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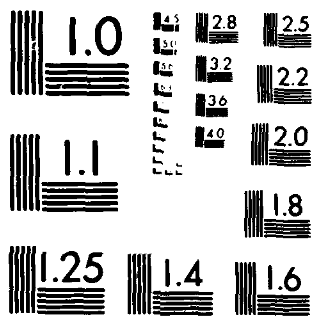
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Geothermal Energy Resources of Navy/Marine Corps Installations on the Atlantic and Gulf Coastal Plain

by
Douglas W. Edsall
U.S. Naval Academy
for the
Public Works Department

MARCH 1980

NAVAL WEAPONS CENTER
CHINA LAKE, CALIFORNIA 93555

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FOREWORD

This interim report presents the results of a study conducted between June and September 1978, by the Naval Weapons Center (NWC), China Lake, California. The investigation was conducted to determine what geothermal energy resources might be expected along the Atlantic and Gulf Coastal Plain where major energy-using Navy/Marine Corps installations are located.

The investigation was funded under Task Z0840-SL.

This report was reviewed for technical accuracy by Carl F. Austin and James A. Whelan.

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(U) The search for alternative energy sources is of great importance to the U.S. Navy. Preliminary examination of data from the literature, bottom hole temperatures from existing deep wells, and heat flow measurements in wells drilled at selected sites as part of a current research program sponsored by the Department of Energy have demonstrated that low-temperature waters (<212°F or 100°C) may be available at moderate depths in the major sedimentary basins along the Atlantic and east Gulf Coastal Plain. Although the possible geothermal energy resources present here are not sufficient for electrical power generation, they appear adequate for space heating and cooling.

(U) The Navy should take a leading role in planning and executing exploratory drilling and resource evaluation programs, especially at the following installations, all of which are major energy users: Norfolk, Portsmouth, and Virginia Beach, Virginia; Charleston, South Carolina; and Pensacola, Milton, and Panama City, Florida.

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INTRODUCTION

The energy crisis of the early 1970s focused the attention of numerous sectors of our nation on the identification and rapid development of such near-term alternative energy resources as geothermal energy. Geothermal energy is the natural heat of the earth and with the earth's volume of 10^{12} km^3, of which the majority is at high temperatures, there is a seemingly inexhaustible source of geothermal energy available for use. This energy is present as heat that can be recovered from heated rocks or water. Its primary disadvantages are low thermodynamic quality, uneven geographic distribution of shallow high heat zones, cost of procurement, and low efficiency of converting it to electrical energy. Although it may not be possible at present to produce electrical power directly from geothermal resources at most locations along the geologically stable Atlantic and Gulf Coastal Plain, it does appear feasible, desirable, and prudent to consider the use of geothermal energy for space heating and cooling. The Navy Department is therefore investigating the geothermal energy resources of the Atlantic and Gulf Coastal Plain, where five of its 10 largest energy-using installations are located.[1]

The theory of Plate Tectonics in the late 1960s has provided a basis for understanding the creation, displacement, and destruction of the surface crust of the earth; i.e., the various crustal plates as well as the distribution of prominent geothermal belts. This theory envisions the driving force as the slow but continuous motion of deep, internal convection currents. Subcrustal convection currents were suggested as early as 1839. These currents were thought to ascend beneath the oceans and descend beneath the continents. Motion was thought to encompass the entire mantle of the earth and to have a regular pattern. Today it is believed that the convection currents affect only the asthenosphere (upper part of the mantle), and it is thought at present that the flow has been steady for tens of millions of years. The exact cause of these currents is not known.

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[1]Naval Weapons Center. *Site Characteristics of the Navy's Ten Largest Energy Users*, by S. M. Lee. China Lake, Calif., NWC, April 1978. 68 pp. (NWC TM 3467, publication UNCLASSIFIED.)

It has been shown that most zones of elevated geothermal gradients and high heat flows are associated with active geological zones characterized by ascending or descending convection currents; i.e., the plate boundaries described by the theory of Plate Tectonics. The major zones illustrated in Figure 1 are (1) *spreading centers* or mid-oceanic ridges, where new oceanic crustal material is created by volcanic processes from magmas generated by the partial melting of upper mantle rocks; (2) *subduction zones* or trenches, where oceanic crust is destroyed by partial melting as it is carried downward into the mantle beneath an overriding plate of either continental or oceanic crust; (3) *geosutures (relic scars)* or old subduction zones, where fold mountains are being formed by uplift caused by collision of two continents and heat is generated by this motion; and (4) *hot spots* or mantle plumes, where rising currents of "solid" hot material from the mantle rise toward the surface. The volcanism and related elevated heat flows of mantle hot spots are not, however, related to the geological processes of creation, destruction, or displacement of crustal plates.

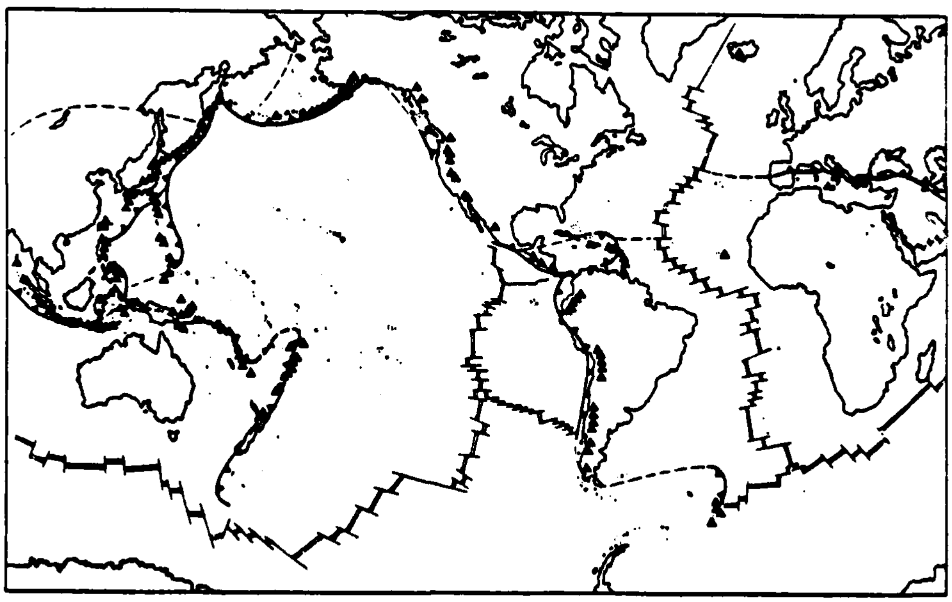

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FIGURE 1. Major Geothermal Resource Regions of the World.[2]

[2]W. K. Hamblin. *The Earth's Dynamic Systems*, 2nd ed. Minneapolis, Minn., Burgess Publishing Co., 1978. Fig. 19.1, p. 308.

The more commonly known and often utilized surface expressions of possible geothermal energy reservoirs are geysers, fumaroles, boiling pools of mud, and hot springs. Although the coastal plain along the Atlantic and eastern portion of the Gulf Coast contains several hot springs, there are few other surface manifestations of geothermal energy resources in the region. The U.S. Navy is interested, however, in determining the possibility of the presence of geothermal energy resources in the vicinity of its major coastal installations between New Jersey and Florida. The major reasons for this determination are that the Navy/Marine Corps have significant investments in property and facilities that are competing for and relying upon commercially available and increasingly expensive sources of electrical energy and other sources of energy. Since over 40% of the country's population lives in the eastern one-eighth of the nation, which has very little indigenous reserves of fossil fuels other than coal, the nonmilitary use and competition for energy of all kinds will continue to increase.

If the Navy is to remain ready to meet future commitments, it must have immediate knowledge of available or potentially available low-grade geothermal energy resources that can be used in nonelectrical power-generating applications. Therefore, Navy interest regarding programs for the exploration, assessment, and development of proven low-grade geothermal energy resources, whether they are located on or adjacent to Navy/Marine Corps property, is warranted

OBJECTIVES

The American Association of Petroleum Geologists and the United States Geological Survey (AAPG-USGS) thermal gradient map of North America, at a scale of 1:5,000,000, gives the hypothesized average depth (by contours) in thousands of feet below the surface of three selected temperatures: (1) 158°F (70°C), (2) 212°F (100°C), and (3) 302°F (150°C). In addition, this map presents the range of bottom hole temperatures of more than 30,000 bore holes by color symbols. The USGS files at the National Center in Reston, Virginia, contain a portfolio of 39 computer contoured and labeled maps at a scale of 1:1,000,000. Only portfolio maps #1 (geothermal gradient of southern Florida) and #2 (geothermal gradient of northern Florida and southern Georgia) pertain to the areas of interest to the Navy on the Atlantic and Gulf Coastal Plain. Because of the absence of an active oil and natural gas industry to date along the Atlantic Coastal Plain and the abundance of surface and shallow subsurface water, an extensive program of deep drilling has not been undertaken in the past by industry. Since there are no large numbers of deep wells, bottom hole temperature data are not available in sufficient quantities to allow contouring of the thermal gradients beneath the Atlantic Coastal Plain north of southern Georgia.

A study of the Atlantic Coastal Plain by the Virginia Polytechnic Institute and State University (VPI-SU), which was sponsored by the Department of Energy, Division of Geothermal Energy (DOE/DGE), has delineated eight potential geothermal resource areas with geothermal gradients greater than the normal 1.5°F/100 ft (25°C/km). These eight areas are shown in Figure 2. Although still in progress, this study has provided sufficient data for the selection of approximately 50 drill sites along the east coast from New Jersey to Florida. At each of these sites, 1,000-foot (0.3-kilometer) holes are being drilled by DOE contractors, and heat flow values will be measured after equilibrium has been reached. The heat flow measured will have been generated in part by the radioactive decay of trace elements in the underlying rock formations of the basement. This heat is expected to have heated water trapped in the sedimentary rocks lying above the basement, resulting in shallower low-grade geothermal reservoirs.

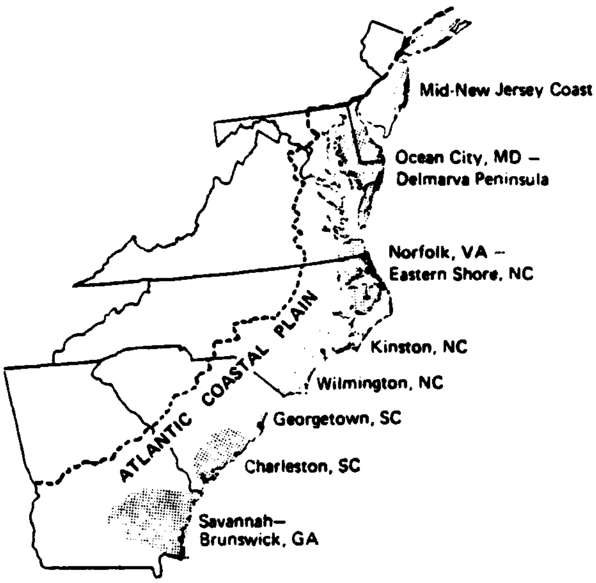

FIGURE 2. Eight Potential Geothermal Resource Areas on the Atlantic Coastal Plain as Determined by DOE/DGE-Sponsored VPI-SU Study.[3]

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[3]J. K. Costain, L. Glover III, and A. K. Sinha. *Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States.* Progress Report, 10/1-12/31, 1977, Virginia Polytechnic Institute and State University, submitted to Dept. of Energy, Div. of Geothermal Energy. (Contract No. ET-78-C-05-5648, publication UNCLASSIFIED.)

Prior to the VPI-SU study, various governmental agencies (DOE, National Science Foundation (NSF), and USGS), state geological surveys or their equivalents (Pennsylvania, New Jersey, Maryland, Virginia, North and South Carolina, Georgia, and Florida), state energy offices or their equivalents (New Jersey, Delaware, Georgia, South Carolina, and Virginia), and universities (Applied Physics Laboratory, Johns Hopkins University (APL/JHU); Florida State University; and University of Florida) have been involved to some degree in determining the geothermal resources available in the Atlantic and Gulf Coastal Plain portion of the United States, which is part of DOE/DGE region V. The work included literature surveys on thermal springs and regional geological and geophysical data; sampling and laboratory analyses of the concentrations of heat-producing radioactive elements in basement rock materials and thermal conductivities of the overlying sedimentary blanket; measuring thermal gradients in abandoned wells; and finally, the selection and drilling of up to fifty 1,000-foot-deep (0.3-kilometer) holes for measuring the heat flow in areas shown by various lines of evidence to possess the probability of higher than normal geothermal gradients.

Unfortunately, most of the data available today are widely spaced, obtained by different methods, of questionable accuracy, and therefore useful only at map scales of 1:5,000,000 to 1:1,000,000. To clearly delineate the areas of highest geothermal gradients, maps at scales of 1:62,500 or 1:24,000 or less will be required, a level of detail that is not available at this time.

The objectives of this report are to (1) locate and summarize all readily available geological, geophysical, geochemical, hydrological, and geothermal information for the Atlantic and Gulf Coastal Plain between Florida and New Jersey; (2) determine the existing data gaps and propose methods for obtaining the needed data; and (3) show the geothermal resource potential at or near facilities as it is predicted to exist at this time.

METHODS

This report is based upon a review of the published literature and personal communications with individuals active in studying potential geothermal resources on the Atlantic and Gulf Coastal Plain. There is extensive world-wide literature on geothermal energy resources, especially on locations in the western United States, Italy, New Zealand, and Japan. Until 1975, however, little information existed on the potential for geothermal resources in the Atlantic and Gulf Coastal Plain portion of DOE/DGE region V. This deficiency is slowly being overcome by DOE/DGE and USGS funded research that has the following specific goals: (1) the measurement and mapping of terrestrial heat flow; (2) dating and determining location, depth, and radioactive mineral content of igneous intrusive bodies thought to supply heat to water in the overlying sedimentary blanket; and (3) confirmation by drilling of geothermal gradients in selected areas.

The U.S. Naval Academy and USGS libraries have been utilized almost exclusively for this study. The majority of information examined was found in the following sources: state and USGS bulletins; USGS professional papers; USGS water resource papers; state and USGS information circulars; USGS open file reports; USGS topographic and geologic maps; AAPG-USGS special geologic maps; APL/JHU reports; VPI-SU progress reports to DOE/DGE; technical reports of the University of Florida, Department of Geology, prepared for the USGS, Office of Geochemistry and Geophysics; 1st annual report (1977) of the Division of Geothermal Energy of the Energy Research and Development Administration (ERDA); published books on geothermal energy; journals; and published proceedings of symposia on geothermal energy.

PHYSIOGRAPHY OF THE ATLANTIC AND GULF COASTAL PLAIN

The Atlantic and Gulf Coastal Plain is an emerged seaward sloping physiographic province of variable width that extends some 2,200 miles (3540 kilometers) between Cape Cod, Massachusetts, and the Mexican border. The submerged portion is called the continental shelf. The emerged coastal plain is narrowest in New England and becomes wider south of Long Island. The boundary between the Atlantic and Gulf portions is arbitrarily drawn in central Georgia, and the demarcation line is extended southeastward down the crest of the Florida peninsula (Figure 3). The majority of the Naval installations to be discussed are sited on the coastal plain portions of New Jersey, Delaware, Maryland, Virginia, North and South Carolina, Georgia, and Florida. The coastal plain province in these states is divisible into five sections: (1) embayed, (2) Cape Fear arch, (3) Sea islands, (4) peninsular arch, and (5) east Gulf Coastal Plain.

EMBAYED SECTION

The coastal plain from Cape Cod to the Neuse River, North Carolina, is deeply embayed. South of Long Island the drowned river valleys extend further inland toward the fall line. Pleistocene terraces are important features of the southern part of the coastal plain. Present also are the offshore bars typical of New Jersey and Virginia.

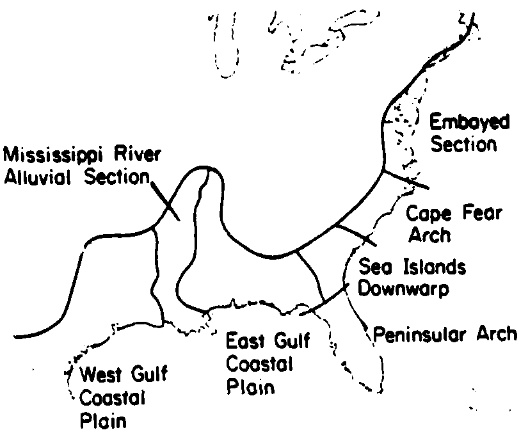

FIGURE 3. Sections of the Atlantic and Gulf Coastal Plain.[4]

CAPE FEAR ARCH SECTION

The Cape Fear arch section differs from those to the north and south because Cretaceous formations are exposed at the surface over most of the plain. This distinctive section is also characterized by three cuspate forelands between Capes Hatteras, Lookout, Fear, and Romain.

SEA ISLANDS SECTION

The Sea islands section has been submerged less than the embayed area to the north and lacks its offshore bars. It does have coastal islands and the Pleistocene terraces found to the north. These terraces are at higher elevations and are more dissected than those of similar age to the north.

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[4]C. B. Hunt. *Physiography of the United States*. San Francisco, Calif., W. H. Freeman and Co., 1967. Fig. 10.4, p. 143.

PENINSULAR ARCH SECTION

The peninsular arch emerged recently and has abundant carbonate deposits and associated karst features. Florida possesses a variable coastline, which is characterized by barrier beaches, coral reefs, and mangrove swamps, as well as rocky stretches on the Gulf coast.

EAST GULF COASTAL PLAIN SECTION

The east Gulf Coastal Plain section is differentiated from the adjacent sections because of a distinctive change in topographic features caused by greater thicknesses and lithologic variability in the Cretaceous and Eocene deposits present. For this reason, several distinct topographic belts are evident (Figure 4).

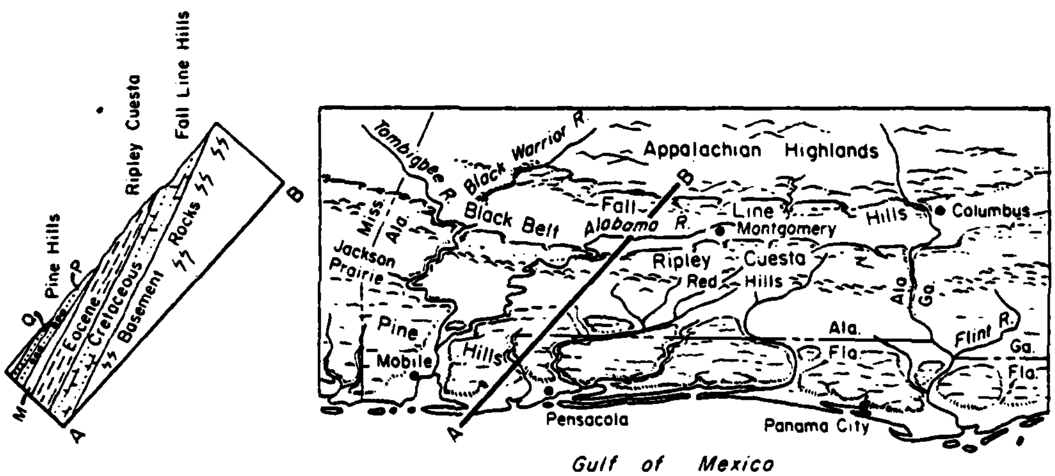

FIGURE 4. Cross Section and Diagrammatic View of East Gulf Coastal Plain. Quaternary deposits (Q) are found along the coast. Pliocene deposits (P, Citronelle formation) extend landward of the (Q) deposits and form the Pine Hills. The Pliocene deposits also unconformably overlie the Miocene deposits (M). Eocene deposits crop out between the Pine Hills and Ripley Cuesta. The major Eocene units are the Midway formation, Wilcox and Claiborne groups, and the Jackson formation. Upper Cretaceous sediments form the Fall Line Hills, Black Belt, and Ripley Cuesta.[5]

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[5] Ibid., Fig. 10.9, p. 147.

STRATIGRAPHY OF THE ATLANTIC AND GULF COASTAL PLAIN

The underlayer of the coastal plain consists of gently seaward dipping, relatively unconsolidated marine and continental sediments ranging in age from Cretaceous to Recent. These sediments, which wedge out against the crystalline rocks of the piedmont province of the Appalachian mountain system to the west, rest unconformably upon a basement section similar in appearance and composition to the adjacent piedmont terrain. Local basement relief is on the order of a few hundred feet.

The outcrop pattern of the Cretaceous, Tertiary, and Quaternary sediments on the coastal plain is roughly parallel to the present coastline (USGS Geologic Map of the United States, 1974). Upper Cretaceous rocks crop out continuously along the fall line between Alabama and the northern flank of the Cape Fear arch and again between Virginia and New York. Seaward of these Cretaceous sediments is a belt of Tertiary materials, which unconformably overlie the Cretaceous sediments. In some locations, the Tertiary materials completely overlap the Cretaceous sediments and rest against the crystalline rocks of the piedmont. On the Cape Fear arch, the Tertiary sediments are present only in a narrow zone that lies northwest of the coastal deposits between Capes Fear and Romain. The Quaternary sediments form a narrow coastal belt, which in general is characterized by elevated Pleistocene terrace features. Figure 5 shows a generalized outcrop pattern of Mesozoic, Cenozoic, and Paleozoic units on the coastal plain.

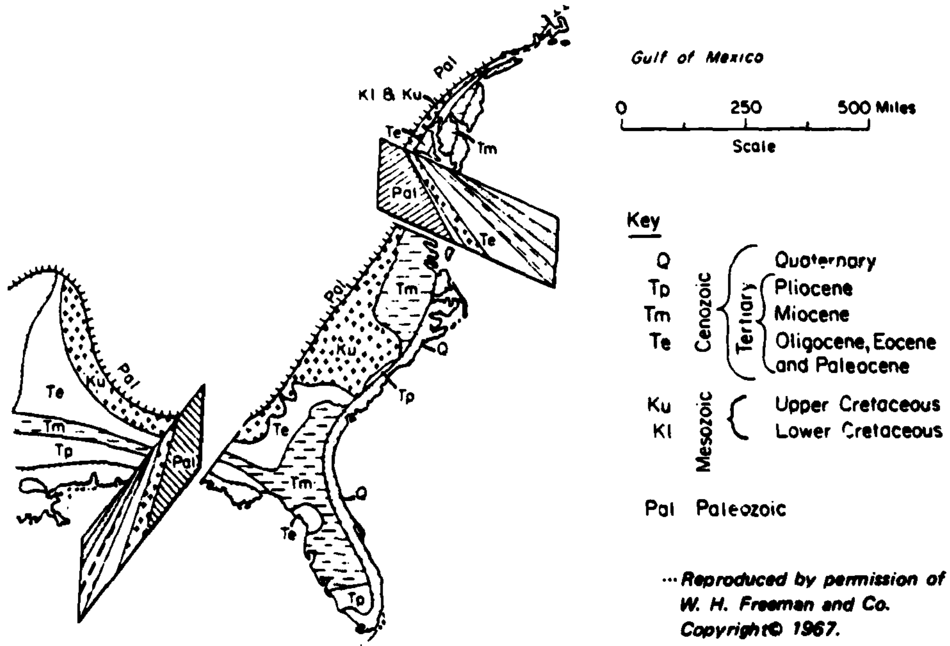

FIGURE 5. Generalized Outcrop Pattern of Mesozoic, Cenozoic, and Paleozoic Units on the Coastal Plain.[6]

[6]Ibid., Fig. 10.3, p. 141.

North of central Georgia, the Cretaceous and Tertiary sediments are nearshore marine and continental clastics, which change seaward to marine sediments and become thicker. In southern Georgia and Florida, Cretaceous rocks do not crop out, and only a portion of the Tertiary sequence is exposed. Both sequences are primarily marine carbonates. A more detailed list of the Atlantic Coastal Plain stratigraphic units and their Gulf coast equivalents is given in Appendix A.

Figure 6 presents a cross section between Cape Hatteras and the Delmarva peninsula. It shows the northern flank of the Albemarle sound (embayment), the Norfolk arch, and the southern flank of the Salisbury embayment.

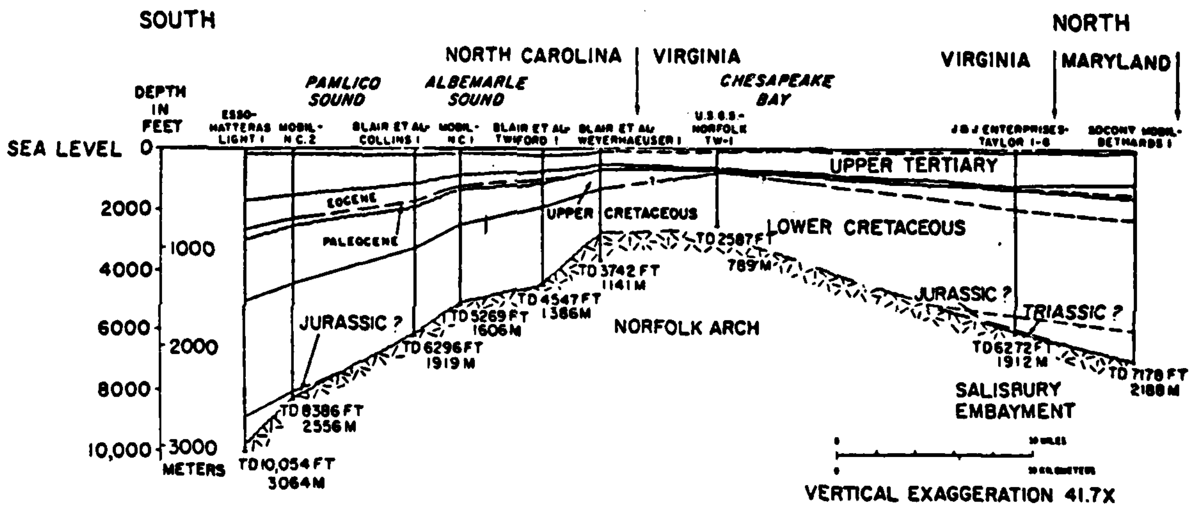

FIGURE 6. Cross Section Parallel to the Coastline Between Cape Hatteras and the Delmarva Peninsula.[7]

[7]U.S. Geological Survey. *Sediments, Structural Framework, Petroleum Potential, Environmental Conditions, and Operational Considerations of the United States Mid-Atlantic Outer Continental Shelf*, by R. E. Mattick, et al. Washington, D.C., Government Printing Office, 1975. Fig. 16, p. 48. (U.S. Geological Survey Open File Report 75-61, publication UNCLASSIFIED.)

Figure 7 presents a cross section between the Delmarva peninsula and Long Island. It clearly shows the Salisbury embayment and the south New Jersey high.

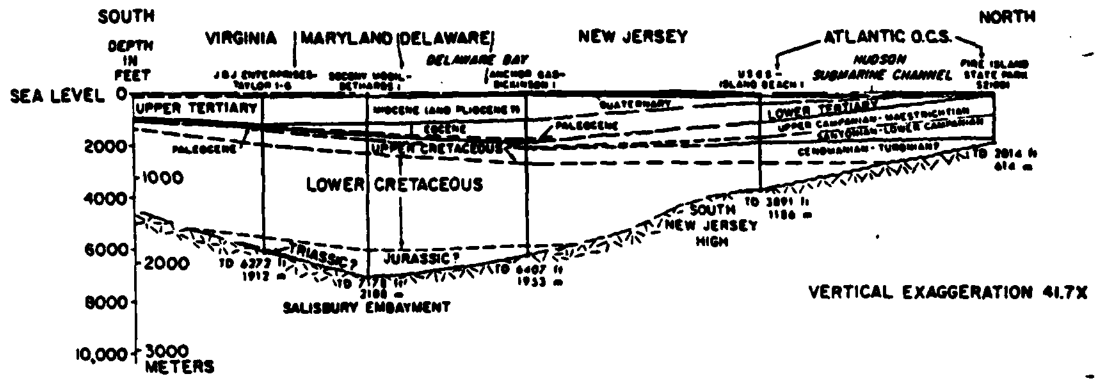

FIGURE 7. Cross Section Parallel to the Coastline Between the Delmarva Peninsula and Long Island.[8]

REGIONAL STRUCTURE OF THE ATLANTIC AND GULF COASTAL PLAIN

The sedimentary deposits of the coastal plain rest upon "basement" rocks of varying types and ages. All basement rocks are considered to be older than Cretaceous. Knowledge of the type, age, and distribution of these rocks is based upon piedmont outcrops and materials recovered from deep wells and is inferred from geophysical surveys.

[8]Ibid., Fig. 17, p. 50.

The basement rocks of the coastal plain are either (1) Precambrian and Paleozoic igneous and metamorphic rocks, (2) Triassic volcanic rocks and sedimentary rocks, or (3) unmetamorphosed Paleozoic sedimentary rocks, depending on location. The location of exposed and buried Triassic sediments and rocks is shown in Figure 8. The distribution of pre-Cretaceous rocks beneath the Florida-Georgia portions of the coastal plain is shown in Figure 9.

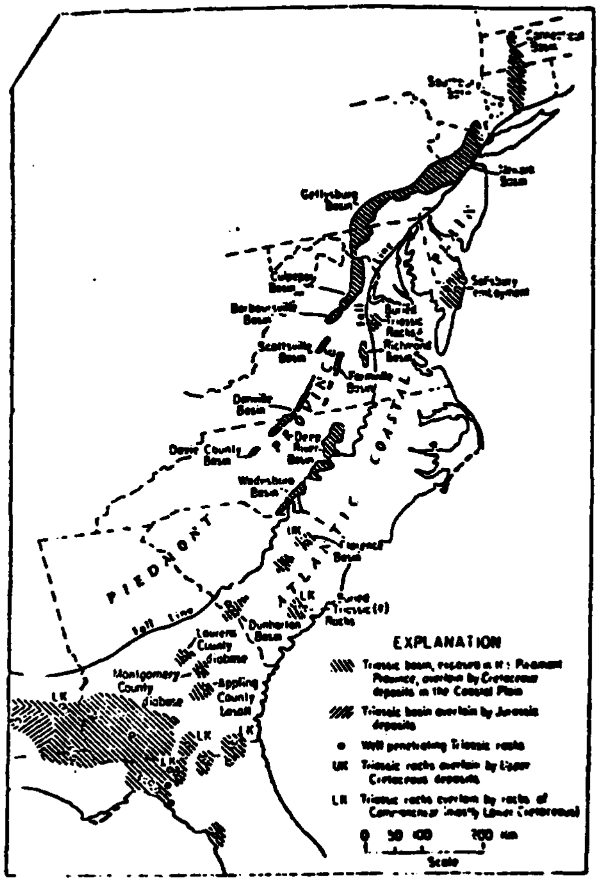

FIGURE 8. Buried and Exposed Triassic Sediments and Rocks Along the Atlantic and East Gulf Coast.[9]

[9]U.S. Geological Survey. *Sediments, Structural Framework, Petroleum Potential, Environmental Conditions, and Operational Considerations of the United States South Atlantic Outer Continental Shelf*, by W. Dillon, et al. Washington, D.C., Government Printing Office, 1975. Fig. 26, p. 60. (U.S. Geological Survey Open File Report 75-411, publication UNCLASSIFIED.)

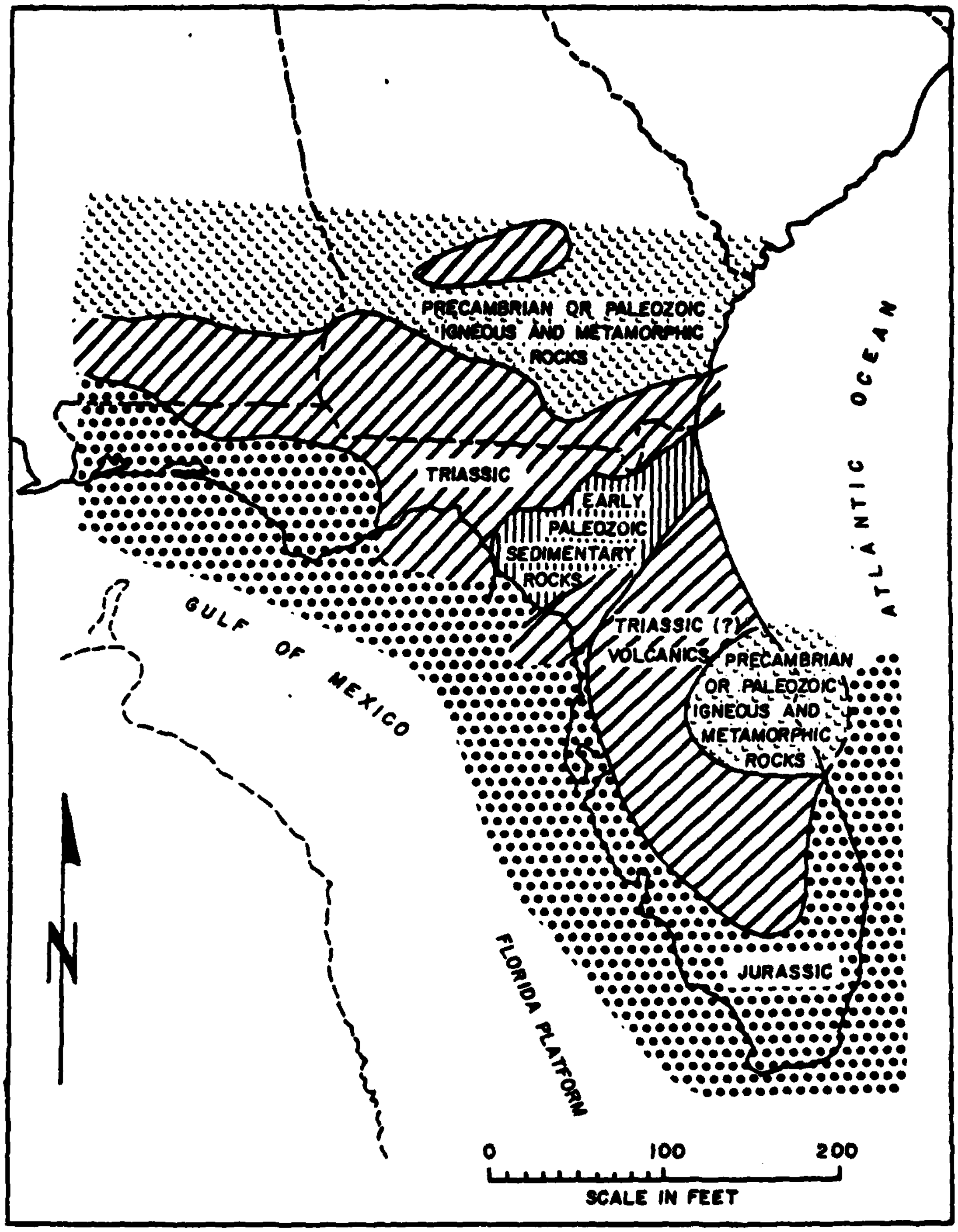

FIGURE 9. Distribution of Pre-Cretaceous Rocks Beneath the Florida-Georgia Portions of the Coastal Plain.[10]

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[10]Ibid., Fig. 25, p. 59.

In general the structural contours on the basement rocks are parallel to the Appalachian mountain system except in the vicinity of the major structural elements, which were produced by post-Paleozoic warping of the basement. The principal elements from north to south are the south New Jersey high, Salisbury embayment, Norfolk arch, Albemarle embayment, Cape Fear arch, southeast Georgia embayment, peninsular arch, south Florida embayment, and the southwest Georgia embayment. Figure 10 shows the major structural features of the Atlantic coastal margin north of Cape Fear arch. Figure 11 shows the major structural features of the southeastern United States.

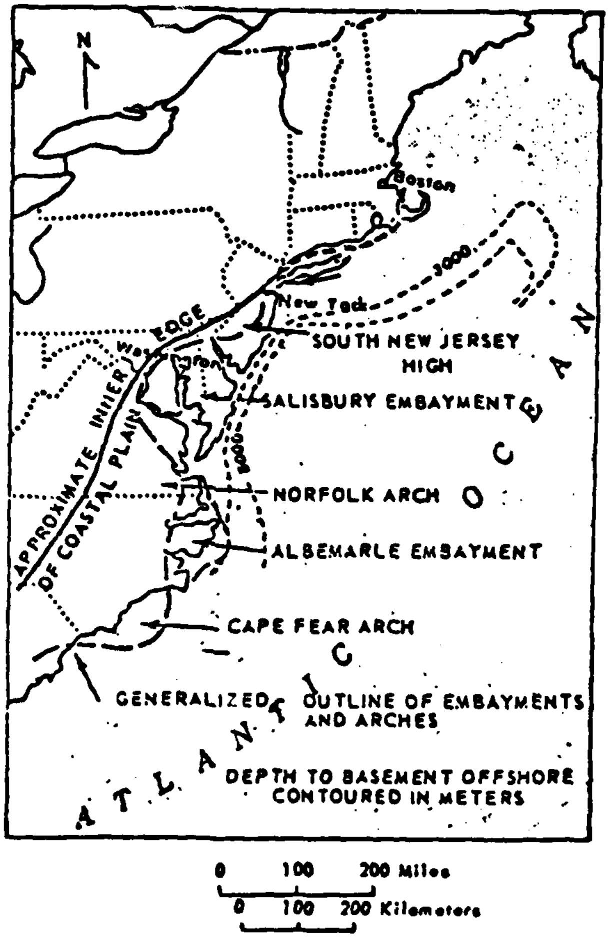

FIGURE 10. Major Structural Features of the Atlantic Coastal Margin North of Cape Fear Arch.[11]

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[11] USGS Open File Report 75-61, op. cit., Fig. 15, p. 46.

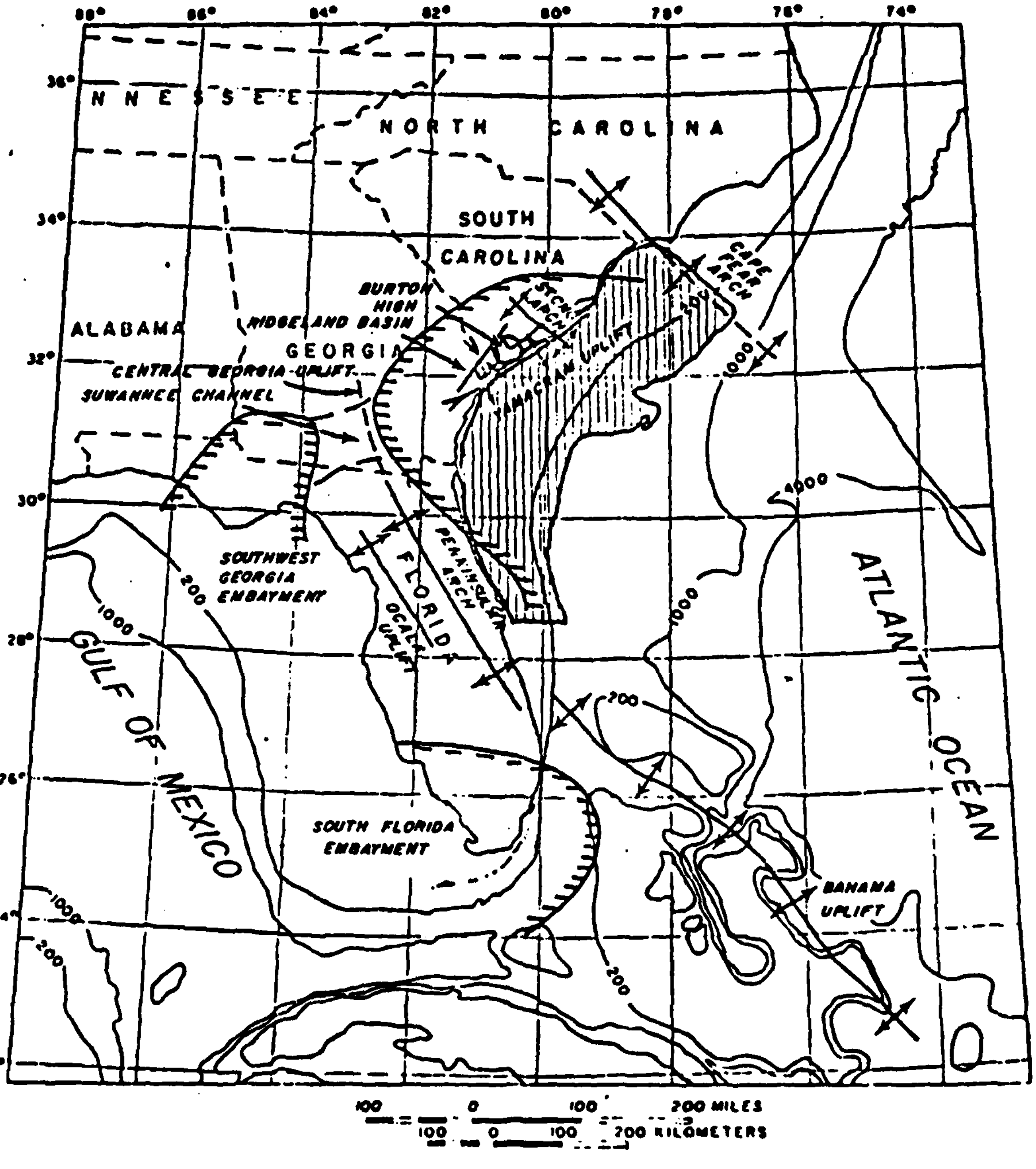

FIGURE 11. Major Structural Features of the Southeastern United States.[12]

[12]USGS Open File Report 75-411, op. cit., Fig. 8, p. 25.

SOUTH NEW JERSEY HIGH

South New Jersey high appears to be a westward extension of the Long Island platform. It is a minor structural high thought to have formed in early Mesozoic times by the separation of the European and American continental plates.

SALISBURY EMBAYMENT

The Salisbury embayment is a low region in the basement rocks between Ocean City, Maryland, and Washington, D.C. It is part of the larger Chesapeake-Delaware embayment and merges offshore with the Baltimore canyon trough.[13] Sediments at the Delaware coast are approximately 10,000 feet (3 kilometers) thick.

NORFOLK ARCH

The Norfolk arch is a relatively narrow east-west striking high separating the Albemarle and Salisbury embayments.

ALBEMARLE EMBAYMENT

The Albemarle embayment is a small eastward striking embayment located on the North Carolina coast. It does not extend far offshore. Basement depths exceed 10,000 feet (3 kilometers) at the coast.

CAPE FEAR ARCH

The Cape Fear arch is an asymmetrical southeastward plunging basement high that extends across the coastal plain onto the continental shelf in the vicinity of Cape Fear. The arch is a very prominent structural feature and is evident from outcrop patterns and well data and is inferred from geophysical evidence.

SOUTHEAST GEORGIA EMBAYMENT

The southeast Georgia embayment is an arcuate southeastward plunging basin that extends offshore from the coastal plain. It appears to have primarily been a tectonically passive feature and contains as much as 6,000 feet (1.8 kilometers) of Cretaceous and Tertiary sediments at the Georgia coast.

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[13] G. E. Murray. *Geology of the Atlantic and Gulf Coastal Province of North America*. New York, Harper and Brothers, 1961. 692 pp.

PENINSULAR ARCH

The peninsular arch is the dominant southeast striking feature of Florida and southeastern Georgia. The arch was a topographic high in Cretaceous times. A secondary Miocene uplift produced the Ocala uplift on the southwest flank of the peninsular arch.

SOUTH FLORIDA EMBAYMENT

The south Florida embayment is a negative relief feature in lower Cretaceous rocks at the southern end of Florida.

SOUTHWEST GEORGIA EMBAYMENT

The southwest Georgia embayment is a shallow reentrant in the upper Cretaceous rocks of southwestern Georgia, southeastern Alabama, and the Florida panhandle.

REGIONAL GRAVITY ANOMALIES OF THE ATLANTIC AND GULF COASTAL PLAIN

Gravity studies of the coastal plain have resulted in the preparation of maps of regional anomalies. These anomalies, while primarily depicting compositional variations at depth in the earth's crust rather than major basement structural features, do demonstrate variations in the structure and composition of the sedimentary sequences beneath the coastal plain as well as in the shallow basement.

Negative gravity anomalies are typical of the coastal plain and continental shelf. Positive anomalies, however, are present in sufficient quantities to produce confused patterns. Although the USGS has acquired large amounts of gravity data on the east coast, large-scale Bouguer gravity maps for selected areas of interest to the Navy have not yet been compiled and published. Some of these data will soon be released as Open File Reports. Figure 12 shows relationships of gravity data and rocks recovered from basement wells for the North Carolina coastal plain and offshore area.

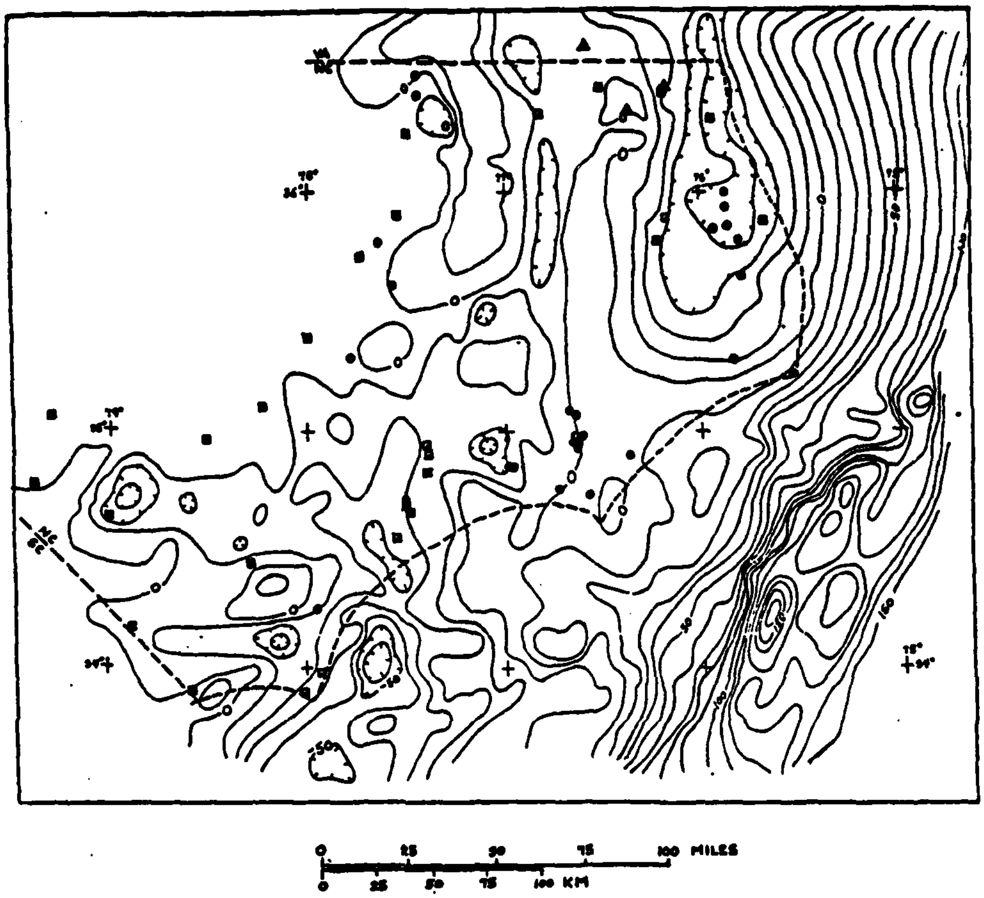

FIGURE 12. North Carolina Coastal Plain and Continental Shelf Area. Bouguer gravity anomaly map (CI 10 milligals) with superimposed data on rocks recovered from basement wells. (Granitic rocks, circles; metamorphic rocks, squares; Triassic rocks, triangles.)[14]

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[14]U.S. Geological Survey. *Geologic Interpretation of Aeromagnetic Maps of the Coastal Plain Region of South Carolina and Parts of North Carolina and Georgia*, by D. L. Daniels and I. Zietz. Washington, D.C., Government Printing Office, 1978. Fig. 3, p. 11. (U.S. Geological Survey Open File Report 78-261, publication UNCLASSIFIED.)

REGIONAL MAGNETIC ANOMALIES OF THE ATLANTIC AND GULF COASTAL PLAIN

The magnetic anomalies appear to reflect the effects of rocks of the upper portion of the basement, and it appears that the magnetic properties of igneous rocks are more variable than density variations. Figure 13 shows magnetic anomalies along the eastern margin of the

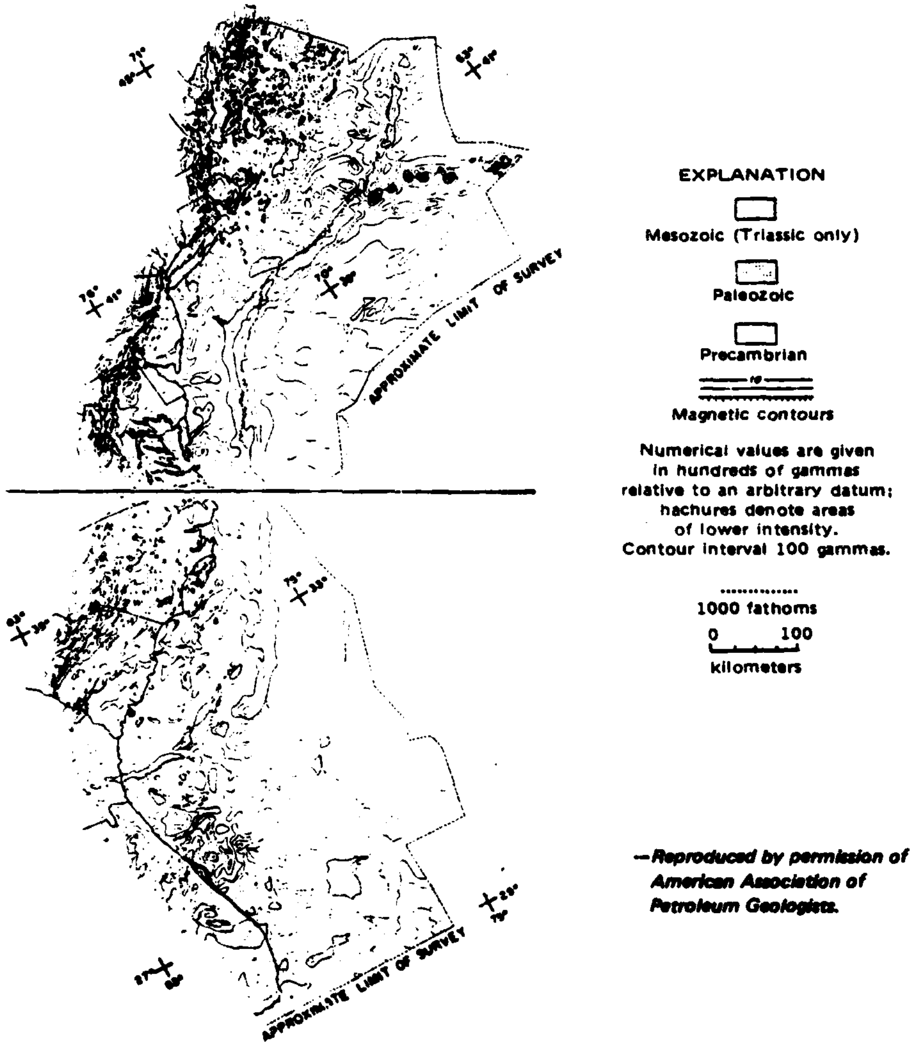


FIGURE 13. Magnetic Anomalies Along the Eastern Margin of the United States.[15]

[15]K. O. Emery and E. Uchupi. *Western North Atlantic Ocean: Topography, Rocks, Structure, Water, Life, and Sediments.* Tulsa, Okla., Amer. Assoc. Petrol. Geol. Mem. 17, 1972. Fig. 113, pp. 134-35.

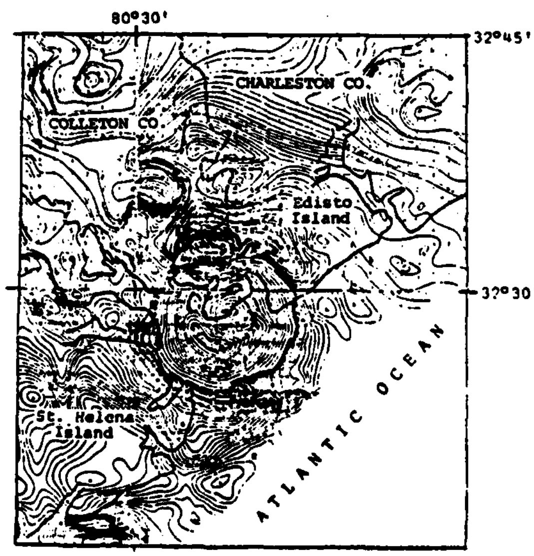
United States. Updated magnetic anomaly maps of the coastal plain are being prepared by the USGS. Maps of several selected areas have been issued as Open File Reports (see report cited in footnote 14) and Geophysical Investigation maps.[16,17]

Aeromagnetic studies of North Carolina, South Carolina, and Georgia have shown that piedmont rocks underlie the coastal plain in North Carolina, but are replaced by a belt of granitic rocks toward the coast (see report cited in footnote 14). This conclusion is supported by materials recovered from basement wells and a change in the magnetic grain characteristic of typical piedmont rocks.

Three different linear magnetic anomaly trends are also present. These are (1) trends that are parallel to the Appalachian trends, (2) curvilinear anomalies representing large fold systems in the metamorphic basement rocks, and (3) transverse linear trends generated by diabase dike swarms of Triassic-Jurassic age.

Large areas of southeast Georgia and southern South Carolina are characterized by circular or oval magnetic highs rather than the magnetic grain characteristic of the piedmont metamorphic rocks. Many of these magnetic highs correspond to gravity highs and are probably caused by gabbroic plutons intruding into an unknown basement.

Figure 14 shows a circular magnetic anomaly on the Atlantic Coastal Plain southwest of Charleston, South Carolina.



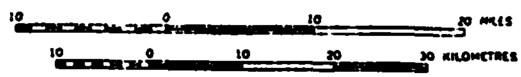


FIGURE 14. Circular Magnetic Anomaly Southwest of Charleston, South Carolina.

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[16]U.S. Geological Survey. *Aeromagnetic Map of Virginia,* by I. Zietz, et al. Washington, D.C., Government Printing Office, 1978. (U.S. Geological Survey Geophysical Investigation Map GP-916, map UNCLASSIFIED.)

[17]U.S. Geological Survey. *Aeromagnetic Map of Maryland,* by I. Zietz, F. P. Gilbert, and J. R. Kirby, Jr. Washington D.C., Government Printing Office, 1978. (U.S. Geological Survey Geophysical Investigation Map GP-923, map UNCLASSIFIED.)

METHODS OF LOCATING GEOTHERMAL RESOURCES

Geothermal sites have generally been identified because of obvious surface manifestations or as accidental discoveries when drilling for other natural resources. The various techniques used today for locating geothermal resources are geological, geochemical, geophysical, hydrological, drilling, well logging and testing, and modeling. Further information has been published on each of these general areas.[18,19]

PREVIOUS STUDIES OF GEOTHERMAL RESOURCES OF THE ATLANTIC AND GULF COASTAL PLAIN

Studies of geothermal resources of the United States have been systematically reported as early as 1920. One report[20] includes data on geothermal waters of Florida, Georgia, Maryland, New Jersey, and Virginia.

Among the more recent reports concerning geothermal resources are USGS Circular 519, 1965;[21] Grossling, 1972;[22] Hickel, 1972;[23] Rex and

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[18] The Futures Group for the National Science Foundation. *A Technology Assessment of Geothermal Energy Resource Development, 1975*, by the Futures Group, Glastonbury, Conn. Washington, D.C., Government Printing Office. 554 pp. (Publication UNCLASSIFIED.)

[19] *Proceedings, Second United Nations Symposium on the Development and Use of Geothermal Resources, San Francisco, California, USA, 20-29 May 1975*. Vol. 1-3. Washington, D.C., Government Printing Office, 1976. (Publication UNCLASSIFIED.)

[20] U.S. Geological Survey. *Geothermal Data of the United States Including Many Original Determinations of Underground Temperature*, by N. H. Darton. Washington, D.C., Government Printing Office, 1920. 97 pp. (U.S. Geological Survey Bulletin 701, publication UNCLASSIFIED.)

[21] U.S. Geological Survey. *Geothermal Energy*, by D. E. White. Washington, D.C., Government Printing Office, 1965. 17 pp. (U.S. Geological Survey Circular 519, publication UNCLASSIFIED.)

[22] B. F. Grossling. "An Appraisal of the Prospects of Geothermal Energy in the United States," in *U.S. Energy Outlook*. Washington, D.C., National Petroleum Council, 1972. Chap. 2, pp. 15-26.

[23] W. J. Hickel. *Geothermal Energy*. Geothermal Resource Research Conference Final Report. Fairbanks, University of Alaska Press, 1972. 95 pp.

Howell, 1973;[24] National Petroleum Council, 1973;[25] USGS Circular 726, 1975;[26] and First Annual Report, ERDA 77-9, 1977.[27] Of prime interest, however, is the work of VPI-SU, University of Flordia, and APL/JHU.

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

The basic objectives of VPI-SU research, sponsored by DOE/DGE, are to use geological, geophysical, and geochemical data to evaluate low-temperature radiogenically derived geothermal resources in the Atlantic Coastal Plain province. Work has included field and laboratory studies of exposed piedmont rocks, collection and interpretation of existing gravity and magnetic potential field data, modeling of selected gravity anomalies, establishing a linear relationship between heat flow and heat generation, and selecting sites for the drilling of approximately fifty, 1,000-foot (0.3-kilometer) holes for measuring heat flow. These holes are now being drilled by Gruy Federal under a DOE/DGE contract.

The four major types of geothermal resources thought to occur in region V are created by:

1. Radiogenic decay in granitic rocks underlying the Atlantic Coastal Plain
2. Heated water escaping from depth through fracture zones
3. Hot dry rock in regions with abnormal gradients resulting from radiogenically derived heat
4. Normal geothermal gradient resources

Data acquired from their studies have shown eight potential geothermal resource areas on the coastal plain (Figure 2).

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[24]R. W. Rex and D. J. Howell. "Assessment of U.S. Geothermal Resources," in *Geothermal Energy, Resources, Production, Stimulation,* by P. Kruger and C. Otte. Stanford, Calif., Stanford University Press, 1973. Pp. 59-60.

[25]National Petroleum Council. *U.S. Energy Outlook-New Energy Forms.* Washington, D.C., Government Printing Office, 1973. 9 pp.

[26]U.S. Geological Survey. *Assessment of Geothermal Resources of the United States-1975,* by D. E. White and D. L. Williams, eds. Washington, D.C., Government Printing Office, 1975. 155 pp. (U.S. Geological Survey Circular 726, publication UNCLASSIFIED.)

[27]Energy Research and Development Administration. *First Annual Report, 1977, Geothermal Energy Research, Development and Demonstration Program.* Washington, D.C., ERDA, Division of Geothermal Energy, 1977. 143 pp. (ERDA 77-9, publication UNCLASSIFIED.)

UNIVERSITY OF FLORIDA

A University of Florida study was performed under contract to the USGS Office of Geochemistry and Geophysics.[28] This study included (1) measurement of 34 new heat flow values for the southeastern United States; (2) analysis of the uranium, thorium, and potassium content and calculation of the heat production of 357 one-gram samples of representative igneous and metamorphic rock samples from the southern Appalachians; and (3) production of maps showing heat flow values in Florida (Figure 15), and in Alabama, Georgia, and South and North Carolina (Figure 16).

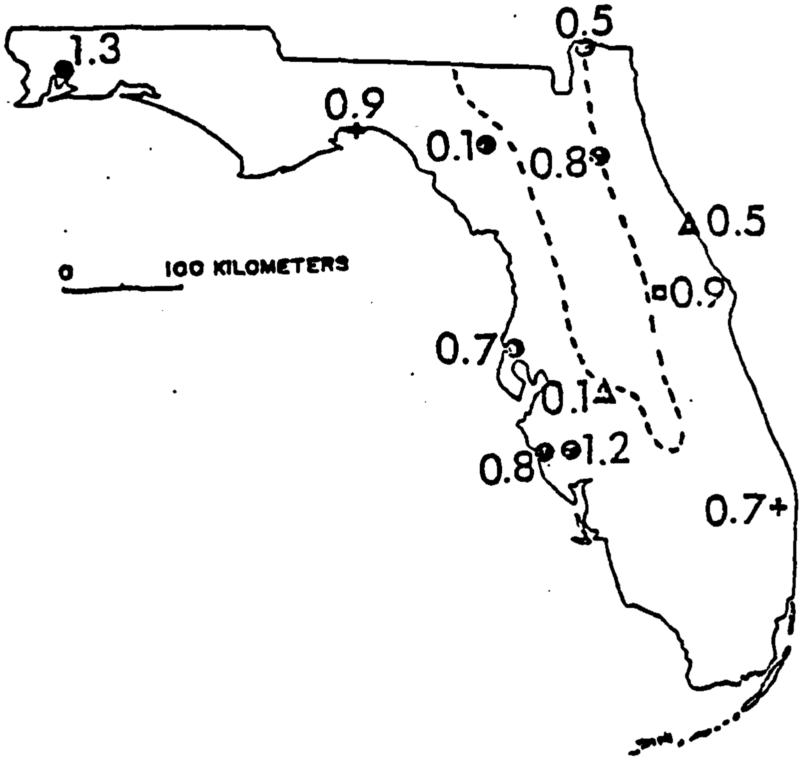

FIGURE 15. Heat Flow Values in Florida. Triangles are estimates, + and open square represent other worker's values. Values are in heat flow units.[29]

[28]D. L. Smith. *Heat Flow and Radioactive Heat Generation Studies in Southeastern United States*. Final Technical Report, 1977. Department of Geology, University of Florida, submitted to U.S. Geological Survey Office of Geochemistry and Geophysics, Grant No. 14-08-0001-G-199.

[29]Ibid., Fig. 9, p. 25.

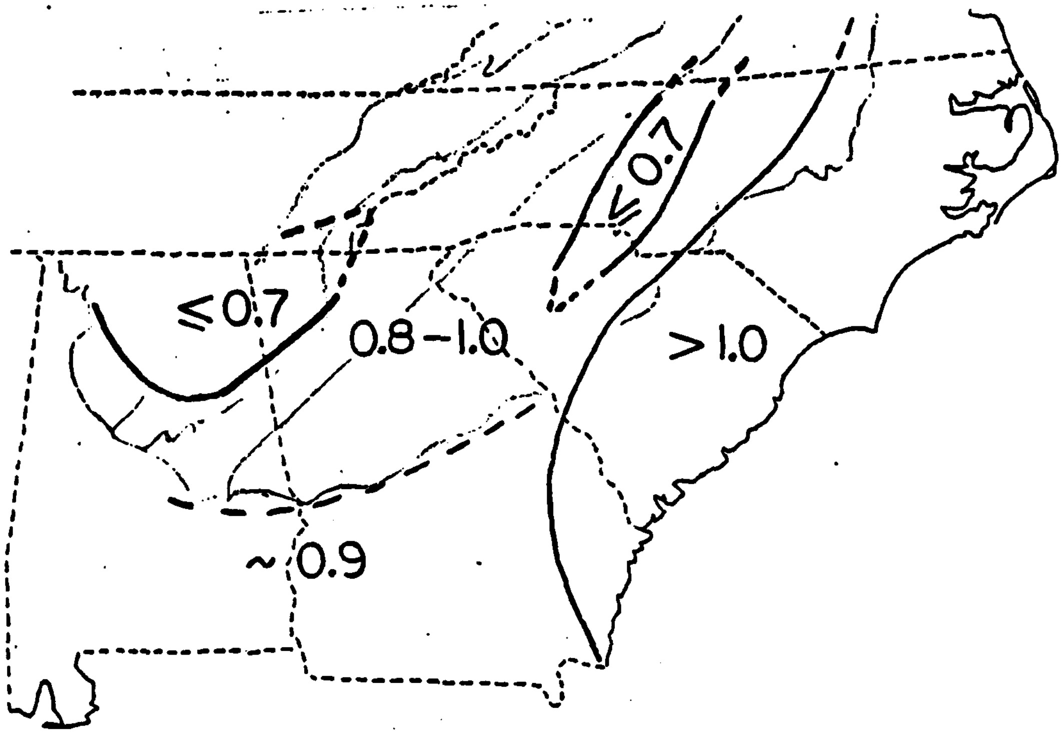

FIGURE 16. Characteristic Heat Flow Zones of Alabama, Georgia, South and North Carolina. Light lines indicate piedmont, Blue Ridge, and valley and ridge physiographic provinces.[30]

The only positive anomalies found suggest that limited space heating and power generation temperatures exist, but are presently at depths that would preclude economic utilization at this time (Figure 16).

APPLIED PHYSICS LABORATORY, JOHNS HOPKINS UNIVERSITY

The APL/JHU has contracts with DOE, NSF, U.S. Maritime Administration, Department of Commerce, and U.S. Fish and Wildlife Service for the development of energy resources, utilization concepts, and energy storage methods. The major project of interest is the operational research study for DOE/DGE of geothermal energy applications in selected areas of the Atlantic Coastal Plain. The hard science, however, is not being done by APL/JHU, but by other DOE/DGE contractors such as VPI-SU.

[30] Ibid., Fig. 10, p. 27.

AVAILABLE GEOTHERMAL ENERGY RESOURCES AT
NAVY/MARINE CORPS INSTALLATIONS ON THE
ATLANTIC AND GULF COASTAL PLAIN

FLORIDA, EAST GULF COASTAL PLAIN SECTION

Figure 17 shows the results of a study sponsored by DOE/DGE of geothermal resource areas in Florida. Table 1 shows the estimated energy content of the geothermal waters in sedimentary deposits in each of the three resource areas located in Florida.

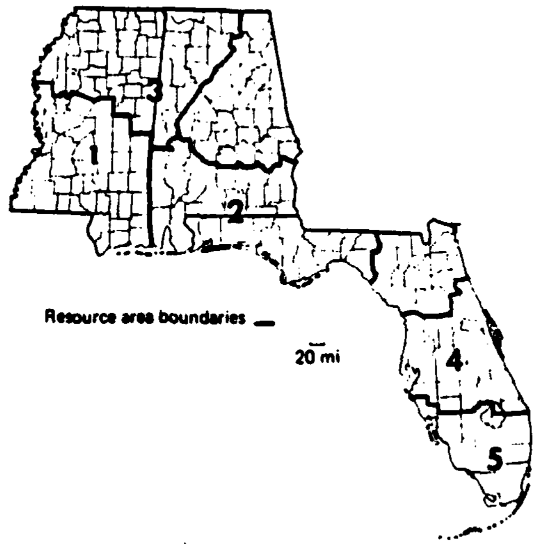

FIGURE 17. Geothermal Resource Areas.[31]

Naval installations in resource area 2 are found at Pensacola, Milton, and Panama City, Florida. Pensacola (eighth on the list of the Navy's ten largest energy users), Milton, and Panama City appear to have considerable quantities of geothermal energy available for their use.

PENINSULAR ARCH SECTION

Naval installations in resource area 5 are found at Key West and Homestead, Florida. By definition, Key West belongs to the east Gulf Coastal Plain section, but has been discussed along with Homestead

[31]Applied Physics Laboratory, Johns Hopkins University. Quarterly Report, *Energy Programs at the Johns Hopkins University Applied Physics Laboratory*. Laurel, Md., APL/JHU, January-March 1978. P. 33. (EQR/78-1, publication UNCLASSIFIED.)

TABLE 1. Estimated Energy Content (in Quads) of Geothermal Waters in the Sedimentary Deposits in Each Resource Area.[32]

1 Quad = 10^{15} Btu.

Temperature range, °F	Resource area				
	1	2	3	4	5
Over 350	2200	≤20	...	...	≤5
300–350	1600	10	...	...	15
250–300	1500	100	≤10	...	170
212–250	480	490	40	...	800
180–212	1100	350	420	170	590
150–180	560	700	300	210	260
120–150	460	520	150	230	190
Total above 120	7900	2190	920	610	2030

because it lies within the same resource area. As Table 1 indicates, considerable quantities of geothermal energy appear to be available for use at these locations.

Naval facilities at Orlando, Florida, are located in resource area 4, which has lower quantities of energy available for use. This is to be expected because this region lies close to the central portion of the peninsular arch where basement depths are shallower, and therefore the overlying sedimentary blanket is thinner. Furthermore, basement rocks in this area appear to be Triassic volcanics, which are relatively depleted in radiogenic heat-producing minerals (Figure 9).

Geothermal resources of any large magnitude would not be expected near the naval facilities at Jacksonville and Mayport, Florida, according to heat flow values in Figure 15.

Navy/Marine Corps facilities at Albany, Athens, and Marietta, Georgia, are not, according to Figure 16, near geothermal resources of any large magnitude.

[32]Applied Physics Laboratory, Johns Hopkins University. Quarterly Report, *Energy Programs at the Johns Hopkins University Applied Physics Laboratory*. Laurel, Md., APL/JHU, January-March 1978. P. 34. (EQR/78-1, publication UNCLASSIFIED.)

SEA ISLANDS SECTION

Marine Corps installations at Parris Island and Beaufort, South Carolina, appear to lie between two major geothermal resource areas in the Atlantic Coastal Plain. These are the Savannah-Brunswick, Georgia, and Charleston, South Carolina, areas.

Geothermal areas with estimated maximum temperatures of 123°F (51°C) at the base of the sedimentary pile (Table 2 and Figure 2) should be expected near the naval installations at Charleston, South Carolina. Charleston is the Navy's fourth largest energy user.

TABLE 2. Estimated Maximum Temperatures at Base of Sedimentary Pile for Different Potential Geothermal Resource Areas.[33]

Resource area	Temperature	
Delmarva peninsula	>217°F	>103°C
Norfolk, Va. to eastern N.C.	>212	>100
Brunswick, Ga.	155	68
Charleston, S.C.	123	50
New Jersey	120	48
Georgetown, S.C.	107	42
Wilmington, N.C.	93	34
Kinston, N.C.	91	33

CAPE FEAR ARCH SECTION

Navy/Marine Corps installations in the Cape Fear arch section are found at Camp Lejeune, Cherry Point, and Buxton, North Carolina. This area is on the north flank of the Cape Fear arch and the south flank of the Albemarle embayment. There is conflicting evidence about the geothermal resource potential of this region (Figures 2 and 16).

[33]Applied Physics Laboratory, Johns Hopkins University. Quarterly Report, *Energy Programs at the Johns Hopkins University Applied Physics Laboratory*. Laurel, Md., APL/JHU, January-March 1978. P. 37. (EQR/78-1, publication UNCLASSIFIED.)

EMBAYED SECTION

Norfolk (largest energy user), Portsmouth (seventh largest energy user), and Virginia Beach, Virginia, contain Navy/Marine Corps installations that, according to Table 2, should encounter maximum temperatures at the top of the basement in excess of 212°F (100°C). Structurally this region straddles the Norfolk arch.

The numerous installations that comprise the Naval District, Washington, D.C., do not appear to lie within one of the major geothermal resource areas (Figure 2).

The naval installation at Lewes, Delaware, is situated within the Ocean City-Delmarva peninsula geothermal resource area, and according to Table 2, maximum temperatures should be in excess of 217°F (103°C) at the bottom of the sedimentary sequence.

Naval installations at Lakehurst and Earle, New Jersey, are located within the mid-New Jersey coast resource area, and temperatures on the order of 120°F (49°C) are to be expected at the bottom of the sedimentary sequence.

CONCLUSIONS

The geothermal resource potential of the Atlantic and Gulf Coastal Plain is just beginning to be studied and understood. For decades, study of the sedimentary sequences and the underlying bedrock of this area has been neglected because of the absence of an active oil and natural gas industry. Studies of piedmont rocks and geologic, geochemical, and geophysical investigations of the coastal plain indicate that low-grade geothermal energy resources are definitely present, and that locally the temperatures at the base of the sedimentary sequences may exceed 212°F (100°C). Radiogenically derived heat from the various kinds of basement rocks present is the major cause of the geothermal resources. Enough is known from available gravity and magnetic data to indicate that more detailed work is needed in order to relate specific anomalies with distinct types of basement rocks containing known amounts of radioactive materials that can generate the varying amounts of heat. This heat will in turn have heated the water present in the overlying sedimentary sequence and give rise to elevated thermal gradients.

It is perhaps misleading that the VPI-SU and University of Florida studies have delineated areas of higher geothermal gradients or heat flow. Although these findings are significant (Figures 2, 15, and 16), the detailed information needed to assess the future of a geothermal program at any one location is not available. To acquire this information, the U.S. Navy must either conduct its own specific studies or else await the results of USGS and DOE studies that will eventually provide the detailed gravity and magnetic anomaly maps for the major Navy/Marine Corps installations located on the Atlantic and Gulf Coastal Plain. The Navy should encourage programs which include deep holes being drilled on Navy property by USGS and DOE contractors. Exploratory drilling programs by the Navy on several of its installations, especially those at Norfolk, Portsmouth, and Virginia Beach, Virginia; Charleston, South Carolina; Pensacola, Milton, and Panama City, Florida; Lewes, Delaware; and Lakehurst, New Jersey, are technically supportable as valid exploration targets appear to be present. Studies of the utilization economics should precede any active field exploration, however.

Until actual heat flow values have been determined for holes drilled at specific bases, a clear understanding of the geothermal resource potential at each base must remain speculative. When the ongoing drilling program on the coastal plain for DOE/DGE by Gruy Federal is completed, a reevaluation of the potential resources at these bases can be made and future work can be planned.

It is unlikely at this time that goethermal energy resources exist within drillable depths in the vicinity of any of the eastern U.S. coastal Navy/Marine Corps installations that can be utilized for other than space heating and cooling, but the potential for these applications appears encouraging at Panama City, Pensacola, and Milton, Florida, at Key West and Homestead, Florida; possibly at Parris Island and Beaufort, South Carolina; at Charleston, South Carolina, and a good potential appears to exist at Norfolk, Portsmouth, and Virginia Beach. The Lewes Delaware area has a good potential and the Lakehurst and Earle area a modest potential.

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Appendix A

ATLANTIC COASTAL PLAIN STRATIGRAPHIC UNITS AND THEIR GULF COAST EQUIVALENTS

System	Series	Gulf coast equivalent	Florida units	Georgia units	South Carolina units	North Carolina units	Maryland units	New Jersey units	Long Island units
Tertiary and Quaternary	Holocene, Pleistocene, and Pliocene	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks	Post-Miocene rocks
	Miocene	Miocene rocks	Miocene rocks	Miocene rocks	Absent on Cape Fear arch	Upper and middle Miocene rocks	Upper and middle Miocene rocks	Miocene and Eocene rocks undifferentiated	Tertiary rocks undifferentiated
						Lower Miocene rocks	Lower Miocene rocks		
Tertiary	Oligocene	Oligocene rocks	Oligocene rocks	Oligocene rocks	Absent on Cape Fear arch	Rocks of uncertain age, possibly Oligocene in part	No Oligocene known		
	Eocene	Rocks of Jackson age	Ocala limestone	Rocks of Jackson age	Rocks of Jackson age	Upper and middle Eocene rocks	Eocene rocks undifferentiated		
		Rocks of Claiborne age	Avon Park limestone Lake City limestone	Tallahatta and Lisbon formations undifferentiated	Middle and lower Eocene and Paleocene rocks undifferentiated				
		Rocks of Wilcox age	Oldsmar limestone	Rocks of Wilcox age		Lower Eocene rocks			
	Paleocene	Rocks of Midway age	Cedar Keys limestone	Clayton formation		Beaufort formation	Paleocene rocks	Paleocene(?) rocks	
Cretaceous	Upper — Gulf	Rocks of Navarro age	Rocks of Navarro age	Rocks of Navarro age	Rocks of Navarro age	Pedee formation	Monmouth formation	Monmouth group	Monmouth group
		Rocks of Taylor age	Rocks of Taylor age	Rocks of Taylor age	Rocks of Taylor age	Black Creek formation	Matawan formation	Magothy formation and Matawan group undifferentiated	Magothy formation and Matawan group undifferentiated
		Rocks of Austin age	Rocks of Austin age	Rocks of Austin age	Rocks of Austin age		Rocks of Austin age		
		Rocks of Woodbine and Eagle Ford age	Atkinson formation	Rocks of Eagle Ford age	Rocks of Eagle Ford age	Rocks of Eagle Ford age	Rocks of Eagle Ford age	Raritan formation	Raritan formation
				Tuscaloosa formation	Tuscaloosa formation	Tuscaloosa formation	Rocks of Woodbine age		
	?								
	Lower — Comanche	Rocks of Washita age	Rocks of Washita age	Lower Cretaceous rocks	Lower Cretaceous rocks	Rocks of Washita(?) age	Rocks of Washita age	Rocks of Washita(?) and Fredericksburg(?) undifferentiated	Lower Cretaceous rocks absent
		Rocks of Fredericksburg age	Rocks of Fredericksburg age			Rocks of Fredericksburg(?) age	Rocks of Fredericksburg(?) age		
		Rocks of Trinity age	Rocks of late Trinity age Sunniland limestone Rocks of early Trinity age			Rocks of Fredericksburg or Trinity age	Rocks of Fredericksburg or Trinity age	Rocks of Trinity(?) age and older	
						Rocks of Trinity(?) age	Rocks of Trinity(?) age		
?	Lower Cretaceous (Neocomian) or upper Jurassic	Lower Cretaceous (Neocomian) or upper Jurassic	Lower Cretaceous (Neocomian) or upper Jurassic	Lower Cretaceous (Neocomian) or upper Jurassic absent	Lower Cretaceous (Neocomian) or upper Jurassic absent	Mesozoic rocks of uncertain age, possibly Cretaceous (Neocomian)	Mesozoic rocks of uncertain age, possibly Cretaceous (Neocomian)		Lower Cretaceous (Neocomian) or upper Jurassic rocks absent

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