of the Duplin Marl. If the overburden and ore zone were removed, only sediments of the Hawthorn Formation would remain to protect the aquifer. In the area considered for mining the Hawthorn Formation averages about 40 feet thick. The thickness of the confining layer, as well as the permeability, determines how effectively salt water contamination can be prevented.

Fifty-two core samples from the confining layer were submitted to the Water Resources Division of the U. S. Geological Survey for permeability tests. The results show that the average vertical permeability of the Hawthorn is .0096 gallons per day per square foot under one foot of hydraulic head. In an open-pit dredging operation to the base of the Duplin Marl, about 100 feet of overburden and ore would be removed and replaced by salt water. With an average of 40 feet of confining layer, the head differential of 15 feet divided by the flow path of 40 feet gives a hydraulic gradient of .375. The coefficient of permeability P, (.0096 g.p.d./sq. ft.) multiplied by the hydraulic gradient I, multiplied by the area A, (1 square foot), will give a rough estimate of the volume (Q) of salt water that will pass through a 40 foot section one foot square, in one day.

$$Q = PIA$$
$$Q = (.0096 \text{ g.p.d/sq. ft.})\ (.375)\ (1 \text{ sq. ft.})$$
$$Q = .0036 \text{ gallons per day per square foot}$$

In this case, the Hawthorn would pass about .0036 gallons per day per square foot into the underlying Oligocene section. At a seepage rate of .0036 gallons per day per square foot, one acre of mine pit would allow about 160 gallons of salt water per day into the Oligocene.

At the present time, even without a mining operation going on, salt water is seeping through the confining layer at a rate of similar magnitude. This amount of salt water, however, when compared with the volume contained in the aquifer and the volume pumped from the aquifer (63 million gallons per day) is negligible and should have no effect on the quality of water supplies of the city of Savannah.

Therefore it is the conclusion of the author that a properly conducted mining operation would have no adverse effect on the principal artesian aquifer or on the quality of fresh water used by the city of Savannah. Inasmuch as there is an adequate thickness of impermeable Hawthorn Formation underlying the phosphate ore zone, fear of breaching the confining layer or contaminating the fresh-water supplies is not a valid reason for prohibiting such a mining operation. The Department of Mines, Mining and Geology recommends, however, that should mining be initiated in eastern Chatham County, a series of monitor wells be drilled into the aquifer, and that a constant surveillance be maintained on these wells for any increase in salt content or fluctuation of water levels.

GEOLOGY OF THE PHOSPHATE ORE ZONE

The second, but no less important, objective of this study was to determine the extent, depth, grade, volume, and value of the phosphorite of eastern Chatham County. Such a determination is, in effect, an economic evaluation of the phosphorite based on available information.

There are a number of factors which cause a mineral deposit to be classed as either economic or uneconomic to mine. Essentially, it must have a relatively high concentration of the mineral (phosphate in this case) which is to be extracted. The mineral deposit must be at a relatively shallow depth beneath the surface, and it must be no less than a certain minimum in thickness. It should extend over a widespread area so that mining can be conducted over a period of years to amortize the cost of mine and plant development.

The phosphate ore zone of eastern Chatham County, as delineated in this report, consists of those Upper Miocene sediments which contain more than 9% BPL by weight. Although the phosphate content of the ore zone may range from the defined minimum of 9% BPL (BPL $= P_2O_5 \times 2.185$) up to a maximum of 40% BPL, the calculated average content is 22.5% BPL. By way of comparison, the Florida Pebble Field, which accounts for about 75 percent of the total United States production, has a phosphate content of 25 to 35% BPL (Beall, 1966, p. 84). In the Lee Creek mine of Beaufort County, North Carolina, the average grade of ore is 33% BPL (Ibid, p. 97). It is obvious that the Chatham County deposit is not as rich as those of Florida and North Carolina, but it is nevertheless a good grade of phosphate that is well worth mining.

The overburden, or thickness of sediments overlying the phosphate ore zone, is of major importance in any consideration of mining. The overburden in eastern Chatham County ranges in thickness from 70 feet under Savannah Beach to about 130 feet under Ossabaw Sound. The average overburden thickness in the area considered for mining is about 80 feet. The overburden increases in thickness by five feet per mile to the southwest (Fig. no. 5).

The thickness of the phosphate ore zone in eastern Chatham County is quite variable. Under the mouth of the Savannah River, where the overburden is thinnest, the ore zone is also thinnest, about 15 feet. The ore zone thickness increases, as does the overburden, to the southwest (Fig. no. 6). In the area of proposed mining the ore zone is 20 to 30 feet thick. Under the western edge of Skidaway Island the ore zone may be as much as 60 feet thick. Under Wassaw and Little Wassaw Islands the ore zone thickness probably increases southward from 35 to 50 feet and then decreases in thickness under an increasingly thick overburden. West of the general marsh area of Chatham County the ore zone decreases drastically in thickness over a short distance and becomes uneconomic.

The extent of the phosphate ore zone may be considerable. In addition to the known resources under the marshlands of eastern Chatham County, there is an excellent probability that the ore zone extends well out to sea. In 1962, two test holes were drilled 10 miles offshore from Savannah Beach for the U. S. Coast Guard. McCollum and Herrick (1964, p. C61-C63) subsequently reported on their extension of the stratigraphic sequence to these offshore test holes. Well cuttings from the holes were saved and stored in the Well Cutting Library of the Georgia Department of Mines, Mining and Geology. While this study was in progress, S. M. Pickering, Jr., of the Georgia Department of Mines, Mining and Geology, examined these samples and found a high concentration of phosphate present at shallow depths beneath the ocean floor (Pickering, 1969, in preparation). Therefore, the possibility does exist that the phosphate ore zone is continuous, richer, and shallower to 10 miles offshore and probably beyond.

The combination of grade, extent, overburden thickness, and ore zone thickness determines the economics of mining. One of the most useful parameters in evaluating a mineral deposit, however, is that of ratio of overburden thickness to ore zone thickness. Mining economics require a minimum ore zone thickness in direct proportion to overburden thickness so that the cost of removing overburden will not outweigh the potential profits. In general, a ratio of overburden thickness to ore zone thickness of 4:1 is the maximum acceptable for a phosphate deposit of the grade as that in eastern Chatham County. Over most of the area considered for mining, the ratio of overburden thickness to ore zone thickness is about 3:1 or less. South of Ossabaw Sound the ratio becomes greater than 4:1 and the phosphorite there is considered uneconomic by present standards.

Proper evaluation of the Chatham County phosphorite is difficult without some industrial standards of comparison. Even within the phosphate industry, however, the standards vary from company to company as to what is considered worth mining and what is not. One major phosphate producer sets the following criteria for mining of a phosphate orebody: ratio of R_2O_3 (where R=Al and Fe) to P_2O_5, 0.08% optimum, 0.12% maximum; ratio of CaO to P_2O_5, 1.5% maximum; average grade of ore, 68% BPL; a minimum of 4000 tons per acre of ore of at least 68% BPL; and a minimum of 20,000,000 tons of ore available for mining to establish a mine and a processing plant.

Another major phosphate producer has these standards for mining: R_2O_3 (R=Al and Fe) content in sediments less than 4%; average grade of ore, 12-15% BPL; ore zone thickness of more than five feet; and a ratio of overburden thickness to ore zone thickness of less than 4:1.

The Kerr-McGee Corporation, while silent on some criteria used in judging the phosphate deposit of eastern Chatham County, has stated that an ore zone thickness of at least 15 feet is necessary for mining phosphate of the grade found there (Hurst and Bellinger, in Cheatum and others, 1968, p. B-1). As seen in Figure no. 6, the ore zone is thicker than 15 feet in all areas of Chatham County which have been considered for mining. In regard to the concentration of minerals which have a detrimental effect on processing, aluminum and iron content (as Al_2O_3 and Fe_2O_3) ranges from 0.7% to 2.0% by weight (Bellinger and others, in Cheatum and others, 1968, p. B-6). CaO content averages about 50%, so that the ratio of CaO to P_2O_5 (P_2O_5= BPL ÷ 2.185 or P_2O_5= approx. 10% by weight where BPL averages 22.5%) is 5:1. Therefore, the aluminum and iron content is within the general limits for mining, but the calcium content as CaO is high. Processing costs to remove the excess calcium will be correspondingly higher, but not prohibitive.

If the economic and practical limitations of mining a particular deposit are known, it is possible to make estimates on the volume and value of minerals present. Assuming that phosphorite under residential developments is not economic to mine, a NE-SW line can be drawn which roughly excludes these areas (Fig. no. 7). East of this line, south of the Georgia-South Carolina line, north of Ossabaw Island, and within the three-mile limit at sea, the resulting rectangle encloses that area of Chatham County which contains phosphorite that could be mined presently and in the next few years with present technology. Within this rectangle there are approximately 4.8 billion cubic yards of phosphorite, or about 7.2 billion tons. At an average grade of 22.5%, there would be 1.6 billion tons of 100% BPL concentrate. Of the 1.6 billion tons present, only about 50%, or 800,000,000 tons, is recoverable with present mining and processing methods. At a present market price of around $10 per BPL ton, the market value of phosphate contained within the rectangular area is approximately eight billion dollars.

These resources, undoubtedly well worth mining, are still only a portion of the total phosphate resources of Georgia. As stated previously, the phosphorite of eastern Chatham County probably extends at least ten miles out to sea. Evaluation of the additional offshore area may well place Georgia high in the ranks of states with large reserves of economically recoverable phosphate.

MINING METHODS

If the phosphate resources of Chatham County are ever to be mined, considerable research must be done in order to determine the most economic, feasible, and publicly acceptable method of mining. At the present time there are at least three methods which might be considered suitable to some extent for this type of mining: 1) open-pit dry mining, 2) open-pit hydraulic dredge mining, and 3) hydro-blast mining.

Open-pit dry mining, as practiced in the Lee Creek phosphate mine in North Carolina, relies on large draglines to remove the overburden and phosphate matrix (Beall, 1966, p. 96-97). As the name implies, the pit, or diked-off mining area, is relatively free of water, and the dragline is able to operate in the bottom of the mine unimpeded by sediment slump and wash. In the North Carolina mine, it was necessary to drill wells for dewatering the underlying artesian aquifer to prevent artesian pressure from rupturing the confining layer. Reduction of artesian pressure in the aquifer in Chatham County has already been accomplished to a great extent by high volume pumping in the city of Savannah. In many other respects, open-pit dry mining in Chatham County would encounter numerous problems already encountered and solved in North Carolina. This, however, does not mean that dry mining is necessarily feasible in Chatham County. Problems dealing with tides, overburden thickness, storms and other factors may weigh in favor of some other mining method. There is a good possibility, nevertheless, that open-pit dry mining would be well suited to certain areas that are more inland and protected from water movements.

Open-pit hydraulic dredge mining, with the most modern equipment, is the method of mining currently being considered by the Kerr-McGee Corporation in its proposed plan of development. Essentially, the mine pit is confined to a dike-enclosed area of about one square mile (Hurst and Bellinger, in Cheatum and others, 1968, p. B-2). A dredge moves across the flooded pit, removing overburden first and then matrix with a revolving cutter head and suction pump. With this method Kerr-McGee anticipated yearly removal of some 36 million cubic yards of overburden and 7.5 million cubic yards of phosphorite. This would require annual mining of about 200 acres (Ibid, p. B-2), a relatively small portion of the marsh area of Chatham County. This method is quite well suited to mining of the marshes and waterways that are subject to tidal action, provided that sufficient dikework is used to give storm protection.

A third method which could be adapted to mining this type of deposit is that of hydro-blast mining (Fly, 1969, p. 56-58). In this method, a small-diameter hole is drilled from the surface down into the matrix. Water is pumped under high pressure down the drill stem to jet nozzles just above the drill bit, where it emerges as a high-velocity stream. This high-velocity jet stream is capable of cutting through unconsolidated and semiconsolidated sediments to a distance of thirty feet out from the drill stem. By simply rotating and lowering the drill bit, a cylinder some sixty feet in diameter by sixty feet high can be quickly cut in the sediments. While the water-jet mining is going on, the matrix is pumped to the surface as a slurry and on to the processing plant.

This type of mining, by its very nature, would not remove all of the phosphorite, since some would have to be left between the walls of successive underground cylinders. Thus it would not be as efficient as dredge mining in the marsh areas, but it might prove to be very well adapted to offshore mining, where diking is not practical. The equipment would certainly be more suitable to offshore operations, where wave action and storms are greater problems than in the marshes. Hydro-blast mining, or some similar technique, may well prove to be the most practical and most acceptable method of developing the phosphate resources of Georgia.

APPENDIX

Well: Chatham 1
Elevation: 12 feet

Depth:

Pleistocene to Recent (undifferentiated):

0- 8	Sand: gray to tan
8- 11	Clay: dark gray to tan, micaceous, sandy
11- 20	Sand with clay: gray to tan
20- 24	Sand: dark green, medium-grained
24- 28	Sand with clay: gray, medium-grained, many shell fragments
28- 36	Clay with sand: dark bluish-gray, many shell fragments
36- 40	Sand: gray, fine to medium-grained
40- 42	Sand with clay: dark gray, shell fragments
42- 48	Sand: tan to gray, medium-grained
48- 49	Sand: tan, medium-grained, with shell fragments
49- 50	Clay with sand: dark gray with shell fragments and rounded, frosted quartz pebbles 1-8 mm.
50- 52	Sand with clay: tan, phosphatic, with shell fragments
52- 55	Sand: dark olive-green, phosphatic, with rounded quartz pebbles up to 3 mm., many shell fragments
55- 58	Sand: olive-green, medium to coarse-grained, phosphatic
58- 64	Sand with clay: dark olive-green, fine to medium-grained, phosphatic, quartz pebbles 1-2 mm.
64- 69	Clay with sand: dark olive-green, phosphatic, with some rounded quartz pebbles to 1 mm.

Upper Miocene: Duplin Marl:

69- 70	Clay: dark olive-green, phosphatic, some sand
70- 79	Clay with sand: dark olive-green, phosphatic
79- 85	Clay: dark olive-green, phosphatic
85-107	Clay with sand: dark olive-green, phosphatic
107-112	Clay: dark olive-green, phosphatic
112-125	Clay with sand: dark olive-green, phosphatic
125-132	Clay: dark olive-green, phosphatic
132-152	Clay with sand: dark olive-green, phosphatic
152-158	Sand with clay: dark olive-green, fine to medium-grained, phosphatic
158-160	Clay with sand: greenish-brown, phosphatic

Middle Miocene: Hawthorn Formation:

160-165	Clay with sand: tan to greenish-black with rounded quartz grains to 1 mm.
165-170	Clay with sand: tan to green
170-175	Clay with sand: olive-green
175-178	Clay: tan to gray
178-188	Clay with sand: olive-green
188-191	Sand with clay: olive-green
191-197	Clay with sand: olive-green to grayish-green
197-200	Clay: olive-green
200-204	Clay with sand: green, medium-grained
204-208	Sand: tan, medium-grained

Oligocene: Undifferentiated:

208-216	Sand: tan, medium-grained
216-218	Marl: light gray, friable, granular
218-229	Marl: cream to gray, friable, sandy

229-246	Sandy with lime: tan to gray, medium-grained
246-248	Marl: cream, friable, some clay
248-249	Marl: white, friable, sandy
249-278	Sand: gray, friable, very calcareous

Well: Chatham 2
Elevation: 15 feet

Depth:

Pleistocene to Recent: Undifferentiated:

0- 30	Sand: tan to cream, fine to medium-grained
30- 40	Clay with sand: gray, with many shell fragments
40- 55	Sand: gray, medium-grained, many shell fragments
55- 65	Sand: green, medium-grained, with shell fragments
65- 70	Sand: green to greenish-black, medium-grained

Upper Miocene: Duplin Marl:

70- 95	Sand with clay: green to greenish-black, medium-grained, phosphatic
95- 97	Sand with clay: dark olive-green, phosphatic
97-100	Sand: green to greenish-black, medium-grained, phosphatic
100-105	Sand with clay: dark green, medium-grained, phosphatic
105-125	Sand: Brownish-green to green, medium-grained, phosphatic
125-145	Clay with sand: green to dark olive-green, phosphatic
145-146	Limestone: cream, vuggy, sandy
146-149	Clay with sand: dark olive-green, phosphatic
149-155	Clay: brownish-green to gray-green, phosphatic
155-159	Marl: tan, much clay, phosphatic
159-160	Marl: cream, very sandy, phosphatic

Middle Miocene: Hawthorn Formation:

160-180	Clay with sand: olive-green, phosphatic

Oligocene: Undifferentiated:

180-190	Clay with sand: olive-green, phosphatic
190-212	Limestone: light gray, granular, dense

Well: Chatham 3
Elevation: 13 feet

Depth:

Pleistocene to Recent:

0- 15	Sand: reddish-brown, some clay
15- 22	Sand: tan, fine to medium-grained
22- 31	Sand: gray, medium-grained, with shell fragments
31- 34	Clay with sand: tan to dark gray
34- 36	Clay: dark gray to bluish-gray, with shell fragments
36- 39	Clay with sand: dark gray to bluish-gray, with shell fragments
39- 40	Sand: tan, medium-grained
40- 45	Sand with clay: tan to dark gray
45- 49	Clay: dark gray
49- 53	Sand with clay: dark gray, medium to coarse-grained
53- 60	Clay with sand: dark gray
60- 63	Sand with clay: greenish-black, medium to coarse-grained, with shell fragments

Upper Miocene: Duplin Marl:

63- 71	Sand with clay; dark olive-green, medium to coarse-grained, phosphatic
71- 75	Sand with clay: dark olive-green, fine to medium-grained, phosphatic
75- 83	Clay with sand: dark olive-green, phosphatic
83- 93	Clay: dark olive-green, phosphatic
93- 95	Clay with sand: dark olive-green, phosphatic
95-101	Clay with sand: brownish-black, phosphatic
101-107	Sand with clay: greenish-black, phosphatic

Middle Miocene: Hawthorn Formation:

107-112	Clay with sand: tan, phosphatic
112-123	Clay with sand: tan to greenish-gray, phosphatic
123-143	Clay with sand: olive-green, phosphatic
143-150	Marl: tan, phosphatic

Oligocene: Undifferentiated:

150-159	Marl: gray to cream, granular, friable, sandy

Well: Chatham 4, 4A
Elevation: 8 feet

Depth:

Pleistocene to Recent: Undifferentiated:

0- 45	Sand with clay: gray
45- 52	Clay with sand: gray-black, with shell fragments
52- 55	Clay: black, with lignite and abundant plant fragments
55- 65	Clay: bluish-gray
65- 75	Sand with clay: gray, fine to medium-grained
75- 80	Sand with clay: gray, medium to coarse-grained, with rounded quartz pebbles up to 2 cm.
80- 85	Clay with sand: dark brown to olive-green, phosphatic
85- 95	Sand with clay: dark olive-green, phosphatic
95- 96	Marl: cream, sandy, phosphatic
96- 97	Sand with clay: dark olive-green, phosphatic

Middle Miocene: Hawthorn Formation:

97- 99	Marl: tan, fine-grained, sandy, phosphatic
99-115	Clay with sand: dark olive-green, phosphatic
115-117	Sand with clay: green, medium-grained
117-138	Marl: cream to gray, sandy

Oligocene: Undifferentiated:

138-160	Marl: cream to gray, sandy
160-176	Limestone: cream, sandy

Well: Chatham 8
Elevation: 5.2 feet

Depth:

Pleistocene to Recent

0- 15	Sand: tan, medium-grained
15- 40	Clay with sand: gray

40- 49	Clay: bluish-green
49- 50	Clay with sand: green
50- 57	Clay with sand: green to tan
57- 60	Clay: bluish-green with seams of sand
60- 64	Sand with clay: tan to brown, medium-grained

Upper Miocene: Duplin Marl:

64- 69	Clay with sand: olive-green, calcareous, phosphatic
69- 80	Clay with sand: greenish-black, phosphatic
80- 84	Clay: olive-green, phosphatic
84- 90	Sand with clay: greenish-black, phosphatic
90- 91	Limestone: greenish-gray, sandy, phosphatic
91- 94	Sand with clay: dark olive-green, phosphatic
94- 97	Sand with clay: tan to gray, fine-grained, phosphatic

Middle Miocene: Hawthorn Formation:

97-102	Sand with clay: tan to gray, calcareous, phosphatic
102-130	Clay with sand: dark olive-green, sandy, phosphatic

Oligocene Undifferentiated:

130-136	Clay: slightly calcareous, phosphatic
136-143	Clay: sandy, slightly calcareous
143-150	Sand: calcareous

Well: Chatham 9
Elevation: 12.5 feet

Depth:

Pleistocene to Recent:

0- 30	Clay with sand: bluish-gray, with shell fragments
30- 39	Sand with clay: bluish-gray, fine-grained
39- 52	Sand with clay: greenish-gray, fine-grained
52- 65	Sand with clay: dark olive-green
65- 70	Sand with clay: tan to green, fine-grained
70- 72	Sand with clay: dark green, fine-grained
72- 75	Sand with clay: dark green, phosphatic
75- 80	Clay with sand: dark olive-green, phosphatic
80-122	Sand with clay: olive-green, phosphatic
122-129	Clay with sand: olive-green, phosphatic

Well: Chatham 10, 10A
Elevation: 15 feet

Depth:

Pleistocene to Recent:

0- 25	Sand: tan, medium-grained
25- 52	Clay: black, with lignite and abundant plant fragments
52- 59	Clay: bluish-gray, with plant fragments
59- 60	Sand with clay: tan, fine to medium-grained
60- 74	Sand with clay: tan to gray, medium to coarse-grained
74- 75	Sand with clay: dark green, coarse-grained, phosphatic

Upper Miocene: Duplin Marl:

75- 84	Sand with clay: greenish-black, medium-grained, phosphatic
84- 85	Limestone: gray, sandy, phosphatic

85- 89 Sand with clay: olive-green, calcareous, phosphatic
89- 99 Sand with clay: greenish-black, phosphatic
99-102 Sand: gray to green, fine-grained, phosphatic

Middle Miocene: Hawthorn Formation:

102-108 Sand: gray to green, fine-grained, phosphatic
108-120 Sand with clay, gray to green, fine-grained, phosphatic
120-128 Clay: dark olive-green, phosphatic
128-135 Limestone: cream to gray, vuggy, fossiliferous, sandy

Oligocene: Undifferentiated:

135-150 Limestone: gray to white, vuggy, sandy, with rounded quartz grains to 2 mm.
150-169 Limestone: gray to white, vuggy, sandy
169-190 Marl: cream, friable, sandy
190-194 Limestone: cream, sandy

Upper Eocene: Ocala Limestone:

194-222 Limestone: cream, very fossiliferous, vuggy

Well: Chatham 12
Elevation: 8 feet

Depth:

Pleistocene to Recent:

0- 25 Clay: bluish-gray, micaceous, with shell fragments and plant remains
25- 40 Clay with sand: bluish-gray, micaceous, with shell fragments
40- 48 Clay: brownish-black to black, carbonaceous, with many plant remains
48- 60 Clay with sand: bluish-gray
60- 70 Sand: tan, medium to coarse-grained

Upper Miocene: Duplin Marl:

70-100 Sand with clay: dark olive-green, with rounded quartz pebbles up to 3 cm., phosphatic

Middle Miocene: Hawthorn Formation:

100-105 Sand with clay: dark olive-green, with rounded quartz pebbles up to 3 cm.
105-106 Dolomitic limestone: dark gray, phosphatic
106-125 Clay with sand: olive-green, phosphatic
125-134 Marl: gray to cream, very fossiliferous, friable

Oligocene: Undifferentiated:

134-165 Marl: gray to cream, very fossiliferous, friable
165-206 Limestone: gray to cream, very fossiliferous, vuggy

Well: Chatham 13
Elevation: 12 feet

Depth:

Pleistocene to Recent:

0- 34 No core: probably sand and clay
34- 38 Sand with clay: bluish-gray, with many shell fragments

48- 75	Clay wtih sand: gray-green

Upper Miocene: Duplin Marl:

75- 85	Sand with clay: olive-green, phosphatic
85-111	Clay with sand: dark olive-green, phosphatic
111-115	Clay: dark olive-green to olive-green, phosphatic
115-119	Clay with sand: dark olive-green to olive-green, phosphatic

Middle Miocene: Hawthorn Formation:

119-120	Dolomitic limestone: gray, dense, phosphatic
120-135	Marl: green, sandy, phosphatic
135-165	Clay: dark olive-green, phosphatic
165-170	Clay with sand: dark olive-green

Oligocene: Undifferentiated:

170-175	Clay with sand: dark olive-green
175-180	Limestone: gray, fossiliferous, sandy
180-250	Marl: gray to cream, friable

Upper Eocene: Ocala Limestone:

250-256	Limestone: greenish to cream, fossiliferous, granular
256-269	Limestone: gray to cream, fossiliferous, granular

Well: D-1
Elevation: 8 feet

Depth:

Pleistocene to Recent:

0- 3	Shells: oyster bar
3- 16	Clay: gray
16- 45	Sand: medium to coarse-grained, with shell fragments
45- 55	Clay with sand: gray, sand is fine to medium-grained
55- 78	Sand: medium to coarse-grained, no clay

Upper Miocene: Duplin Marl:

78- 90	Sand with clay: dark green, medium to coarse-grained
90- 96	Sand with clay: dark green, fine to medium to coarse-grained, phosphatic
96- 99	Sand with clay: green, fine-grained, phosphatic
99-100	Clay: green, phosphatic
100-102	Clay: light green
102-105	Clay: brownish to olive-green, phosphatic
105-110	Sand with clay: greenish-brown, fine-grained, phosphatic
110-116.5	Sand with clay: green, phosphatic

Middle Miocene: Hawthorn Formation:

116.5-117	Dolomitic limestone: gray, hard, dense
117-122	Clay with sand: green, phosphatic
122-127	Clay: light green
127-131	Clay with sand: green, sand very fine-grained
131-140	Sand: light green, very fine-grained
140-142	Clay: light green
142-157	Clay with sand: green with sand silty to very fine-grained
157-160	Clay: green, silty
160-161	Limestone, gray, hard

161-162 Sand: calcareous
162-165 Limestone: gray, hard, vuggy

Oligocene: Undifferentiated:

165-167 Sand: calcareous
167-169 Limestone: gray, hard, fossiliferous, vuggy
169-172 Limestone: white, friable, sandy

Well: D-6
Elevation: 8 feet

Depth:

Pleistocene to Recent:

0- 10 Clay: gray to black; silty
10- 15 Sand: gray, fine to medium-grained
15- 30 Sand with clay: green, fine-grained, with shell fragments
30- 45 Clay: green, with numerous small pelecypod shells
45- 57 Clay: green
57- 60 Clay with sand: olive-green, sand very fine-grained

Upper Miocene: Duplin Marl:

60- 70 Clay with sand: olive-green, silty to very fine-grained
70- 75 Sand with clay: light to dark green, fine-grained, phosphatic
75- 80 Sand with clay: dark green, fine-grained, phosphatic
80- 83 Clay with sand: light green, phosphatic
83- 87 Clay: green, phosphatic
87- 89 Sand: green, fine-grained, phosphatic
89- 92 Sand with clay: green, phosphatic
92- 93 Sand: gray, very fine-grained, calcareous

Middle Miocene: Hawthorn Formation:

93-117 Clay with silt: light green
117-120 Sand with clay: very fine-grained, calcareous

Oligocene: Undifferentiated:

120-121 Limestone: gray, fossiliferous
121-122 Limestone: light gray to white, sandy, fossiliferous
122-129 Limestone: gray to white, sandy, fossiliferous, friable

Well: PC-1
Elevation: 8 feet

(Well log adapted from log provided by Dr. Robert E. Carver, Geology Department, University of Georgia.)

Depth:

Pleistocene to Recent:

0- 30 Sand: gray to black, fossiliferous
30- 45 Sand with clay: dark gray
45- 55 Clay with sand: interbedded sand and sandy clay with many fossils and plant remains
55- 57 Sand: medium-grained, with shell fragments
57- 61 Sand: medium-grained, well sorted
61- 63 Sand with clay: dark gray, medium-grained
63- 73 Sand: medium-grained, strong H_2S odor
73- 77 Sand; gray, medium to coarse-grained, gravel

Upper Miocene: Duplin Marl:

77- 83	Clay with sand: gray-green, fossiliferous, phosphatic
83- 93	Sand: olive-green, fine to coarse-grained, very phosphatic
93-104	No recovery to 107 feet, probably olive-green phosphatic sand
104-111	Sand: dark olive-green, fine-grained, phosphatic

Middle Miocene: Hawthorn Formation:

111-112	Dolomite: gray, hard, dense
112-122	Sand with clay: olive-green, fine to medium-grained
122-135	Clay with sand: light green, plastic, tough clay with thin beds of fine sand
135-149	Clay: green, tough, fossiliferous, sandy at base, phosphatic
149-158	Marl: light gray to white, sandy, friable
158-165	Sand: light gray to white, very calcareous, friable, phosphatic

Oligocene Undifferentiated:

165-188	Sand: light gray to white, very calcareous, friable, phosphatic
188-193	Limestone: gray, hard, granular, fossiliferous
193-215	Sand: greenish-gray, very calcareous, friable
215-250	Limestone: light gray to white, hard to soft, very fossiliferous, vuggy, poorly consolidated in some beds, interbeds of sand with phosphate

Upper Eocene: Ocala Limestone:

250-286	Limestone: light gray to white, hard, fossiliferous, vuggy

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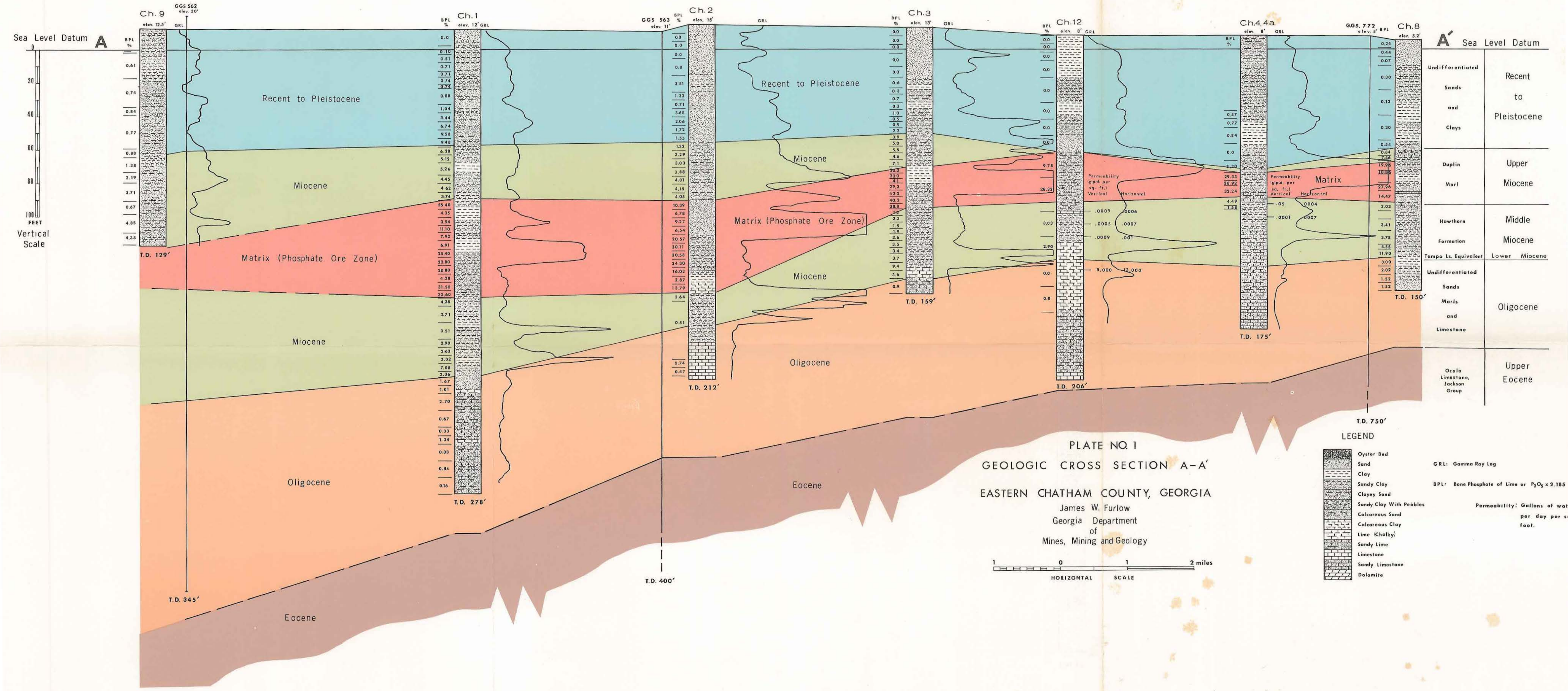
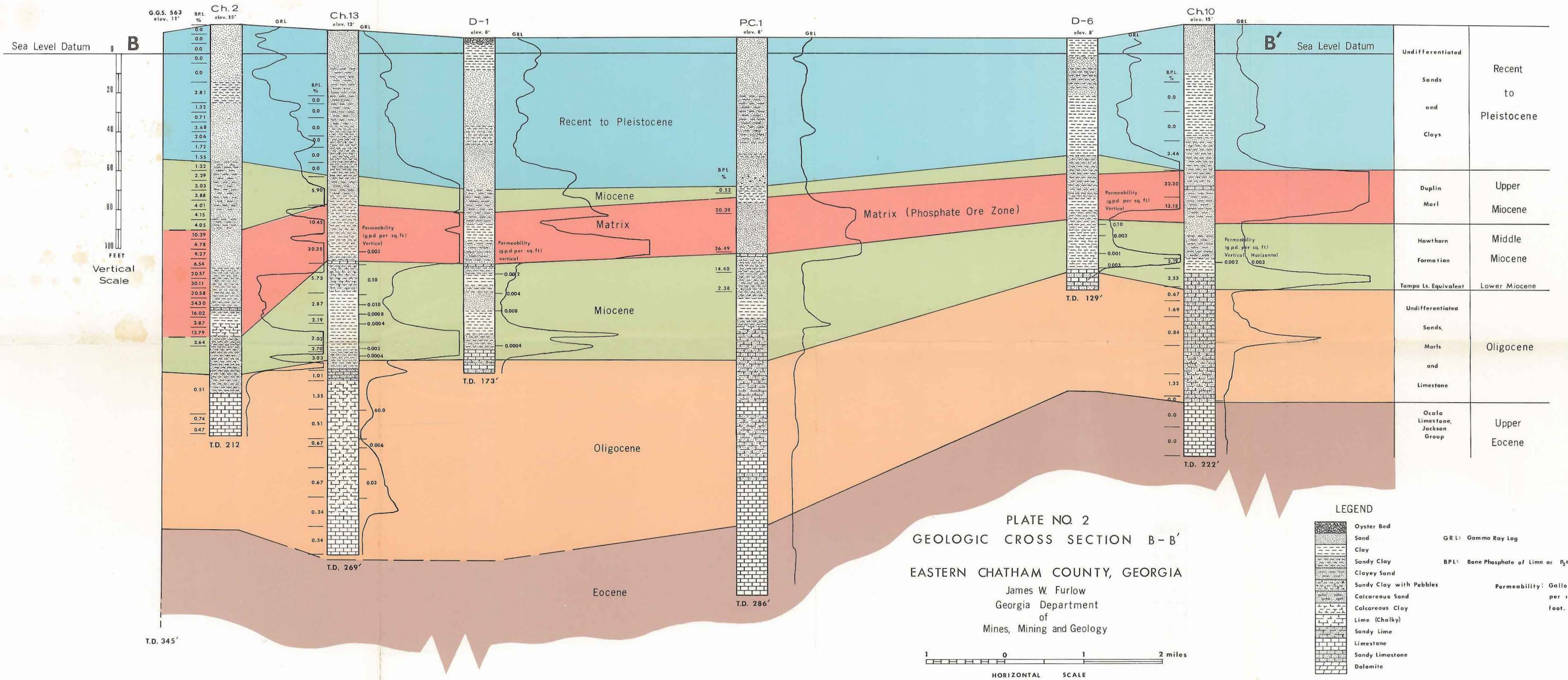


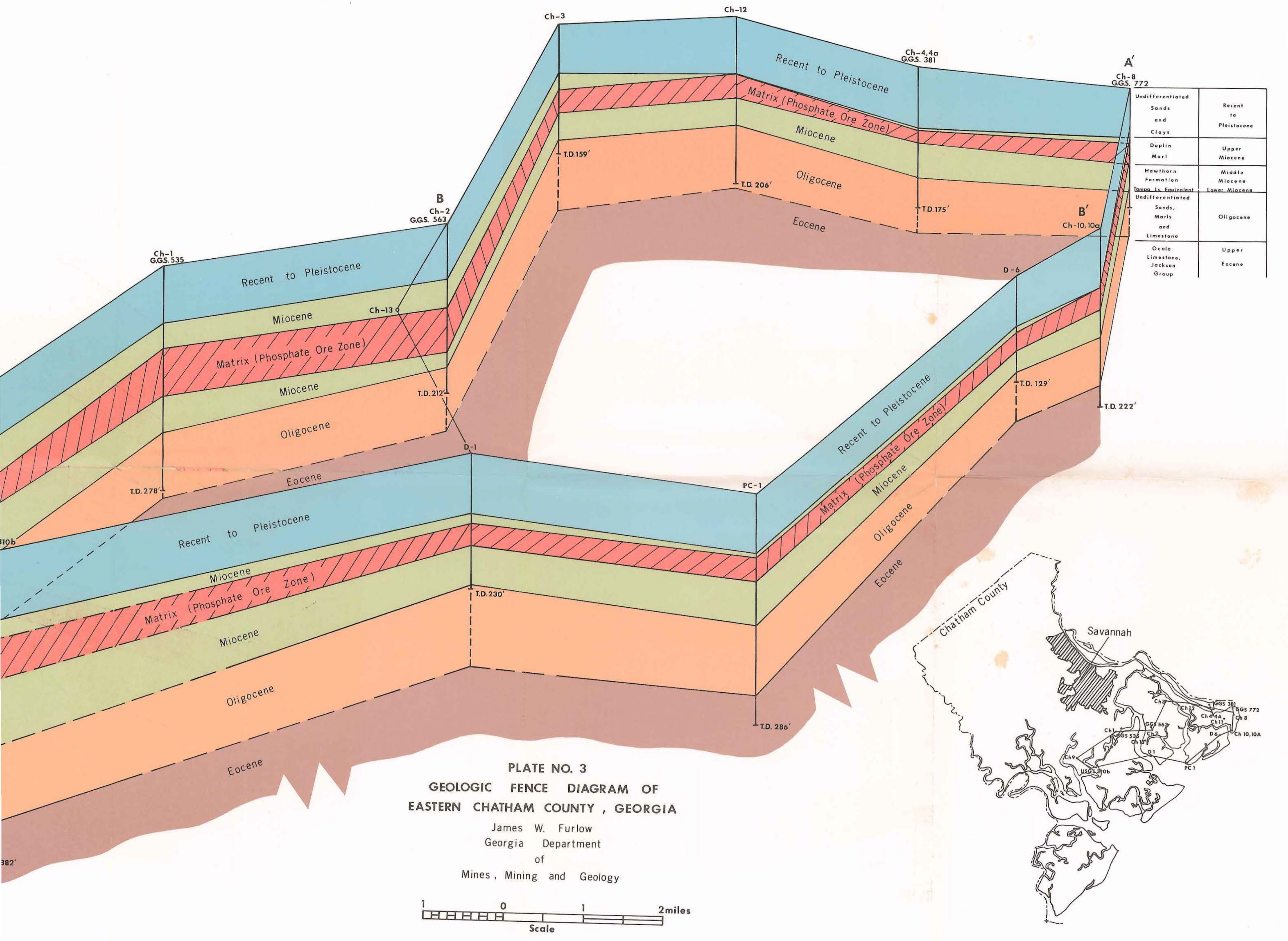
PLATE NO. 1
GEOLOGIC CROSS SECTION A-A'
EASTERN CHATHAM COUNTY, GEORGIA

James W. Furlow
Georgia Department
of
Mines, Mining and Geology

PLATE NO. 2
GEOLOGIC CROSS SECTION B-B′
EASTERN CHATHAM COUNTY, GEORGIA

James W. Furlow
Georgia Department
of
Mines, Mining and Geology





Undifferentiated Sands and Clays	Recent to Pleistocene
Duplin Marl	Upper Miocene
Hawthorn Formation	Middle Miocene
Tampa Ls. Equivalent	Lower Miocene
Undifferentiated Sands, Marls and Limestone	Oligocene
Ocala Limestone, Jackson Group	Upper Eocene

PLATE NO. 3

GEOLOGIC FENCE DIAGRAM OF EASTERN CHATHAM COUNTY, GEORGIA

James W. Furlow
Georgia Department
of
Mines, Mining and Geology

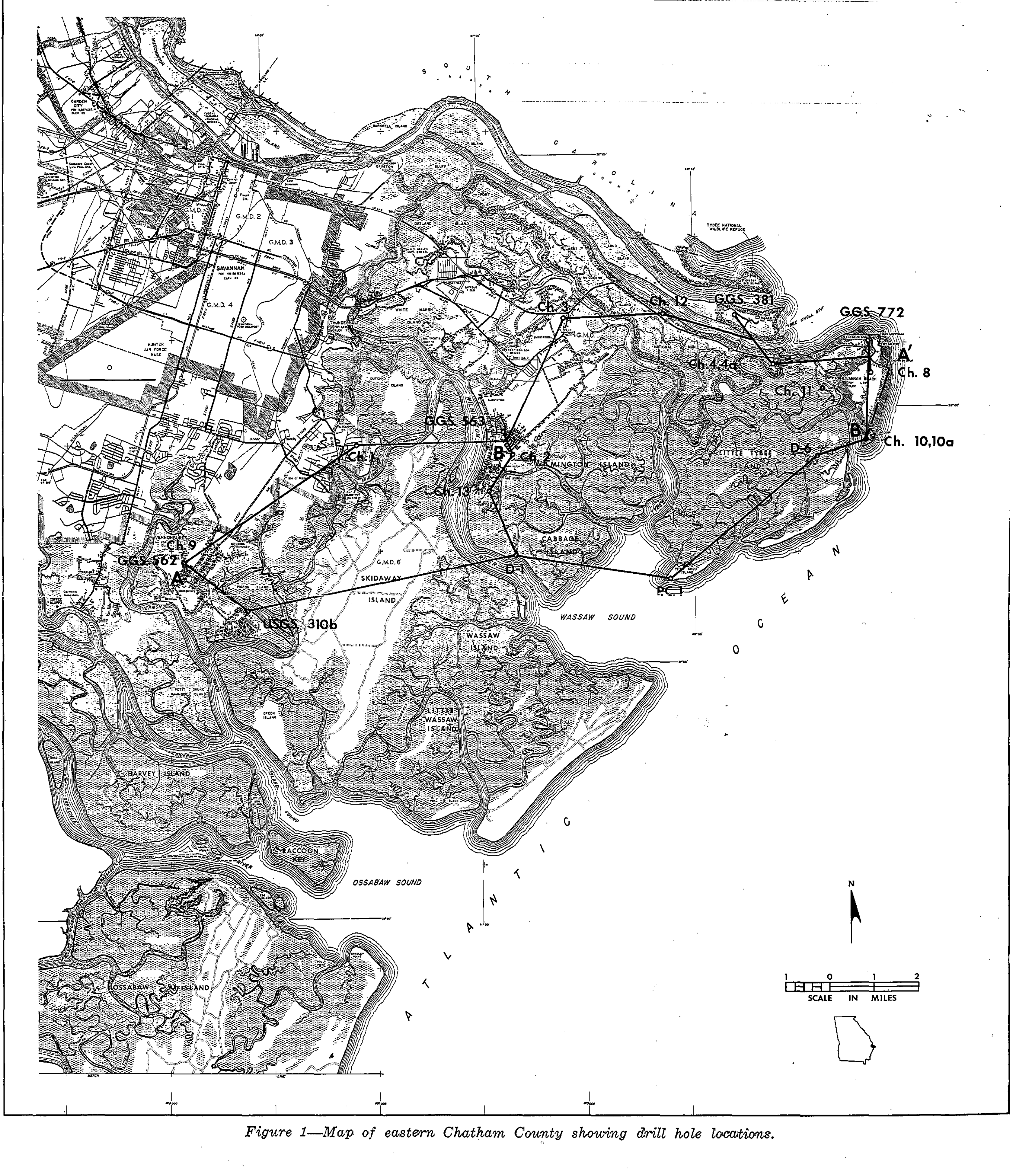


Figure 1—Map of eastern Chatham County showing drill hole locations.

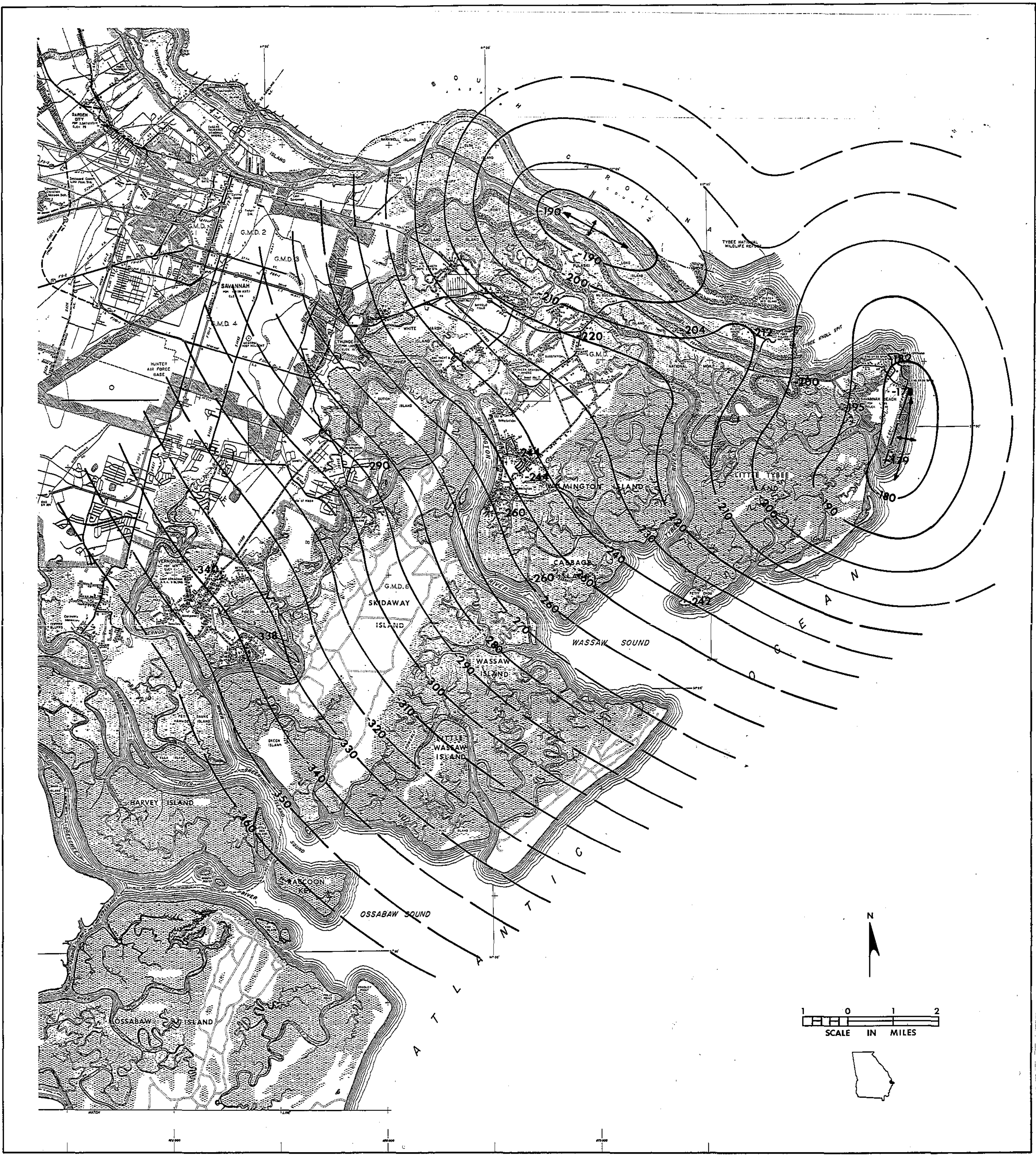


Figure 2—Structure contour map on top of Eocene; contour interval 10 feet.

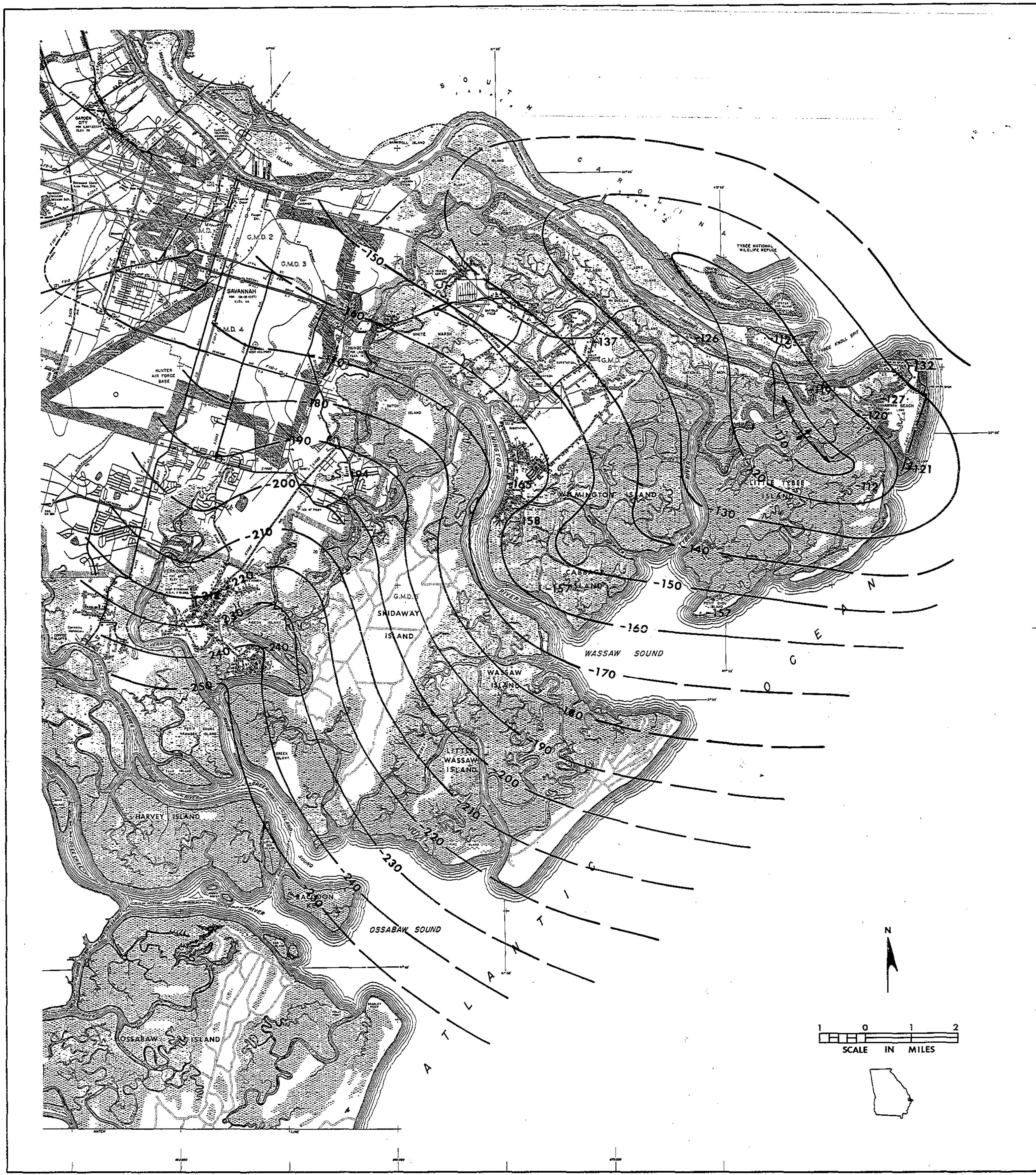


Figure 3—Structure contour map on top of Oligocene; contour interval 10 feet.

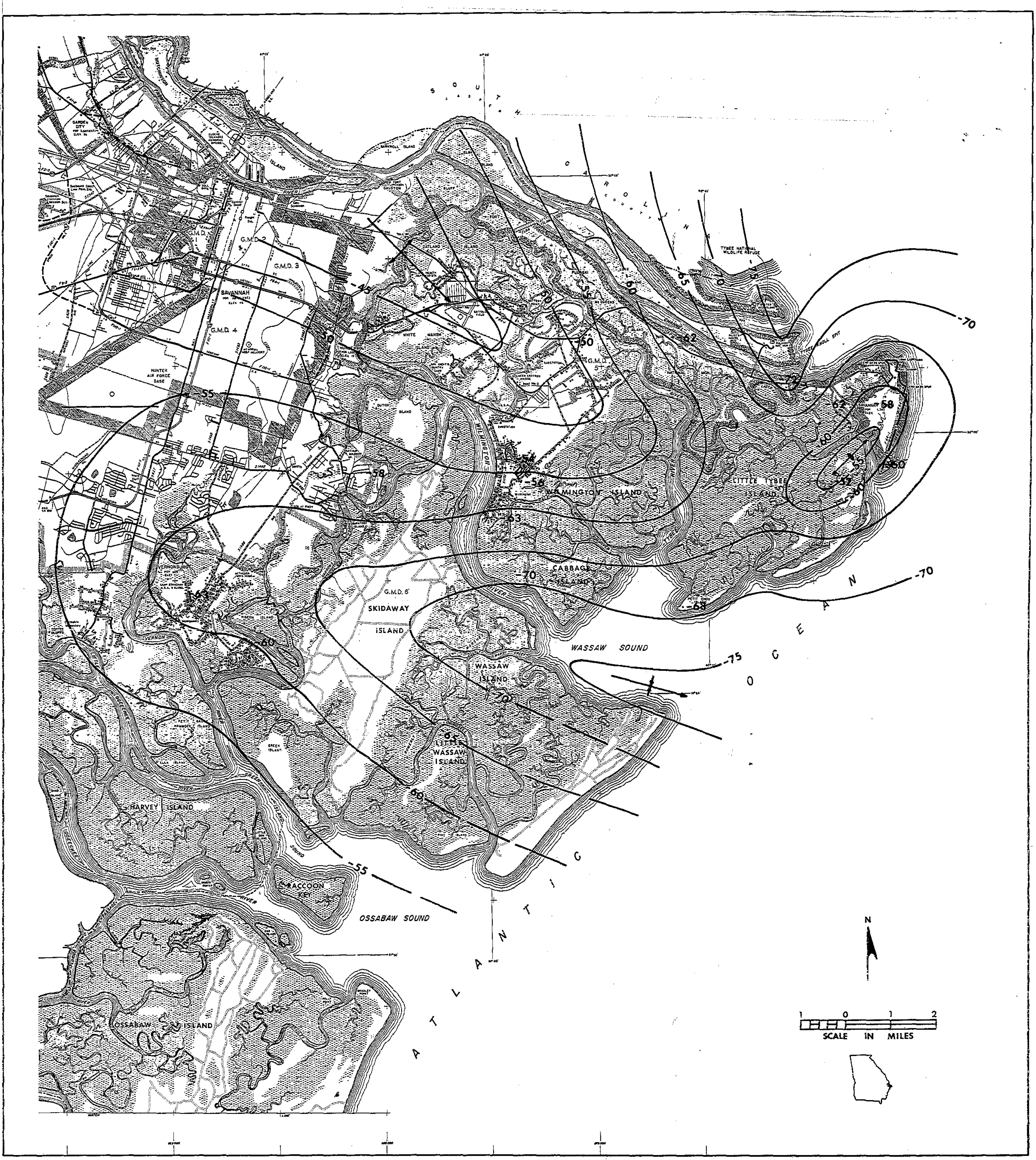


Figure 4—Structure contour map on top of Miocene; contour interval 5 feet.

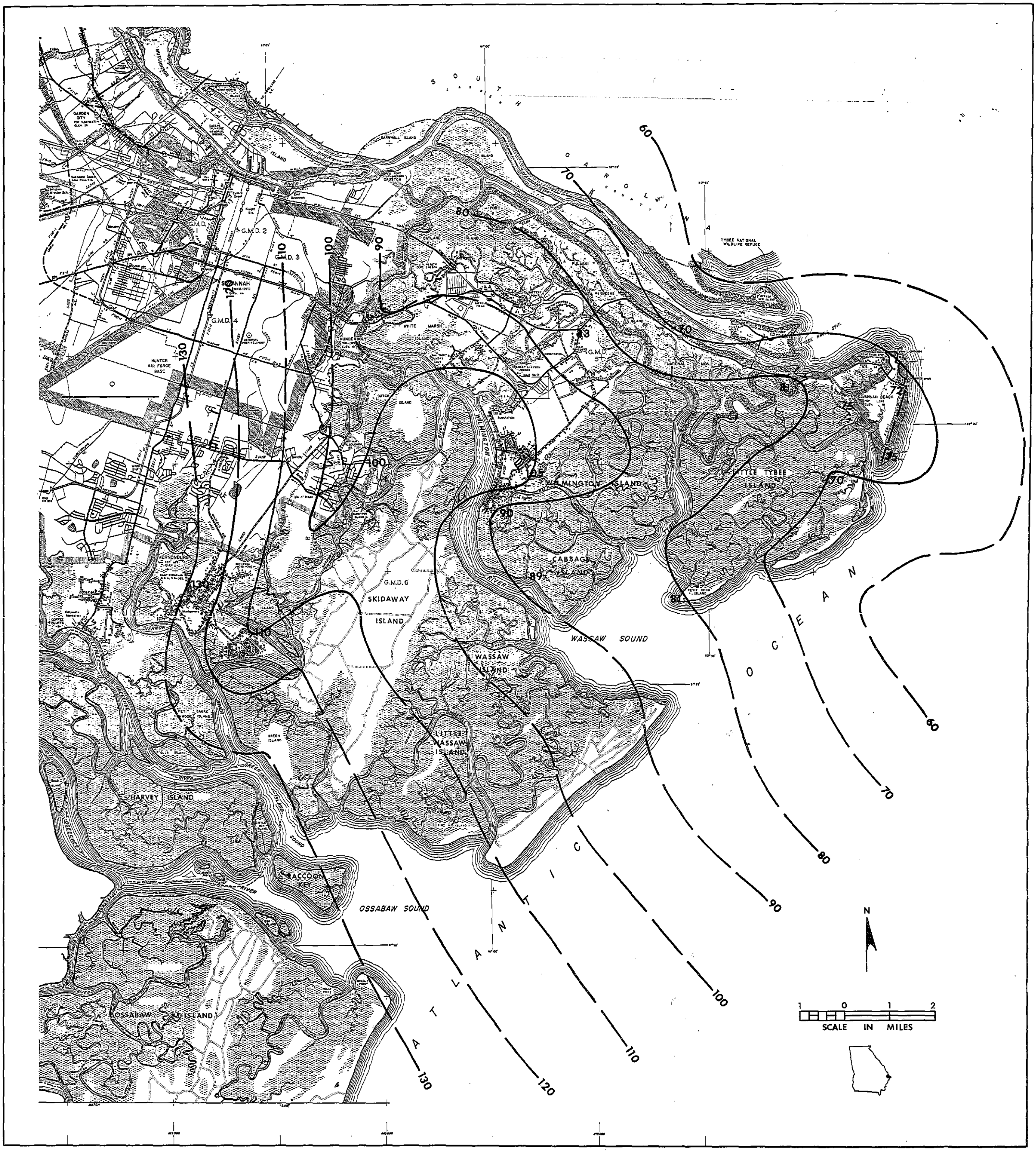


Figure 5—Isopach map of overburden thickness; contour interval 10 feet.

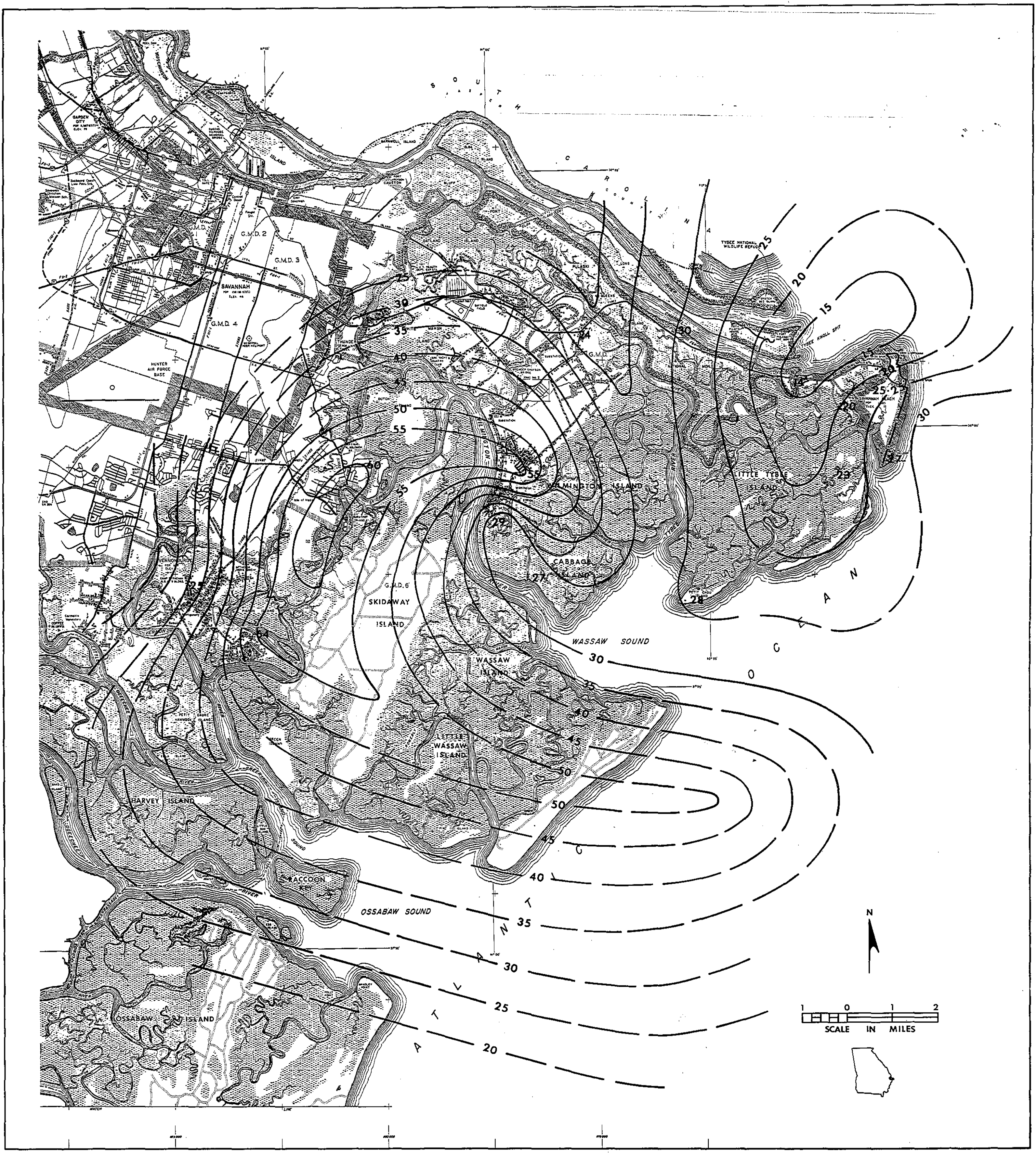
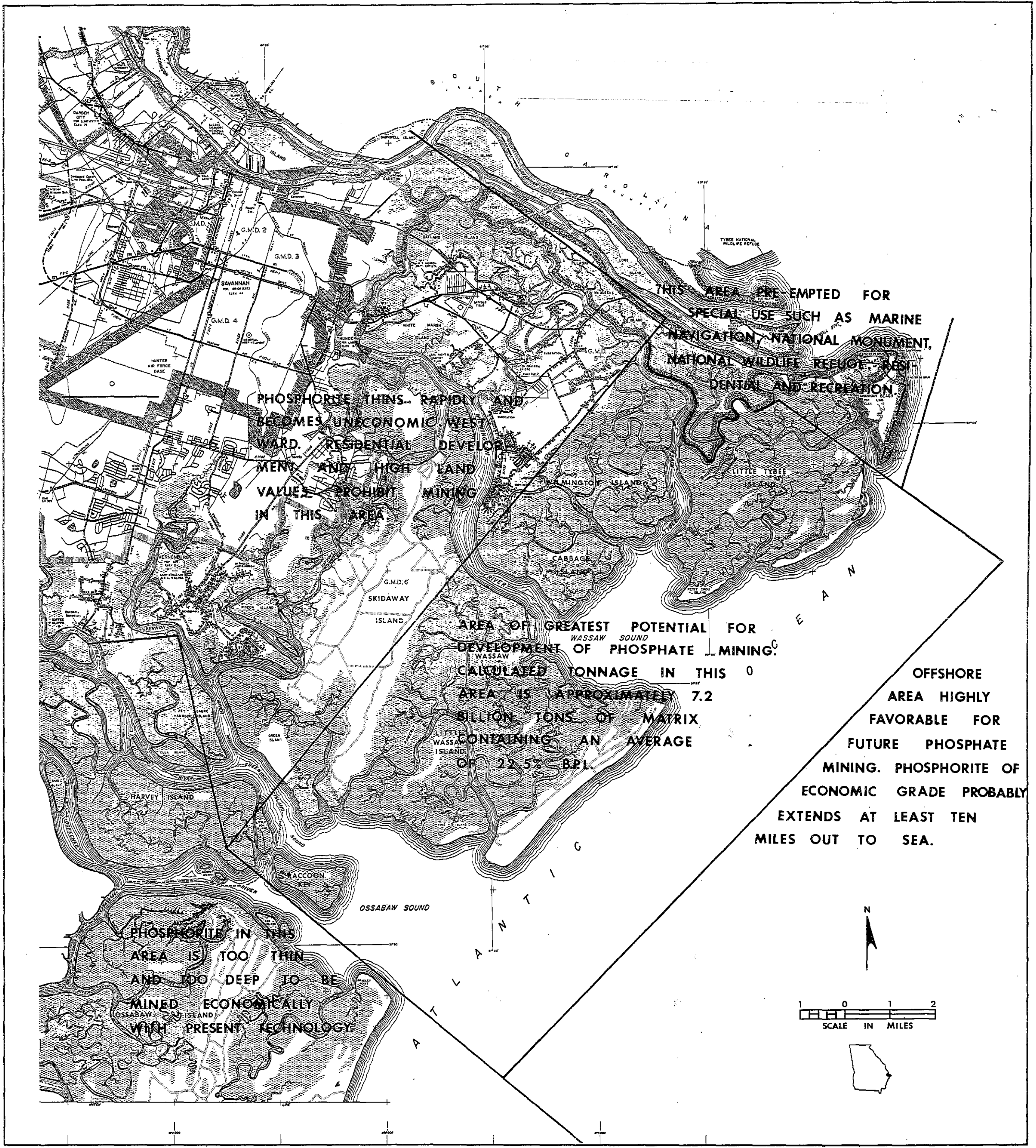


Figure 6—Isopach map of phosphate matrix greater than 9% BPL; contour interval 5 feet.



THIS AREA PRE-EMPTED FOR SPECIAL USE SUCH AS MARINE NAVIGATION, NATIONAL MONUMENT, NATIONAL WILDLIFE REFUGE, RESIDENTIAL AND RECREATION.

PHOSPHORITE THINS RAPIDLY AND BECOMES UNECONOMIC WESTWARD. RESIDENTIAL DEVELOPMENT AND HIGH LAND VALUES PROHIBIT MINING IN THIS AREA.

AREA OF GREATEST POTENTIAL FOR DEVELOPMENT OF PHOSPHATE MINING. CALCULATED TONNAGE IN THIS AREA IS APPROXIMATELY 7.2 BILLION TONS OF MATRIX CONTAINING AN AVERAGE OF 22.5% B.P.L.

OFFSHORE AREA HIGHLY FAVORABLE FOR FUTURE PHOSPHATE MINING. PHOSPHORITE OF ECONOMIC GRADE PROBABLY EXTENDS AT LEAST TEN MILES OUT TO SEA.

PHOSPHORITE IN THIS AREA IS TOO THIN AND TOO DEEP TO BE MINED ECONOMICALLY WITH PRESENT TECHNOLOGY.

Figure 7—Map of eastern Chatham County showing areas of potential phosphate mining and areas of no potential for mining.