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Assesses the feasibility of geothermal energy use at naval installations in Norfolk, VA, Jacksonville, FL, and Charleston, SC. Geophysical and geological studies of the above areas were performed. Engineering and economic factors, affecting potential energy use, were evaluated. The Norfolk and Jacksonville facilities are identified as candidates for geothermal systems. System costs are predicted. Economic benefits of the proposed geothermal systems are forecast, using the net present value method of predicting future income.

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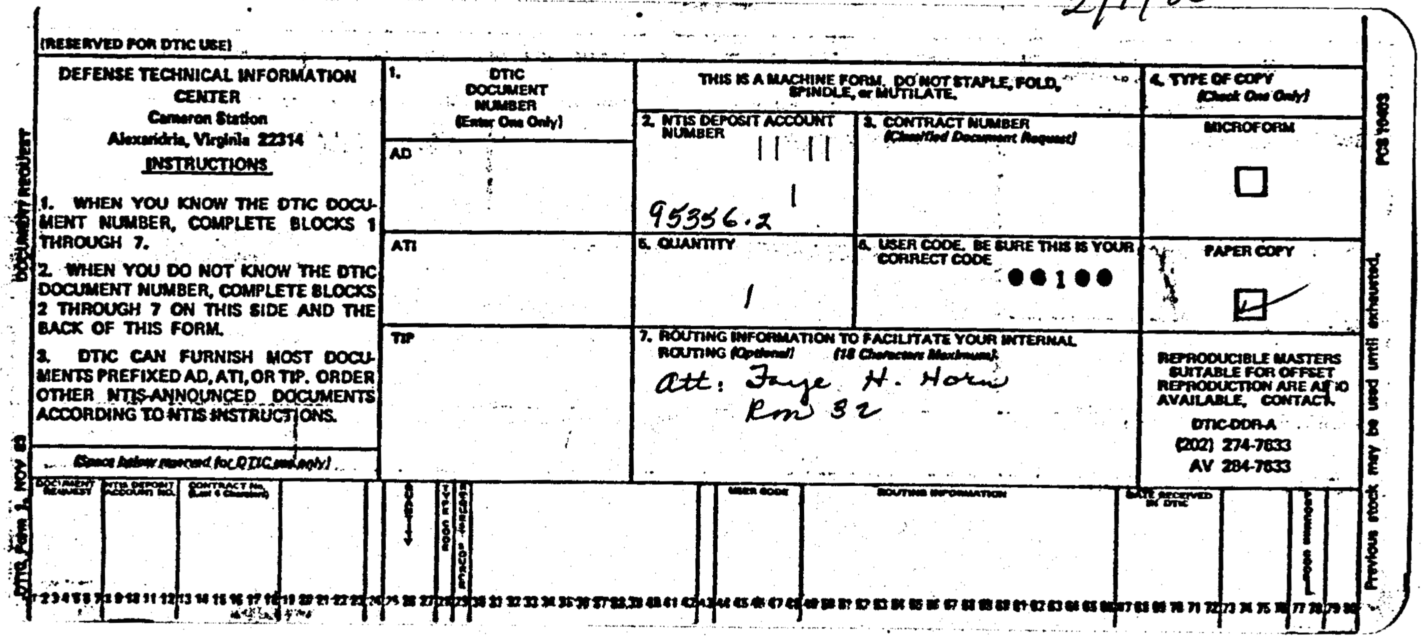

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(U) *Potential Geothermal Energy Use at the Naval Air Rework Facilities, Norfolk, Va., and Jacksonville, Fla., and at the Naval Shipyard, Charleston, S.C.*, by John K. Costain and Lynn Glover, III, Virginia Polytechnic Institute and State University; and R. W. Newman, Applied Physics Laboratory, Johns Hopkins University. China Lake, Calif., NWC, May 1984. 118 pp. (NWC TP 6535, publication UNCLASSIFID.)

(U) In the Navy Energy R&D Program to assess the feasibility of geothermal energy use at East Coast naval installations, the Naval Air Rework Facilities (NARFs), Norfolk, Va., and Jacksonville, Fla., and the Naval Shipyard, Charleston, S.C., were investigated. Geophysical and geological studies of the Norfolk, Jacksonville, and Charleston areas were performed, and engineering and economic factors affecting potential energy use were assessed.

(U) The Norfolk and Jacksonville NARFs are identified as candidates for geothermal systems, and system costs are predicted. Economic benefits of the proposed geothermal systems are evaluated by the net present value method of evaluating future income.

CONTENTS

INTRODUCTION

The Department of the Navy's energy program has three major objectives: (1) to ensure that adequate energy supplies are available to sustain peacetime and combat operations, (2) to improve the energy efficiency of the shore establishment and operating forces, and (3) to substitute more plentiful energy for natural petroleum where cost effective.

The Facilities Energy Research and Development Program is a major part of the Navy's efforts to find solutions to energy problems. This program focuses on energy technologies being developed outside the Navy (e.g., by the Department of Energy and by industry) for the purposes of adapting those technologies to Navy use and of making the Navy an informed customer of energy conservation and energy source-substitution technologies. It is important that facility engineers be able to evaluate the costs, benefits, and risks of implementing existing and future technologies in the naval shore establishment.

Integral to the Navy effort is the geothermal energy R&D program that was established to verify geothermal resources on Navy lands and to evaluate risks and benefits associated with their development. The Naval Weapons Center, China Lake, acting for the Naval Civil Engineering Laboratory, has been designated the lead laboratory for the Navy geothermal program. This report documents geothermal R&D investigations of three East Coast naval facilities.

In an earlier survey of Navy and Marine Corps installations on the Atlantic Coastal Plain, the Applied Physics Laboratory (APL) of Johns Hopkins University, Laurel, Md., identified facilities in Norfolk, Va., north-central Florida, and Charleston, S.C., as potentially feasible for development of geothermal systems (Naval Weapons Center, 1983; Johns Hopkins University, 1982).

The present report contains studies prepared by Virginia Polytechnic Institute and State University, Blacksburg, Va., on the geophysical and geologic aspects of geothermal energy potential for the Norfolk, Jacksonville, Fla., and Charleston areas.

The report also contains summaries prepared by APL of the engineering and economic factors affecting possible use of geothermal energy at the Norfolk Naval Air Rework Facility (NARF); the Jacksonville NARF; Cecil Field Naval Air Station; Naval Training Center, Orlando; the Charleston Naval Shipyard; and the Polaris Missile Facility Atlantic, Charleston. The Norfolk and Jacksonville NARFs were identified as the two installations best suited for geothermal energy use. The report contains economic analyses developed by APL for possible geothermal systems at these facilities.

GEOPHYSICAL AND GEOLOGICAL ASPECTS OF GEOTHERMAL ENERGY POTENTIAL AT NORFOLK

a) Geologic framework.

The crystalline basement rocks of eastern Virginia are overlain by an eastward-thickening wedge of relatively unconsolidated sediments beneath the Atlantic Coastal Plain. The line of onlap, or fall line, extends in an arc from Alexandria through Richmond, Petersburg, and Emporia. Directly west of the fall line, the exposed Piedmont comprises the Richmond Triassic basin, the Precambrian Goochland Terrane, and the Paleozoic eastern Carolina slate belt. East of the fall line, some of these lithologies continue beneath the Coastal Plain sediments; in addition, rock types not exposed in the Piedmont also occur, as described below. In a few localities, drill holes that penetrate the basement surface provide definitive evidence of the lithologies present. Over broader areas, lithologies can be inferred from geophysical data.

It is the relatively unconsolidated sediments beneath the Atlantic Coastal Plain and above the relatively impermeable pre-Cretaceous basement rocks that are of interest for the evaluation of geothermal energy potential. Although data about permeability are scarce, the pre-Cretaceous rocks (including Triassic basins) are believed to be too impermeable for geothermal applications. Brown (1972) divides the unconsolidated sediments into two segments: a northern segment that extends from Long Island, New York, through North Carolina, and a southern one that includes South Carolina and Georgia. For descriptive purposes, the segments can be further divided into Mesozoic and Cenozoic sedimentary rocks. In the northern segment the sediments have been divided into 17 regional chronostratigraphic sequences, 9 of Mesozoic age and 8 of Cenozoic age. Brown and others (1972) compiled a series of structure maps and a series of isopach-lithofacies-permeability-distribution maps.

There are three general depositional systems that can be recognized in the basal Atlantic Coastal Plain sediments: non-marine, marginal marine and shallow marine. Non-marine deposits are characterized by relatively high sand/clay ratios and comparatively small sand bodies which tend to be physically adjacent so that they often form large, composite aquifer systems. Marginal marine deposits have relatively less sand, but tend to form large sand bodies that are more isolated from each other by clay deposits than are non-marine sand bodies. Shallow marine deposits have even lower sand/clay ratios but larger and more isolated sand bodies than marginal marine deposits. Generally, the basal Coastal Plain units tend to be more non-marine at the north and west, and more shallow marine at the east and south. Also, depositional systems often change vertically in the sedimentary section. There are few drill holes that penetrate the basal units. Electric logs from these holes indicate that there are several potential aquifers in these units. We have used VIBROSEIS reflection seismic data to evaluate the use of such data for the determination of the areal extent of potential aquifers, and to explore for potential aquifers in areas where there are no drill hole data.

b) Thickness of Coastal Plain sediments.

In the northern segment of Brown (1972) the maximum depth to the top of basement is about 3 km (10,000 ft) below mean sea level at Cape Hatteras, N. C. (Brown and others, 1972, Plate 5). In the southern one, the maximum depth to the top of the pre-Cretaceous surface is about 2100 m (7,000 ft) below mean sea level in Seminole County, Georgia (Brown and others, 1979b, Plate 3A).

In the Portsmouth - Norfolk area, the thickness of the Coastal Plain sediments increases from approximately 600 m (2000 ft) near Portsmouth to about 900 m (3000 ft) at Virginia Beach (Gleason, 1982). One Norfolk well-log, VA-T-12, is reported to bottom in impermeable rocks at 2567' in Cretaceous/Jurassic(?) clay (Brown,1972). Another older well-log from Ft. Monroe, Va., reports penetrating crystalline rock at 2,243' (Cederstrom, 1945).

A structure contour map of the basement surface is shown in Figure 1. The nearest hole (C25A west of Portsmouth) to basement, drilled 13 km northwest of Portsmouth encountered basement at 555 m (1820 ft).

c) Intrinsic permeability and other hydrologic properties.

Intrinsic permeability, k, is independent of fluid properties, and depends only on the medium. It is a fluid-free conductance parameter that depends on mean grain diameter, distribution of grain sizes, grain sphericity and roundness, and the nature of packing.

Relative intrinsic permeabilities of the Mesozoic and Cenozoic aquifer systems of the Atlantic Coastal Plain from North Carolina to Long Island, New York are summarized in Tables 1 and 2 from Brown (1979a). The oldest (deepest and therefore hottest) aquifer system is designated 'H' by Brown and others (1972). The deepest aquifer systems have low to moderate intrinsic permeabilities, but pump test data are lacking.

Brown and others (1977) have regionally estimated the relative intrinsic permeability of Coastal Plain sediments by using sand/shale ratios as interpreted from geological and geophysical well data. Brown and others (1972) hydraulically tested Brown's (1972) unit F at Norfolk. These tests measured a hydraulic conductivity of 3×10^{6} m/s, a storage coefficient of 1.5×10^{-4}, and a transmissivity of 770 m^3/d-m for the whole unit. Specific sections have transmissivites ranging from 1540 to 498 m^3/d-m. The hydraulic data serve to calibrate relative intrinsic permeability of Brown and others (1972) for Norfolk. Brown's 'moderate' category compares to the reported ranges of hydraulic

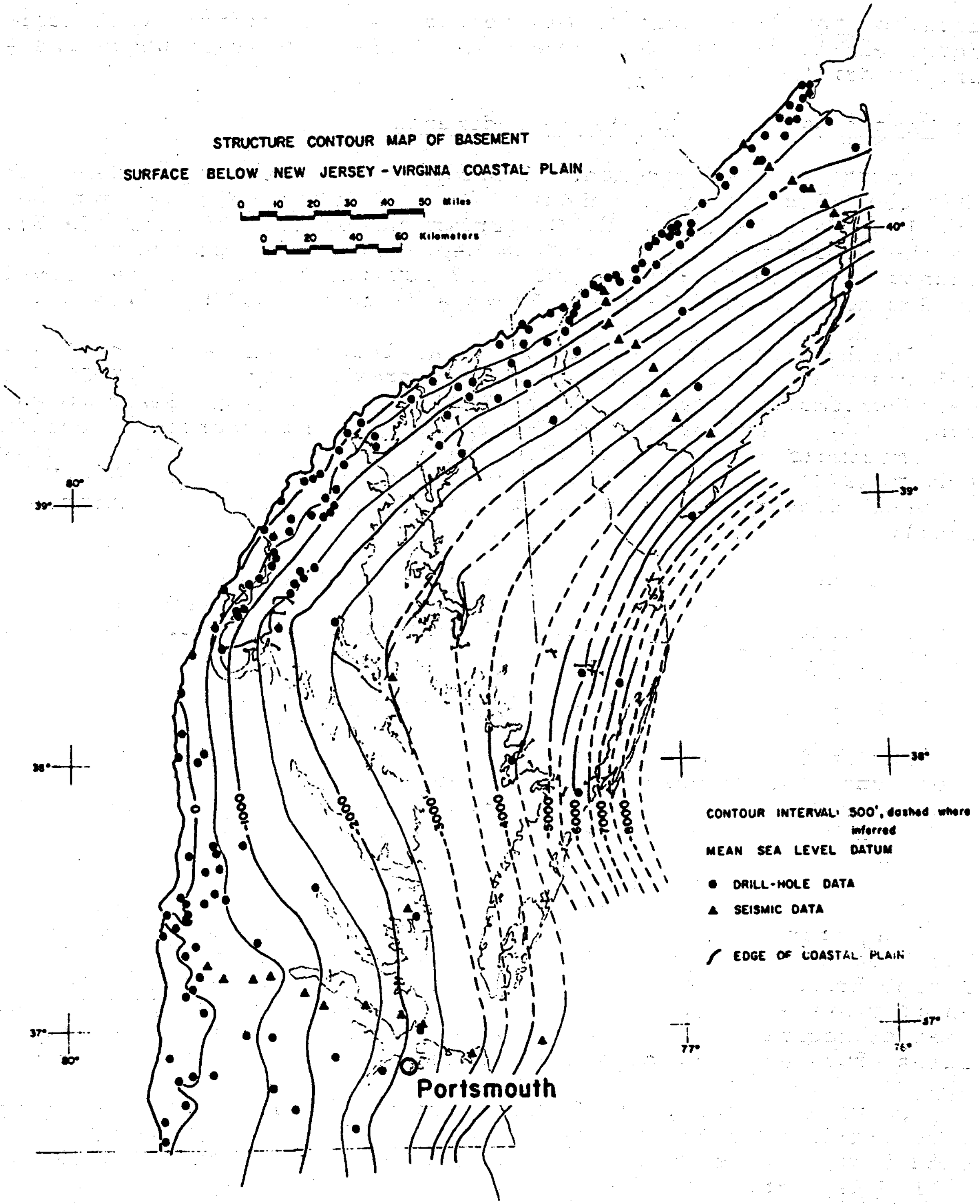

Figure 1. Structure contour map on the basement surface in the Portsmouth, Va. area. (From Gleason, 1982)

Table 1. Lithologic facies and relative intrinsic permeabilities for Cenozoic aquifer systems, Atlantic Coastal Plain, North Carolina to Long Island, New York (from Brown, 1979).

	Midway aquifer system	Sabine aquifer system	Claiborne aquifer system	Jackson aquifer system	Oligocene aquifer system	Middle Miocene aquifer system
Total volume[1]	971	217	1,062	263	261	1,661
Total area[2]	34,500	16,730	28,360	8,445	6,800	30,205
Lithologic facies						
Sand: 75-100%						
Volume	82.1	50.8	22.7	9.6	5.1	8.1
Area	4,775	3,140	2,175	310	345	1,580
Sand: 50-75% Shale: 25-50%						
Volume	260	20.8	98.8	135	7.6	197
Area	11,900	1,295	5,200	2,775	280	4,200
Shale: 50-75% Sand: 25-50%						
Volume	211	16.9	103	56	-	966
Area	7,125	1,720	4,575	1,400	-	15,125
Shale: 75-100%						
Volume	188	72.2	78.8	61.2	-	425
Area	5,450	7,300	4,150	3,550	-	8,275
Limestone: 25-50% Clastics: 50-75%						
Volume	118	25.3	7.2	0.1	12.5	55
Area	2,800	1,645	435	31	375	840
Limestone: 50-75% Clastics: 25-50%						
Volume	44.4	24.1	70.5	0.9	37.8	9.8
Area	1,100	1,225	1,225	290	1,100	175
Limestone: 75-100%						
Volume	67.5	6.9	681	0.2	198	0.1
Area	1,350	405	11,100	89	4,700	10
Relative intrinsic permeabilities						
Very high						
Volume	-	-	-	-	198	-
Area	-	-	-	-	4,700	-
High						
Volume	0.6	-	681	-	-	9.4
Area	95	-	11,100	-	-	115
Moderately high						
Volume	13.7	0.9	7.9	7.5	42.4	58.8
Area	1,150	230	655	195	1,400	1,100
Moderate						
Volume	74.7	51.3	18.9	3.3	12.9	4.8
Area	4,300	3,025	1,650	500	405	1,390
Moderately low						
Volume	390	43.5	173	135	7.7	197
Area	15,800	2,625	6,755	2,800	295	4,200
Low						
Volume	238	42.2	103	56	-	966
Area	6,555	3,150	4,550	1,400	-	15,125
Very low						
Volume	254	79.1	78.2	61.2	-	425
Area	6,600	7,700	4,150	3,550	-	8,275

[1] Volume - mi^3

[2] Area - mi^2

Table 2. Lithologic facies and relative intrinsic permeabilities for Mesozoic aquifer systems, Atlantic Coastal Plain, North Carolina to Long Island, New York (from Brown, 1979).

	Aquifer system H	Aquifer system G	Aquifer system F	Aquifer system E	Aquifer system D	Aquifer system C	Aquifer system B	Aquifer system A
Total volume[1]	4,662	3,124	5,321	888	900	1,215	1,099	711
Total area[2]	29,220	28,495	55,455	22,835	24,885	35,685	31,650	28,555
Lithologic facies								
Sand: 75-100%								
Volume	20.4	9.4	81	18.3	38.5	104	35	69
Area	795	475	1,125	820	1,325	3,375	980	2,700
Sand: 50-75% Shale: 25-50%								
Volume	643	71.7	974	70.8	176	338	101	181
Area	7,730	2,125	10,975	2,125	6,320	10,250	3,650	6,400
Shale: 50-75% Sand: 25-50%								
Volume	3,785	2,552	3,855	126	548	618	293	324
Area	19,610	22,100	29,200	5,125	13,600	15,400	10,500	11,850
Shale: 75-100%								
Volume	40	444	408	539	124	155	656	124
Area	460	3,550	4,050	12,240	3,450	6,660	16,075	6,635
Limestone: 25-50% Clastics: 50-75%								
Volume	96.2	46.9	3	103	13.5	-	14	11.8
Area	360	245	105	2,050	190	-	445	815
Limestone: 50-75% Clastics: 25-50%								
Volume	77.4	-	-	30.9	-	-	-	1.2
Area	265	-	-	475	-	-	-	155
Limestone: 75-100%								
Volume	-	-	-	-	-	-	-	-
Area	-	-	-	-	-	-	-	-
Relative intrinsic permeabilities								
Very high								
Volume	-	-	-	-	-	-	-	-
Area	-	-	-	-	-	-	-	-
High								
Volume	14.9	9.4	-	0.9	1.2	21.5	-	-
Area	665	475	-	187	100	465	-	-
Moderately high								
Volume	-	-	84	0.7	36.9	22.5	4.6	1.1
Area	-	-	1,225	48	1,175	1,675	265	190
Moderate								
Volume	644	62.7	716	16.4	189	259	58.4	70.9
Area	7,725	1,805	7,775	590	6,550	8,425	2,380	2,715
Moderately low								
Volume	83.1	2,561	3,854	153	540	181	158	179
Area	395	22,420	39,220	5,500	12,910	5,500	5,080	6,200
Low								
Volume	3,880	46.9	259	178	8.9	576	222	324
Area	19,975	245	3,180	4,255	700	12,970	7,850	11,850
Very low								
Volume	40	444	408	539	124	155	656	136
Area	460	3,550	4,055	12,255	3,450	6,650	16,075	7,600

[1] Volume - mi^3

[2] Area - mi^2

conductivities for silty sands (Freeze, 1979). This conductivity is consistent with pump tests. Because the unit tested was chosen for its thick continuous sand section, the surrounding sediments probably have smaller overall hydraulic conductivities because of vertically thinner sand-rich sections.

Locations of wells near Norfolk, Va., screened in the Lower Cretaceous Aquifer are shown in Figures 2 and 3. Screened intervals at depths of approximately 300 m (1,000 ft) have yields of approximately 200 gpm (gallons per minute) to 700 gpm (personal communication, 1983, John Harsh, U. S. Geological Survey). Two wells in the City of Norfolk have a combined capacity of <u>8 million gallons per day</u> (<u>Table 4</u>). These wells have been installed for emergency use, and are not intended for continuous production. Screened intervals are listed in Table 3, and extend from depths of 133 m (435 ft) to 322 m (1055 ft). Two of the wells (P1 and P2) less than 16 km (10 mi) southeast of the Sewells Point Naval Complex have total dissolved solids concentrations of several thousand mg/l (milligrams/liter) to over 17,000 mg/l, respectively. Quality control over water chemistry may not be entirely reliable everywhere. The screened interval for P1 was 316-326 m (1038-1070 ft) and for P2 was 368-417 m (1207 - 1367 ft).

Non-equilibrium problems in hydrology require knowledge of the storage coefficient, S, and the transmissivity, T. As equilibrium (steady-state) conditions are approached, the storage coefficient becomes less important. The transmissivity (hydraulic conductivity X aquifer thickness) is always important, however, because transmissivity is a measure of the quantity of water obtainable from the aquifer. Few values of the storage coefficient, S, are available for aquifers of the Atlantic Coastal Plain. Although, for many purposes, a knowledge of S is not as important as understanding regional and local changes in T, some local non-equilibrium hydrologic problems arising from geothermal applications might require knowledge of S. Regional ground water modeling programs are often forced to use crude values of the storage coefficient because of lack of data. Estimates of transmissivity, T, are more important and are commonly obtained by multiplying hydraulic conductivity by <u>total sand thickness</u>. Hydraulic conductivity is often estimated from lithology. Total sand thickness is obtained by analysis of geophysical logs in existing wells. Correlation of geophysical logs between wells on the Atlantic Coastal Plain is well known to be difficult, but this is at present the only way to estimate transmissivity between wells. Pump tests are often not useful, especially if they involve only a few hundred gallons per minute (gpm) and do not sufficiently stress the aquifer. A few thousand gpm would adequately stress the aquifer, but the test would be site specific and may not be regionally representative. Large well fields will require more data about numerical values of the storage coefficient and aquifer transmissivity than are currently available.

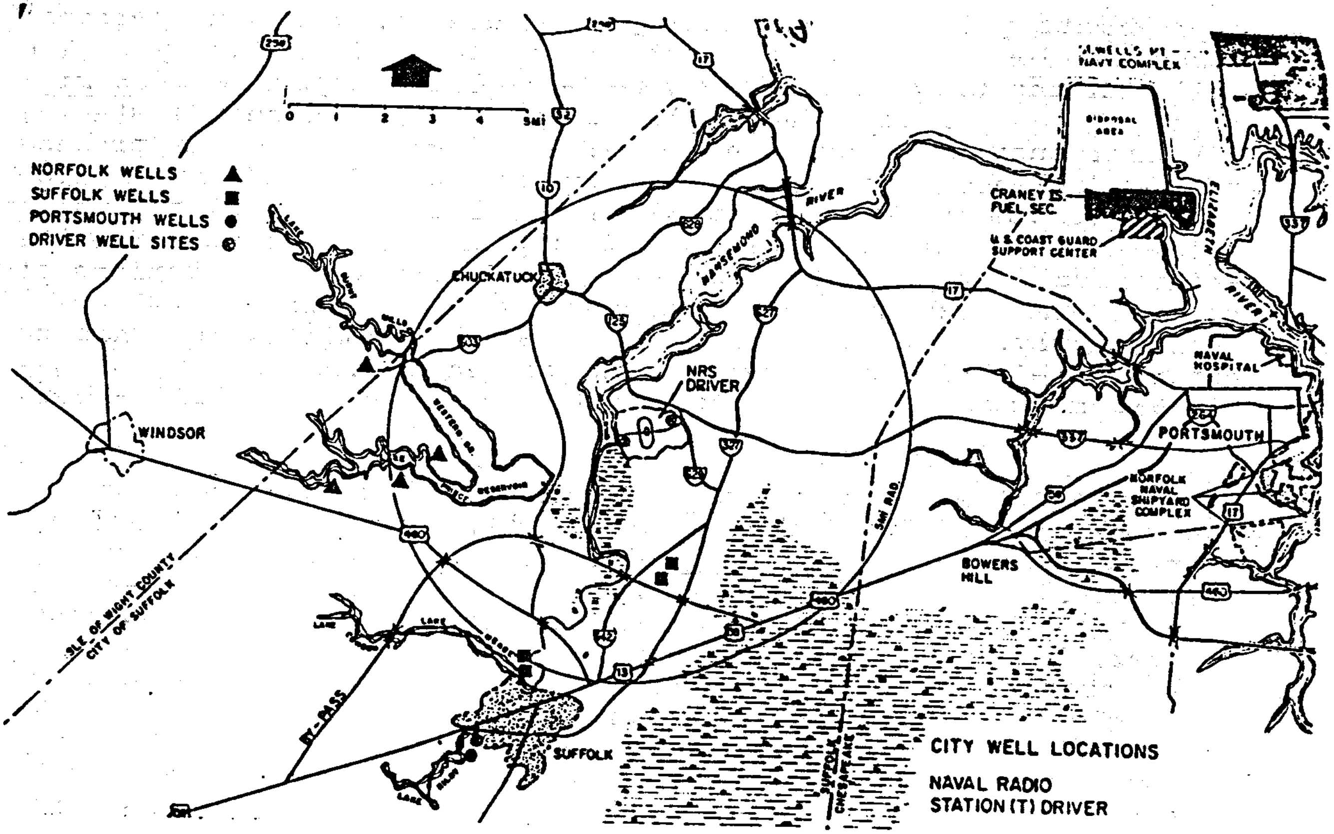

Figure 2. Map of Norfolk-Virginia Beach area showing locations of wells screened in the Lower Cretaceous aquifer (provisional data, courtesy John Harsh, U. S. Geological Survey).

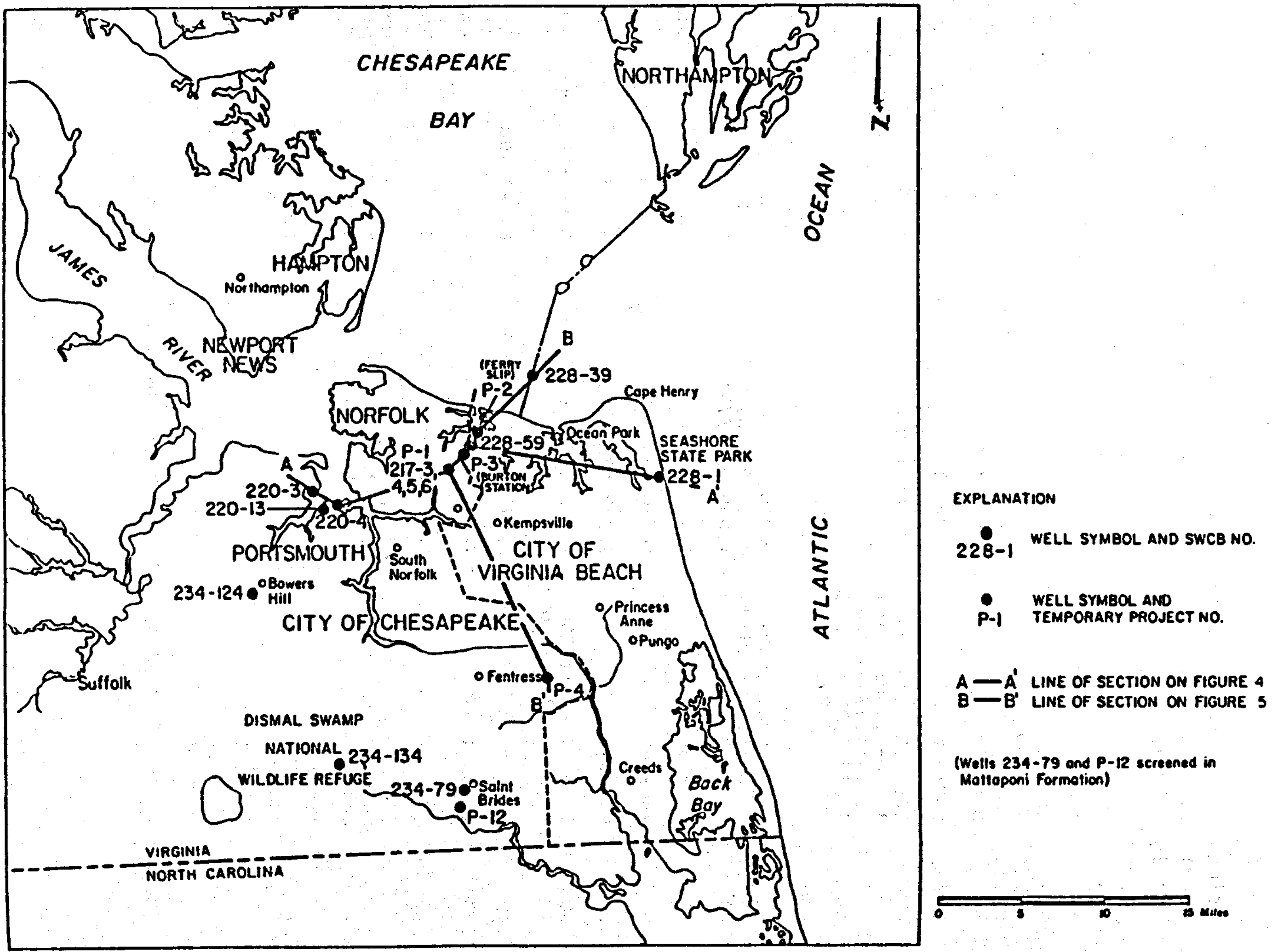

Figure 3. Map showing locations of wells in the Norfolk-Suffolk-Portsmouth area (courtesy John Harsh, U.S. Geological Survey).

Table 3. Principal findings (provisional) from wells screened in Lower Cretaceous aquifer in and adjacent to City of Virginia Beach.

Well No.[1]	Owner or Location	Date Drilled	Total Depth (ft)[2]	Screened Interval (ft)	TDS Concentration In MG/L (Date Sampled)	Chloride Concentration In MG/L	Use
P-1	Moores Bridges	1890-98	1,762	1038/70	3,345/3,652(1896-1898)	1,650/1,714	Not in use
217-3	Moores Bridges	10/68	1,019	900-990	2,960 (10/15/68)	1,360	Observation Well
217-4	Moores Bridges	11/68	1,004	900-981	3,010 (11/14/68)	1,400	Observation Well
217-5	Moores Bridges	6/70	1,017	896-976	3,010 (1970)	1,360	Test-injection Well
217-6	Moores Bridges	3/68	2,587	900-960	2,820 (2/21/68)	1,280	USGS Test Well
228-1	Virginia House	6/64	1,693	345-350 865-875; 886-896; 1,130-1,150; 1,164-1,174;1,178-1,188 1,232-1,242; 1,252 1,262; 1,297-1307	10,792 (1964) 11,300 (1970)	5,041 5,400	Not in use
228-39	Chesapeake Bay Bridge Tunnel	10/63	1,500	--	--	--	Exploratory Well
228-59	Nepratex Industries	9/74	1,142	993-1,028;1,049-1,084;1,110-1,120	(1975) 4,139 (3/78)	1,900 2,135	Industrial
220-3	Va. Chemicals, Inc.	8/68	1,015	642-714	1,005(7/19/74)	254	Industrial
220-4	City of Portsmouth	7/68	1,459	750-850	1,126	262	Municipal
234-79	Tidewater Chemical[3]	2/75	760	740-760	(4/10/75)	1,450	Industrial
P-12	City of Chesapeake[3]	1976	709	630-640	3,902 (2/4/76)	1,653	Test Well
P-2	Ferry Slip	4/79	1,600	1,207-1,229;1,250-1,264; 1,286-1,306; 1,345-1,367	17,482-19,426 (5/79)	8,881- 9,600	Test Well (Yield 200 gpm)
P-3	Burton Station	5/79	1,333	1,000-1,010;1,023-1,068;1,081-1,124	3,695-3,864 (5/79)	815-1,700	Test Well (Yield 200 gpm)
P-4	SWCB Fentress	5/79	1,200	1,040-1,060	--	--	Observation Well
220-13	Murro Chemical Co.		700	--	1,054 (1974)	334	Industrial Well
234-124	a) SWCB			674-679	889 (1/77)	185	Observation Well
	b) Bowers Hill			805-810	1,326(1/77)	400	Observation Well
234-134	SWCB Fennema Tract		855	824-834	1,391 (11/77)	392	Observation Well
234-161	City of Chesapeake	1/81	979	714-734 738-758 786-796 833-853 898-908 930-945 982-992	838	131	(Yield 750 gpm)

1) State Water Control Board Well numbers except P-1, P-2, P-3, P-4, and P-12, which are temporary project well numbers
2) Land Surface datum
3) Screened in Mattaponi Formation

Table 4. Locations and depths of city wells in the Norfolk-Portsmouth-Suffolk area.

CITY	STATE WATER CONTROL BOARD NUMBER	WELL DEPTH (FT)	SCREEN LOCATION (FT)
City of Norfolk (Combined capacity of both wells = 8 MGD)	201	1015	435 to 465, 515 to 535, 571 to 591, 811 to 831
	200	949	435 to 515, 706 to 746, 820 to 870, 438 to 458, 510 to 530, 551 to 580, 1025 to 1055
	203	911	NA
Portsmouth (one well = 2200 gpm) (other = 1600 gpm)	264	802	590 to 650
	265	691	546 to 576, 600 to 625, 634 to 649, 676 to 686
City of Suffolk (Each = 2100 gpm)	330	1007	850 to 875, 895 to 955, 967 to 1007
	331	1010	835 to 860, 897 to 959 960 to 1005
		995	858 to 868, 882 to 942, 987 to 990
		609	539 to 544, 577 to 602

NA - Not Available

Source: Information provided by Department of Health, Division of Water Programs, Commonwealth of Virginia.

Reflection seismology data is a promising approach to the determination of both regional and local values of transmissivity, and the solution of the problem of correlation of geophysical logs between wells. Seismic lines tied to wells from which geophysical logs have been obtained can be used to identify sand thickness, and therefore transmissivity, between wells. It has been our experience that the Coastal Plain 'shoots' as well, if not better, than offshore areas. Data quality is excellent (Fig. 4).

The relationship between porosity and permeability is, in detail, not a simple one. However, for geothermal applications on the Atlantic Coastal Plain, general relationships are sufficient. Chilingar (1963) showed that when sand and sandstones are grouped according to grain-size categories, there are well-defined trends of increasing permeability with increasing porosity (Figure 5). Most importantly, an increase in porosity of just 5-7% can correspond to an order of magnitude increase in permeability. It is therefore important to develop a reliable surface method of estimating changes in aquifer porosity. We suggest that it might be possible to determine porosity, and therefore permeability, from surface seismic measurements if shear vibratory sources are used as well as standard compressional vibratory sources. This is discussed further below.

<u>Thermal lifetime of a hydrothermal resource beneath the Atlantic Coastal Plain</u>. The geothermal resources of the southeastern United States are classified as liquid-dominated low-temperature systems (Costain and others, 1980), characterized by temperatures less than 90°C (White and Williams, 1975). The development of an efficient method of obtaining thermal energy from low temperature systems requires an in-depth study of each unique system (Johns Hopkins University, 1981).

Major problems facing the utilization of geothermal energy in the eastern United States are land subsidence, aquifer collapse, and the disposal of large quantities of saline waters. One solution is to inject the water back into the aquifer. This maintains piezometric pressures, and thus prevents subsidence and insures a continuous supply of water. Of concern is the possibility of adverse chemical and physical reactions caused by the injected fluid. Laczniak (1980) modeled a simple two-well system to investigate numerically the effects of pumping and injection in a Coastal Plain environment. Although this topic is somewhat beyond the scope of this report, the results of Laczniak's study are positive with respect to the development of geothermal energy in the eastern United States. The discussion that follows is extracted from his study.

Two basic methods of aquifer reinjection are: (1) the forward and return flow method, and (2) the flow-through method (Ingenjorsbyran, 1972). The first method utilizes a single pumping-injection well. Water is pumped, stored, and later reinjected by way of a single well (Lippman and others, 1977; Claesson and

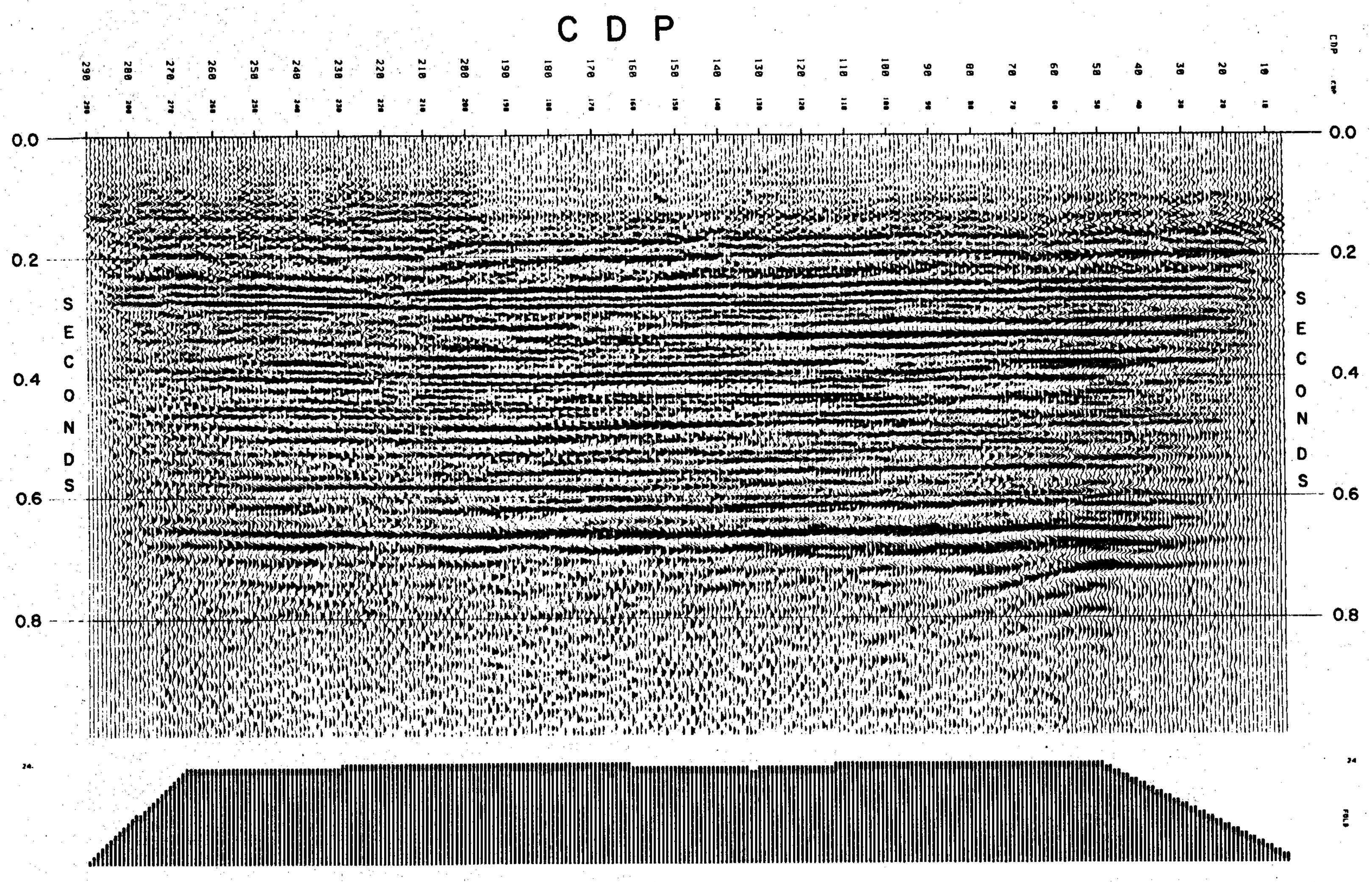

Figure 4. Multifold reflection seismic data obtained by Virginia Tech in the Portsmouth, Va., area.

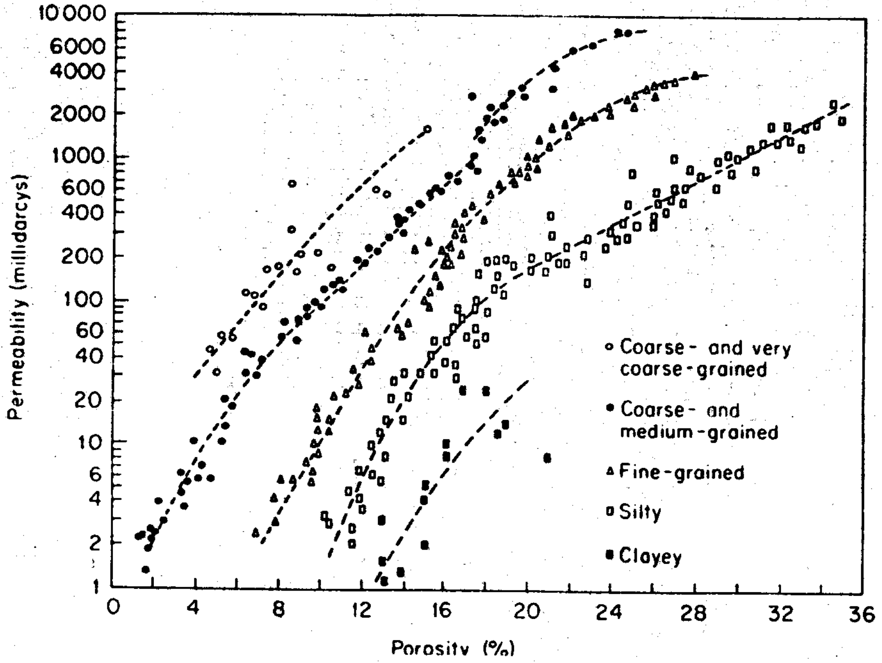

Figure 5. Empirical relationship between porosity and permeability for sandstone in various grain-size categories (From Freeze and Cherry, 1979, after Chilingar, 1963).

others, 1978). The flow-through method uses separate pumping and injection wells which comprise a sink-source, or doublet system. The energy extracted from either system by a heat exchanger is directly proportional to the temperature of the water at the production well.

The subject of Laczniak's study is an evaluation of the thermal energy output and longevity of a doublet system. As the well spacing between the sink and source increases, engineering costs increase and land acquisition may become more difficult. Because economic considerations are crucial to the success of any energy producing system, well spacing should be minimized. The topic of well spacing has been discussed by Gringarten and Sauty (1975) for the Dogger aquifer near Paris, France, where the optimum well spacing was found to be 900 m.

As additional hydrologic and geothermal data become available for the aquifers of the Atlantic Coastal Plain, it becomes possible to investigate by means of numerical modeling on the computer, the relationship between the energy extracted and the distance between the source and sink well in a doublet system. Such modeling can aid in the evaluation of a particular doublet by defining such limiting characteristics as the thermal lifetime of the system, and the optimum well spacing for the specific application.

The subject of Laczniak's study (1980) is the relationship between well spacing and the amount of energy extracted from a "typical" Atlantic Coastal Plain geothermal system. Various well spacings, aquifer permeabilities, and pumping-injection rates are considered in the numerical simulations over a period of 15 years. The numerical method is based upon the method of Lippmann and others (1977) and uses computer code CCC (compaction-convection-conduction) developed at Lawrence Berkeley Laboratories. Program CCC is used to calculate the thermal and fluid-flow fields for a three-dimensional rectangular liquid-dominated low-temperature system. CCC is a computer program written in FORTRAN IV for execution on the CDC 7600 system at Lawrence Berkeley Laboratories. It was modified by Laczniak (1980) for execution on the IBM 370 computer at Virginia Tech. Program CCC uses the "integrated finite difference method" (IFDM) for the numerical solution of the heat and mass flow equations (MacNeal, 1953; Todd, 1959; Tyson and Weber, 1964; Cooley, 1971; Narasimhan and Witherspoon, 1976). The equations of mass and flow are coupled by interlacing them in the time domain. A complete and detailed discussion of the derivations is found in papers by Narasimham and Witherspoon (1976, 1978) and Sorey (1975).

The basic concept of the IFDM is to discretize a region into a number of smaller subregions. Each element of the system is then described by a finite difference approximation to the partial differential equation governing confined transient groundwater flow (Laczniak, 1980, p. 5-6).

The sediments beneath the Atlantic Coastal Plain (Brown and others, 1972) consist of a seaward-thickening wedge of interbedded sands and clays deposited by fluvial, deltaic, and marine processes. These strata consist of a sequence of moderate to highly productive aquifers overlying a pre-Cretaceous basement complex (Brown and others, 1972). The principal water-bearing units are relatively unconsolidated sands. The less permeable clays act as confining beds and subdivide the system into numerous semi-independent aquifer systems.

As noted above, the sediments beneath the Atlantic Coastal Plain are divided into two general subsystems according to geologic age: (1) the Tertiary system; and (2) the Cretaceous system. An uppermost hydrologic unit of Quaternary age overlies the first major clay layer, and is a water-table, or unconfined aquifer.

The Tertiary and Cretaceous systems underlie the Quaternary system, and are a series of confined and semi-confined aquifers. Both are moderate to highly productive and are major sources of water for domestic and industrial use. Thickness of individual sands varies from 30 to 120 m.

Regional recharge is by direct precipitation and runoff. Recharge to the underlying aquifers occurs east of the Appalachian Mountains, the major groundwater divide. Local recharge is by direct vertical leakage from precipitation. The relative contribution of regional (horizontal) recharge to vertical recharge is not well known. Vertical recharge by leakage to any particular aquifer is controlled by the vertical permeability of the sediments above the aquifer. The low permeability of the clays of Tertiary and Cretaceous age retard vertical recharge; therefore, without reinjection the potential yield of the aquifers may be limited if very large quantities of water are withdrawn over a short period of time.

Water quality depends upon the mineral constituents and the chemical properties of the host formation. These vary with location. One general trend is the presence of high concentrations of total dissolved solids along the eastern shore; for example, concentrations of total dissolved solids were measured at 72,039 ppm in a deep test well near Crisfield, Md. (Hartsock, 1979).

The following characteristics of a "typical" Atlantic Coastal Plain geothermal system are taken from data and information obtained from the Crisfield, Md., geothermal test well drilled during June, 1979 (Dashevsky and McClung, 1979) and supplemented with information from the literature (Brown and Silvey, 1972; Cedarstrom, 1945; U.S. Geological Survey, 1967).

The homogeneous aquifer is bounded on top by an aquitard consisting of semi-permeable sands, clays, and shales. The aquitard is overlain by another aquifer. The bottom of the principal aquifer is assumed to be bounded by impermeable material represented by either well consolidated sediments or crystalline rocks. In the horizontal direction, the system is unbounded (i.e., horizontally infinite). The vertical thickness of the aquifer is 50 m.

The hydraulic operation of the system is kept simple. Water is pumped out of the aquifer at the production well where it is passed through a heat exchanger. Reinjection of the cooler water takes place through an injection well located at a distance, d, from the production well.

Water entering the aquifer at the injection well flows at a rate, v(d), toward the production well. Heat is transferred by forced and natural convective and conductive processes. Cooler water flowing in the direction of the production well gains heat due to the higher ambient temperatures in conjunction with the heat flow through the system. The surrounding temperatures are lowered due to the loss of heat to the cooler injected fluid.

The point in time when the injected water lowers the temperature at the production well by 1°C is called "breakthrough." Breakthrough depends upon the well spacing and the pumping-injection rate. At some distance, d, and some pumping-injection rate, Q(p), the temperature of the injected water will recover totally, and thus inhibit breakthrough. In this special case, the geothermal resource is classified as a <u>totally renewable</u> resource.

Laczniak's simulated system is located at a depth centered around 1375 m. The system is artesian with an initial total hydraulic head producing a slight flow at the surface in a well tapping the reservoir. The overlying sediments are assumed to have an average geothermal gradient of 40°C/km, which results in a temperature of the system of 55°C. The heat flow entering the system depends upon the thermal conductivity and thermal gradient and is assumed to be 75 mW/m^2.

The amount of energy extracted from a geothermal system using a heat pump depends upon the thermal output and the pumping rate (Paddison and others, 1978).

A geothermal system which is pumped at 500 gpm, has an output temperature of 55°C, and an input temperature of 43°C produces 5,443,200 Btu's per hour. The amount of energy extracted from the geothermal water could be raised considerably by inputting enough electrical energy to power a special type of heat pump called a temperature amplifier (Neiss, 1979).

A general simulation model was constructed to simulate the pressure and temperature fields in a "typical" Atlantic Coastal Plain geothermal system. The integrated finite difference method was used to solve the mass and heat flow equations. The model makes use of the symmetry present in a doublet system by modeling one-half of the whole system.

Laczniak's model consists of a three-dimensional layered mesh containing 1342 three-dimensional elements each defined by a nodal point. The nodal elements are interconnected via 4172 element interfaces. Temperatures and pressures are obtained at the nodal points during the simulations.

The mesh design subdivides the geothermal system into three hydrologic units based upon the geology. The upper and lower hydrologic units each consist of one grid layer and have a vertical thickness of 25 m. The upper grid layer represents a semipermeable unit and the lower grid layer a confining unit. The main reservoir is represented by the central five grid layers, each grid layer having a thickness of 10 m.

The design utilizes the natural convection present within the geothermal system due to water density and viscosity variations with temperature (Lippman and others, 1977). Thus, the production well is located in the upper portion of the reservoir with the injection well located in the lower portion of the reservoir.

The horizontal dimensions are scaled according to the horizontal distance, d, between the production and injection wells. Well spacings of 100, 250, 500, and 1000 m were tested in the simulations.

Fluid and material properties used in the simulation model are chosen to describe a "typical" Atlantic Coastal Plain geothermal system. Values for these properties are obtained from the Crisfield, Md., geothermal test well (Dashevsky and McClung, 1979) and from literature pertaining to deeper wells in the Atlantic Coastal Plain (Brown and Silvey, 1972; Cederstrom, 1945; U.S. Geological Survey, 1967).

Material properties used in the simulation are given in Laczniak (1980). The model consists of a caprock, a bedrock, and an aquifer defining an aquitard, an aquiclude, and a reservoir, respectively. Permeabilities are varied in the test simulations from 9.862×10^{-15} to 9.862×10^{-13} m^2 (10 to 1000 millidarcys).

The fluid properties are based upon a total dissolved solid content of 15,000 ppm. Fluid properties of the saline water are estimated from those of pure water using the equations developed by Wahl (1977) and are listed in Laczniak (1980). The values for density, specific heat, and viscosity are functions of temperature and are calculated by the program. Density was assumed to vary with temperature. Variations with temperature in specific heat and viscosity are determined linearly from upper and lower limits supplied as inputs to program CCC.

The initial and boundary conditions are determined using geothermal and hydrologic data obtained from the Crisfield well site (Dashevsky and McClung, 1979; Hartsock, 1979). The conditions are based upon the system being located at an average depth of 1.375 km.

Fluid pressures were chosen to simulate an artesian system. Initially, water is assumed to be under sufficient pressure to cause the piezometric surface to be located at ground level in a well tapping the aquifer. Initial pressure gradients describe a system where water velocities are zero because the value of hydraulic head is constant throughout the system. The initial temperature at the upper boundary is determined using a geothermal gradient of 40°C/km for the overlying sediments. The initial temperature gradients are chosen in conjunction with the thermal conductivities of each hydrologic unit to produce a heat flow of 75.38 mW/m^2 (1.8×10^{-6} cal/cm^2-sec).

The criterion used to determine the location of the upper and lower boundary nodes relative to the rest of the system is that no more than a 10% change in heat flow should take place through the lower boundary-system interface. This criterion was satisfied in all simulations with the greatest change in heat flow being +7.2%. The boundaries enclosing all sides of the system are placed at a distance two times the distance between the production and injection wells. The boundary conditions used are:

a) the upper and lower boundaries are constant pressure (11648852 and 12608247 Pa, respectively) and constant temperature (53.875 and 56.875°C, respectively) boundaries;

b) the vertical boundaries along the caprock and bedrock are adiabatic and impermeable;

c) the reservoir boundaries along the vertical sides perpendicular to distance, d (well spacing), are constant pressure and temperature boundaries equal to the initial conditions defined for each respective layer;

d) the reservoir boundary along the vertical sides parallel to distance, d, are impermeable and isothermal with values defined by the initial conditions.

The upper constant pressure boundary simulates an overlying system of aquifers and serves as the source for recharge by leakage through the semi-confining unit. Leakage is induced only when pumping induces a hydraulic gradient across this interface. The constant pressure boundaries along the vertical sides of the reservoir perpendicular to distance, d, act as a line source or sink depending upon the hydraulic gradients across these interfaces. There is no flow through the lower boundary-system interface because of the zero permeability of the material.

Well spacings of 100, 250, 500, and 1000 m are compared. Each individual well spacing is modeled using intrinsic permeabilities of 9.862×10^{-15}, 9.862×10^{-14}, and 9.862×10^{-13} m^2 (10, 100 and 1000 millidarcys, respectively). Pumping and injection rates of 6.31×10^{-3} and 3.15×10^{-2} m^3/sec (100 and 500 gallons/minute) are considered. The water is injected into the system at a temperature of 43.5°C. Individual doublet systems are pumped for 15 years or until thermal and fluid flow steady-state conditions are reached.

This procedure is used to investigate the relationship between the temperature at the production well (energy output) and well spacing. The results produced by this procedure are also used to evaluate, in detail, a "typical" Atlantic Coastal Plain geothermal system by:

a) analyzing the temperature field to evaluate the thermal lifetime of each individual doublet system;

b) analyzing the pressure field to evaluate the ability of each system to supply adequate amounts of water;

c) analyzing the response of the system to different permeabilities; and

d) analyzing the pressure and temperature fields under relatively low and high pumping-injection stresses.

A final group of simulations considers the effect of resting on the system. A period of rest is defined as an interval of time in which the system is allowed to recover from previously-applied pumping-injection stresses. To mimic heating demands during the winter and summer seasons, six-month periods of production-injection are alternated with six-month periods of rest over a five-year interval. One well spacing of 100 m and permeabilities of 100 and 1000 md are considered. A pumping-injection stress of 100 gpm with an injection temperature of 43.5°C is applied.

The pressure field was assumed to have reached steady-state when the change was "small," i.e., less than 2.5% of the maximum allowed pressure change over a specified number of consecutive time steps (Laczniak, 1980). As expected, an increase in the pumping-injection rate or a decrease in the permeability produces a greater pressure differential within the system.

The influence of the injection well on the production well is displayed by the pattern of the contour lines of equal hydraulic head. The effect is less pronounced in the large separations where there is a greater independence between the production and injection wells.

Map views of the steady state thermal distribution through the center section of the reservoir are given in Laczniak (1980).

Laczniak shows temperature versus time plots comparing output temperatures (temperature at the production well) in four well spacings for a permeability of 100 md and pumping-injection rates of 100 and 500 gpm. The results clearly illustrate the effect of well spacing on the temperature distribution. The general trend is an increase in the output temperature with an increase in the distance bewteen the production and injection wells. For all pumping-injection rates and permeabilities, breakthrough in the 100-m spacing occurs rapidly (less than two years), while in the 1000-m separation breakthrough is altogether absent.

Differences in the pumping-injection rate also affect the temperature distribution and the time of breakthrough within the system. As expected, a greater pumping-injection rate lessens the time it takes for breakthrough to occur. The result is a decrease in the temperature differential between the pumping and injection wells.

The response of the temperature field to different permeabilities is shown through a comparison of the various temperature plots (Laczniak, 1980). A lowering of the permeability by one order of magnitude results in only a small gain in the final output energy. This independence between the temperature field and the permeability is understood by analyzing heat transfer in conjunction with Darcy's law. Heat is transferred by conduction and convection. Conduction depends upon the physical conduction of the materials which are held constant throughout the simulations. Convection is controlled by the fluid velocity field. Darcy's law states that the velocity is proportional to both the permeability and the hydraulic gradient. For a given pumping stress, increasing the permeability decreases the hydraulic gradient; therefore the change in the magnitude of the velocity is small. The combined effect of conduction and convection results in a similar net heat transfer among systems in which all parameters except permeability are kept constant.

The placement of the pumping and injection well is reinforced by the results of the modeling. Although the pumping well is located in the coolest portion of the reservoir, warmer temperatures migrate quickly to the perforated zone of the production well. This phenomenon is displayed by the initial increase in the temperature at the production well (Laczniak, 1980, Figs. 15-18) and is due to recharge of warmer waters from the lower portions of the reservoir.

Aside from a simple doubling of the life span, subjecting the system to alternating six-month periods of continuous pumping and resting produces only negligible changes in the overall temperatures at the injection and production wells. Laczniak (1980) compared the temperatures at the injection well in a rested system to the temperature at the injection well in a continuously pumped system over a period of five years. The recovery of heat from terrestrial heat flow at the injection well over the six-month rest period was minimal. Varying the permeability has little effect on the system.

Engineering data about fluid transmission, drilling, pumping equipment, and land acquisition costs are needed for a complete evaluation of the economics of the system. Studies of this type have been carried out by the Applied Physics Laboratory of the Johns Hopkins University (1981).

The results of the numerical modeling quantify, without doubt, the existence of potentially useful geothermal resources beneath the Atlantic Coastal Plain. Heat from a groundwater source (the aquifers beneath the Atlantic Coastal Plain) is adequate to run heat pumps at a high coefficient of performance (Neiss, 1979). A doublet system with direct injection back into the reservoir is shown by the numerical simulations to be a feasible method of extracting heat in the low-temperature liquid-dominated geothermal systems of the Atlantic Coastal Plain. The doublet system with a spacing, d, of 1000 m pumped at 500 gpm produces approximately 5.5 million Btu's per hour. Assuming a value of 70,000 Btu's per hour for energy expenditure to heat an average insulated home, the system would support over 75 households. If pumped for only six months a year, the thermal lifetime of the system is shown to be at least 30 years (Laczniak, 1980).

The optimum geologic environment for the implementation of a groundwater geothermal system is one in which the highest temperatures are encountered at the shallowest depths. Throughout much of the Atlantic Coastal Plain there exist areas where isotherms are warped upward over radioactive heat-producing granites within the crystalline basement beneath the Coastal Plain sediments (Costain and others, 1980). In the future, aquifers over these "radiogenic" sources may be located. At such locations, drilling costs would be reduced and the use of lower energy output systems might be economically justified. Systems with close well spacings and/or low pumping-injection rates could then be implemented depending upon the application.

Modifications of the injection scheme intended to increase the thermal lifetime of the system; for example, injection into an independent reservoir or injection into a zone separated by a low permeability lens should be carefully analyzed before being implemented. If the deeper reservoirs of the Atlantic Coastal Plain are of low permeability, the influence of the injection well is shown by this study to be necessary in order to maintain adequate fluid pressures within the system to prevent aquifer collapse. This influence of the injection well is required, and must be taken into account in the design of a successful heat extraction system.

Reinjection of the thermally spent cooler water back into an independent or semi-independent reservoir may cause adverse chemical or physical reactions within that reservoir. In this case, extensive modeling of the total system should be performed. Such modeling should incorporate not only the equations of heat and mass flow, but must simultaneously solve for hydrodynamic dispersion and heat production due to the decomposition of reactants. The sensitivity of the reservoir water to the injected water and the resulting chemical reactions should be incorporated into the model.

In-depth studies of each proposed Atlantic Coastal Plain geothermal system are strongly recommended before any application. Such studies should include extensive hydrologic and heat flow data collection. The data should then be used in numerical models to analyze various system designs. Program CCC is applicable and appropriate for the evaluation of the low-temperature geothermal systems of the Atlantic Coastal Plain.

d) <u>Probable basement lithology beneath Norfolk area</u>.

Basement rocks surrounding the Portsmouth pluton are thought to consist of low-to-medium grade metavolcanic, metagranitic, and metapelitic rocks similar to lithologies in the exposed Carolina slate belt (Fig. 6). Basement lithologies east of the Portsmouth drill hole are not well-constrained; drill holes to basement to the north, south, and west are shown in Figure 7 and Table 5. Cores recovered from these holes suggest a north-south trending belt of low to medium grade metasedimentary and metavolcanic rocks cut by granitic plutons and a Triassic basin (Fig. 6).

The basement core obtained by Virginia Tech from drill site C25A (Fig. 7) at Portsmouth is a post-metamorphic granitoid that yields a whole-rock Rb-Sr isochron age of 263 ± 24 m.y. (Russell and Russell, 1980).

A second drill site (C26) at Isle of Wight, Va. (latitude 36°54.5', longitude 76°42.2') was located 20 km from the center of the Portsmouth gravity anomaly (Fig. 8). The hole was cored to sample and measure the heat flow of the country rocks surrounding the buried granite body at Portsmouth. Drill site C26 was drilled to 325 m (1065 ft.) by Gruy Federal, Inc. between September 20 and 26, 1978. From April 1, 1980 to May 6, 1980, the hole was deepened to 512 m (1680 ft.) by Virginia Tech. Core samples were obtained from 406-413 m and from 424-512 m.

The core samples of the interval from 406 to 413 m resemble saprolitized granitoid or heterogeneous arkosic sandstone. Drilling resistance increased noticeably at 424 m (1390 ft), correlating with a sharp spike in the gamma log (Fig. 9). Crystalline basement was cored beginning at this depth. The base of the Coastal Plain sediments has therefore been picked at 424 m. Lithologic and gamma logs are shown in Figure 9. The basement consists primarily of a fine- to medium-grained (1-4 mm) foliated biotite granitoid which is cut locally by a more leucocratic facies. There are several fine-grained (<1 mm), weakly foliated melanocratic sections of the core ranging from 25 cm to 7 m in length, but contacts with the granitoid generally are fractured, and any intrusive relation to the granitoid is not readily apparent.

Figure 9 also shows the zones of alteration in the core which is weathered from 424-427 m. Below this zone, alteration is

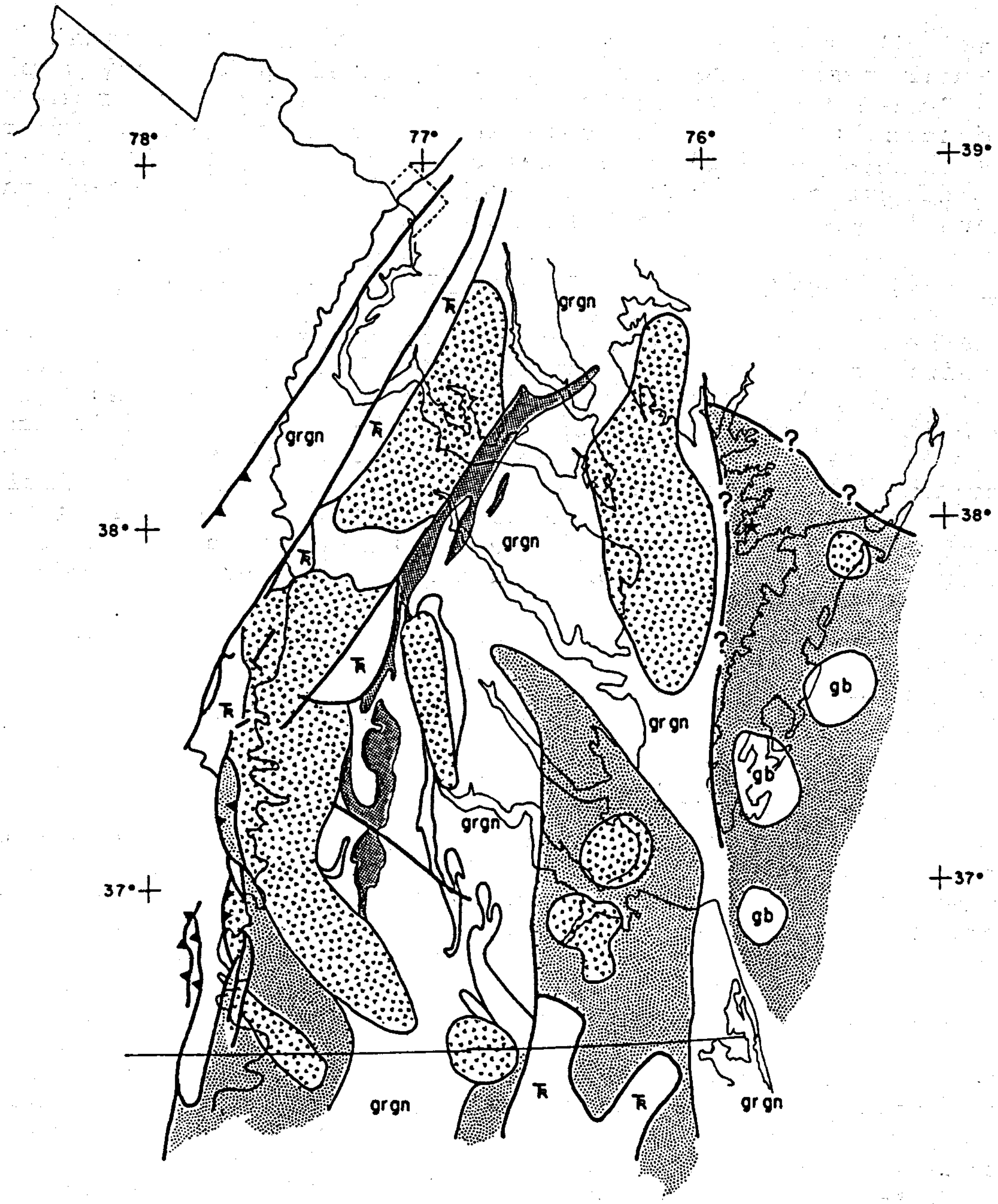

Figure 6. Generalized basement lithologies in eastern Virginia. gr=granitoid gneiss; v pattern = granite; fine stipple = low grade volcanics; dark cross line pattern = diorite or gabbro; gb=gabbro; Tr = Triassic/Jurassic ss. Interpretation by Glover and Costain from available basement samples, magnetic, and gravity data.

Table 5. Summary of drillcore data for holes located in Figure 7.

Hole	Basement Rock Encountered	Reference
Virginia		
1	granite	Johnson (1975)
2	granite	"
3	low-grade lithic/crystal tuff	"
4	metagranite	Gleason (1982)
5	granite	Johnson (1975)
6	Triassic(?) sandstone	"
North Carolina		
7	syndeformational granite (Dort)	Becker (1981)
8	metarhyolite	Coffey (1977)
9	quartzite	"
10	basalt/diabase (Triassic?)	Richards (1954)
11	red shale/basalt (Triassic?)	Richards (1954)
12	felsic lithic/crystal metatuff	Dennison et al. (1967)
13	garnet-biotite-muscovite-schist	"

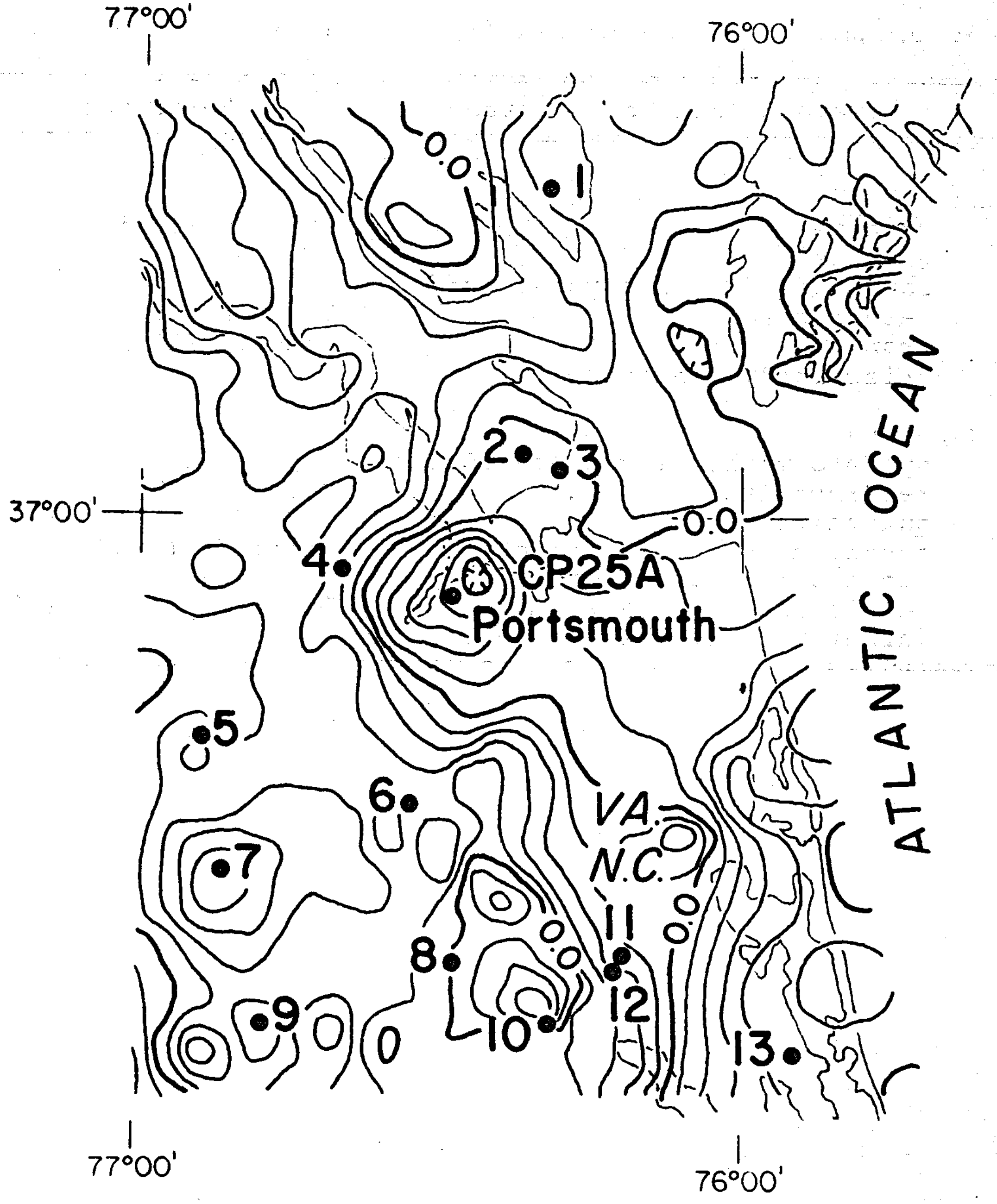

Figure 7. Locations of drillholes to basement near Portsmouth, Virginia.

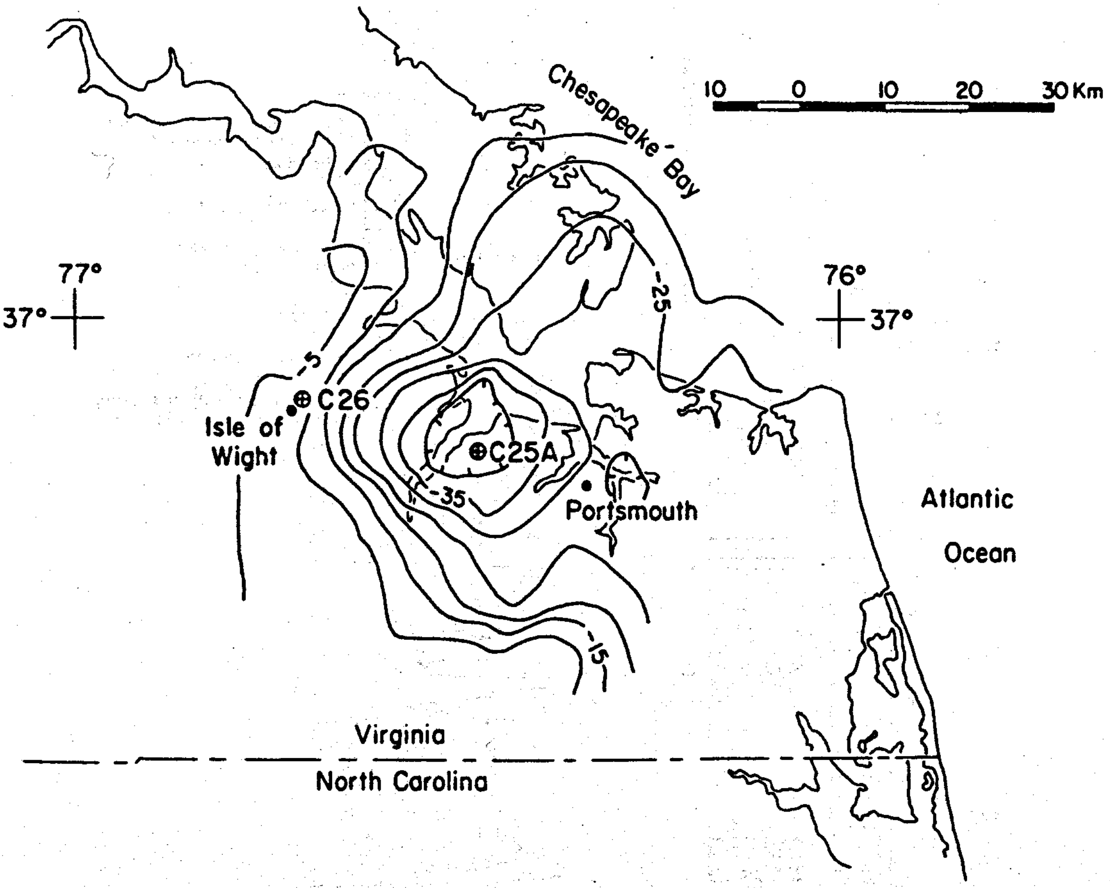

Figure 8. Drill sites C26 and C25A near Portsmouth gravity anomaly.

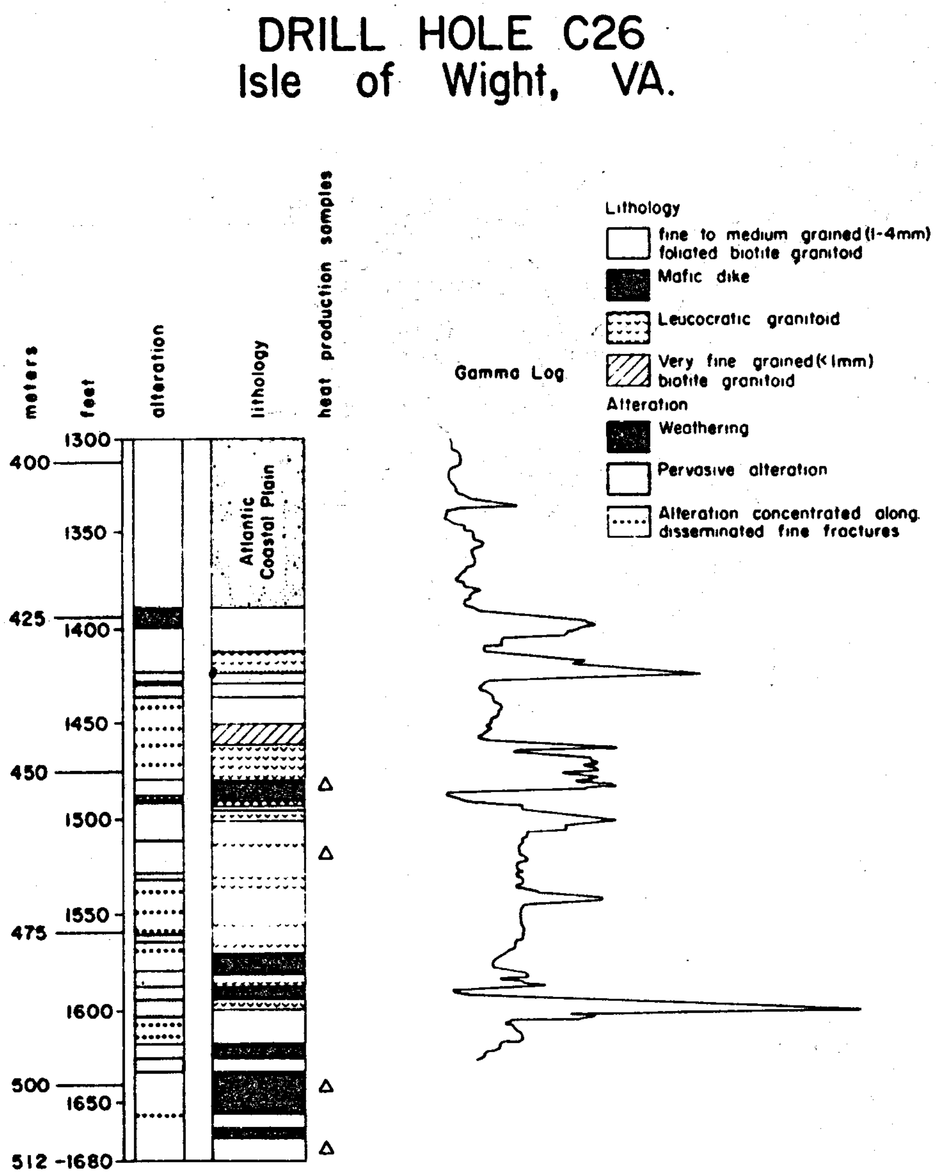

Figure 9: Lithologic and gamma logs from basement portion of geothermal test drill-site C26, Isle of Wight, Virginia (Gleason, 1982). Logged by Virginia Tech.

controlled by intricate fine fractures. The core is brecciated along many of these fractures, and quartz or carbonate veinlets are associated with the fractured, altered zones.

The granitoid rocks of the drill core range modally from tonalite to monzogranite.

Microscopic textures and mineral assemblages of the granitoid rocks were modified during a post-emplacement, lower greenschist facies metamorphism. Quartz and carbonate veinlets up to 1 mm in width postdate the greenschist metamorphic assemblage.

Mafic dikes. The intrusive relation of the mafic sections to the host granitoid rocks is visible microscopically. Locally, these sections show chill textures near contacts with the granitoid. Rare small (1-2 mm) pods of the granitoid are present as xenoliths in the mafic dikes.

The dikes are pre-metamorphic and were subjected to the same greenchist facies metamorphism that affected the granitoid. The original mineralogy was partially obscured by this metamorphism, but relict mineralogical and textural evidence suggests that the dikes were basaltic, composed of calcic plagioclase, pyroxene, and hornblende, with pyrite, apatite, ilmenite-magnetite, quartz, calcite, and spinel as accessories.

The basement at Isle of Wight is lithologically distinct from the Portsmouth granite and has undergone deformation and greenschist metamorphism assumed to have predated the 263 ± 24 Ma age of the Portsmouth pluton. The granitoid rocks which form the basement beneath the Atlantic Coastal Plain in Isle of Wight, Virginia, originated as a deep-seated intrusion of biotite tonalite-granodiorite. With progressive crystallization of this magma, the last phase was a leucocratic monzogranite-granodiorite which intruded the earlier phases. The lack of sharp contacts between the earlier and later phases suggests that the granitoid was not fully crystallized until after the intrusion of the late monzogranite.

Following crystallization of the granitoid, the basaltic dikes were intruded. The presence of spherical, calcite-filled features resembling amygdules in one of the dikes (sample from 452 m) suggests that the emplacement of the dikes was shallow, requiring an uncertain time interval between the granitoid plutonism and the dike emplacement, in order for uplift or erosion to expose the formerly deep-seated pluton to near-surface conditions.

The greenschist metamorphic overprint evident in both the granitoid and mafic dikes shows that the basement rocks were subjected once again to burial sufficient to produce an epidote-chlorite-white mica assemblage in the granitoid rocks and an actinolite-epidote-chlorite assemblage in the mafic dikes. Strained quartz and feldspar and a weak foliation of metamorphic chlorite and white mica in the granitoid rocks indicate that the greenschist metamorphic overprint was a result of a progressive dynamothermal event and not a retrograde deuteric or hydrothermal effect following the injection of the basaltic dikes. Following the greenschist facies metamorphism, minor zeolite-facies hydrothermal alteration formed veinlets of an unidentified zeolite and a low-temperature potassium feldspar in the dikes and quartz-carbonate veinlets in the granitoid rocks. The macroscopically visible alteration indicated in Figure 9 was a result of this hydrothermal activity.

e) Gravity data and age of the Portsmouth granite.

Gravity data for the Commonwealth of Virginia have been compiled by Johnson (1977) at a scale of 1:500,000. In addition, new data are available for eastern Virginia as part of the latest digital data set available from NOAH. These data are accessed and contoured as needed by CalComp program GPCP using software developed at Virginia Tech as displayed in Figure 10 from Costain and Perry (1982).

A -40 mgal anomaly in the Portsmouth area is indicated by gravity data. The anomaly is centered at the mouth of the Nansemond River (Figs. 7, 8, and 10). Similar gravity signatures occur in the exposed Piedmont over postmetamorphic granitic plutons, and have been found to characterize plutons buried beneath the Coastal Plain (Speer, 1982b; Becker, 1981; Pratt and others, in press). A hole was drilled near the center of the anomaly by Virginia Tech under a contract with the Department of Energy; granite was encountered at 555 m (1820 ft). The rock, a monzogranite, is similar in mineralogy and whole rock chemistry to the other coarse-grained granites of the southern Appalachians (Speer, 1982a). Isotopic dating using the Rb-Sr system yields a whole rock age of 263 +/-24 Ma with an initial Sr87/Sr86 =0.7073 (Russell and Russell, 1980). The biotite age is identical to the whole rock age, indicating that the granite cooled rapidly past the blocking temperature of biotite.

The Portsmouth granite may be the easternmost and youngest of the post-metamorphic, coarse-grained granitoid rocks of the southern Appalachians.

f) Seismic data.

Virginia Tech has acquired VIBROSEIS seismic reflection data near Portsmouth, VA, as part of a geothermal program sponsored by the Department of Energy (Costain and Glover, 1982b). A sample of the reflection seismology data from near Portsmouth is shown in Figure 4. The aquifer/aquitard system of the Coastal Plain sediments obviously contains a number of excellent reflectors, suggesting that reflection seismology has much to contribute to our knowledge of the subsurface geometry and areal extent of deep aquifers and aquitards.

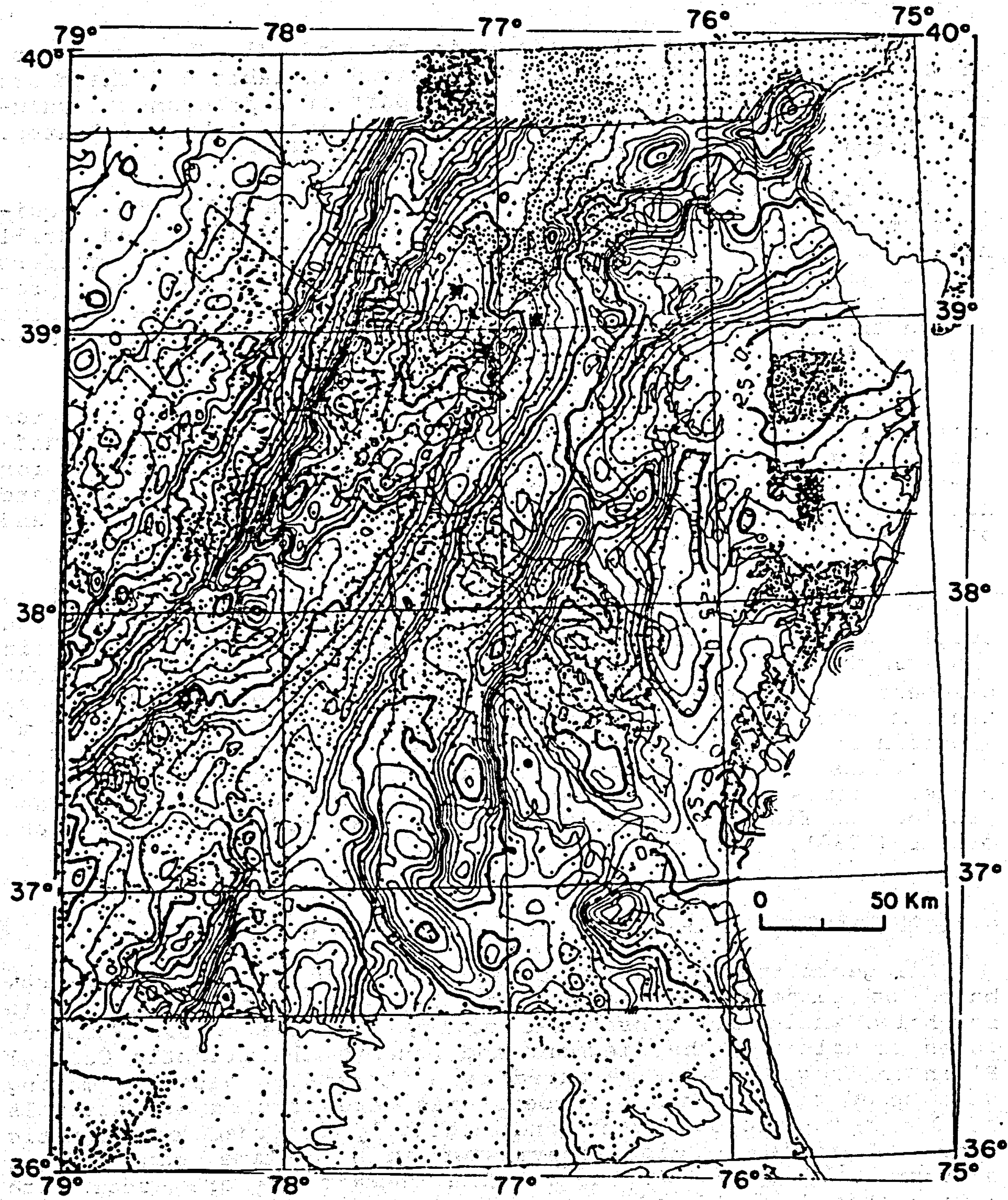

Figure 10. Bouguer gravity map and distribution of gravity stations in Delaware, Maryland, and Virginia. Contour interval 5 mgals. Contoured using GPCP software at Virginia Tech.

No known proprietary seismic data are available in the Norfolk, Va. area.

g) Heat flow sites.

Locations of heat flow sites in the Norfolk, Va., area are shown in Figure 11, with results tabulated in Table 6. These are sites established by Virginia Tech as part of a program to evaluate the geothermal energy potential in the eastern United States. The program was supported by the Department of Energy.

Heat flow determinations by Virginia Tech are based on equilibrium gradients measured in undisturbed fluid-filled drill holes. Due to the confined and semi-confined nature of aquifers beneath the Atlantic Coastal Plain, holes drilled for this program in Coastal Plain sediments were cased, and the annulus around the casing cemented to prevent vertical circulation between aquifers via the bore hole.

In every case, care was taken to determine heat flow only for intervals over which the gradient was linear and apparently unaffected by groundwater flow, and which were adequately sampled for thermal conductivity. The heat flow values are, except where noted, believed to belong to Category I as defined by Sass and others (1971). Category I values are accurate to within 5%.

Heat production from the Portsmouth granite was measured as 4.1 ± 0.3 μW/m^3, and heat flow through the sedimentary section overlying the granite was measured as 81.2 ± 3.2 mW/m^2 (Costain and others, 1982a). The heat production of the Isle of Wight basement rocks averages 1.1 ± 0.5 μW/m^3, and the heat flow measured in the overlying sedimentary section is 54.6 ± 6.6 mW/m^2 (Costain and others, 1982a). These lower heat production and heat flow values of the metamorphosed country rocks contrast with the higher values of the post-metamorphic Portsmouth granite, and provide verification of the radiogenic heat model of Costain and others (1980).

h) Temperatures, temperature gradients, and gamma logs.

All geothermal gradients determined by Virginia Tech are now based on temperature measurements made at discrete depths in boreholes while the sensor was moving down the hole. Temperatures in holes in the Piedmont and beneath the Atlantic Coastal Plain of Virginia were measured by a thermistor assembly moving at a speed of 30 m/min. Temperatures were sampled at intervals of 0.5 m by microcomputer and digitally recorded on magnetic tape. A rapid-response thermistor with a time constant of approximately 1 sec was used. The thermistors are precise to better than 0.01°C, and are believed to be accurate to aproximately 0.1°C. Thermal gradients determined by each system in a 300-m hole at thermal equilibrium agree to within 0.33°C/km over the entire hole and typically to within 0.87°C/km over a 25 meter

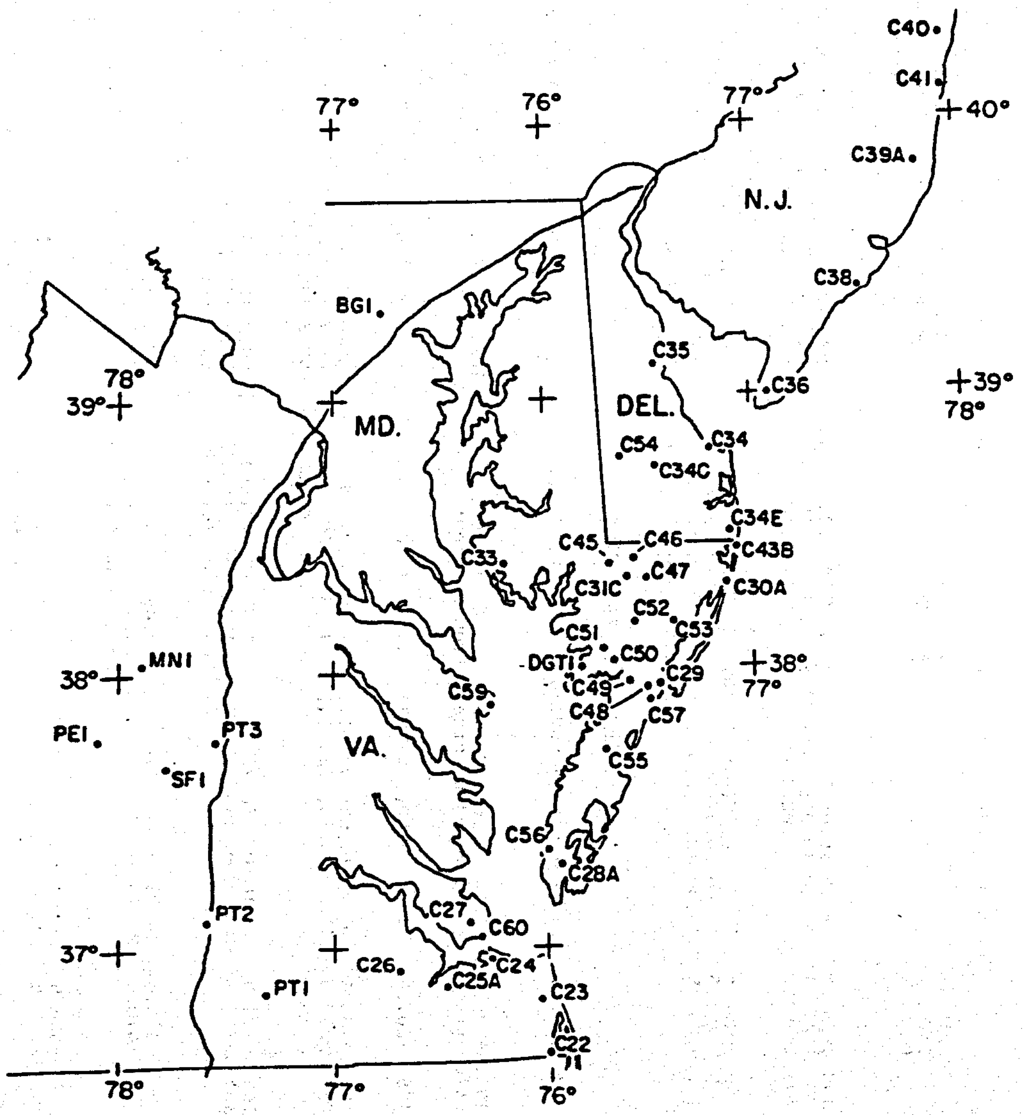

Figure 11. Locations of heat flow sites established by Virginia Tech in Virginia, Maryland, and Delaware.

Table 6. Summary of selected heat flow and heat production data from heat flow sites established by Virginia Tech.

HOLE	LATITUDE (North)	LONGITUDE (West)	DEPTH INTERVAL, (m)	GRADIENT, °C/Km	THERMAL CONDUCTIVITY, W/m-°C	HEAT FLOW, q,mW/m^2	QUAL	HEAT PRODUCTION, A,μW/m^3
Piedmont, Blue Ridge, and Valley and Ridge Provinces								
PETERSBURG GRANITE, VA								
PT1	36°49'45"	77°19'15"	190.0-251.0	18.92 ±0.08(0.998 123)	2.75 ± 0.31(23)	52.0 ± 5.9	1	2.6 ±0.2(10)
PT2	37°05'44"	77°35'37"	70.1-210.1	17.30 ±0.01(1.000 276)	3.28 ± 0.18(61)	56.8 ± 3.2	1	3.3 ±0.7(18)
PT3	37°45'11"	77°33'02"	107.3-201.0	18.37 ±0.02(1.000 185)	3.19 ± 0.10(42)	58.6 ± 1.8	1	3.7 ±0.7(16)
STATE FARM, VA								
SF1	37°40'01"	77°46'48"	50.0- 92.5	15.29 ±0.10(0.999 18)	2.42 ± 0.3(10)	37.0 ± 4.0		
			185.0-192.5	17.60 ±0.57(0.998 4)	2.52 ±0.3(4)	44.4 ± 6.0		
			197.5-207.5	16.40 ±0.77(0.993 5)	2.37 ±0.1(3)	38.8 ± 2.6		
					Best value for SF1	40.1 ± 3.9	1	
Atlantic Coastal Plain								
SPRINGFIELD, SC (C9 = SL1)								
SL1 (SL1)	33°26'12"	81°14'12"	292.5-346.9	21.32 ± 0.03(1.000 108	3.29 ±0.17 (34)	70.1 ±3.6 B	1	2.70 ± 0.3(5
STUMPY POINT, NC								
C19	35°45'07"	75°47'39"	196.4-205.5	63.05 ±0.70(.998 19)	1.62 ±0.10 (14)	102.2 ±6.2 S	2	
SP19 (near C19) - heat production from core recovered by others from basement								2.31 ± 0.3 (7)
CREEDS, VA								
C22	36°36'23"	76°00'26"	196.7-207.4	44.04 ±0.50(.997 22)	1.30 ±0.06 (20)	57.0 ±2.7 S	1	
OCEANA, VA								
C23	36°48'05"	76°02'30"	181.5-188.1	46.15 ±1.04(.994 14)	1.30 ±0.27 (12)	60.0 ±12.5 S		
			293.2-299.8	33.66 ±1.18(.986 14)	1.33 ±0.19 (25)	44.7 ±6.7 S		
					Best value for C23	52.3 ±10.8	2	
NORFOLK, VA								
C24	36°57'24"	76°16'09"	164.4-171.5	42.10 ±0.67(.997 15)	1.44 ±0.21 (46)	60.5 ±8.7 S		
			301.0-314.2	24.93 ±0.45(.992 27)	1.89 ±0.55 (40)	47.2 ±13.7 S		
					Best value for C24	53.8 ±9.4	2	
PORTSMOUTH, VA								
C25A	36°51'01"	76°28'50"	295.8_306.0	34.33 ±0.24(.999 21)	2.43 ±0.30 (48)	83.5 ±10.4 S		
			557.0-610.4	22.70 ±0.02(1.000 106)	3.48 ±0.15 (27)	78.9 ±3.4 B		
					Best value for C25A	81.2 ±3.2	1	4.09 ± 0.3(8)
ISLE OF WIGHT, VA								
C26	36°54'31"	76°42'08"	297.5-304.5	26.83 ±0.70(.991 15)	2.21 ±0.23 (20)	59.3 ±6.5 S		
			287.1-332.4	21.77 ±0.20(.999 10)	2.29 ±0.18 (11)	49.9 ±4.0 S		
					Best value for C26	54.6 ±6.6	2	1.1 ± 0.5(7)
CHERITON, VA								

Table 6. (Continued).

C28A	37°17'47"	75°55'52"	211.0-223.7	44.24 ±0.77(.993 26)	1.35 ±0.11 (30)	59.9 ±4.9 S		
			295.9-307.0	66.83 ±4.95(.897 23)	0.89 ±0.08 (26)	59.4 ±6.7 S		
					Best value for C28A	59.6 ±0.3	1	
WALLOPS ISLAND, VA								
C29	37°56'36"	75°27'16"	180.0-185.6	45.74 ±1.03(.995 12)	1.52 ±0.04 (6)	69.4 ±2.4 S		
			296.4-299.9	19.21 ±8.97(.696 4)	1.94 ±0.18 (8)	37.2 ±17.7 S		
					Best value for C29	53.3 ±22.8	3	
CRISFIELD, MD (heat production from basement core of nearby deep geothermal test, DGT-1)								
C32A	38°00'58"	75°49'34"	163.4-173.0	61.23 ±0.50(.999 20)	1.11 ±0.12 (59)	68.1 ±7.3 S	2	1.2 ± 0.2(6)
WATTSVILLE, VA								
C48	37°56'04"	75° 30'36"	50-302	35				
WITHAMS, VA								
C49	37°57'31"	75°35'38"	209.2-221.4	49.93 ±0.46(.998 25)	1.31 ±0.20 (22)	65.6 ±9.9 S	2	
TASLEY, VA								
C55	37°42'32"	75°42'51"	164.4-173.6	32.26 ±0.43(.997 19)	2.05 ±0.23 (81)	66.1 ±7.5 S	1	
EASTVILLE, VA								
C56	37°21'16"	75°59'34"	118.1-124.7	24.79 ±0.96(.982 14)	2.24 ±0.28 (30)	55.5 ±7.3 S		
			121.1-125.7	25.77 ±1.84(.961 10)	2.41 ±0.16 (17)	62.0 ±6.0 S		
					Best value for C56	58.7 ±4.6	1	
ATLANTIC, VA								
C57	37°53'14"	75°30'02"	175.0-186.7	41.96 ±0.45(.997 24)	1.63 ±0.34(110)	68.3 ±14.5 S	2	
SMITH POINT, VA								
C59	37°53'01"	76°15'05"	144.1-155.3	51.18 ±0.73(.996 23)	1.24 ±0.09 (77)	63.3 ±4.9 S	1	
HAMPTON, VA								
C60	37°02'13"	76°18'54"	278.5-285.2	30.07 ±1.11(.984 14)	1.95 ±0.38 (31)	58.5 ±11.7		
			251.6-291.8	27.53 ±0.06(1.000 80)	1.95 ±0.38 (31)	53.5 ±10.6		
					Best value for C60	56.0 ±3.5	1	

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1) Values in parentheses are the coefficient of linear regression and the number of data pairs in the interval.

The regression coefficient of a least squares fit can be loosely interpreted as the percentage of variation in the dependent variable due to variation in the independent variable.

2) Value in parenthesis is the number of thermal conductivity values used to compute the mean.

B) Indicates a heat flow value from the basement (core) of the Atlantic Coastal Plain.

S) Indicates a heat flow value from the sediments (core) of the Atlantic Coastal Plain.

Table 6. (Continued).

3) The standard deviation of a heat flow value calculated from two or more intervals is the standard deviation calculated from the mean of the heat flow values rather than the mean of the standard deviation of the heat flow values.

4) Category 1. Heat flow determinations of the highest quality. Temperature profiles are linear over intervals of heat flow calculations with no sign of hydrologic disturbances. Sufficient samples of rock or sediment core are available to characterize the effective conductivity of the measured section, and no variations that cannot be explained and corrected are apparent. If conductivity stratification is present, component heat flows for the various individual strata are in good agreement. Typical uncertainties for category 1 are less than ±10%.

Category 2. Heat flow values in which the uncertainty is greater than for category 1, but it probably is no greater than ± 20%. Included here are temperature profiles in which there are suggestions of local hydrologic disturbances. Also included are cases where the conductivity sample is unsatisfactory, owing to either too few samples or an unusually larger scatter in conductivity values.

Category 3. Heat flow values which are little more than rough estimates, and taken individually, do not not yield much information. Uncertainty in heat flow is greater than ±20%, but when combined with higher-quality data on a regional basis, these heat flow values can be quite useful. (Excerpted from Sass and others, 1971, J. Geophys. Res., v. 76, p. 6383.)

1 HFU (heat flow unit) = 10-6 cal/cm^2-sec = 41.84 X 10-^{3} W/m^2

1 HGU (heat generation unit) = 10-1^3 cal/cm^3-sec = 0.4184 X 10-6W/m^3

interval.

Geothermal gradients were computed from a least-squares fit of a straight line to linear intervals of the temperature versus depth curves. No corrections to the geothermal gradient for the effects of topography, topographic or geologic evolution, refraction of isotherms, or climatic change have been applied. These corrections are not important for the Atlantic Coastal Plain.

Several observation water wells have also been logged by Virginia Tech in the area of interest. Well locations are indicated in Figures 12 and 13. Temperature profiles and gradients from observation wells (OW1, OW5, OW87, OW90A, 47, 76, 61C3, 42, 4, and 77-3) are shown in Figures 14 and 15. The average geothermal gradients in the area of the observation wells is about 30 °C/km. The gradient decreases somewhat with depth because of the increase in thermal conductivity of the Coastal Plain sediments. Based on our experience with the deep test well at Crisfield, Maryland, it is unlikely that the decrease in gradient would exceed 20%.

Temperatures at 300 m at OW76 and OW61C3 are about 19 °C and 25 °C, respectively. These variations are due to a combination of eastwardly-increasing clay content in the Coastal Plain sediments and/or changes in the nature of the U and Th-bearing crystalline basement rocks. The relative importance of these two effects is not known because of lack of data.

i) Thermal conductivity.

Samples for determinations of thermal conductivity by Virginia Tech were selected from core from the holes. For basement core from crystalline rock, core diameters ranged from AQ (2.7 cm) to NQ (4.76 cm). Each sample was machined to a right circular cylinder of thickness 0.197 cm. All samples were saturated with water while in an evacuated container.

Fifty heat flow values were determined at sites located on the Atlantic Coastal Plain. At nine of these sites, a minimum of 100 m of core was obtained from basement, and the heat flow value was determined over the cored basement interval. At all other sites on the Atlantic Coastal Plain, heat flow values were determined over an interval in the sedimentary section. All thermal conductivity determinations were made on core samples. Attempts were made to recover two 16-m cores, one sand, one clay, from each 300-m hole in Coastal Plain sediments. Core recovery was approximately 50%. Selected results are summarized in Table 6.

Thermal conductivity determinations were made at Virginia Tech using a divided bar apparatus with fused quartz as a reference standard. The entire fused quartz-sample stack was insulated with styrofoam. Contact resistance at the quartz-sample interface was minimized by using Vaseline petroleum jelly on the interface and axial pressures of about 1500 psi. A stack

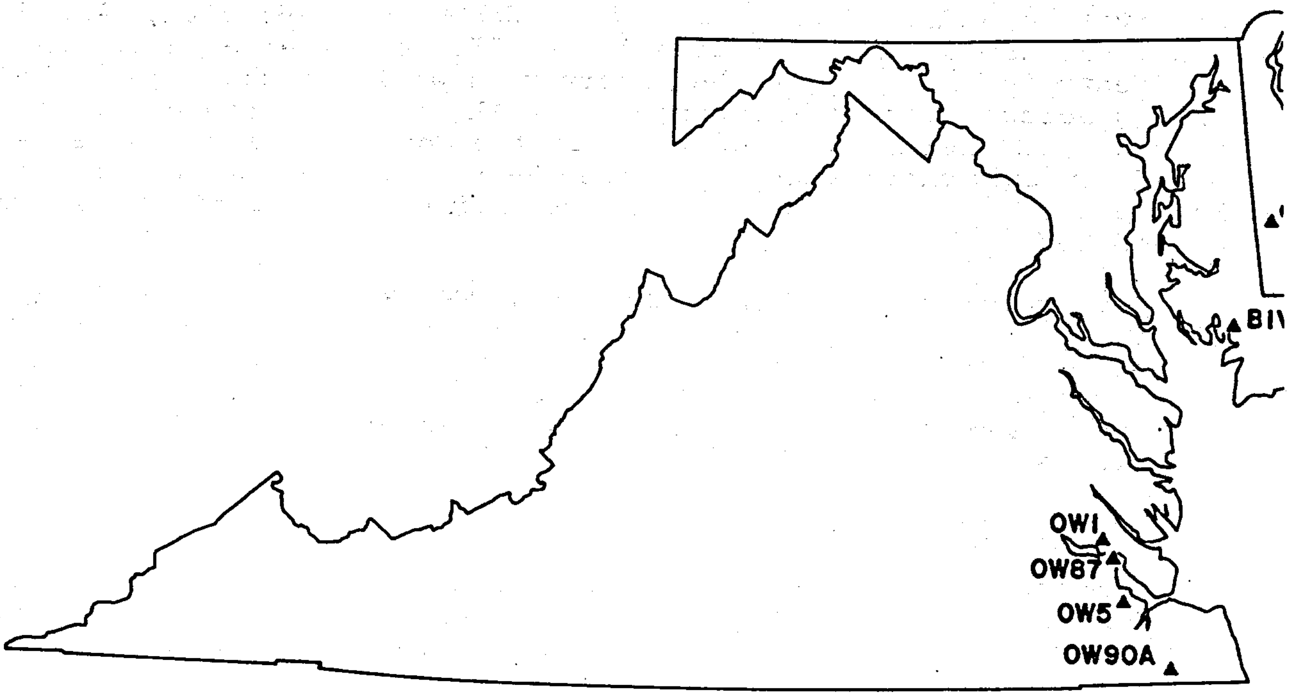

Figure 12. Observation wells logged for temperature by Virginia Tech in the Portsmouth, Va., area.

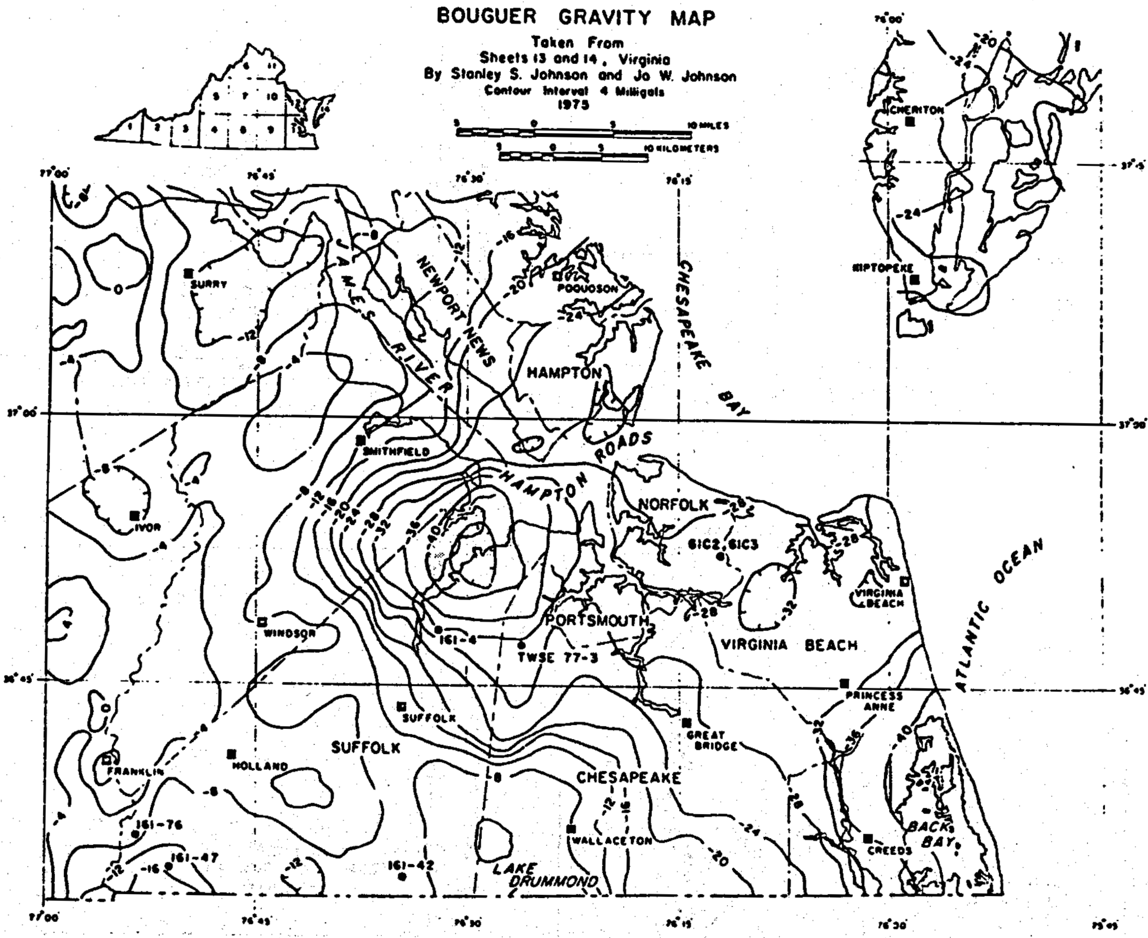

Figure 13. Wells logged by Virginia Tech in eastern Virginia.

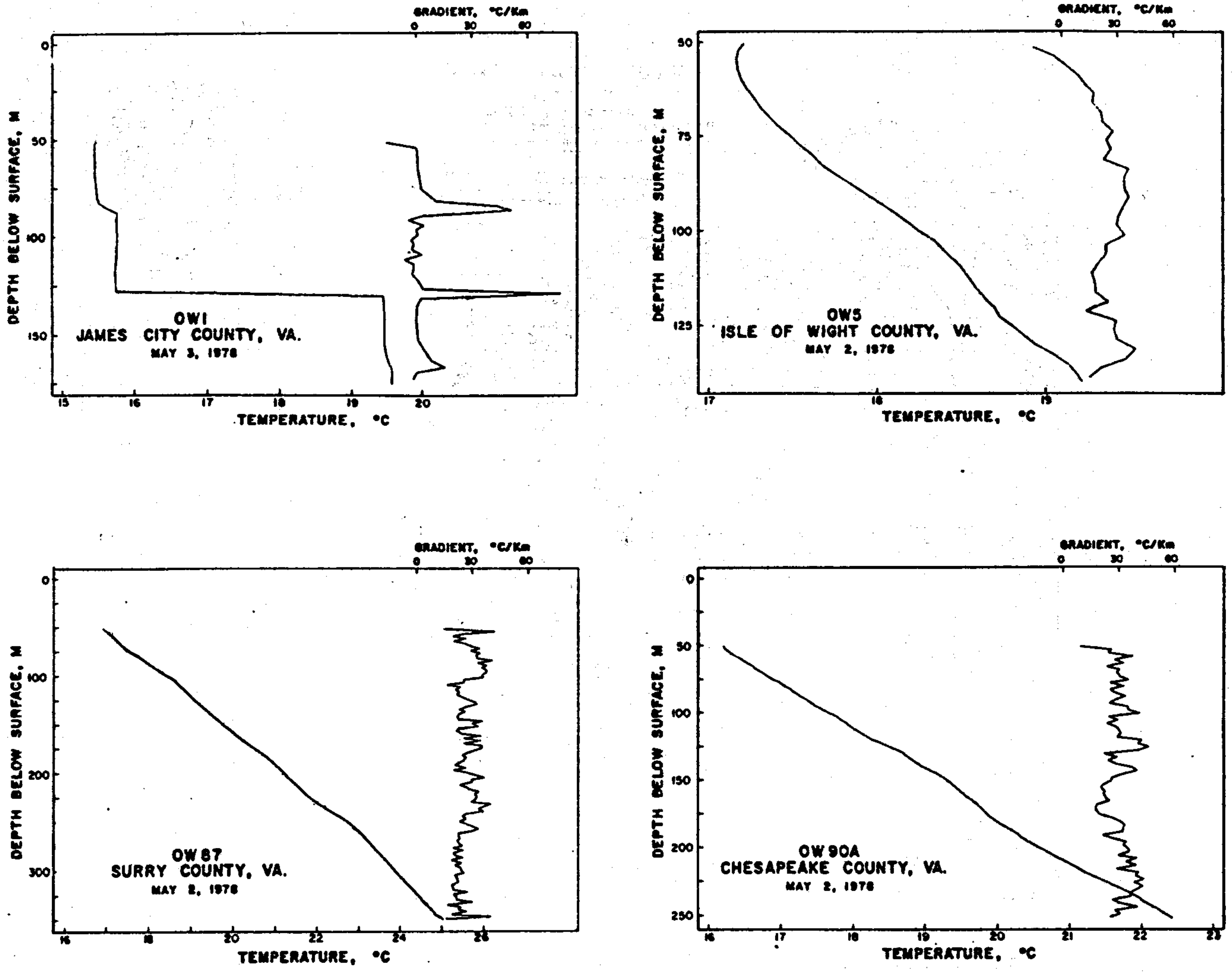

Figure 14. Temperature logs from observation wells shown in Figure 12.

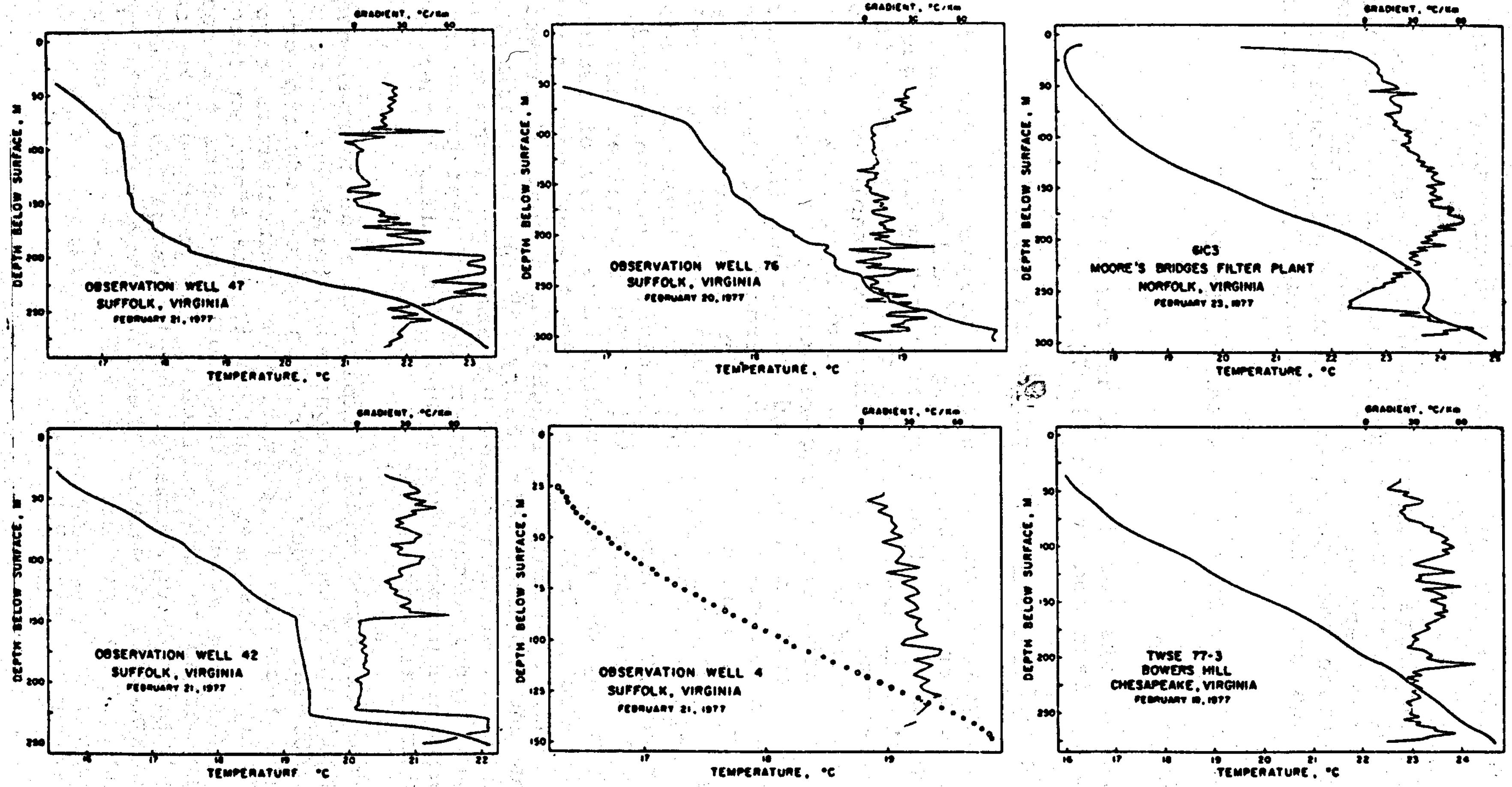

Figure 15. Temperature logs from wells shown in Figure 13.

correction of 1-2% was determined by calibrating with fused quartz.

A 10°C temperature gradient was imposed across the quartz-sample stack by two constant-temperature baths. The temperature of the sample was kept within 1 C° of its in situ temperature. Temperatures within the stack were measured with copper-constantan thermocouples and a Leeds and Northrup Type K-3 potentiometer.

Thermal conductivities are listed in Table 6.

j) Aeromagnetic data.

Aeromagnetic data for Virginia has been published at a scale of 1:500,000 by Zietz and others (1977).

k) Discussion of Virginia Tech 'radiogenic model'.

The objectives of the geothermal program at Virginia Tech have been to develop and apply geological and geophysical targeting procedures for the discovery of low-temperature geothermal resources related to heat-producing granite. Optimum sites for geothermal development in the tectonically stable eastern United States are associated with areas of high heat flow derived from crustal igneous rocks containing relatively high concentrations of uranium (U), thorium (Th), and potassium (K). Exploration strategy has been directed toward confirmation of the "radiogenic model" (Costain and others, 1980a). In this model, granite plutons with relatively high concentrations of U, Th, and K relative to the surrounding country rock occur in the crystalline basement concealed beneath the wedge of relatively unconsolidated sediments of the Atlantic Coastal Plain. Such granites are sources of heat produced by the natural radioactive decay of isotopes of U, Th, and K (Birch, 1954). Because the thermal conductivity of the Coastal Plain sediments is roughly half that of crystalline rocks (Ziagos and others, 1976; Perry, 1979), the sediments act as a thermal insulator, and raise geothermal gradients within the sediments. In a sedimentary section above a heat-producing granite, isotherms are warped upward, and anomalously higher temperatures occur at shallower depths.

The storage of commercially exploitable geothermal heat at accessible depths (1-3 km) also requires favorable reservoir conditions in sedimentary rocks overlying heat-producing granite. The geothermal resource is primarily a hydrothermal resource. The yield of water from deep aquifers is therefore an important consideration because water is the medium by which the heat at depth is transferred to the surface. The yield must be sufficient to meet energy requirements. This is partly an economic problem, but it also involves the intrinsic permeability and transmissivity of the aquifers. There is little data concerning the temperature and hydrology of deep aquifers in the sediments beneath the Atlantic Coastal Plain.

No economic factors related to the use of eastern geothermal resources were considered at Virginia Tech; however, our program was closely coordinated with the work sponsored by the Department of Energy at the Applied Physics Laboratory of Johns Hopkins University where economic and engineering factors related to the development of an eastern geothermal resource were being considered (Johns Hopkins University, 1981).

In order to locate optimum sites systematically, a methodology employing geological and geophysical methods of investigation was developed and applied. Heat-producing granites similar to those in the basement beneath the Atlantic Coastal Plain are exposed to the northwest in the Piedmont province. The petrology, radioelement distribution, and bulk chemistry of several of these young (254-420 Ma.) granites was studied in detail (Speer and others, 1980, 1982). These late Paleozoic granitoids in the central and southern Appalachians are the youngest known to date, and are generally coarse-grained granites with alkali feldspar megacrysts. Because the source of excess heat flow above the background flux is primarily from the radioactive decay of isotopes of U and Th, an understanding of the horizontal and vertical distribution of these heat-producing elements in granites is important for efficient targeting of sites of high heat flow. The distribution of U and Th to crustal depths can only be inferred from heat flow-heat generation data.

A linear relation, $q = q^* + DA$ between surface heat flow, q, and surface heat generation, A, was confirmed for many heat flow sites in granites exposed in the Piedmont of Virginia, North Carolina, South Carolina, and Georgia (Figures 16 and 17). This is a significant result of the program because from this relationship a crustal temperature profile can be computed (Lachenbruch, 1968). The drill sites defining the linear relationship were located along a region parallel to the major structural trend of the Appalachians. Although the interpretation of the physical significance of the parameter D is ambiguous (Birch and others, 1968; Lachenbruch, 1968), limited seismic data (Clark and others, 1978; Cook and others, 1978) suggest that D could represent thickness of pluton (Costain and Glover, 1980b). Values of (q,A) that do not lie on an established relationship may therefore represent granites of different thickness beneath which different crustal temperature profiles would presumably be different. Important exceptions to this generalization will be found, however, if U and Th have been mobilized from a relatively uniform distribution within a granite body to a "rind" or thin peripheral zone surrounding the granite. A heat flow determination directly over such a granite may be approximately the same as that over a similar volume of granite with the same total U and Th content uniformly distributed (Green's theorem), but the heat generation value from the same site will not be consistent with an interpretation of D as thickness of pluton. This appears to be true for the Castalia pluton in North Carolina (Costain and others, 1982)

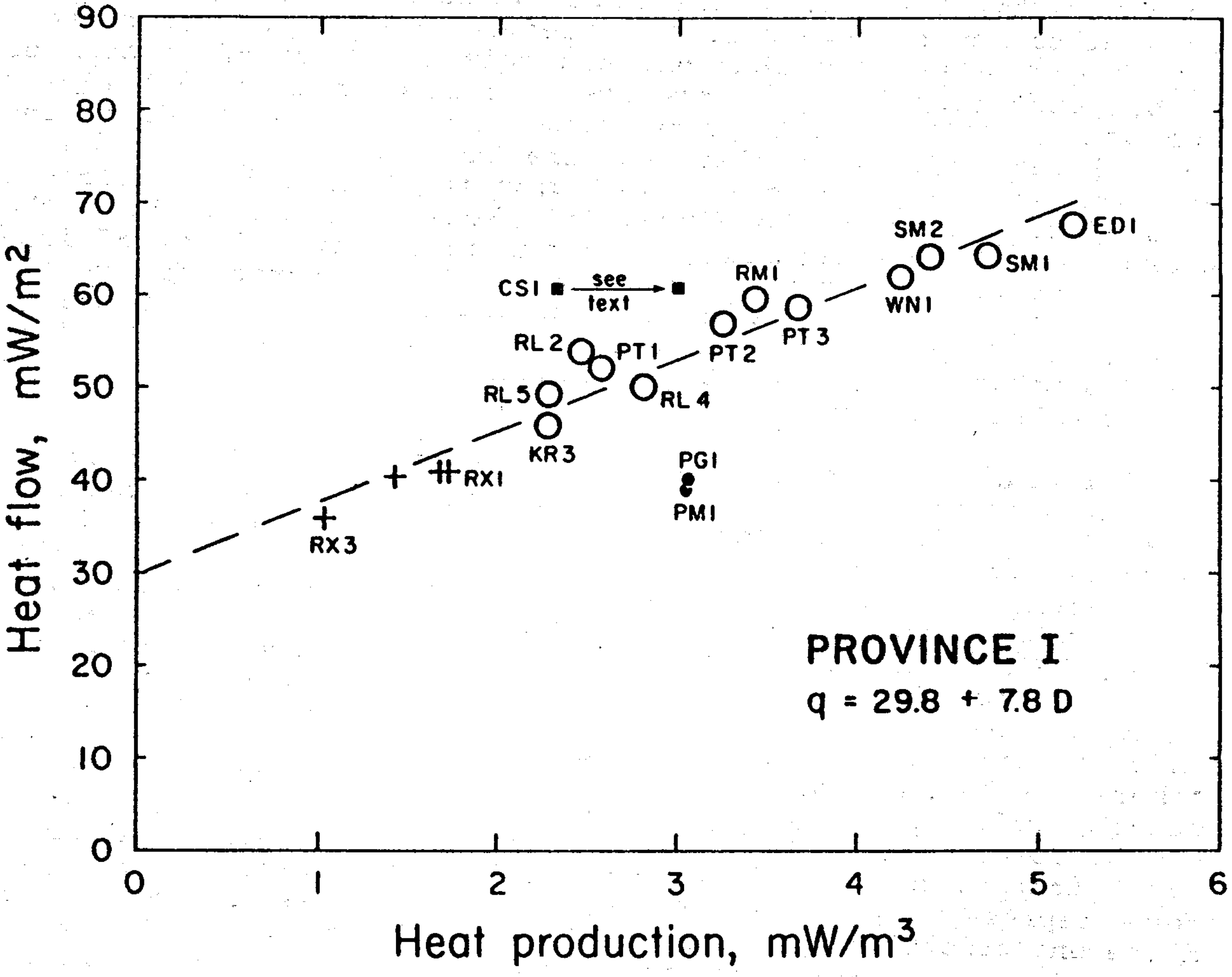

Figure 16. Linear relation between heat flow and heat generation for 'Province I' in the southeast United States (Costain and others, 1982a).

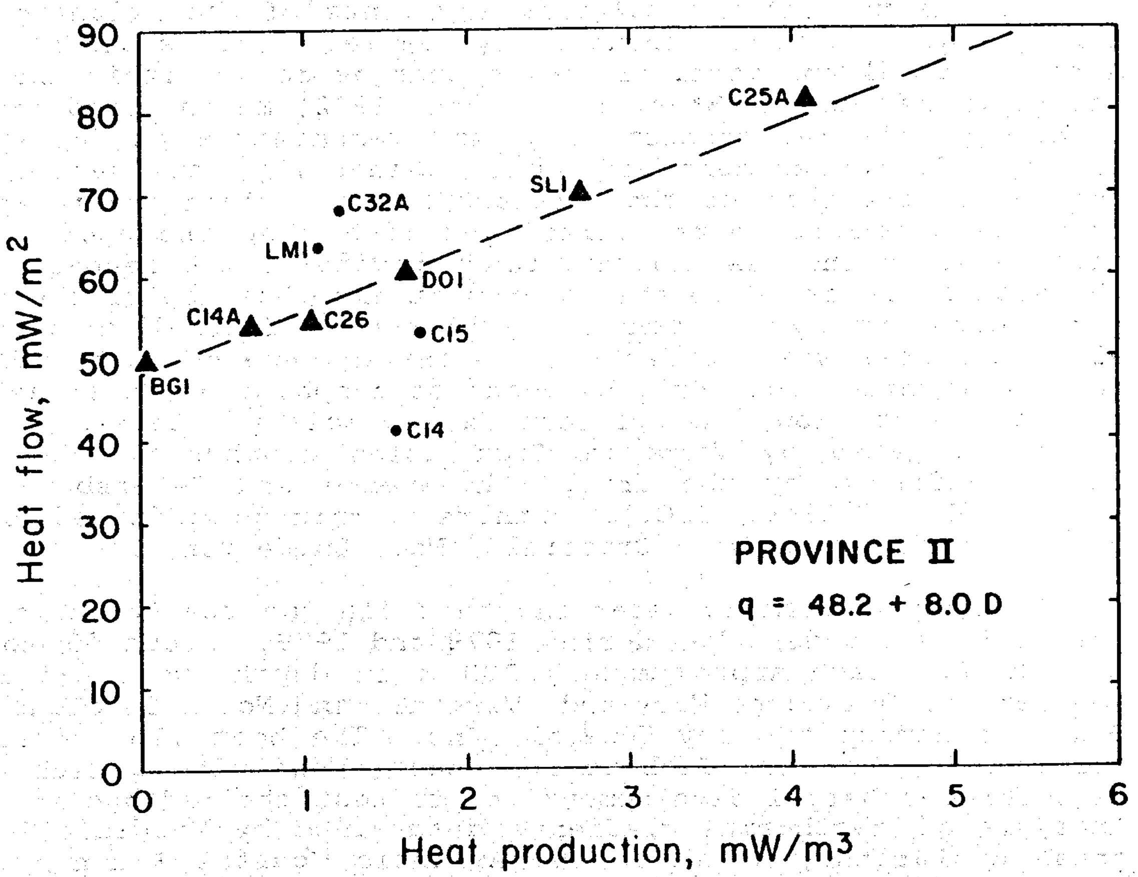

Figure 17. Linear relation between heat flow and heat generation for 'Province II' in the southeast United States (Costain and others, 1982a).

An understanding of the linear relation between heat flow and heat generation remains an important unsolved problem wherever it has been observed on continents, and has important implications for predicting crustal temperatures in areas of potential hot-dry-rock applications (Smith and Ponder, 1982).

Following detailed study of selected heat-producing granites exposed in the Piedmont, emphasis shifted to granitoids concealed beneath the thermally insulating sediments of the Atlantic Coastal Plain. Thermal conductivity varies with sediment type. Abrupt lateral and vertical facies changes occur within the Coastal Plain sediments (Brown and others, 1972) making prediction of lithology, thermal conductivity, and temperature at the surface of crystalline basement difficult. Generally, the sediments in the deeper sections of the northern Coastal Plain are non-marine deposits which are more quartz-sand rich than the upper 300 m; this tends to increase thermal conductivity in the deeper part of the section relative to the upper part and thus lowers the geothermal gradient by as much as 15 percent. Thermal conductivity also increases with compaction. Granites beneath such sediments must be located indirectly by means of geophysical data including gravity, heat flow, and reflection seismology. Several granite bodies targeted by Virginia Tech using geophysical data were later confirmed by the drill (Chesapeake and Petersburg, Va.; Dort, N.C.; Salley, S.C.). Others remain unconfirmed by the drill (Smith Point, Va.; Crisfield, Md.; Lumberton, N.C.).

A major program to determine heat flow on the Atlantic Coastal Plain was undertaken during 1978 and 1979. About 50 exploratory holes, each approximately 300 m in depth, were drilled in New Jersey, Delaware, Maryland, Virginia and North Carolina under D.O.E. contract to Gruy Federal, Inc. The heat flow sites were selected by Virginia Tech to represent areas with a high potential for geothermal development and to test the radiogenic model. Analysis of geothermal gradients determined by Virginia Tech in these exploratory holes in the Atlantic Coastal Plain indicate that in many areas temperatures exceed 40°C at the base of the sediments. Water of such temperature, provided it is available in sufficient quantity, represents a viable geothermal resource. In the eastern United States, geothermal gradients were found to be in the range of 10 to 50°/km.

Results of the gradients on the northern Atlantic Coastal Plain have been reported by Lambiase and others, (1980) and Costain and Glover, 1982b).

1) Recommendations for future work.

1) Determination of aquifer geometry and transmissivity from seismic data. Much of the uncertainty about the nature and magnitude of the geothermal resources in the eastern United States is a direct result of lack of information about the geometry and hydrologic properties of the hydrothermal resource. Virginia

Tech has found that the sediments of the Atlantic Coastal Plain from Georgia to Virginia contain a number of excellent reflectors, comparable to those commonly found in offshore reflection seismology data. Although reflection seismology is widely recognized as the most successful technique for defining subsurface geometry, the method has not been widely used on the Atlantic Coastal Plain to define the thickness and lateral extent of aquifers and aquitards primarily because it is relatively expensive ($170,000 to $200,000 per month). However, compared to the costs and results from drilling, reflection seismology has been underutilized. This is particularly true where a few drill holes have penetrated the greatest depths of interest, but where stratigraphic correlations between drill holes are uncertain, even with a full suite of geophysical logs available. Reflection seismology traverses can provide the necessary continuity between drill holes in areas where stratigraphic and/or structural discontinuities make subsurface interpretation difficult or impossible.

Aquifer transmissivity in the eastern United States is commonly determined by multiplying sand thickness obtained from well logs by a 'reasonable' hydraulic conductivity. Correlation between wells is difficult and often ambiguous.

We recommend the acquisition of P-wave reflection seismology data in the Norfolk and nearby area to determine aquifer geometry and sand thickness for estimates of hydraulic transmissivity.

2) Determination of porosity from shear and compressional seismic data. Much of the recent proprietary results from an experimental shear wave program supported by the petroleum industry are now becoming available (Laing, 1983a, 1983b). Results of the determination of sandstone and limestone porosity from shear and compressional wave velocity (Domenico, 1983) have shown that sandstone S-wave velocity is by far the most sensitive to porosity variation. Least sensitive is limestone P-wave velocity. Limestone S-wave velocity is less sensitive than is sandstone P-wave velocity to porosity variation, except at very low pressures. Domenico (1983) reports that sandstone, dolomite, and limestone are separable by Poisson's ratio, or equivalently, by P to S-wave velocity ratio. The factor separating sandstone from limestone appears to be the difference in matrix (quartz and calcite, respectively) S-wave velocity and, therefore, difference in Poisson's ratio. The substantially higher quartz S-wave velocity results in a Poisson's ratio less than two-tenths that of calcite (Domenico, 1983). Domenico as well as others (Robertson and Pritchett, 1983) have concluded, therefore, that S-wave velocity will be useful in the definition of sandstone porosity. We propose to use shear as well as compressional vibratory sources to develop a relationship between sandstone aquifer porosity, permeability, hydraulic conductivity, and transmissivity, T. The relationship between porosity and hydraulic conductivity will be an extension of the empirical results of Chilingar (1963).

3) Generation of synthetic seismic data from continuous

velocity logs. A common approach to the interpretation of reflection seismology data is through the comparison of synthetic data generated from continuous velocity logs (CVL's) obtained in drill holes with actual multifold reflection seismology data. A reflectivity function is generated from the CVL by taking the derivative of the log of the 'velocity function' as a function of time (Sengbush and others, 1961). The reflectivity function is then convolved with the seismic source wavelet (a Klauder wavelet for the case of VIBROSEIS data). The result is a multiple-free synthetic seismogram which can then be compared with the real seismic data.

We suggest that all sonic logs (CVL's) available from wells in the Norfolk area be digitized and reflectivity functions and synthetic seismograms be constructed for comparison with real data.

4) Continued investigation of recent faulting in Coastal Plain sediments in eastern Virginia using reflection seismology data. A recent summary publication by Prowell (1983) documents the widespread occurrence of faulting in sediments of the Atlantic Coastal Plain. The data in his report represent the presently available knowledge of fault characteristics and distribution of Cretaceous and younger faults in the eastern United States. Documentation of faulting in Coastal Plain sediments is poorly known, but will have an important effect on prediction of well yields and management of hydrologic resources associated with geothermal applications. The reflection seismology data proposed above can also be used to detect and document faulting in Coastal Plain sediments.

5) Temperature-logging of additional holes. All available holes in the Norfolk area should be logged for temperature at a relatively small depth interval (0.5 m). It has been our experience that differentiation of this temperature profile when sampled at a close depth spacing yields valuable information about water movement in and across the hole.

ECONOMIC ANALYSIS FOR GEOTHERMAL ENERGY USE AT NORFOLK NAVAL AIR REWORK FACILITY

SUMMARY

A study of the Norfolk NARF indicates that geothermal water at 107°F could be used to preheat make-up water entering the public works boiler. The energy saved would be 14.4×10^{10} Btu per year, which would reduce fuel costs by $918,000 per year. This would require an average geothermal water flow rate of 690 gal/min. One geothermal well could probably not supply this quantity of water. However, five wells would probably be adequate. One well producing 150 gal/min could provide 2.8×10^{10} Btu per year, with a net savings of $174,000 per year. On a net present value basis, this savings is equivalent to $2,600,000. Since the geothermal system is expected to cost only $929,000, Norfolk NARF is a good candidate for geothermal energy use, and should be investigated further.

GEOTHERMAL SYSTEM DESIGN OPTIONS

There are several options for using the heat from a geothermal well. They fall into the following categories, in order of economic viability. The heat can be

1. Used at the well head, directly through a heat exchanger
2. Piped to remote sites, where it is used directly through heat exchangers
3. Used at the well head and boosted in temperature with a heat pump
4. Piped to remote sites where it is boosted in temperature with a heat pump

A geothermal feasibility study for the Naval Air Rework building at Norfolk (Johns Hopkins University, 1980) indicated that the use of heat pumps was not as cost effective as direct use through a heat exchanger. Therefore, heat pumps have not been included in this study.

NORFOLK NARF PROPOSED GEOTHERMAL SYSTEM

The Norfolk NARF is located in a region of above average temperature gradient and has a predicted geothermal water temperature of 107°F at the top of the basement at 2700 ft. (Gruy

Federal, Inc., 1979). Its primary energy source is steam supplied by four power stations. Most of this steam is supplied by power station #1, which uses #6 fuel oil at an energy content of 142,968 Btu/lb.* Currently the condensed steam is not returned to the boiler, although a system has been proposed which would return between 10 and 20% of the condensate. Steam is supplied to the facility at an average rate of 690 gal/min. The 1981-82 monthly steam production rates are presented in Figure 18. These values have been derived from the fuel usage (V_{oil} gal/mo) (Table 7) using the following equation

$$m_{steam} = 1.1\ V_{oil}\ 142{,}968\frac{\text{Btu}}{\text{gal}}\ .83/(1187 - 29) = 112\ V_{oil}\ \text{(lbs/month)}$$

which assumes a combustion efficiency of 83%, a steam output pressure of 100 psi (i.e., 328°F, h_s = 1187 Btu/lb), a water inlet temperature of 61°F (h_{H_2O} = 29 Btu/lb), and 10% of the water is used to blow out the heat exchanger. The steam production values indicate a seasonal variation with approximately 325 x 10^6 lb of steam used in the winter months and 175 x 10^6 lb in the summer months. The summer use of steam is high since absorption air conditioners use the steam for cooling and ships require it for process steam. The relatively high year-round requirement for steam makes geothermal energy use attractive since the large fixed costs of the well, heat exchangers, and piping can be paid back faster with year-round usage.

The proposed geothermal system would use hot water at 107°F to preheat the make-up water (Figure 19). Under these conditions, geothermal energy could provide 3.4% of the yearly energy needs, which is equivalent to $918,000 of fuel oil per year (Table 7). After accounting for the electrical energy required for pumping the geothermal water, the net energy savings is equivalent to $881,763 of fuel (Table 7). Due to the relatively high make-up water inlet temperature in the summer, over 90% of this energy is provided during the months from October through May (Figure 20).

PRESENT VALUE ANALYSIS

The net present value method of evaluating the proposed Norfolk geothermal system has been implemented using the nominal conditions presented in Table 8. Since some of these values are not well known prior to actually drilling a geothermal well, parametric studies have been performed on flow rate, well water temperature, drawdown depth, and fuel costs.

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*Discussion with Don Persinger, Public Works Center, Norfolk, Va.

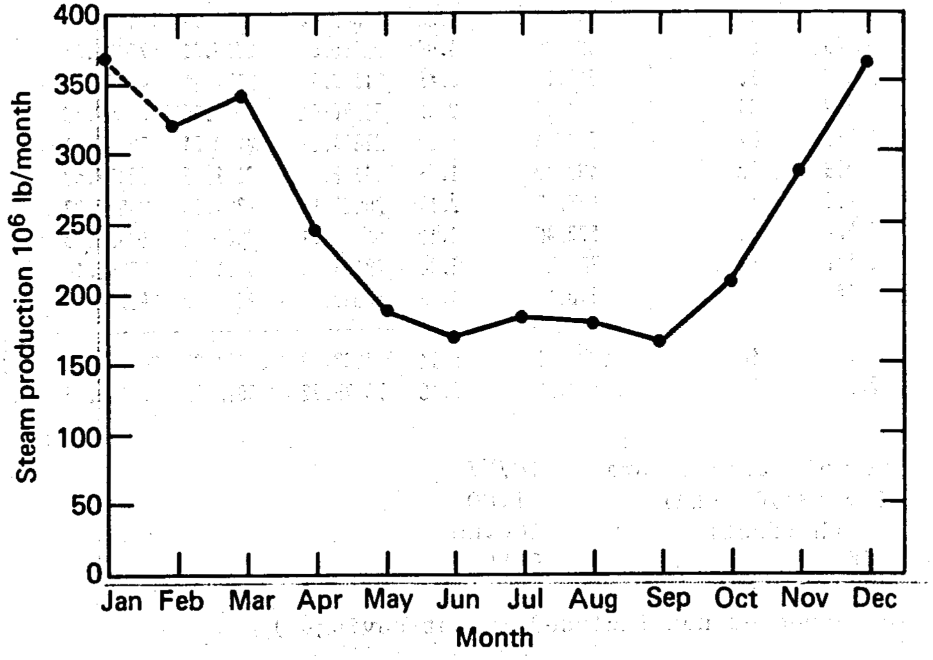


Figure 18. Norfolk NARF monthly steam production September 1981--August 1982.

Table 7. Economic Analysis of a Geothermal Well at the Norfolk Naval Air Rework Facility.

MONTH	OIL USED 10E6 GAL	MAKE UP WATER TEMP. DEG. F	MAKE UP WATER FLOW GAL/MIN	GEOTHERMAL ENERGY %	GEOTHERMAL ENERGY $	PUMPING ELECTRICITY COST $	NET SAVING $	NET SAVING %
JAN	3.279	40	1006.39	5.26	156913.64	4402.46	152511.18	17.30
FEB	2.856	45	880.30	4.86	126184.60	3850.86	122333.74	13.87
MARCH	3.041	52	942.94	4.28	118565.12	4124.90	114440.23	12.98
APRIL	2.188	55	680.20	4.04	80395.84	2975.51	77420.33	8.78
MAY	1.631	62	510.11	3.46	51312.36	2231.45	49080.91	5.57
JUNE	1.469	74	464.25	2.45	32690.06	2030.88	30659.18	3.48
JULY	1.569	84	500.23	1.59	22643.37	2188.24	20455.13	2.32
AUGUST	1.538	82	489.48	1.76	24618.82	2141.23	22477.59	2.55
SEPT	1.432	77	453.75	2.19	28527.15	1984.93	26542.22	3.01
OCT	1.824	66	572.45	3.12	51825.01	2504.16	49320.85	5.59
NOV	2.501	62	782.20	3.46	78683.15	3421.75	75261.40	8.54
DEC	3.242	44	998.42	4.94	145627.88	4367.60	141260.28	16.02
SUM	26.57	40	8280.71	5.26	917987.00	36223.95	881763.04	100.00
AVERAGE	2.21	61.9	690.06	3.45	76498.92	3018.66	73480.25	8.33

Geothermal well temperature	107°F
Electricity ($/$10^6$ Btu)	11.80
Pumping Depth (feet)	400.00
Pumping Eff	0.50

(Operating expenses not included in net savings.)

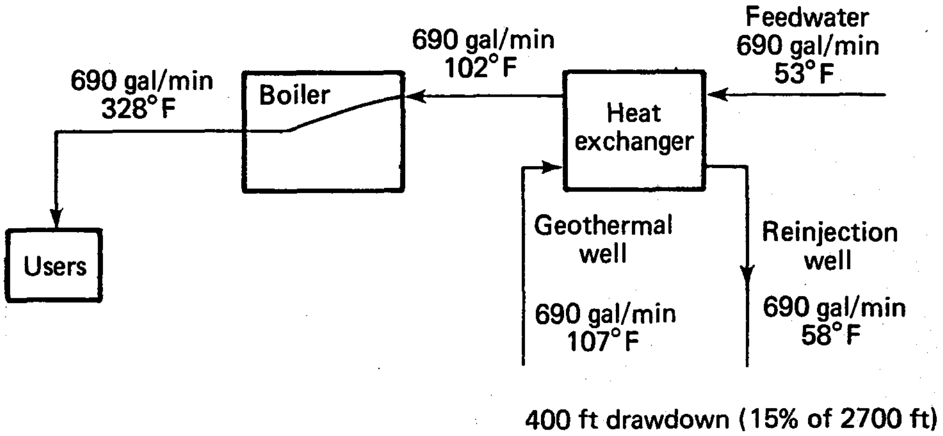


Figure 19. Geothermal system to preheat feedwater at Norfolk NARF.

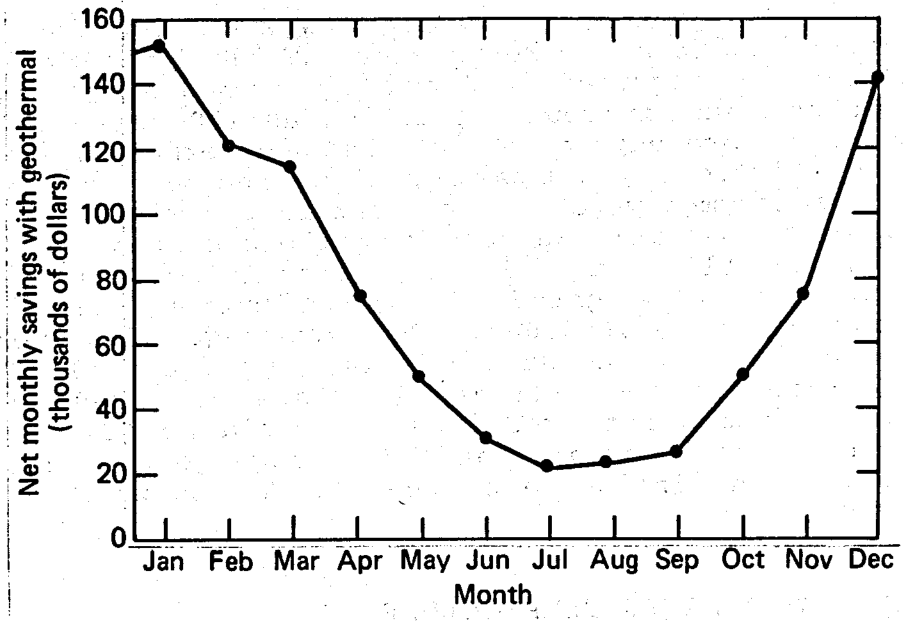


Figure 20. Net savings per month of a geothermal system to preheat all the make-up water at Norfolk (from Table 7).

Table 8. Estimated Geothermal System Characteristics for Norfolk NARF.

Water flow rate (gal/min)	150
Drawdown depth (ft)	400 (15% of well depth)
Water temperature (°F)	107
Cost of money (%)	10
Inflation rate (%)	5
Cost of fuel (M Btu)	$6.36
Cost of electricity (M Btu)	$11.80
Annual operating and maintenance costs	$20,000

FLOW RATE

An average geothermal water flow rate of 690 gal/min is required to preheat all make-up water (Table 7). Flow rates over 1000 gal/min are required in January. Although the flow rate at Norfolk is unknown, it could be as low as 100 gal/min. With this flow, the net present value of the geothermal system is only $1,150,000 (Figure 21). However, since the energy extracted per gallon of geothermal water is greatest in the winter months, it is advantageous to use more water during these months and less in the summer, while still maintaining an average flow of 100 gal/min for the year. With a weighted flow distribution, the net present value increases to $1,650,000. The advantage of a weighted flow rate is significant. Consequently only weighted flow rates will be considered. If the average flow rate were 200 gal/min, the geothermal system's net present value would be $3,570,000. From these data, it is apparent that the average geothermal water flow rate has a strong influence on the effectiveness of a geothermal system.

GEOTHERMAL WELL WATER TEMPERATURE

Like flow rate, well water temperature is unknown. However, since 1000-ft geothermal test wells have been drilled in the area and a deep well has been drilled 150 miles to the north in Chrisfield, Md., the actual well water temperature should be relatively close to the predicted 107°F value. The effect of small changes in temperature are linear and will not unduly influence the net present value as the temperature is within a few degrees of 107°F (Figure 21).

DRAWDOWN DEPTH

Another factor that influences flow rate is drawdown depth. With a drawdown of 15% (400 ft), the geothermal water flow rate will be less than for a drawdown of 1000 ft but pumping costs per gallon will also be less. The effect of drawdown depth on pumping costs is shown in Figure 22. Increasing drawdown depth from 400 ft to 1000 ft reduces the net present value from $2,600,000 to $2,470,000. Although a drawdown depth to the bottom of the well (2700 ft) is not anticipated, its results have been included in Figure 22 to show that even a very large drawdown depth has only a modest effect on present value. We have found that, although the energy required for pumping increases with drawdown depth, the added costs do not appear to be prohibitive. After the well is drilled and its flow characteristics are known, a trade-off study between pumping costs and well flow rate should be made as a function of drawdown depth.

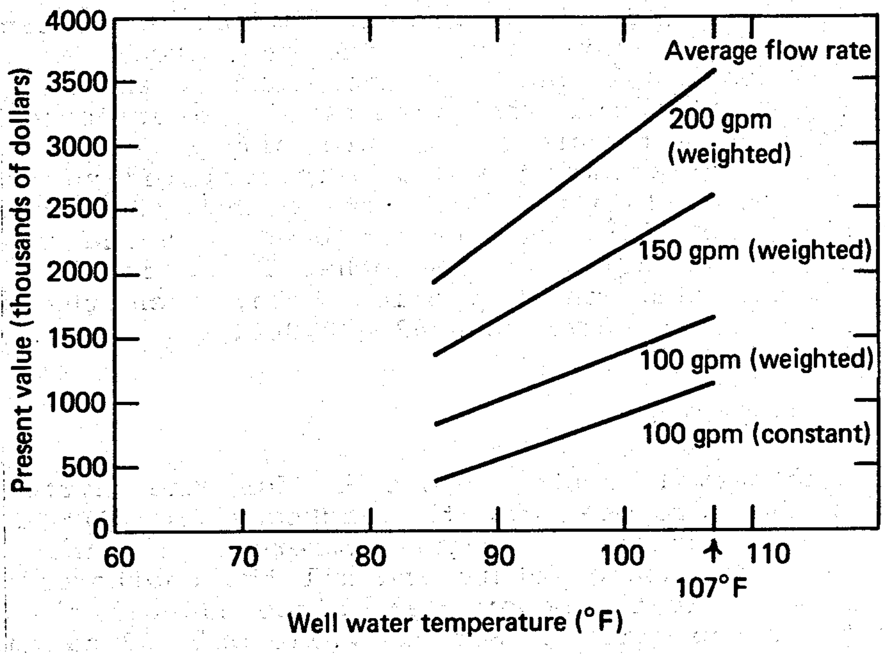


Figure 21. Net present value of Norfolk geothermal system as a function of water flow rate and temperature.

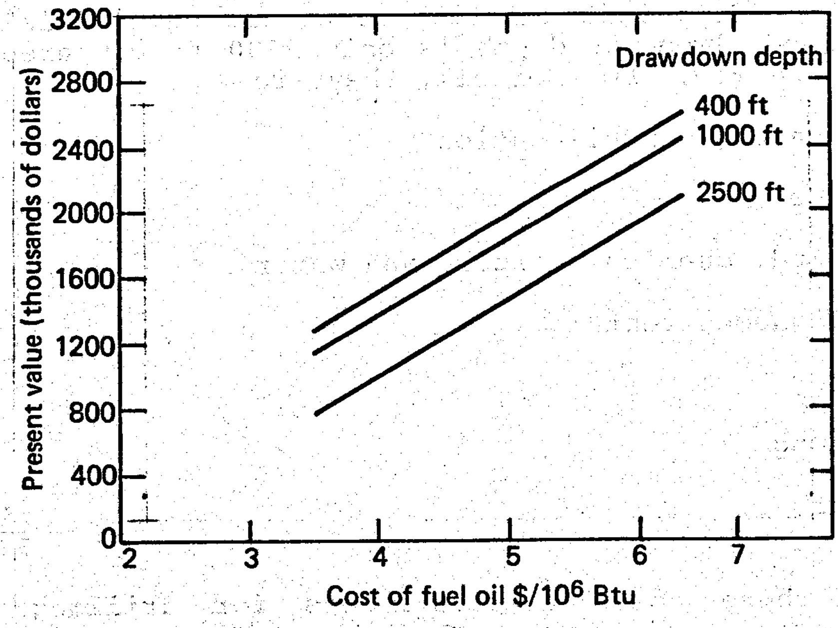


Figure 22. Present value of Norfolk geothermal energy system as a function of drawdown depth and the cost of fuel oil.

FUEL OIL COSTS

Future fuel oil costs are an important consideration in obtaining a net present value of the geothermal system. In the analysis, current fuel costs are increased by the inflation rate. The large fluctuations in the price of oil experienced in the past make it difficult to predict future oil prices. Therefore an analysis was done assuming a lower initial oil price but still increasing with inflation. The results show that even at a cost of only \$3.50 per 10^6 Btu the net present value would be over \$1,200,000 (Figure 22). On the other hand, if fuel oil prices increase faster than the inflation rate, then the net present value will be even greater than \$2,600,000.

NORFOLK SYSTEM COSTS

The geothermal system proposed for the Norfolk NARF is similar to that proposed for the Jacksonville NARF described in the following section. A major difference is that at Norfolk there is not condensate return and all the geothermal heat would be used directly at the power plant since 690 gal/min can be used to preheat make-up water at Norfolk while only 88 gal/min could be used in this manner at Jacksonville.

The depth-independent drilling costs at Norfolk are nearly the same as at Jacksonville. They range from \$345,000 for a peak flow rate of 100 gal/min to \$360,000 for a flow rate of 600 gal/min.

The depth-dependent drilling costs are substantially less at Norfolk, since the well depth is only 2700 ft compared with 5000 ft at Jacksonville. For Norfolk, they are

Mobilization/demobilization	\$ 15,000
Rig time	45,000
Bits, mud, chemicals, fuel, and water	17,000
Miscellaneous rentals	12,000
Logging	29,000
Cementing	30,000
Tubulars	137,000
	\$285,000

Since these costs are estimates for drilling along the Atlantic Coastal Plain between Georgia and New Jersey, they should be good estimates of the actual costs at Norfolk.

The local fresh water in Norfolk comes from near the surface; therefore, a reinjection well 2000 ft deep should be adequate to keep salt water out of the fresh water supply. The depth-dependent reinjection well costs are

Rig time	$ 32,000
Bits, mud, chemicals, fuel, and water	15,000
Rentals	10,000
Logging	25,000
Cementing	25,000
Tubulars	100,000
	$207,000

The total cost of both wells is $847,000.

HEAT EXCHANGER COSTS

The water to water heat exchanger cost in 1980 dollars is

$$0.057\ (Q)^{0.84}$$

For the weighted 150 gal/min well water flow rate presented in Table 9 the peak flow rate is 450 gal/min. This corresponds to a heat flow Q of 14 x 10^6 Btu/hr; therefore, the water to water heat exchanger in Figure 19 costs $57,000.

The cost of piping required to carry the water to the public works building and back to the reinjection well is an additional $25,000.

The total cost for the system shown in Figure 19, producing at a weighted average flow of 150 gal/min, is $929,000 (Table 10). The projected net present value of this system is $2,600,000. For a system producing 100 gal/min the total cost is $902,000 and the net present value is $1,650,000. In fact, extrapolating the results (Figure 23) shows that even at flow rates as low as 60 gal/min the geothermal system is still economical. In addition, geothermal water temperature could be as low as 80°F and the system would still be practical at flow rates over 110 gal/min (Figure 23). From a net present value criterion a geothermal energy system at Norfolk NARF looks promising.

Table 9. Economic Analysis of Geothermal Well at Norfolk NARF.

MONTH	OIL USED 10E6 GAL	MAKE UP WATER TEMP. DEG. F	MAKE UP WATER FLOW GAL/MIN	GEOTHERMAL ENERGY %	GEOTHERMAL ENERGY $	PUMPING ELECTRICITY COST $	NET SAVING $	NET SAVING %
JAN	3.279	40	450.00	2.35	70162.69	1968.52	68194.16	29.73
FEB	2.856	45	300.00	1.65	43002.94	1312.35	41690.59	18.17
MARCH	3.041	52	150.00	0.68	18860.94	656.17	18204.76	7.94
APRIL	2.188	55	150.00	0.89	17729.28	656.17	17073.11	7.44
MAY	1.631	62	150.00	1.02	15088.75	656.17	14432.58	6.29
JUNE	1.469	74	0.00	0.00	0.00	0.00	0.00	0.00
JULY	1.569	84	0.00	0.00	0.00	0.00	0.00	0.00
AUGUST	1.538	82	0.00	0.00	0.00	0.00	0.00	0.00
SEPT	1.432	77	0.00	0.00	0.00	0.00	0.00	0.00
OCT	1.824	66	150.00	0.82	13579.88	656.17	12923.70	5.63
NOV	2.501	62	150.00	0.66	15088.75	656.17	14432.58	6.29
DEC	3.242	44	300.00	1.48	43757.38	1312.35	42445.03	18.50
SUM	26.57	40	1800.00	5.26	237270.59	7874.09	229396.50	100.00
AVERAGE	2.214	61.9	150.00	0.80	19772.55	656.17	19116.38	

Geothermal well temperature	107°F
Electricity ($/$10^6$ Btu)	11.80
Pumping Depth (feet)	400.00
Pumping Eff	0.50

Table 10. Geothermal Systems Costs and Net Present Value, Norfolk NARF.

	100 gal/min	150 gal/min	200 gal/min
Production well depth independent	$350,000	$355,000	$360.000
Production well depth dependent	285,000	285,000	285,000
Reinjection well (3000 ft) 11,400	207,000	207,000	207,000
Heat exchangers and piping	60,000	82,000	120,000
Total Cost	$902,000	$929,000	$972,000
Net Present Value	$1,650,000	$2,600,000	$3,560,000

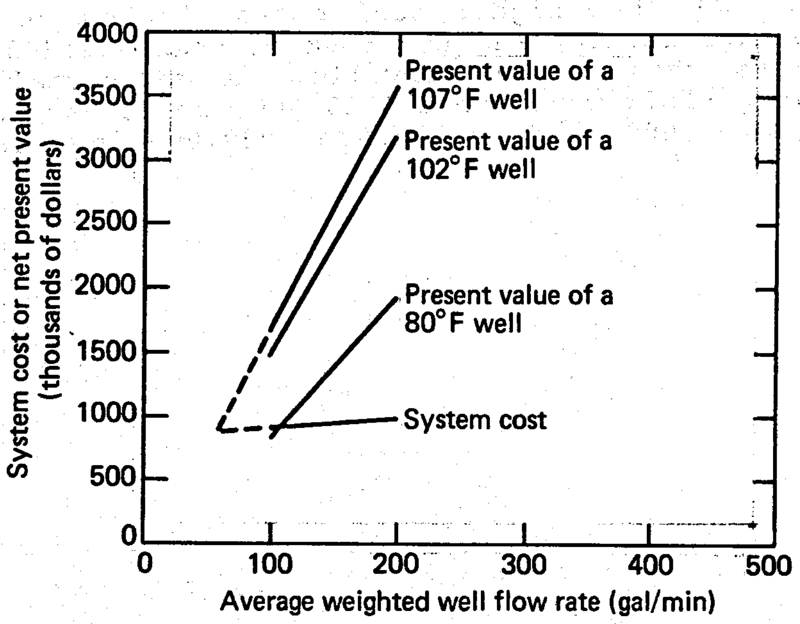


Figure 23. System cost and net present value as functions of average weighted well flow rate (Norfolk).

ENERGY SAVINGS PER DOLLAR

Another criterion for evaluating future energy investments is to look at the ratio of energy saved per dollar spent. For the nominal conditions presented in Table 8, this ratio is 38.8 KBtu/$. This is a good energy return per dollar and indicates that a geothermal system at Norfolk NARF is worth investigating further.

CONCLUSIONS

A geothermal system at the Norfolk NARF looks even more promising than a system at the Jacksonville NARF, the economic analysis for which is included in a later section of this report. The Norfolk NARF has higher fuel costs, higher energy use, and less condensate return; and the risk of unexpected drilling costs is much less than at Jacksonville. A geothermal system constructed at Norfolk would cost $929,000, would have a net present value of $2,600,000, and would save $229,000 in energy costs per year.

GEOPHYSICAL AND GEOLOGICAL ASPECTS OF GEOTHERMAL ENERGY POTENTIAL AT JACKSONVILLE

a) Geologic framework.

Jacksonville is located on the Atlantic Coastal Plain, an eastern-thickening wedge of Cretaceous to Recent sediments (Arden and others, 1979). In southern Georgia and Florida, the Coastal Plain sediments are predominantly marine carbonates with minor amounts of clay, sand, chert, and shale.

The basement underlying the Coastal Plain sediments is a sequence of flat-lying Paleozoic sedimentary rocks. The top of the basement in northern Florida ranges in depth from about 900 m (3000 ft) to about 1550 m (5000 ft). In north-central Florida, the basement is domed upward in a structure called the Peninsular Arch (Figure 24).

The lithology of the units beneath the Paleozoic sequence is not definitely known, but is thought to consist of felsic volcanics.

b) Thickness of Coastal Plain sediments.

Extrapolation from wells in the surrounding area suggests that the thickness of Coastal Plain sediments at Jacksonville is approximately 1395 m (4500 ft) (King, 1959). The thickness of sediments with relatively high transmissivities, however, is apparently considerably less than 1395 m.

c) Intrinsic permeability and other hydrologic properties.

The groundwater of Florida is derived from (1) artesian water from the Floridan aquifer and (2) several shallow formations of relatively small areal extent. See, for example, Fairchild (1972), Legrand (1964), Meyer (1974), and Miller (1979). The Floridan aquifer system underlies most of Florida and consists of a series of limestone and dolomite formations, mainly Eocene in age, with a total thickness of about 610 m (2000 ft) (Cooper, 1953; Stringfield, 1936, 1964). In the Jacksonville area, the top of the Floridan aquifer is at a depth of approximately 90-183 m (300-600 ft) (Leve and Goolsby, 1969, p. 13; Vernon, 1973). The base of the Floridan aquifer is in the Cedar Keys Limestone of Paleocene age at a depth of approximately 640 m (2100 ft). Below 640 m, one deep well in the Jacksonville area penetrated relatively impermeable limestone and gypsum beds containing highly mineralized water (Leve and Goolsby, 1969, p. 13). Most of the recharge to the aquifer in northeast Florida occurs in an area about 48 km (30 mi) to 96 km (60 mi) southwest of Jacksonville. Groundwater moves laterally away from the recharge area through the aquifer toward Jacksonville and other areas in northeast

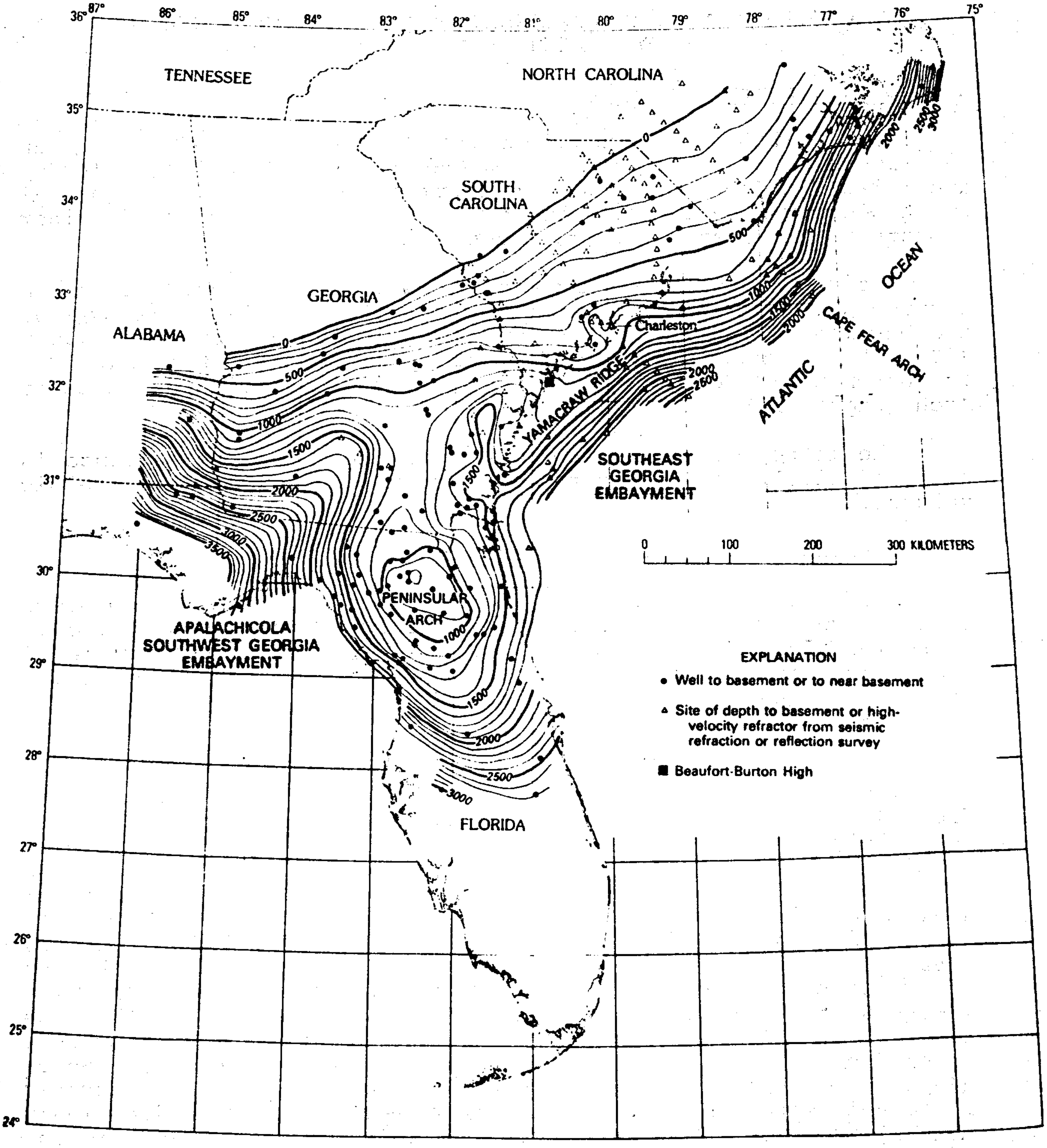


Figure 24. Structure-contour map of the surface of the geophysical basement in parts of Florida and Georgia (Popenoe and Zietz, 1977).

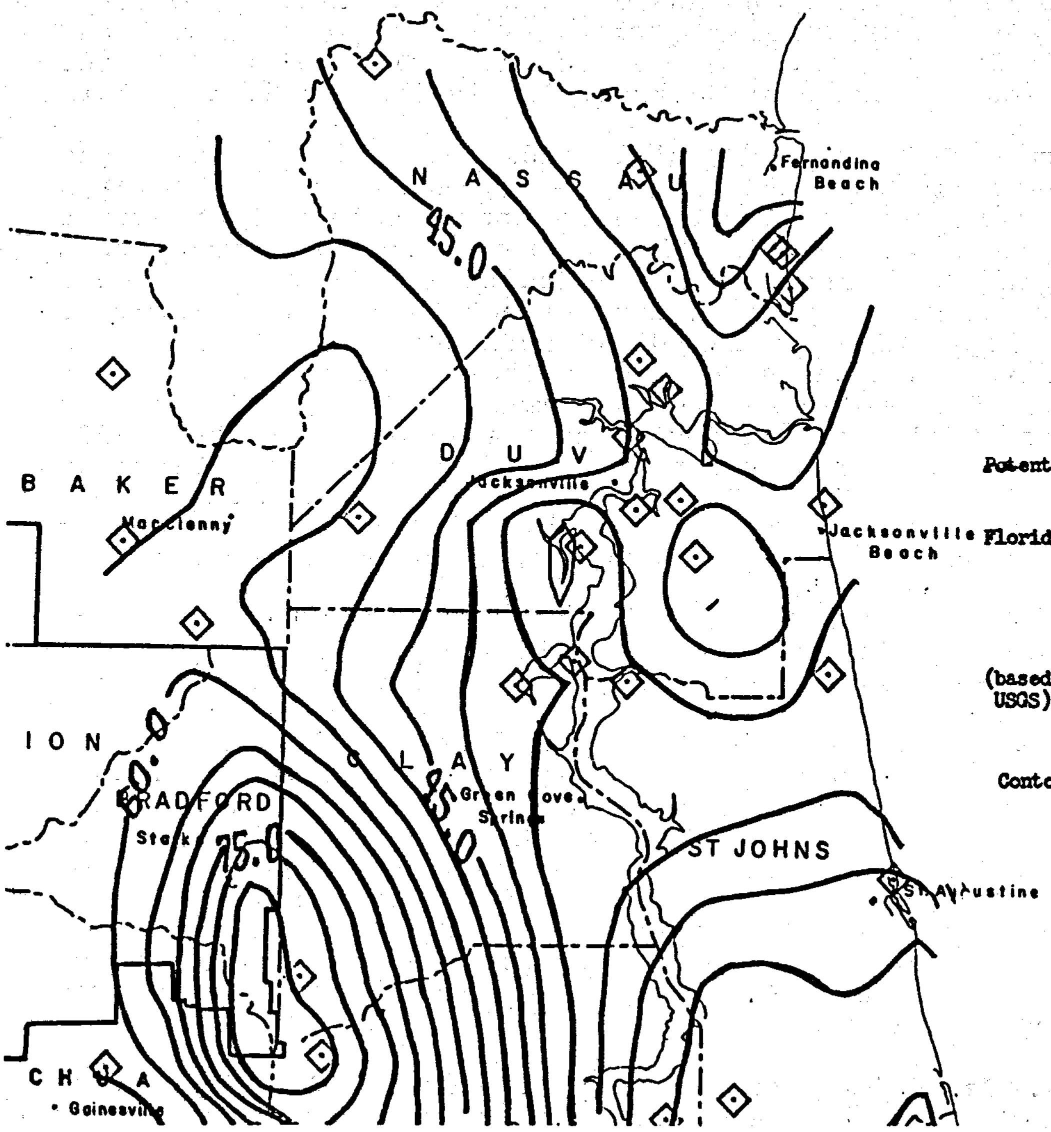
Florida where it is discharged by springs, upward leakage through the overlying confining beds, and by wells (Leve and Goolsby, 1969, p. 13).

Intrinsic permeability, k, is independent of fluid properties, and depends only on the medium. It is a fluid-free conductance parameter that depends on mean grain diameter, distribution of grain sizes, grain sphericity and roundness, and the nature of their packing. The intrinsic permeability of the Paleozoic basement rocks near Jacksonville is low (Barnett, 1975).

In general, different hydraulic heads are associated with the upper and lower Floridan aquifer. The hydraulic head associated with the lower part of the Floridan is approximately 2 ft higher than the upper part. Values of the hydraulic head range from about 55 ft in the corner of DuVal County to about 25 ft near Jacksonville, but drawdown conditions affect these values locally. A series of maps of potentiometric surfaces for the Floridan aquifer has been available since 1976. These maps cover different time periods; for example, May-September. No recent summary publication is available, but a copy of the latest (November 1983) USGS-SJRWMD potentiometric surface map for the top of the Floridan is shown in Figure 25. (R. Johnson, personal communication, 1983). No data are apparently available for the potentiometric head of the lower Floridan (R. Johnson, personal communication, 1983).

Transmissivity (transmissibility) is the product of hydraulic conductivity and thickness of saturated aquifer. Transmissivity at the base of the Floridan aquifer in Hole N-117 north of Jacksonville at Fernandina Beach ranges from T = 200,000 to T = 250,000 ft^2/day (standard English system of units). Transmissivities greater than 15,000 ft^2/day represent good aquifers for water well exploitation (Freeze and Cherry, 1979, p. 60). Much of the high transmissivity within the Floridan may be associated with carbonate solution along formational contacts (personal communication, Eugene Hayes, U.S.G.S.). The extent to which cavernous permeability within the Floridan is interconnected is unknown. Below the Floridan, transmissivities are poorly known, but may be several orders of magnitude less.

The U.S. Geological Survey has recently (1982) completed a major study of the carbonate aquifers in the southeast United States as part of the RASA program (Jim Miller, Geologist, U.S.G.S. Atlanta office, (404) 221-5174; also Craig Sprinkle, same number). Heat pump applications are apparently common in this part of Florida (Frazee). Although this study was concerned primarily with the carbonate aquifers, some information regarding the deeper aquifers may have been collected that is relevant to possible geothermal applications.



Potentiometric Surface of the Floridan Aquifer 7/31/83

(based upon provisional data of the USGS)

Contour Interval = 5 ft.

Figure 25. Potentiometric surface of the Floridan aquifer.

d) Probable basement lithology beneath Jacksonville area.

The basement in the Jacksonville area consists of essentially flat-lying Paleozoic sedimentary rocks (Applin, 1951; Applin and Applin, 1964; Milton (1972); Milton and Grasty, 1969; Gohn, 1983; Chowns and Williams, 1983, and references therein). The rocks range in age from Early Ordovician to Middle Devonian and include fossiliferous shales, siltstones, sandstones, and quartz arenites. The thickness of the Paleozoic sequence is presumably variable; gravity modeling suggests a thickness of up to 2500 m (8200 ft) (Wicker and Smith, 1978); a well that was drilled through the Paleozoic sequence in central Florida showed a thickness for the sequence of 375 ft.

The nature of the crystalline rocks underlying the Paleozoic section in the Jacksonville area is not definitely known; it is thought to correlate with the late Precambrian to Early Paleozoic felsic volcanic terrane which borders the Paleozoic sequence to the north in southeastern Georgia, and to the south, on the eastern flank of the Peninsular Arch, in central Florida. In two locations, the felsic volcanic terrane is known to underlie the Paleozoic sequence: (1) a well in central Florida encountered the felsic volcanic terrane below lower Ordovician strata (E. Ord. 4240-4615 ft; pre-Mesozoic volcanic agglomerate 4615-4637 ft); (2) seismic profiles in the Florida panhandle show volcanic rocks underlying Paleozoic sediments (Chowns and Williams, 1983, and references therein).

Lithologies in the felsic volcanic terrane include vitric crystal tuff, tuffaceous arkose, porphyritic rhyolite, and granite. The granites that have been drilled in southeast Georgia are unfoliated and have granophyric intergrowths, suggesting that they intruded the volcanic sequence.

No wells have penetrated crystalline basement in the Jacksonville area (personal communication, Walter Schmidt, U.S.G.S., Florida). Three wells in the DuVal County-Jacksonville area bottomed in quartz sandstone of Ordovician age at depths ranging from approximately 1067 m (3500 ft) to 1219 m (4000 ft). Additional information about these wells is given in Barnett's (1975) Appendix.

e) Gravity data.

A compilation of the available gravity data for the area around Jacksonville has been published at a small scale by Daniels and others (1983, Figure 12). See also Oglesby and others (1973). Jacksonville lies in a broad area of relatively low gravity values. A circular gravity minimum lies east of Jacksonville, partially offshore.

f) Seismic data.

Virginia Tech has acquired no VIBROSEIS data in Florida but data are available from other sources. Richardson Seismic Services, Inc. is a brokerage firm for all proprietary onshore reflection seismology data available for the Jacksonville area. For example, Richardson is a broker for Chevron, Amoco, Shell, Sun, etc. Data are available for DuVal, Nassau, and Clay Counties, Florida. Apparently no proprietary data are available for St. Johns County. The cost of purchasing record sections showing the data is approximately $1,200 to $1,500/mi (5-mi minimum) depending on how recently the data were acquired. Most (98%) of their data is in the $1,200/mi range. If data tapes are also requested, the average additional cost is approximately 15% of the total order. Samples of data cannot be sent to interested parties for inspection, but after interest in the amount and location of data has been defined, samples of data are obtained from the company's vaults, and data quality can be examined in the Richardson Seismic Services office in New Orleans. Each request for data is handled on an individual basis, and must be approved by the company selling the data. A lease agreement between the purchaser and seller must be signed. This kind of data, although it is required to have restricted circulation, is a valuable guide to the data quality and data acquisition problems to be expected in the area. Richardson Seismic Services has some offshore proprietary data for about 20 km (12 mi) from the beach in DuVal County.

Multichannel seismic reflection data have been collected as part of a program by the U.S. Geological Survey to survey the geological framework of U.S. coastal areas. These data are in the public domain. Many of these seismic lines tie with the offshore COST GE-1 well and could provide important regional control of depth to basement. Additional high-resolution seismic reflection data are available for offshore near Jacksonville. These data were acquired to help evaluate geologic hazards related to oil and gas development activities (NOAA Data Announcement 1980 SE-QQ). These high-resolution data sets might prove useful to define regional joint sets that might control the solution of carbonates in the Floridan aquifer.

The problem of seismic data acquisition over cavernous terrane in northern Florida is well known. Data quality is often poor because of scattering of energy by karst near-surface topography. However, contract companies continue to use conventional methods of data acquisition which include summing of individual VIBROSEIS sweeps in the field. We have started a practice of recording on tape each individual sweep in order that proper editing of individual sweeps can be carried out on the VAX computer during the processing of the data. In an area such as northern Florida where near-surface conditions affect data quality, this may be an important extra step. Our preliminary comparisons of data that have been summed in the field versus data that have been summed on the computer clearly favor recording each individual sweep in the field with no summing, and summing after editing on the computer. In addition, a smaller group spacing (35 m) would allow more continuous subsurface coverage in those local areas where carbonate solution is less of a problem. The quality of the data to be expected can be determined by inspecting and purchasing some of the proprietary seismic data.

g) Heat flow sites.

Smith and others (1981) published heat flow determinations for Florida. Reported values near Jacksonville are less than 0.8 HFU (1 HFU = 1 heat flow unit = 10^{-6} cal/gm/cm^2) and as low as 0.5 HFU. The published data indicate that few good quality heat flow determinations are available for the Jacksonville area.

Lowell and Long (1977) suggest that the Peninsular Arch in northern Florida (Figure 24) may be a consequence of lateral differences in heat production from uranium and thorium in the continental metamorphic crystalline basement rocks of northern Florida and the oceanic basement of the adjacent ocean basins. That is, conductive heat flow should be greater over the Peninsular Arch than over the adjacent basins. Their results suggest that the temperature gradient should be about 3°C/km greater in the basement over the Arch than over the adjacent basins. Unfortunately, no heat flow values in basement rocks are available to test this attractive model.

h) Temperatures, temperature gradients, and gamma logs.

Representative temperature-depth plots commonly show disturbed gradients. Smith and others (1981) attribute the disturbances to moving groundwater and suggest that the heat flow values derived from these gradients may be suspect. Problems include extensively interconnected aquifers and drilling that is too shallow for meaningful geothermal gradients. The Floridan aquifer is not a simple aquifer system; it is characterized by convective overturn and lateral migration of groundwater. If convection dominates over conduction within the aquifer, anomalously high gradients will be found immediately above and below the convecting system, with a low to zero geothermal gradient within the aquifer (White, 1973).

Two temperature logs from non-flowing (at the surface) wells are shown in Figure 26 (logs obtained from Richard A. Johnston, Geologist, Resource Evaluation Division, Water Resources Department, St. Johns River Water Management District, Palatka, FL 32077). Temperature at 1200 m is approximately 86°F.

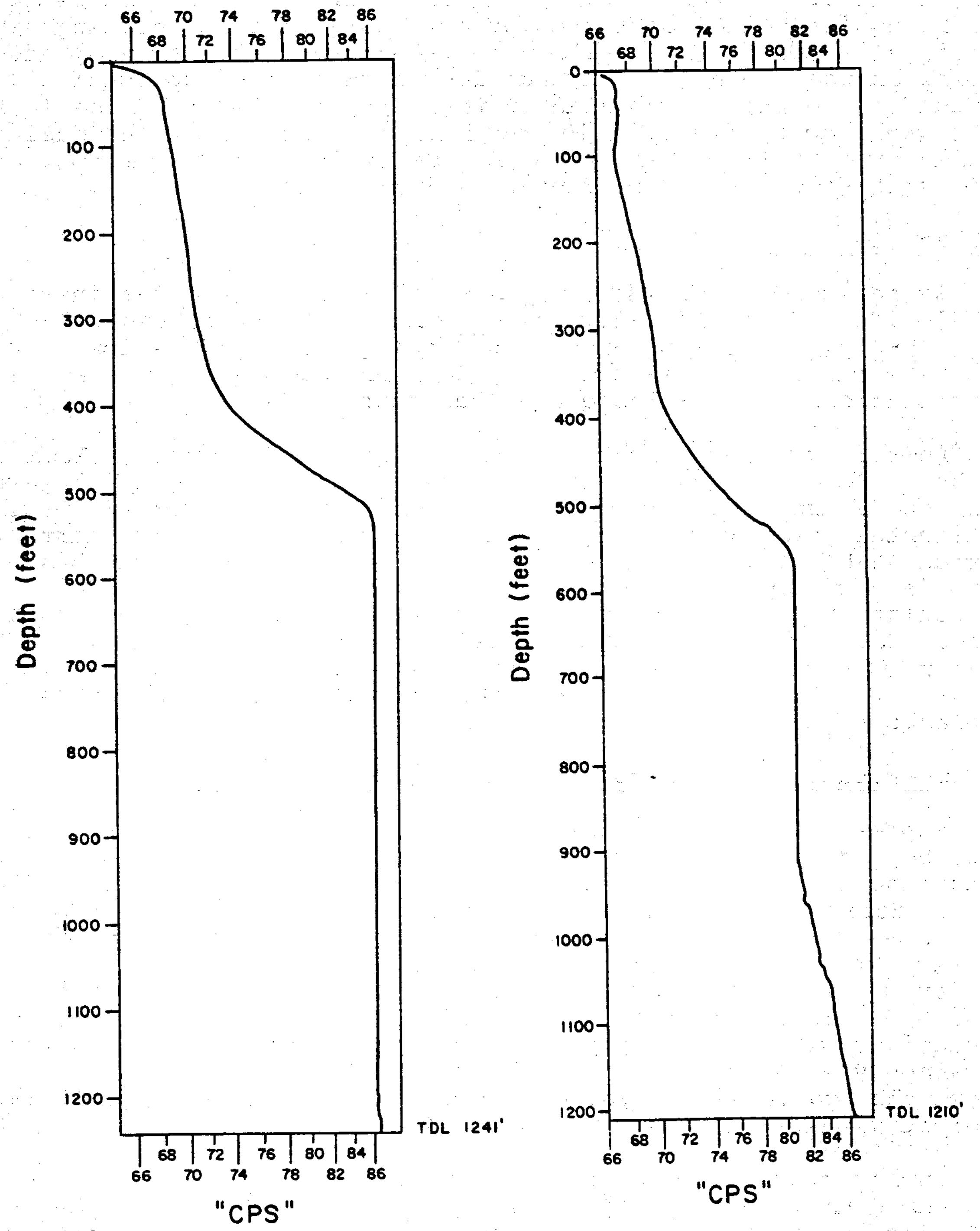


Figure 26. Temperature logs in Jacksonville area showing effect of convection in Floridan aquifer. Horizontal axis 'cps' is approximately equal to °F.

The temperature profile in a water supply well near East Palatka in Putnam County (Smith and Fuller, 1977) has least squares temperature gradients of approximately 26°C/km (91-274 m), 14°C/km (243-487 m), 1.9°C/km (426-487 m), and 16°C/km (100-487 m). According to Smith and Fuller, the depths of gradient discontinuities can be correlated to formational changes. Bottom-hole temperature was approximately 32°C (90°F) at 510 m (1673 ft), corresponding to an overall average geothermal gradient of approximately 20°C/km.

According to Leve and Goolsby (1969, p. 6), water from wells "greater than 305 m (1000 ft)" in depth in an area 40 km by 40 km (25 mi by 25 mi) approximately centered around Jacksonville and including the Naval Air Station, Jacksonville, and the Naval Air Station, Mayport, has a temperature of about 27°C (81°F). Well N-117 just north of Jacksonville was cased to 610 m (2000 ft) and left open at the bottom for approximately 45 m. Bottom-hole temperatures ranged from 29-31°C (84-88°F) (personal communication, Eugene Hayes, U.S.G.S). Well D-425 in downtown Jacksonville bottomed at approximately 760 m (2500 ft) and temperatures ranging from 28°C (82°F) to 31°C (88°F) were recorded (Hayes, personal communication). These wells bottomed in the Cedar Keys Limestone.

McClung and others (1979) described an excellent correlation between geothermal gradient logs and gamma logs in shallow holes (305 m) in the sediments of the Atlantic Coastal Plain. In clastic sequences, geothermal gradient logs and gamma logs might have a similar shape because high gamma-producing units tend to be predominantly clay, and clays have a low thermal conductivity so that the geothermal gradient is high. The trend is readily apparent in the plots of McClung and others (1979) for 35 test holes in the Atlantic Coastal Plain. Correlation of geothermal gradient and gamma logs over depth intervals containing clastic sediments should therefore help to distinguish between convective and conductive flow.

Numerical modeling studies of the type undertaken by Laczniak (1980) may eventually be of use in understanding the hydrology of the Floridan aquifer, but at present there does not appear to be enough basic data to make this practical.

i) Thermal conductivity.

Smith and Fuller (1977) obtained values of 5.2 TCU (1 TCU = 1 thermal conductivity unit = 10^{-3} cal/cm-sec-°C) from two samples of carbonate rocks from a depth greater than that penetrated by the Palatka hole, and from a location about 30 km (19 mi) west of Palatka. If these samples can be considered approximately representative of an average thermal conductivity in the Palatka hole, the heat flow would be about 1 HFU (1 HFU = 1 heat flow unit = 10^{-6} cal/cm^2-sec). As Smith and Fuller note, the uncertainty in heat flow based on this determination is large, but this value does appear to be in general agreement with background values for the southeastern Piedmont as reported by Costain and others (1982a).

j) Compilation and interpretation of available aeromagnetic data.

Aeromagnetic data for the southeastern United States have been compiled at a scale of 1:500,000 by Klitgord and others (1983, Plate 1) and Daniels and others (1983, Plate 1). See also Klitgord and Behrendt (1978). On both maps, Jacksonville lies at the west edge of an area of relatively low magnetic intensity. This coincides with a gravity low and may indicate a granitic body at depth below the Paleozoic strata.

k) Discussion of Virginia Tech "radiogenic model."

Virginia Tech has been involved in the evaluation and targeting of geothermal energy resources in the southeastern United States since 1977 (Costain and Glover, 1982a). The objectives of the geothermal program at Virginia Tech have been to develop and apply geological and geophysical targeting procedures for the discovery of low-temperature geothermal resources related to heat-producing granite. Optimum sites for geothermal development in the tectonically stable eastern United States are associated with areas of high heat flow derived from crustal igneous rocks containing relatively high concentrations of uranium (U), thorium (Th), and potassium (K). Exploration strategy has been directed toward confirmation of the "radiogenic model" (Costain and others, 1980a). In this model, granite plutons with relatively high concentrations of U, Th, and K relative to the surrounding country rock occur in the crystalline basement concealed beneath the wedge of relatively unconsolidated sediments of the Atlantic Coastal Plain. Such granites are sources of heat produced by the natural radioactive decay of isotopes of U, Th, and K (Birch, 1954). Because the thermal conductivity of the Coastal Plain sediments is roughly half that of crystalline rocks (Ziagos and others, 1976; Perry, 1979), the sediments act as a thermal insulator, and raise geothermal gradients within the sediments. In a sedimentary section above a heat-producing granite, isotherms are warped upward, and anomalously higher temperatures occur at shallower depths.

Very little is known about the nature of metamorphic crystalline rocks below the Paleozoic section in the Jacksonville area. No wells have penetrated to these depths. Because of the convective nature of the Floridan aquifer, heat flow determinations made above or in the Floridan aquifer appear to be unreliable. At this writing, it appears that the targeting strategy employed by Virginia Tech elsewhere in the eastern United

States would not be immediately applicable in the Jacksonville area. Lateral convection in the Floridan aquifer would tend to diffuse local concentrations of heat flow caused by radioactive granites in the crystalline basement. In any event, no samples of crystalline basement are available to define lateral trends in basement heat production, and the depth to basement may be too great to justify exploratory holes. Although the transmissivity of the Cretaceous and Paleozoic rocks below the Floridan system is unknown, if convective transport within the Floridan is important, then temperatures between the Floridan and crystalline basement are probably lower than if pure conductive heat transport were operating. This might mean an unattractive combination of low transmissivity (T) and lower than expected temperatures beneath the Floridan aquifer system. At the present time, with the sparse to nonexistent data base below the Floridan in the Jacksonville area, we do not envision a targeting strategy based on the basement-controlled radiogenic model.

1) Recommendations for future work.

1) Compilation of existing well data with regard to temperature profiles and available core.

2) Temperature logging of selected holes based on results of 1). Holes in the Jacksonville area should be logged for temperature at a relatively small depth interval (0.5 m). Differentiation of this temperature profile when sampled at a close depth spacing yields information about water movement in and across the hole. This procedure at the Savannah River test site yielded temperature gradient profiles which correlated well with fracture permeability as determined by pump tests made in crystalline basement rocks.

Virginia Tech has precision logging equipment consisting of a vehicle equipped with two independent logging systems, each with logging cable hoist and associated up-hole electronics and recording equipment; the hoists are electrically operated (110 V) with a portable Onan generator. Unit 1 is a Well Reconnaissance logger with 3000 ft of single-conductor cable and up-hole electronics to record natural gamma ray, self-potential, or single-point resistivity. Unit 2 is a Gearheart Owens logger with 8000 ft of Rochester-brand 4-conductor armored cable. Because of the finite shelf-life of cable, this needs to be replaced. Unit 2, used primarily for precision digital temperature logs, can be used for gamma ray and electric logs in holes deeper than 3000 ft that cannot be reached by the Well Reconnaissance unit. A Fluke Model 8500A multimeter is triggered by a Tektronics 4051 graphics terminal and microprocessor to sample a Fenwal thermistor (nominal resistance of 4000 ohms) at depth intervals of 0.5 m. Data are recorded on magnetic tape. The Tektronics 4051 is used for graphics plotting in the field and data transmission is via mobile telephone modem to the IBM 3081 computer at Virginia Tech in Blacksburg. Also available are a Rosemont Model 913AC constant-temperature bath and ice bath for calibration of probes.

3) Reprocessing of available proprietary seismic data. Proprietary reflection seismic data are available for the Jacksonville area. These data should be examined in New Orleans, and selected data segments purchased and reprocessed at Virginia Tech.

Our Reginal Geophysical Laboratory operates a full-time research VIBROSEIS crew. Our staff is therefore aware of all aspects of data acquisition as well as data processing. Processing is done on a VAX 11/780 with Digicon DISCO software.

4) Acquisition of new P-wave VIBROSEIS reflection seismology data. Much of the uncertainty regarding the nature of the geothermal resources in the eastern United States is due to lack of information about the geometry of the hydrothermal resource. Virginia Tech has found that the sediments of the Atlantic Coastal Plain from Georgia to Virginia contain a series of excellent reflectors, comparable to those commonly found in offshore reflection seismology data. Although reflection seismology is recognized as the most successful technique for defining the geometry of subsurface geology, the method has not been widely used on the Atlantic Coastal Plain to define the thickness and lateral extent of aquifers and aquitards primarily because it is relatively expensive ($170,000 to $200,000 per month). However, compared to the costs and results from drilling, reflection seismology has been underutilized. This is especially true where a few drill holes have penetrated the greatest depths of interest, but where stratigraphic correlations between drill holes are uncertain, even with a full suite of geophysical logs available. Reflection seismology traverses can provide the necessary continuity between drill holes in areas where stratigraphic and/or structural discontinuities make subsurface interpretation difficult or impossible.

The Jacksonville area may offer a special set of problems for P-wave reflection seismology because of the presence of near-surface carbonates. Degradation of P-wave data is common under these circumstances; for example, in the folded Appalachians the onset of near-surface carbonates is coincident with the disappearance of reflections. Use of shear wave data has had some remarkable successes (Domenico, 1983; Robertson, 1983; Robertson and Pritchett, 1983) over the past five years in obtaining data over hard (carbonate) surfaces, but it is not known if shear sources will be as effective in areas of karst topography. Much of the proprietary shear data of petroleum companies is just now appearing in the literature (Laing, 1983a, 1983b).

If logistics permit, we recommend a short experimental shear wave line to supplement the P-wave data. Acquisition of shear wave data is usually done only on secondary roads or off roads because of road damage caused by the shear vibrator. Access to a relatively remote part of a military installation might offer an opportunity to investigate the potential contributions from shear recording.

A recent summary publication by Prowell (1983) documents the widespread occurrence of faulting in sediments of the Atlantic Coastal Plain. The data in his report represent the presently available knowledge of fault characteristics and distribution of Cretaceous and younger faults in the eastern United States.

In the Jacksonville area, fault No. 79 (81° 40', 30° 20', Orange Park quadrangle) is located in the downtown Jacksonville area just east of the junction of U.S. routes 90 and 1 along the St. Johns River (Leve, 1966, p. 19-20). The fault is described as vertical (?) and striking N12°E. The sediments affected by faulting are the clayey sands of the Hawthorne Formation (Miocene), limestone of the Ocala Group, and the Avon Park Limestone (Eocene). The greatest vertical displacement (apparent offset) is given as 38 m (125 ft). The structural marker horizon is the top of the Avon Park Limestone (Eocene). The fault is recognized in drill hole data from water wells in the vicinity of Jacksonville. The east side is down. The fault extends from northern Clay County, through Jacksonville to northern DuVal County. Similar faults are undoubtedly still undiscovered and may significantly affect the size and distribution of convection cells in the Floridan aquifer system. Unknown fault geometry can affect predictions of well yields and the behavior with time of hydraulic heads associated with confined and semi-confined aquifers.

We propose to acquire 24-fold reflection seismic data at a station spacing of approximately 35 m near and on the U.S. Naval Air Station.

5) Generation of synthetic seismograms. A common approach to the interpretation of reflection seismology data is through the comparison of synthetic data generated from continuous velocity logs (CVLs) obtained in drill holes with actual multifold reflection seismology data. A reflectivity function is generated from the CVL by taking the derivative of the log of the "velocity function" as a function of time (Sengbush and others, 1961). The reflectivity function is then convolved with the seismic source wavelet (a Klauder wavelet for the case of VIBROSEIS data). The result is a multiple-free synthetic seismogram which can then be compared with the real seismic data. We suggest that all sonic logs (CVLs) available from wells in the Jacksonville area be digitized and reflectivity functions and synthetic seismograms be constructed for comparison with real data.

6) New drill holes for determination of temperature gradients and heat flow. The size and distribution of convection cells in the Floridan aquifer are unknown. Upwelling water will be

warmer than water circulating downward. These are therefore possibly better locations to develop a geothermal resource. We suggest that the determination of the nature of convection in the Floridan system is important, and can be investigated using a combination of reflection seismology and high-resolution temperature gradient profiles supplemented by the large data base and expertise of the individuals mentioned in this report. At this time, it appears that predictions of temperature in new deeper holes extending below the Floridan aquifer system might be significantly affected by the hydrology of the overlying Floridan aquifer.

ECONOMIC ANALYSIS FOR GEOTHERMAL ENERGY USE AT JACKSONVILLE NAVAL AIR REWORK FACILITY

SUMMARY

A study of the Jacksonville NARF shows that a small well with an average flow rate of only 88 gal/min could preheat the make-up water to save 1.8×10^{10} Btu of fuel per year and reduce fuel costs by $53,000 per year. A larger well producing an average flow of 300 gal/min could supply additional heat directly to individual buildings for space heat in the winter and heating dehumidified air in the summer. This would save 6.3×10^{10} Btu of fuel per year and reduce the annual fuel costs by $181,000. However, these energy savings would not come without a price. An investment of approximately $1,200,000 would be required and there are some risks. The two major risks are (1) the geothermal water flow rate could be lower than expected since no flow rate tests have been conducted in Florida, and (2) drilling costs could be higher than expected since the subsurface limestone is likely to have voids that can cause lost circulation of drilling fluid and increase drilling costs.

Geothermal energy at Jacksonville NARF could be implemented economically if the flow rates are greater than 200 gal/min and extraordinary well drilling costs are not incurred. Since drilling costs are a large portion of the geothermal system cost, it is important that they be thoroughly investigated.

JACKSONVILLE GEOTHERMAL SYSTEM DESIGN

Three naval facilities were visited in the north-central Florida area. Their yearly energy usages are Jacksonville NARF, 870×10^9 Btu; Cecil Field NAS, 280×10^9 Btu; and Orlando Training Center, 190×10^9 Btu. A central steam power plant supplies most of the energy needs for the Jacksonville NARF, and 38% of the condensed steam is returned. The central power plant at Cecil Field supplies only half the heating needs of the facility and 80% of the condensate is returned. In Orlando, heating is decentralized in individual units. Of these three facilities the Jacksonville NARF is the most promising since it uses the most energy, has a central power plant, and returns less condensate to the boiler. All of these factors make it desirable as a geothermal energy user.

The Jacksonville NARF is located in a region with a slightly below average temperature gradient. However, its impermeable basement rock is relatively deep at 4900 ft, giving it a relatively high potential geothermal water temperature of 124°F. The subsurface material is limestone, which extends from the surface to the basement. Depths below basement rock have not been considered in this study since no naturally occurring water flow is anticipated there. The hot-dry-rock fracturing process currently under study (Cummings, 1982; Smith and Ponder, 1982) is not considered practical at this time. Additional testing is required to determine the feasibility of this method of tapping the earth's geothermal energy.

Most of the energy used at Jacksonville NARF is electrical. Most of the remaining energy needs are supplied by 125-psi steam, generated in a central power station that can burn either #6 fuel oil or natural gas on an interruptable basis. With natural gas in plentiful supply at a cost of only \$3.11 per 10^6 Btu, nearly all of the steam produced in the last 3 years has been generated with natural gas. Steam production in 1981 (Figure 27) was 89 x 10^6 lb per month at the peak in January and leveled off to 39 x 10^6 lb per month during the warmer months from April to October. A relatively large amount of steam is used in the summer months to reheat the air after the air conditioning units cool it to lower its humidity. The total steam generated in 1981 was 612 x 10^6 lb. At a pressure of 125 psi, the energy content of steam is 1075 Btu/lb, and the total energy of the steam generated in 1981 was 660 x 10^9 Btu. If even a small percent of this energy were replaced with geothermal energy, the amount of natural gas saved would be substantial.

ECONOMIC ANALYSIS FOR JACKSONVILLE NARF

The Jacksonville NARF currently generates steam for the facility in a central boiler and distributes it at 125 psi to users on the base. At present approximately 38% of the condensed steam is recovered and returned to the boiler at approximately 135°F. A geothermal well can be incorporated into this system as shown in Figure 28. The geothermal hot water would be used to preheat the make-up water for the boiler. This system would have several advantages over using the geothermal well water in individual buildings. It would require only one heat exchanger, need less overall floor space, and be easier to maintain. In addition, heating individual buildings would require water to air heat exchangers, which are larger and more expensive. For the conditions given in Figure 28, geothermal energy would provide 18 x 10^9 Btu (nearly 3% of the total energy use) and save \$56,000 of natural gas per year at current natural gas prices of \$3.11 per million Btu.

If the geothermal well is capable of supplying more than an average flow of 88 gal/min, the additional water can be used directly in individual buildings to heat the air as shown in Figure 29. On a per Btu basis this system is not as cost effective as the application of preheating make-up water since additional piping and water to air heat exchangers are required.

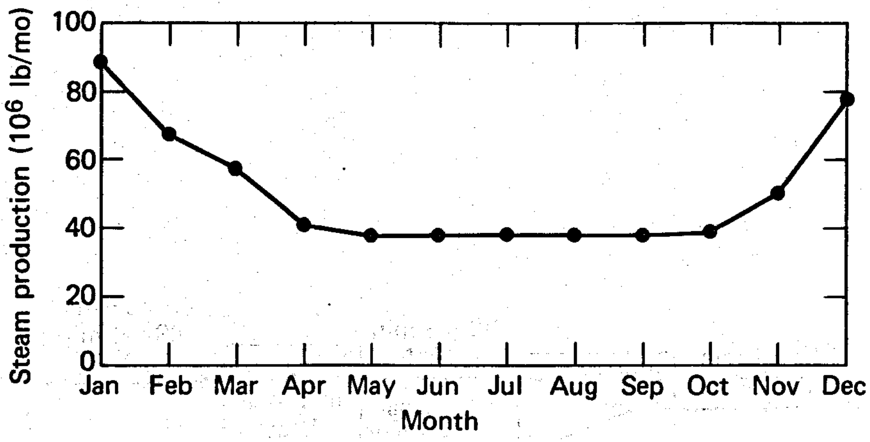


Figure 27. Jacksonville NARF monthly steam production--1981.

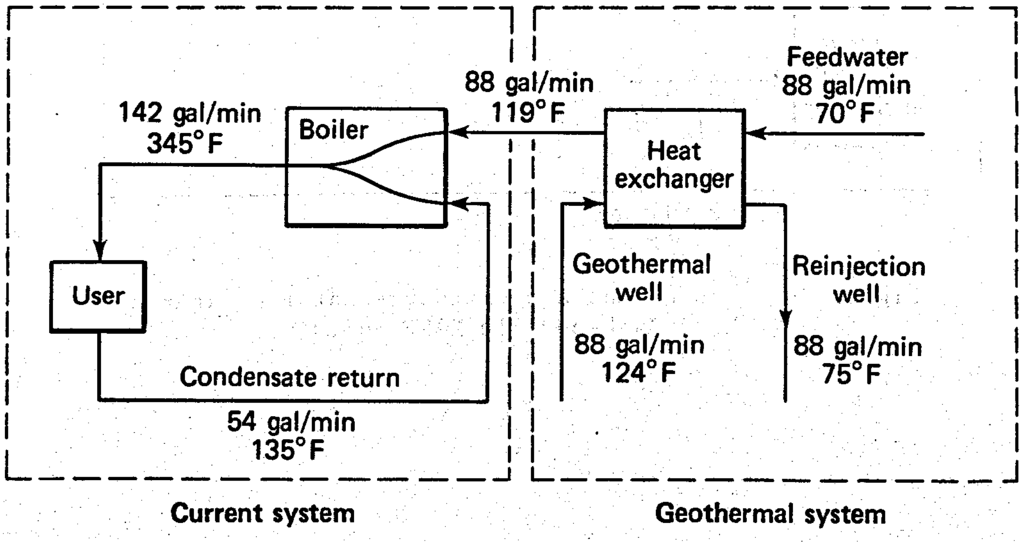


Figure 28. Geothermal system to preheat feedwater at Jacksonville NARF.

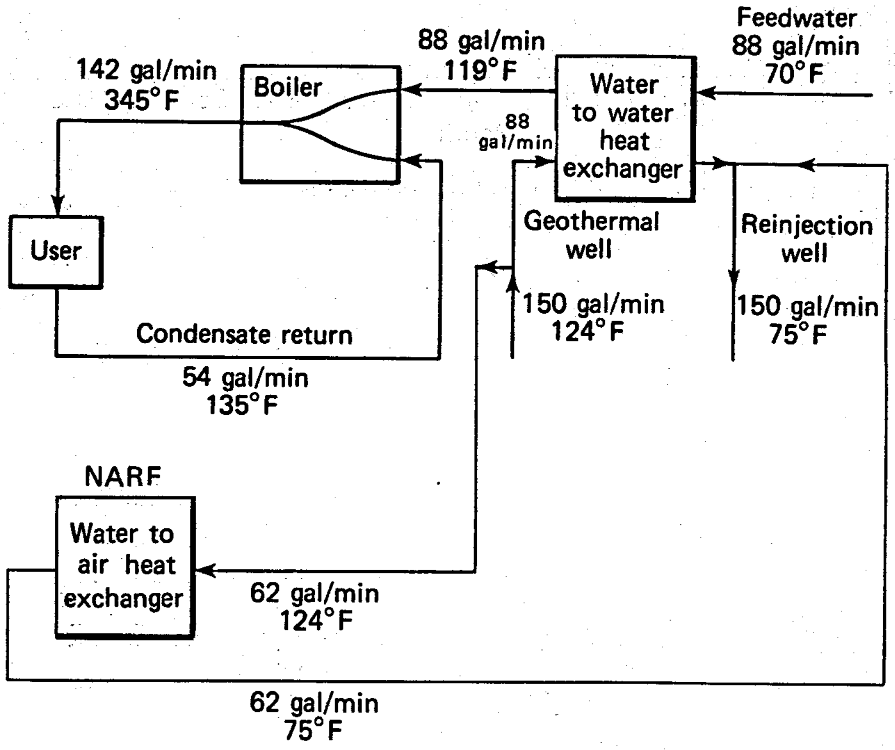


Figure 29. Geothermal system to preheat feedwater and heat Jacksonville NARF building.

ECONOMIC PARAMETERS

The evaluation of a geothermal system is complicated by the fact that the well characteristics are not known precisely, but instead fall in a probable range of values. This is especially true in the Jacksonville area, where geothermal test wells have not been drilled. Some of the well characteristics that are not precisely known are

1. Water flow rates
2. Drilling costs
3. Drawdown depth
4. Water temperature

Other important parameters that are not associated with the geothermal well but that are subject to change with time over the life of the well are

5. The cost of fuel (i.e., natural gas and/or #6 fuel oil)
6. The cost of money
7. The inflation rate
8. Operating and maintenance expenses

Parametric analyses were performed using best estimated values for parameters 2, 6, 7, and 8 and a range of values for parameters 1, 3, 4, and 5. The present value method has been used to evaluate the value of a geothermal system. In this method future income and expenses are discounted by the time value of money to the Navy. For example, at a time value of money of 10% per year, $20,000 to be received 10 years from now is equivalent to $7710 received today. The present value indicates how much one can afford to spend for a geothermal system based on the value of its future net income.

The present value analysis was performed using as a baseline the estimated characteristics of the geothermal system presented in Table 11. In the calculation, the fuel costs and operating expenses are assumed to increase at the inflation rate. The calculated net present value is $800,000. Consequently, if a geothermal system can be implemented for less than $800,000 it is economically advantageous to construct it. This, of course, assumes that the conditions presented in Table 11 apply to the well. Figure 30 shows the effect of varying some of these conditions. In this figure the well temperature is varied from 100°F to 140°F and the flow rate varies from 50 to 300 gal/min. The

Table 11. Estimated Geothermal System Characteristics for Jacksonville NARF.

Water flow rate (gal/min)	150
Drawdown depth (ft)	750 (15% of well depth)
Water temperature (°F)	124
Cost of money (%)	10
Inflation rate (%)	5
Cost of fuel (M Btu)	$3.11
Cost of electricity (M Btu)	$11.70
Annual operating and maintenance costs	$20,000

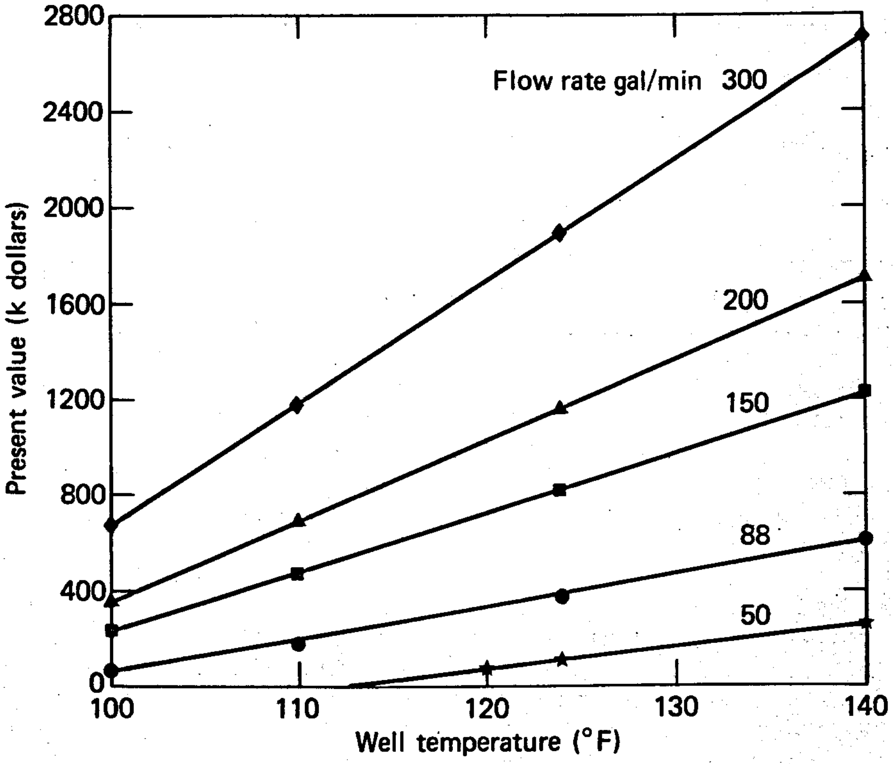


Figure 30. Present value of geothermal energy as a function of well temperature and flow rate (Jacksonville).

nominal well water temperature of 124°F was determined from an extrapolation of surface temperature gradients. Since subsurface material is under greater pressure loading than at the surface, it often has a higher conductivity and lower temperature gradient. This effect could lower the predicted well temperature several degrees. From Figure 30 the present value decreases linearly with well temperature. A decrease of 4°F decreases the present value by 12%.

The effects of varying flow rate also have a pronounced effect on present value. Water flow rates are not as predictable as temperature, and flow rates ranging from 0 to 300 gal/min and greater are possible. One hundred and fifty gal/min was chosen as a nominal value. However, since geothermal test wells have not been drilled in this area, it is difficult to predict a flow rate. At 150 gal/min and 124°F well water, the net present value is $800,000. At 300 gal/min, the present value increases to $1,900,000. The risk factor associated with the flow rate is not negligible and must be taken into account in any decision to develop a geothermal system.

The effects of drawdown depth and cost of natural gas are shown in Figure 31. Increasing the drawdown depth increases the cost of pumping water from the well. At the nominal gas price of $3.11/MBtu, increasing drawdown depth from 10 to 20% of the well depth (i.e., 500 to 1000 ft) reduces the net present value by 18%. The benefits of increasing drawdown depth to increase well flow rate will have to be weighed against the increased pumping costs, to determine an optimum drawdown depth for the well.

The future price of natural gas has a strong influence on the net present value of the geothermal system (Figure 31). With the recent excess of natural gas and the pending decontrol of natural gas prices, it is difficult to predict future natural gas prices.

JACKSONVILLE SYSTEM COSTS

The proposed geothermal system shown in Figure 29 consists of a geothermal well 4900 ft deep, a downhole pump, a water to water heat exchanger, air to water heat exchangers, a reinjection well, and piping connecting these components.

Well costs and downhole pump costs have been obtained from cost estimates developed by Gruy Federal (Herron, 1982). This company has an excellent background in geothermal drilling, having drilled 50 geothermal test holes 300 m (1000 ft) deep to measure heat flows along the Atlantic Coastal Plain, under the sponsorship of DOE. In addition, it has drilled a research well 1695 m (5562 ft) deep and tested three production zones (Gruy Federal, Inc., 1979).

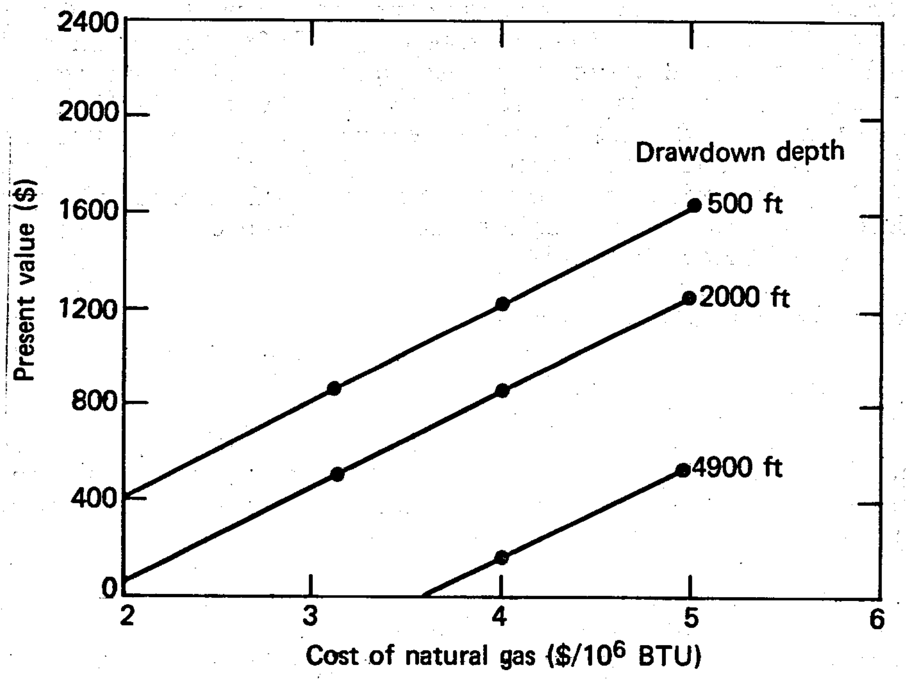


Figure 31. Present value of geothermal energy as a function of drawdown depth and the cost of natural gas (Jacksonville).

Well costs are divided into three categories: (1) depth-independent costs of the production and reinjection wells, (2) depth-dependent production well costs, and (3) depth-dependent reinjection well costs. In the first category the cost breakdown in 1980 dollars is as follows (Herron, 1982):

Insurance	$ 10,000			
Site work	20,000			
Wellhead equipment	20,000			
Gravel pack	35,000			
Flow testing	135,000			
Engineering fees	100,000			
Downhole pump (750-ft drawdown)	20,000	(88 gal/min)	45,000	(300 gal/min)
	$340,000		$365,000	

In the second category the depth-dependent production well costs for a 5000-ft well are

Mobilization	$ 40,000
Rig time	100,000
Bits, mud, chemicals, fuel, and water	20,000
Miscellaneous rentals	20,000
Logging	45,000
Cementing	45,000
Tubulars	255,000
	$525,000

Note that these costs are estimates for drilling along the Atlantic Coastal Plain between Georgia and New Jersey. Drilling costs in Jacksonville may be even greater due to the fact that the drilling will be in limestone, which has voids that can cause lost circulation. Difficulties with lost circulation could easily increase rig time costs by $100,000.

The fresh water aquifer in the Jacksonville region extends 2200 ft; therefore, a reinjection well must be at least 2200 ft deep to keep salt water out of the fresh water supply. For cost estimate purposes, a depth of 3000 ft has been chosen. The depth-dependent reinjection well costs are

Rig time	$ 50,000
Bits, mud, chemicals, fuel, and water	20,000
Rentals	10,000
Logging	30,000
Cementing	30,000
Tubulars	110,000
	$250,000

The total cost of both wells is $1,115,000. Excluding downhole pump costs, this is an average cost of $130 per foot. This is relatively high compared with some estimates. For example, predicted drilling costs for a 1980 study at Norfolk NARF (Smith and Ponder, 1982) are $75/ft. This is more in line with current oil and gas drilling costs. Geothermal wells on the Atlantic Coastal Plain may eventually come down to this value. However, other sources use drilling cost comparable to $130 per foot (U.S. Department of Energy, 1982; Kestin). The Gruy Federal estimate is probably more realistic for the first few geothermal wells to be drilled, especially in Jacksonville where lost circulation could be a problem.

The water to water heat exchanger cost (Johns Hopkins University, 1979) in 1980 dollars is

$$0.057\ (Q)^{0.84}$$

where Q is the heat exchanger throughput in Btu/hr. At a well water flow rate of 88 gal/min,

$$Q = 18 \times 16^{9} \text{ Btu/yr}$$

$$= 2 \times 10^{6} \text{ Btu/yr}$$

therefore, the water to water heat exchanger in Figure 29 costs $11,400.

The water to air heat exchanger in Figure 29 costs $28,000. On a per Btu basis, this is three times as much as the water to water heat exchanger (Johns Hopkins University, 1978). The cost of piping required to carry the water to NARF building 1000 and back to the reinjection well is an additional $46,000 (Naval Facilities Engineering Command, 1981).

The total cost for the system shown in Figure 28 producing at 88 gal/min is $1,126,000 (Table 12). The projected net present value of this system is only $350,000. For a system producing

Table 12. Jacksonville Geothermal System Cost and Net Present Value.

	88 gal/min	150 gal/min	300 gal/min
Production well depth independent	$340,000	$340,000	$340.000
Production well depth dependent	525,000	525,000	525,000
Reinjection well (3000 ft) 11,400	250,000	250,000	250,000
Heat exchangers and piping	11,400	85,400	195,000
Total Cost	$1,126,400	$1,200,400	$1,310,000
Net Present Value	$350,000	$817,000	$1,900,000

150 gal/min (Figure 29) the total cost is $1,200,400 and the net present value is $817,000. If the system shown in Figure 29 could produce 300 gal/min the cost would increase slightly to $1,310,000, but the net present value would increase greatly to $1,900,000. At a flow rate greater than 210 gal/min the geothermal system is economical (Figure 32). It is clear that water flow rate is an important parameter and greatly influences the viability of the geothermal system.

LEGAL CONSIDERATIONS

The city of Jacksonville and DuVal County have an ordinance prohibiting the use of aquifer water for the primary purpose of a heat source or a heat sink. This ordinance does not apply to geothermal wells, however, since they are below the fresh water aquifer, which extends to 2200 ft.* Therefore, the supply well does not require approval of the City of Jacksonville Environmental Protection Board. According to section 554.213 of the code, the reinjection well will require approval of the Board and will also need to be approved by the St. Johns River Water Management Center. No problems are anticipated as long as the reinjection well is below the fresh water aquifer level of 2200 ft.

CONCLUSIONS

Implementation of a geothermal system at the Jacksonville NARF looks economically feasible, if flow rates above 210 gal/min can be attained and unexpected drilling costs are not incurred. Flow rates of 210 gal/min are possible, although it is difficult to predict flow rates in advance since no wells have been drilled and flow rate tested at the depths being considered.

Unexpected drilling costs due to lost circulation could increase geothermal system cost. This extra cost is a risk factor that must be fully evaluated prior to developing a geothermal system at the Jacksonville NARF.

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*Telephone conversation with Gary Weise, Jacksonville, Fla., City Water Department.

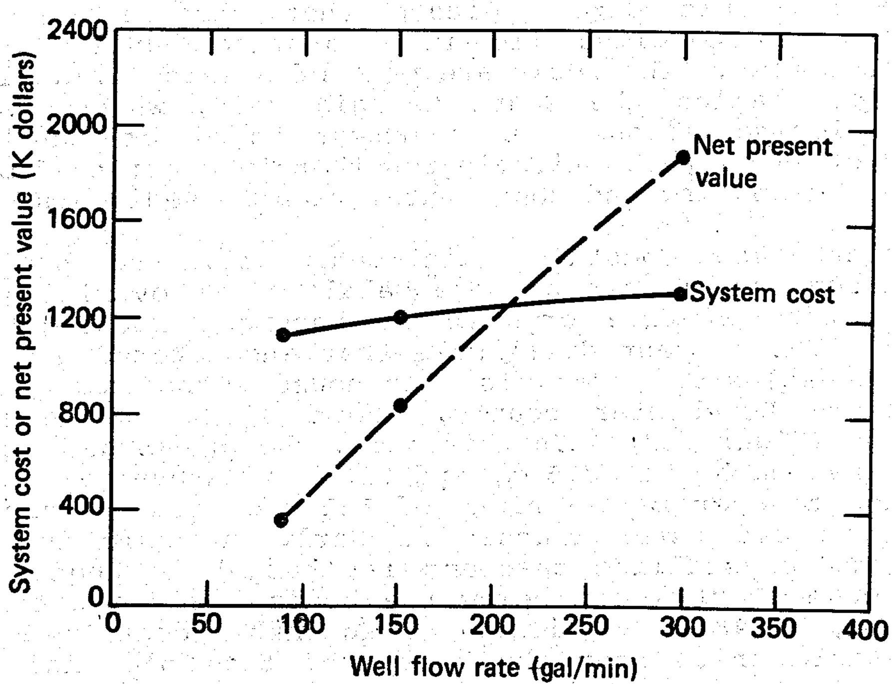


Figure 32. System cost and net present value as a function of well flow rate (Jacksonville).

GEOPHYSICAL AND GEOLOGICAL ASPECTS OF GEOTHERMAL ENERGY POTENTIAL AT CHARLESTON

a) Geologic framework.

Charleston lies on the Atlantic Coastal Plain. Although relatively few holes have been drilled to basement in the Coastal Plain sediments of South Carolina, basement lithologies can be inferred from geophysical data and scarce drill core samples.

The available data indicate that the basement rocks of southern South Carolina lie in a province unlike any in the exposed Piedmont. The rocks are part of a large Triassic-Jurassic rift basin, called the South Georgia rift, which extends from western Florida across the southern third of South Carolina (Daniels et al, 1983). Lithologies therein consist of basalts and rhyolites, diabases, and continental clastic sediments.

Beneath the Coastal Plain sediments, the pre-Cretaceous basement consists of one or more basalt flows overlying red beds, which in turn overlie crystalline basement rocks of uncertain affinity. The deepest drill hole that encountered basement rocks in the Charleston area is Clubhouse Crossroads No. 3 in southwestern Dorchester county, about 40 km west-northwest of Charleston (Figure 33). In this hole, the pre-Cretaceous basement surface was reached at 775 m, and 256 m of subaerial basalt flows were found to overlie a minimum of 121 m of sedimentary red beds. These units are Late Triassic to Early Jurassic in age (Gohn, 1983). The crystalline basement is thought to underlie the red bed sequence about 100 m below the bottom of the hole at 1150 m (Ackermann, 1983). Lithic fragments contained in the conglomeratic units near the bottom of the hole, and presumably derived from the crystalline basement, consist of granodiorite, mylonite, microbreccia, and basalt (Gohn, 1983).

Seismic studies in the Charleston area (Ackermann, 1983) suggest that the surface of the pre-Mesozoic crystalline basement has large relief. Between Clubhouse Crossroads No. 3 and Charleston, though, the surface dips gently toward the southeast, reaching a depth of roughly 2500 m at Charleston (Ackermann, 1983).

b) Thickness of Coastal Plain sediments.

The thickness of Cenozoic and Upper Cretaceous sediments at Clubhouse Crossroads is 750 m (2462 ft) (Gohn and others, 1978). This is the thickness (at this location, about 20 km northwest of Charleston) that might contain aquifers of sufficient transmissivity for useful geothermal applications. Although actual hydrologic data are lacking, below 750 m the information available indicates that the hydraulic conductivity of the rocks is too low to recover adequate amounts of water. Figure 34 is a

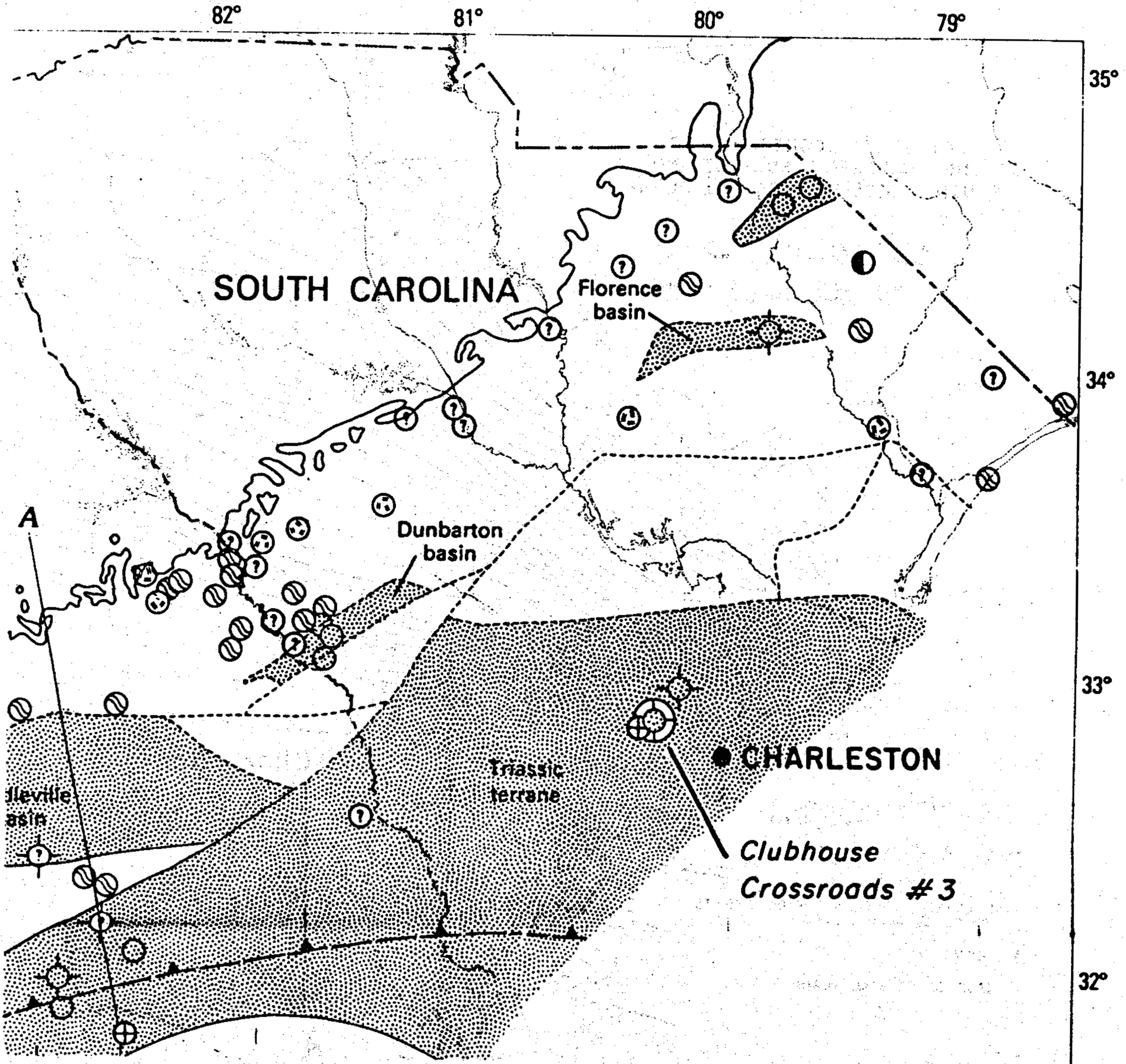


Figure 33. Geologic map of the basement of southern South Carolina (from Chowns and Williams, 1983).

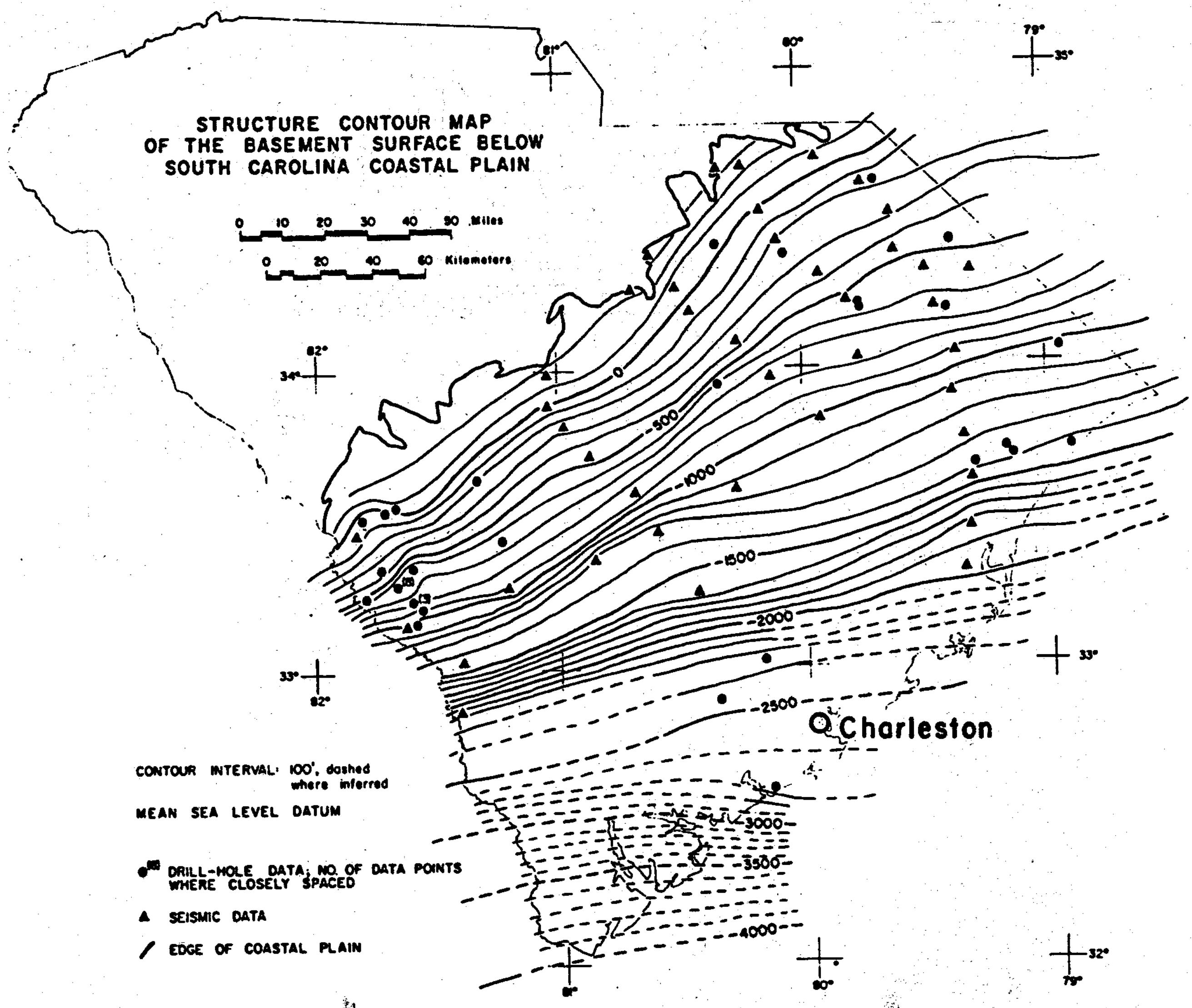


Figure 34. Structure contour map of the basement surface below the South Carolina Coastal Plain (Gleason, 1982).

structure contour map of the basement surface in the Charleston area (from Gleason, 1982).

c) Intrinsic permeability and other hydrologic properties.

Relative intrinsic permeabilities of the Mesozoic aquifer systems in Georgia and South Carolina are summarized in Table 13 from Brown (1979a). As in Virginia, hydrologic tests of deep aquifers are lacking.

The intrinsic permeability of the sediments beneath Charleston is moderate to poor. Brown and others (1979) evaluated the Mesozoic aquifers of the southeastern United States in search of potential waste-storage units. They uniformly assigned sand/shale ratios less than 1, which is indicative of limited permeability. The data base is inadequate, however, and hydrologic properties of the deeper aquifers are poorly known.

d) Probable basement lithology beneath Charleston area.

The investigation of low-temperature geothermal energy resources in the Atlantic Coastal Plain relies upon an understanding of (1) the lithology and structure of the crystalline rocks ("basement") below the Coastal Plain sediments and (2) the thickness and lithology of the overlying sediments. The former types of data, basement lithology and structure, are necessary to interpret the heat production from basement heat sources, while the latter type of data concerning the overlying sediments are fundamental to the evaluation of the insulating properties of the Coastal Plain sedimentary sequence.

Basement depth and lithologic information may be obtained from geophysical data such as seismic investigations and regional gravity or magnetic studies, or through subsurface drilling data. A considerable amount of drilling data has been published in the geologic literature, including professional journals, oil and gas exploration reports, U.S. Geological Survey publications, and state survey publications.

A considerable portion of the pre-Coastal Plain surface in South Carolina is comprised of arkosic sedimentary rocks or basalts highly suggestive of rocks exposed in the Triassic-Jurassic grabens of the eastern United States (Marine and Siple, 1974; Marine, 1974; Gottfried et al, 1977; Popenoe and Zietz, 1977; Gohn et al, 1978). For the purpose of this compilation, these rocks are considered as pre-Cretaceous basement.

Thirty-six wells drilled through the entire Coastal Plain sedimentary sequence have been included in the South Carolina compilation (Figure 34). These wells are unevenly distributed across the South Carolina Coastal Plain, with a large number

Table 13. Lithologic Facies and Relative Intrinsic Permeabilities for Mesozoic Aquifer Systems in Georgia and South Carolina (from Brown, 1979).

	Aquifer system H(?)	Aquifer system G(?)	Aquifer system F	Aquifer system E	Aquifer system D	Aquifer system C	Aquifer system B	Aquifer system A
Total volume[1]	583	872	4,875	852	4,496	2,648	3,146	3,410
Total area[2]	4,678	6,257	60,000	30,725	48,090	55,590	50,050	50,450
Percentage of aquifers containing usable ground water								
Volume	0	0	57	48	89	76	87	90
Area	0	0	73	55	85	84	86	88
Aquifers containing usable ground water								
Volume	0	0	2,795	409	4,023	2,009	2,735	3,061
Area	0	0	43,681	17,072	40,850	46,714	42,818	44,626
Aquifers containing non-usable ground water								
Volume	583	872	2,080	443	473	639	411	349
Area	4,678	6,257	16,319	13,653	7,240	8,876	7,232	5,824

[1] Volume - mi^3

[2] Area - mi^2

clustered near the Savannah River atomic energy facility in the southeastern part of the state. Descriptions of basement lithology have been found for twenty-six of the thirty-six wells. Depths to basement have been compiled for all thirty-six of the wells.

e) Gravity data.

The Charleston area is one of the most intensively studied areas in the eastern United States because of the studies related to the Charleston earthquake of 1886 (Rankin, 1977; Gohn, 1983). The relative density of gravity stations is high (Figure 35). Correlation of local anomalies with basement rock type is uncertain because of the lack of basement core.

f) Seismic data.

Results of the first seismic work in the Charleston area were published by Yantis and others (1983). This work was followed by more modern recording and processing techniques (Coruh and others, 1981). Available seismic lines in the Charleston area are shown in Figures 36 and 37. The lines shown in Figure 37 are VIBROSEIS lines shot by Virginia Tech as part of a cooperative program with the U.S. Geological Survey. Preliminary results have been published (Coruh and others, 1981). Results from the COCORP reflection seismic data have been published in Gohn (1983).

The meizoseismal area of the 1886 earthquake was located just northwest of Charleston, and most of the seismic lines are in this area. These lines are close enough to Charleston to conclude that the quality of any new data acquired in Charleston will be excellent. Like the Coastal Plain of Virginia, the quality of the onshore data approaches or exceeds that of offshore data. Arguments similar to those made for acquiring seismic data in Virginia can also be made for the Charleston area. Aquifer transmissivities can be determined from seismic data; faulting, if present, can be detected by conventional reflection seismic methods. Non-standard methods such as shear recording that are still in the experimental stage can be used to advantage in this area because an excellent P-wave data set (Coruh and others, 1981) already exists for comparison with shear data that could be acquired.

g) Heat flow sites.

A heat flow determination for the South Carolina Coastal Plain was made by Sass and Ziagos (1977). The plot of the gradient along with the tabulated thermal conductivities are reproduced in Figure 38. No heat flow values are available in the immediate area of Charleston. Sass and Ziagos (1977) report the heat flow as 1.3 ± 0.2 HFU (1 HFU = 10^{-6} cal/cm^2-sec) (or 54 ± 8.4 mW/m^2), for which they conclude that no thermal anomaly exists at this site.

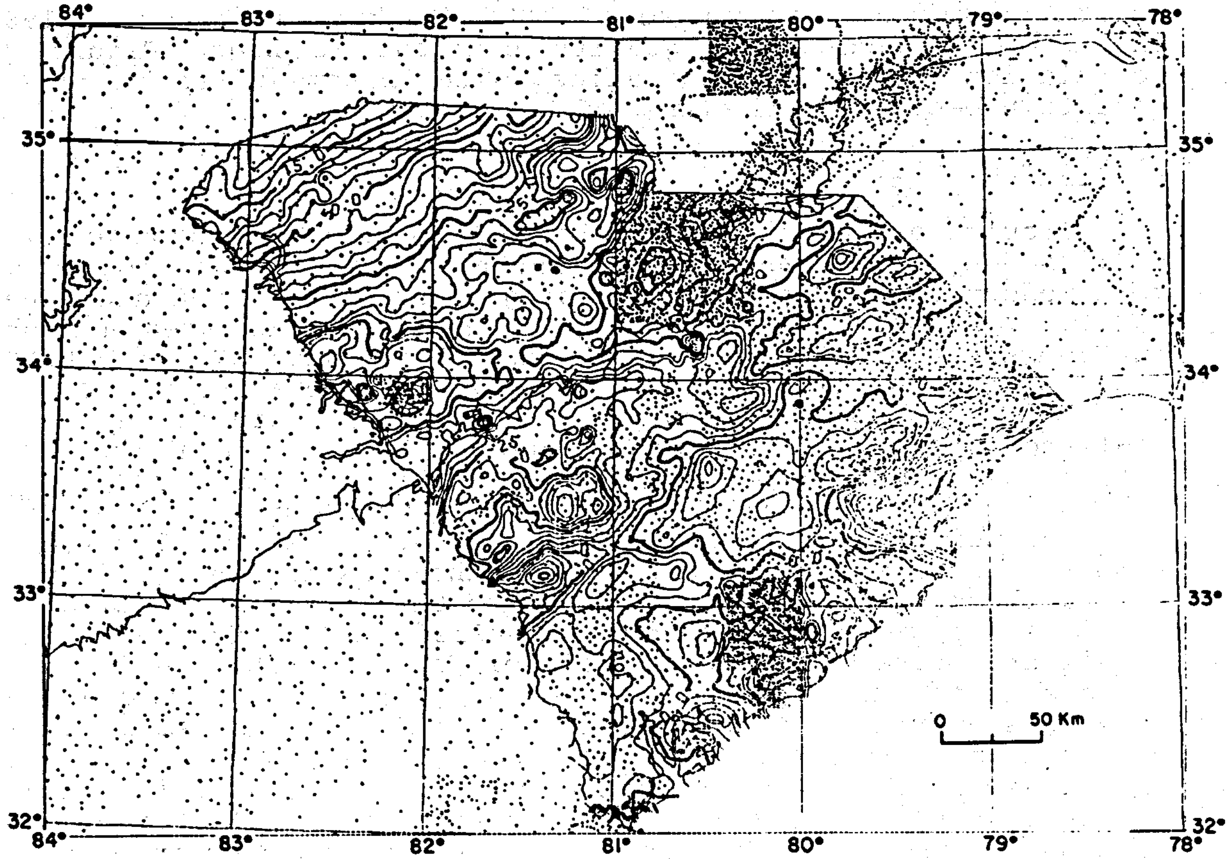


Figure 35. Distribution of gravity stations and Bouguer anomaly map of South Carolina. Contour interval 5 mgals (from Costain and Perry, 1982).

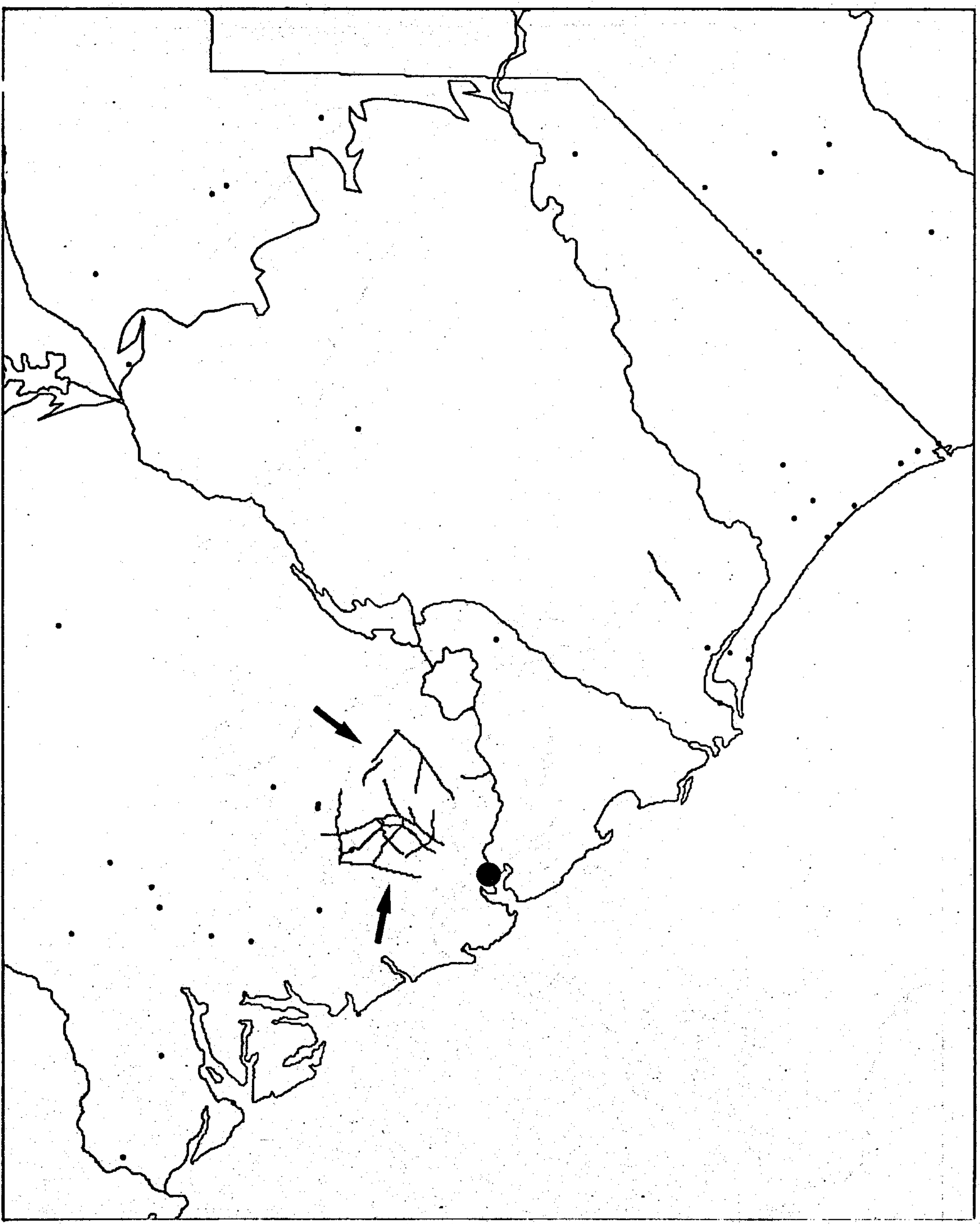


Figure 36. Seismic lines (including GSI) in the Charleston area.

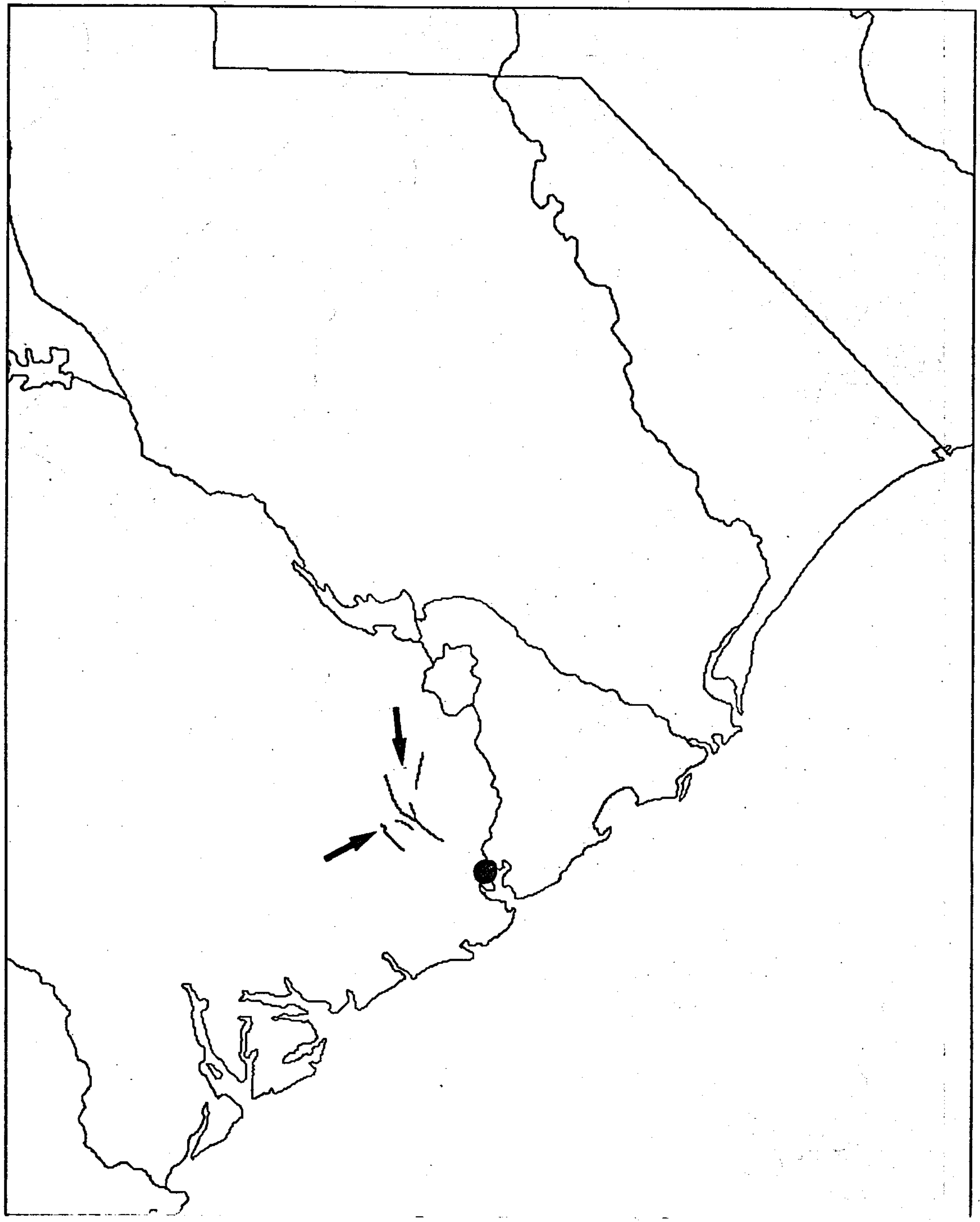
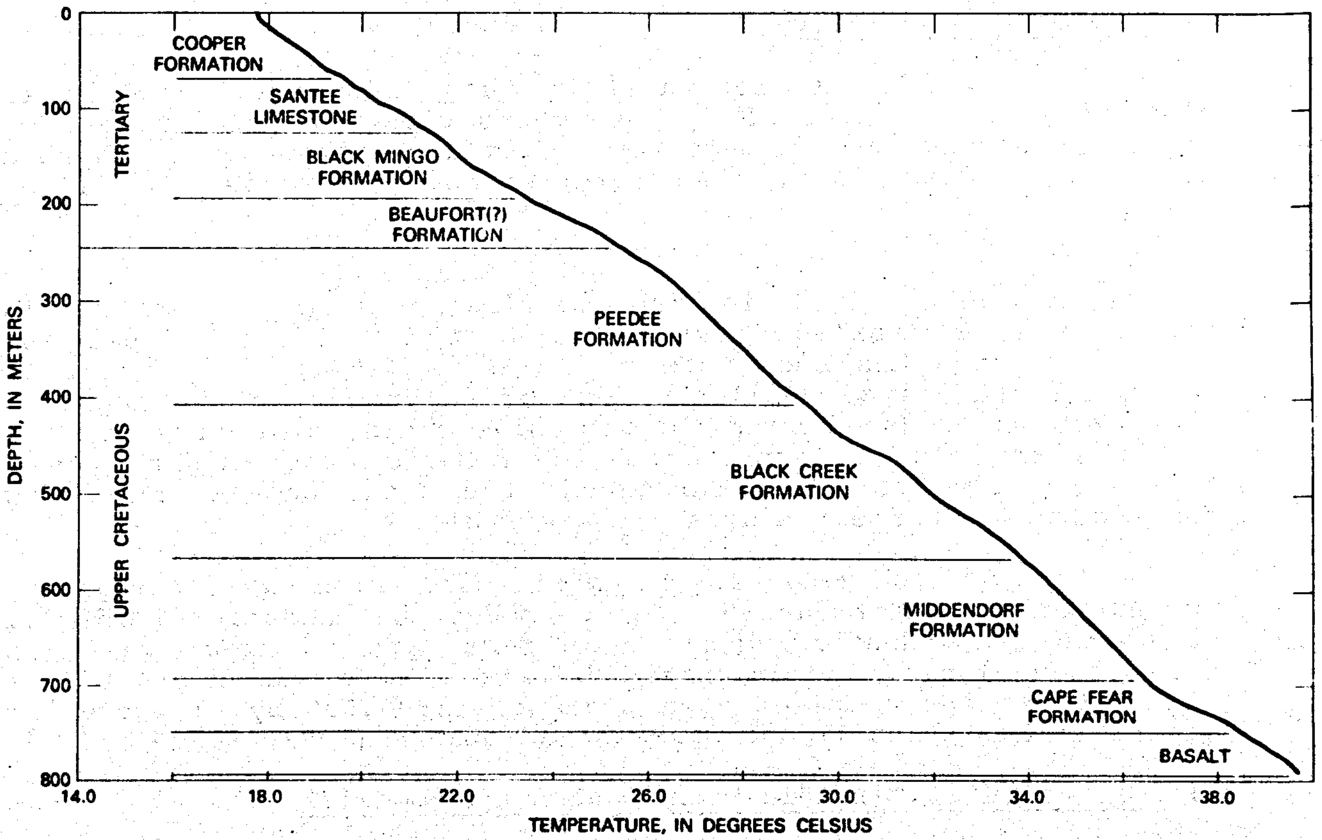


Figure 37. Seismic lines (arrows) shot by Virginia Tech in Charleston area.



Temperature versus depth in Clubhouse Crossroads corehole 1. Temperatures were measured at 3-m intervals. Lithologic column based on figure 2 of Gohn and others, this volume.

Figure 38. Temperature versus depth in Clubhouse Crossroads corehole No. 1 (from Sass and Ziagos, 1977).

h) Temperatures, temperature gradients, and gamma logs.

Several Coastal Plain gradient holes were drilled and completed by Virginia Tech during the fall and winter of 1980. Holes C10 at Charleston, S.C., and C7A at Savannah, Ga., were both drilled to approximately 300 m. Overall least square gradients are 34°C/km and 33°C/km respectively. A third 300-m hole (KB-1) was drilled at Kings Bay Naval Submarine Support Base approximately 25 miles south of Brunswick, Ga. The temperature profile of the upper part of this hole is disturbed by groundwater circulation; a gradient of 22°C/km was determined for the lower 140 m of the hole.

i) Thermal conductivity.

Thermal conductivities given by Sass and Ziagos (1977) will also be representative of the sediments closer to the Charleston area. These values were determined from a continuously cored hole at Clubhouse Crossroads. These are reproduced here as Table 14.

j) Magnetic data.

Aeromagnetic data in the Charleston area are shown in Figure 39. A detailed interpretation of the field (Figure 40) near Charleston has been made by Phillips (1977). According to the model studies of Phillips, most of the power in the magnetic anomalies is produced by mafic intrusive bodies at depths of 2 to 4 and 5 km. The interpretation of a mafic crust might mean a relatively low heat flow throughout the area, but no heat flow data near the Charleston area are available.

With more samples of basement core from which magnetic susceptibility determinations can be made, the magnetic field will be useful for identifying basement rock type in areas where no core is available. Aeromagnetic data for the southeastern United States have been compiled at a scale of 1:500,000 by Klitgord and others (1983, Plate 1) and Daniels and others (1983, Plate 1).

k) Discussion of Virginia Tech "radiogenic model."

The radiogenic model was discussed in detail in the section on Norfolk and that discussion will not be repeated here. At this time, it is difficult to predict what the concentrations of U, Th, and K are in the basement rocks in the Charleston area, and therefore how applicable the radiogenic model might be in the Charleston area. In New England, large lateral changes in basement heat flow are known, but these changes are associated with granites of a much younger age than are presently known in the Charleston area. More heat flow values and determinations of heat production from basement core are needed. There are no values of heat production from basement rocks in the Charleston area.

Table 14. Values of Thermal Conductivity at Clubhouse Crossroads (Sass and Ziagos, 1977).

Depth interval (m)	Temperature gradient (°C/km)	Thermal conductivity (10^{-3}cal/cm-sec-°C)
274-399	21.0	5.99 ± 0.29
405-442	23.0	6.38 ± 0.83
442-469	40.1	3.39 ± 0.16
469-515	25.3	5.28 ± 0.55
509-555	30.1	3.76 ± 0.82
555-698	18.4	3.88 ± 0.32
713-738	42.2	3.43 ± 0.11
754-789	30.4	4.23 ± 0.13

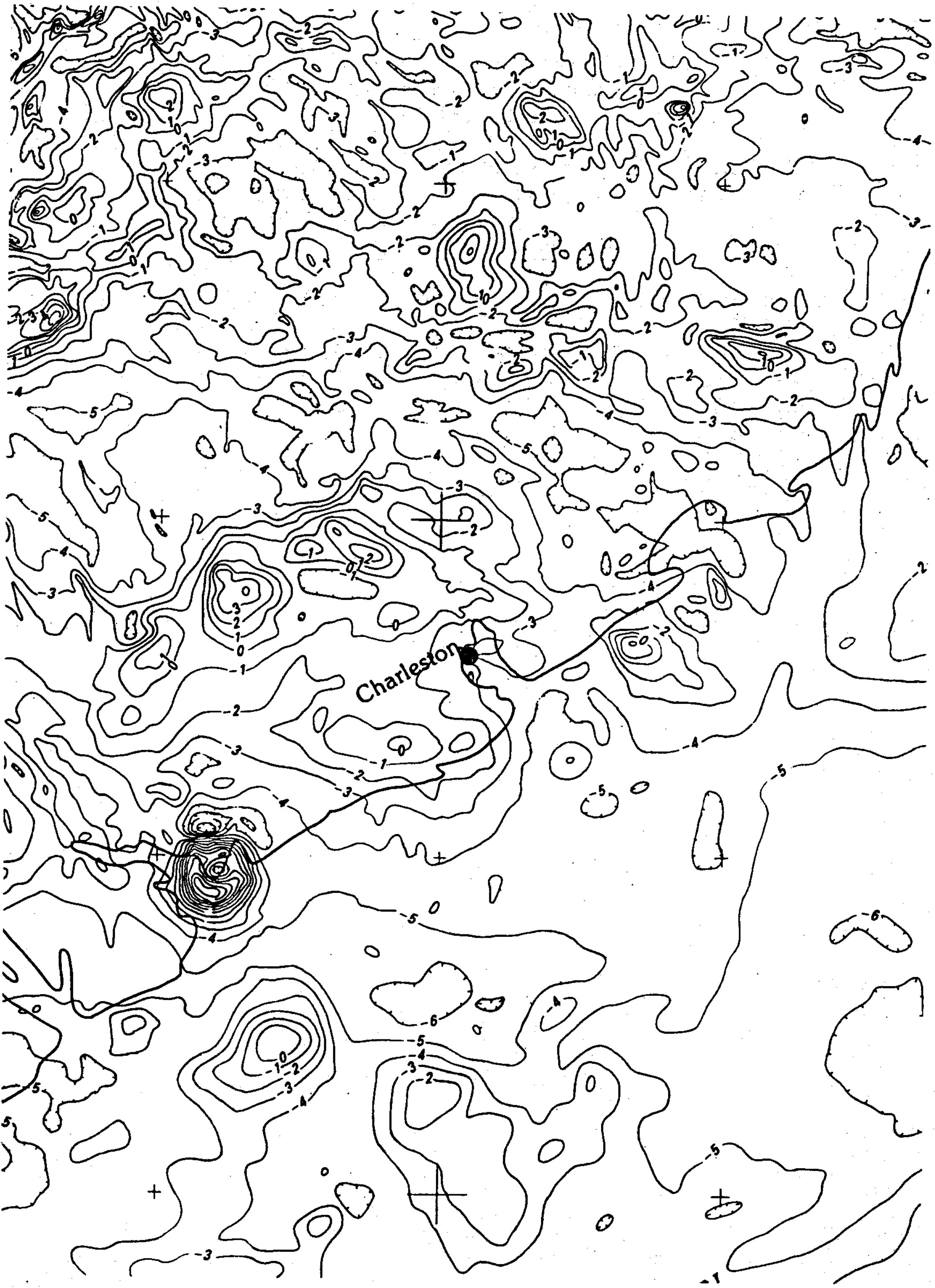


Figure 39. Aeromagnetic map of the Charleston area. Contour interval 100 nT (from Daniels and others, 1983).

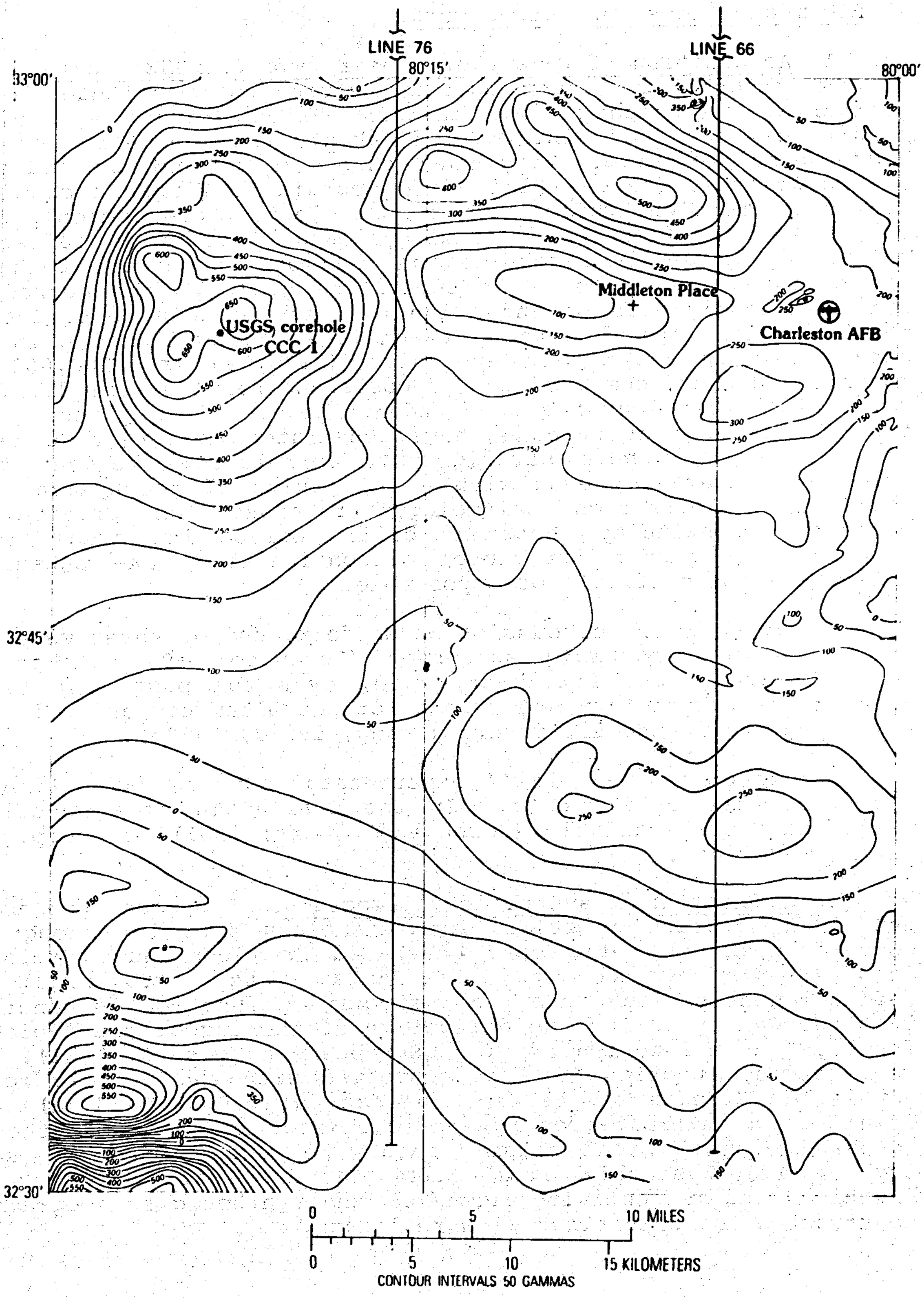


Figure 40. Aeromagnetic map of the Charleston area (from Phillips, 1977).

1) Recommendations for future work.

1) Acquisition of P-wave and shear wave VIBROSEIS data. Much of the uncertainty regarding the nature and magnitude of the geothermal resources in the eastern United States is a direct result of lack of information about the geometry of the hydrothermal resource. Virginia Tech has found that the sediments of the Atlantic Coastal Plain from Georgia to Virginia contain a series of excellent reflectors, comparable to those commonly found in offshore reflection seismology data. Although reflection seismology is widely recognized as the most successful technique for defining the geometry of subsurface geology, the method has not been widely used on the Atlantic Coastal Plain to define the thickness and lateral extent of aquifers and aquitards primarily because it is relatively expensive ($170,000 to $200,000 per month). However, compared to the costs and results from drilling, reflection seismology has been underutilized. This is especially true where a few drill holes have penetrated the greatest depths of interest but where stratigraphic correlations between drill holes are uncertain, even with a full suite of geophysical logs available. Reflection seismology traverses can provide the necessary continuity between drill holes in areas where stratigraphic and/or structural discontinuities make subsurface interpretation difficult or impossible.

As noted in the discussion on Norfolk, use of shear wave data has had some remarkable successes (Domenico, 1983; Robertson, 1983; Robertson and Pritchett, 1983) over the past five years. Much of the proprietary shear data for petroleum companies is just now appearing in the literature (Laing, 1983a, 1983b).

We recommend a short experimental shear wave line to supplement the P-wave data. In the Charleston area, excellent P-wave data are available (Coruh and others, 1981) for comparison with S-wave data.

2) Generation of synthetic seismograms. A common approach to the interpretation of reflection seismology data is through the comparison of synthetic data generated from continuous velocity logs (CVLs) obtained in drill holes with actual multifold reflection seismology data. A reflectivity function is generated from the CVL by taking the derivative of the log of the "velocity function" as a function of time (Sengbush and others, 1961). The reflectivity function is then convolved with the seismic source wavelet (a Klauder wavelet for the case of VIBROSEIS data). The result is a multiple-free synthetic seismogram which can then be compared with the real seismic data. We suggest that all sonic logs (CVLs) available from wells in the Charleston area be digitized and reflectivity functions and synthetic seismograms be constructed for comparison with real data.

3) Reprocessing of COCORP reflection seismic data. Reflection seismic data (COCORP) are available for the Charleston area. At this time it is not certain if the data are of adequate quality to justify purchase of all of the available data. We recommend the purchase of a limited amount that happens to be coincident with one of the lines shot by Virginia Tech. If the reprocessed COCORP data are satisfactory, a decision can be made to purchase and reprocess additional segments in the Charleston area.

4) Investigation and further compilation of faulting in Coastal Plain sediments. A recent summary publication by Prowell (1983) documents the widespread occurrence of faulting in sediments of the Atlantic Coastal Plain. The data in his report represent the presently available knowledge of fault characteristics and distribution of Cretaceous and younger faults in the eastern United States. The presence of faulting in the Charleston area is questionable (Coruh and others, 1981). Additional P-wave data are desirable.

5) Logging of existing holes for temperature. Available holes in the Charleston area should be logged for temperature at a relatively small depth interval (0.5 m). Differentiation of such a temperature profile when sampled at a close depth spacing yields information about water movement in and across the hole. This procedure at the Savannah River test site yielded temperature gradient profiles which correlated well with fracture permeability as determined by pump tests made in crystalline basement rocks.

ECONOMIC ANALYSIS FOR GEOTHERMAL ENERGY USE AT CHARLESTON NAVAL SHIPYARD

The Charleston Naval Shipyard and Charleston Polaris Missile Facility Atlantic (POMFLANT) both use large amounts of energy. The Naval Shipyard supplies most of its energy needs from a coal-fired boiler which burns 35,000 tons/year at a total cost of over $2,000,000. However, the cost per 10^6 Btu is only $1.60.

The boiler make-up water requirements are a substantial 120 x 10^6 gal/year. However, plans have been made to construct return lines for the spent steam, which would substantially reduce the requirement for make-up water. In addition, inexpensive alternative sources of energy are available from either a nearby chrome smelting plant or a municipal trash incinerator.

Although Charleston Naval Shipyard has a very high predicted geothermal temperature (130°F), it doesn't appear to be a good candidate for geothermal energy for the following reasons:

1. The coal boiler currently gives it a relatively inexpensive source of energy.
2. There are other sources of energy available that are also relatively inexpensive.
3. In the future, a condensate return line will greatly reduce the demand for preheating make-up water.

Geothermal utilization at the Charleston POMFLANT facility appears to be even less promising, since most of its heating energy requirements are supplied by individual oil-fired burners located throughout the facility. Geothermal energy appears to be impractical since these facilities consist of many small buildings spread over several miles. Geothermal water piping costs would be extremely high. Consequently a geothermal system for POMFLANT has not been analyzed.

BIBLIOGRAPHY

Ackermann, H. D., 1983. Seismic-Refraction Study in the Area of the Charleston, South Carolina, 1886 Earthquake, USGS Prof. Paper 1313, pp. F1-F20.

Applin, P. L., 1951. Preliminary Report on Buried Pre-Mesozoic Rocks in Florida and Adjacent States, USGS Circular 91, 28 pp.

Applin, E. R., and P. L. Applin, 1964. Logs of Oil Tests in the Coastal Plain of Georgia, Georgia Geologic Survey Bull. 74, 229 pp.

Arden, D. D., B. F. Beck, and E. Morrow, 1979. Second Symposium on the Geology of the Southeastern Coastal Plain, Georgia Geological Survey, IC 53, 219 pp.

Barnett, R. S., 1975. "Basement Structure of Florida and Its Tectonic Implications," Gulf Coast Association of Geological Societies Transactions, Vol. 25, pp. 260-78.

Becker, S. W., 1981. "Petrography of the Granitic Basement Beneath the Coastal Plain, Gates County, North Carolina," Southeastern Geol. 22, pp. 39-44.

Birch, F., 1954. "Heat From Radioactivity," in Nuclear Geology, H. Faul, ed.; New York, John Wiley and Sons. Pp. 148-74.

Birch, F., R. F. Roy, and E. R. Decker, 1968. "Heat Flow and Thermal History in New England and New York," in Studies of Appalachian Geology, E-an Zen, W. S. White, F. J. B. Hadley, and J. B. Thompson, Jr., eds.; New York, Interscience. Pp. 437-51.

Brown, D. L., and W. D. Silvey, 1972. Artificial Recharge to a Freshwater Sensitive Brackish-Water Sand Aquifer, Norfolk, Virginia, USGS Prof. Paper 939.

Brown, P. M., J. A. Miller, and F. M. Swain, 1972. Structural and Stratigraphic Framework and Spatial Distribution of Permeability of the Atlantic Coastal Plain, North Carolina to New York, USGS Prof. Paper 796, 79 pp.

Brown, P. M., 1979a. "Cenozoic and Mesozoic Aquifer Systems of the Atlantic Coastal Plain," in A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, Geothermal Resources Council, P.O. Box 98, Davis, CA 95616. Pp. 31-36.

Brown, P. M., D. L. Brown, M. S. Reid, and O. B. Lloyd, Jr., 1979b. Evaluation of Geologic and Hydrologic Factors Related to Waste-Storage Potential of Mesozoic Aquifers in Atlantic Coastal Plain, USGS Prof. Paper 1088, 47 pp.

Cederstrom, D. J., 1945. Selected Well Logs in the Virginia Coastal Plain North of James River, Virginia Geological Survey Circular 3, 82 pp.

Chilingar, G. V., 1963."Relationship Between Porosity, Permeability, and Grain-Size Distribution of Sands and Sandstones," Proc. Intern. Sedimentol. Congr., Amsterdam, Antwerp.

Chowns, T. M., and C. T. Williams, 1983. Pre-Cretaceous Rocks Beneath the Georgia Coastal Plain--Regional Implications, USGS Prof. Paper 1313, pp. L1-L42.

Claesson, J., B. Eftring, G. Hellstrom, and P. Olanders, 1978. Theoretical Analysis and Computer Simulation of Solid-Fluid Heat Storage Systems in the Ground. Extraction of Earth Heat. Department of Mathematical Physics and Building Science, Lund Institute of Technology, Lund, Sweden.

Clark, H. B., J. K. Costain, and L. Glover, III, 1978. "Structural and Seismic Reflection Studies of the Brevard Ductile Deformation Zone Near Rosman, North Carolina," Amer. J. Sci., 278, pp. 419-41.

Coffey, J. C., 1977. Exploratory Oil Wells of North Carolina, 1925-1976, North Carolina Department of Natural and Economic Resources Information Circular 22, 52 pp.

Cook, F. A., D. S. Albaugh, L. D. Brown, Sidney Kaufman, J. E. Oliver, and R. D. Hatcher, Jr., 1979. "Thin-Skinned Tectonics in the Crystalline Southern Appalachians; COCORP Seismic-Reflection Profiling of the Blue Ridge and Piedmont," Geology, Vol. 7, No. 12, pp. 563-67.

Cooley, R. L., 1971. "A Finite Difference Method for Variably Saturated Porous Media: Application to a Single Pumping Well," Water Resources Research, Vol. 7, No. 6.

Cooper, H. H., W. E. Kenner, and E. Brown, 1953. Groundwater of Central and Northern Florida, Florida Bureau of Geology, Report of Investigation 10, 37 pp.

Coruh, C., J. K. Costain, J. C. Behrendt, and R. M. Hamilton, 1981. "New Reflection Seismic Evidence for Deformation of Mesozoic Sediments Near Charleston, S.C.," paper given at GSA Annual Meeting, Cincinnati, Ohio; GSA Abstracts With Programs, Vol. 13, No. 7, Sept. 1981.

Costain, J. K., and L. D. Perry, 1982. "Gravity Maps: Eastern United States," in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Final Report VPI&SU-78ET-27001-12 prepared for DOE, pp. 147-54.

Costain, J. K., L. Glover, III, and A. K. Sinha, 1980a. "Low-Temperature Geothermal Resources in the Eastern United States," EOS, Trans. Amer. Geophys. Union, Vol. 61, No. 1, pp. 1-3.

Costain, J. K., and L. Glover, III, 1980b. "Heat Flow in Granites--Implications for Crustal Structure in the Appalachians," in The Caleonides in the U.S.A., D . R. Wones, ed.; Department of Geological Sciences, VPI&SU, Memoir No. 2, pp. 215-20.

Costain, J. K., J. A. Speer, L. Glover, III, L. Perry, S. Dashevsky, and M. McKinney, 1982a. "Heat Flow in the Southeastern United States," in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Final Report to DOE under Contracts E-(40-1)-5103, ET-78-C-05-5648, and DE-AC05-78ET-27001, pp. 103-34.

Costain, J. K., and L. Glover, III, 1982b. Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Final Report to DOE under Contracts E-(40-1)-5103, ET-78-C-05-5648, and DE-AC05-78ET-27001, 218 pp.

Cummings, R. G., et al, 1982. The Use of Hot Dry Rock Geothermal Resources for Space Heating: A Case Study; Los Alamos National Laboratory, LA-9541-MS, September 1982.

Daniels D. L., I. Zietz, and P. Popenoe, 1983. Distribution of Subsurface Lower Mesozoic Rocks in the Southeastern United States as Interpreted From Regional Aeromagnetic and Gravity Maps, USGS Prof. Paper 1313K, 24 pp.

Dashevsky, S., and W. McClung, 1979. "Summary of Temperature Logging at the Crisfield, Maryland Geothermal Test Hole," in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Progress Report to DOE VPI-78ET-27001-6; Springfield, Va., National Technical Information Service.

Dennison, R. E., H. P. Roveling, and J. T. Rouse, 1967. Age and Description of Subsurface Basement Rocks, Pamlico and Albemarle Sound Areas, N.C., Amer. Assoc. Petrol. Geol. Bull. 51, pp. 268-73.

Domenico, S. N., 1983. "Sandstone and Limestone Porosity Determination From Shear Compressional Wave Velocity," Soc. Explor. Geophysicists Expanded Abstracts, 53rd Ann. Meeting, Las Vegas, Nevada, pp. 353-55.

Fairchild, R. W., 1972. The Shallow-Aquifer System in Duval County, Florida, Florida Bureau of Geology RI 59, 50 pp.

Frazee, J., St. Johns Water Management District, Palatka, Fla., (904)328-8321.

Freeze, R. A., and J. A. Cherry, 1979. Groundwater, New York, Prentice-Hall, 604 pp.

Fullagar, P. D., and J. R. Butler, 1979. "325 to 265 Ma-Old Granitic Plutons in the Piedmont of the Southeastern Appalachians," Amer. J. Sci., Vol. 279, pp. 161-85.

Gleason, R. J., 1982. "Structure Contour Map of Basement Below Northern Atlantic and South Carolina Coastal Plains," in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, J. K. Costain and L. Glover, III, eds.; Final Report to DOE, Contracts E-(40-1)-5103, ET-78-C-05-5648, and DE-AC05-78ET-27001, pp. 67-70.

Glover, L., III, 1979. "General Geology of the East Coast With Emphasis on Potential Geothermal Energy Regions: A Detailed Summary," in A Symposium on Geothermal Energy and Its Direct Uses in the Eastern United States, Special Report No. 5, Geothermal Resources Council, P.O. Box 98, Davis, CA.

Gohn, G., ed., 1983. Studies Related to the Charleston, South Carolina, Earthquake of 1886--Tectonics and Seismicity, USGS Prof. Paper 1313.

Gohn, G. S., 1983. "Geology of the Basement Rocks Near Charleston, South Carolina--Data From Detrital Rock Fragments in Lower Mesozoic (?) Rocks in Clubhouse Crossroads Test Hole #3," in Studies Related to the Charleston South Carolina, Earthquake of 1886--Tectonics and Seismicity, USGS Prof. Paper 1313.

Gohn, G. S., D. Gottfried, M. A. Lanphere, and B. B. Higgins, 1978. "Regional Implications of Triassic or Jurassic Age for Basalt and Sedimentary Red Beds in the South Carolina Coastal Plain," Science, Vol. 202, pp. 887-90.

Gottfried, David, C. S. Annell, and L. J. Schwarz, 1977. "Geochemistry of Subsurface Basalt From the Deep Corehole (Clubhouse Crossroads Corehole 1) Near Charleston, South Carolina--Magma Type and Tectonic Implications," in Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report, D. W. Rankin, ed.; USGS Prof. Paper 1028, pp. 91-113.

Gringerten, A., and J. Sauty, 1975. "A Theoretical Study of Heat Extraction From Aquifers With Uniform Regional Flow," J. Geophys. Res., Vol. 80, No. 35.

Gruy Federal, Inc., 1979. Geothermal Drilling and Testing Plan, Chrisfield Airport No. 1 Well; Houston, Tex., Gruy Federal, Inc., March 1979.

Hartsock, J. H., 1979. "Analysis of Test Data From D.O.E. Chrisfield Airport Well No. 1," Geothermal Energy and the Eastern United States, Minutes; Applied Physics Laboratory, Johns Hopkins University, QM-79-261.

Herrick, S. M., 1961. "Well Logs of the Coastal Plain of Georgia," Water Wells Cretaceous and Cenozoic, 400 Wells, Georgia Geol. Surv. Bull. 70, 461 pp.

Herron, E. H., 1982. "Estimating Energy Costs in the Eastern United States," Geothermal Energy, Vol. 10, No. 7 & 8 (July/August 1982).

Ingenjorsbryan, A., 1972. Heat Storage in Natural Groundwater Basins, Scandinavian Engineering Corporation.

Johns Hopkins University, Applied Physics Laboratory, 1978. Heat Exchanger Costs, by R. W. Newman; Laurel, Md., JHU/APL, September 1978; EAM-5797.

Johns Hopkins University, Applied Physics Laboratory, 1979. Heat Exchanger Cost, Geothermal--Water To Process Water, by R. N. Henderson; Laurel, Md., JHU/APL, March 1979; BTT-1089-79.

Johns Hopkins University, Applied Physics Laboratory, 1980. Technical Assistance Report No. 5, Geothermal Space Heating--Naval Air Rework Facility, Norfolk, VA, by F. H. Hill and R. W. Henderson; Laurel, Md., JHU/APL, June 1980; WM-80-102.

Johns Hopkins University, Applied Physics Laboratory, 1981. Geothermal Energy Development in the Eastern United States; Laurel, Md., JHU/APL; Final Report JHU-APL QM-81-130.

Johns Hopkins University, Applied Physics Laboratory, 1982. Geothermal Survey of Atlantic Coast Naval Bases, by R. W. Newman; Laurel, Md., JHU/APL, September 1982; RQR/82-3.

Johnson, S. S., 1975. "Bouguer Gravity in Eastern Virginia," Virginia Division of Mineral Resources Report of Investigations, Vol. 39, 42 pp.

Johnson, S. S., 1977. Gravity Map of Virginia, 1:500,000 Scale, Virginia Division of Mineral Resources.

Kestin, J. Sourcebook on the Production of Electricity From Geothermal.

King, E. R., 1959. "Regional Magnetic Map of Florida," Am. Assoc. Petrol. Geol., 43, pp. 2844-54.

Klitgord, K. D., and J. C. Behrendt, 1977[1978]. Aeromagnetic Anomaly Map of the United States Atlantic Continental Margin: USGS Miscellaneous Field Studies Map MF-913, scale 1:1,000,000, 2 sheets.

Klitgord, K. D., W. P. Dillon, and P. Popenoe, 1983. Mesozoic Tectonics of the Southeastern United States Coastal Plain and Continental Margin, USGS Prof. Paper 1313P, 15 pp.

Lachenbruch, A. H., 1968. "Preliminary Geothermal Model for the Sierra Nevada," J. Geophys. Res., Vol. 73, pp. 6977-89.

Laczniak, R. J., 1980. Analysis of the Relationship Between Energy Output and Well Spacing in a Typical Atlantic Coastal Plain Geothermal Doublet System; MS thesis, Department of Geological Sciences, VPI&SU, 98 pp.

Laing, W. E., 1983a. "Shear Wave I: Interpretation," Soc. Explor. Geophys. Expanded Abstracts, Las Vegas Annual International Meeting, pp. 347-59.

Laing, W. E., 1983b. "Shear Wave II: Field Techniques, Well Logging, and Interpretaton," Soc. Explor. Geophys. Expanded Abstracts, Las Vegas Annual International Meeting, pp. 414-30.

Lambiase, J. J., S. S. Dashevsky, J. K. Costain, R. J. Gleason, and W. S. McClung, 1980. "Geothermal Resource Potential of the Northern Atlantic Coastal Plain," J. Geol., Vol. 8, pp. 447-49.

LeGrand, H. E., 1964. "Hydraulic Framework of the Gulf and Atlantic Coastal Plain," Southeastern Geology, Vol. 5, No. 4, pp. 177-94.

Leve, G. W., 1966. Ground Water in Duval and Nassau Counties, Florida, Florida Bureau of Geology Report of Investigations No. 43, 91 pp.

Leve, G. W., and D. A. Goolsby, 1969. Production and Utilization of Water in the Metropolitan Area of Jacksonville, Florida, State of Florida Information Circular No. 58.

Lippman, M. J., C. F. Tsang, and P. A. Witherspoon, 1977. "Analysis of Response of Geothermal Resources Under Injection and Production Procedures," Paper No. 6537, Society of Petroleum Engineers; Berkeley, Calif., Lawrence Berkeley Laboratory.

Lowell, R. P., and L. T. Long, 1977. "Thermal Model for the Florida Crust," in The Geothermal Nature of the Floridian Plateau, D. L. Smith and G. M. Griffin, eds.; Florida Bureau of Geology, Division of Resource Management, Department of Natural Resources, Special Publication No. 21, pp. 149-61.

McClung, W., S. Dashevsky, and B. Thoreson, 1979. "Comparison of Geothermal Gradients and Gamma Logs in Shallow Holes (300 m) in the Atlantic Coastal Plain," in Evaluation and Targeting of Geothermal Energy Resources in the United States; J. K. Costain, L. Glover, III, and A. K. Sinha, eds.; NTIS Progress Report VPI&SU-27001-7, prepared for DOE under Contract No. DE-AC05-78ET27001.

MacNeal, R., 1953. "An Asymmetric Finite Difference Network," Quart. Appl. Math., Vol. 2.

Marine, I. W., 1974. "Geohydrology of Buried Triassic Basin at Savannah River Plant, South Carolina," Amer. Assoc. Petrol. Geol. Bull., Vol. 58, pp. 1825-37.

Marine, I. W., and G. E. Siple, 1974. "Buried Triassic Basin in the Central Savannah River Area, South Carolina and Georgia," Geol. Soc. Amer. Bull., Vol. 85, pp. 311-20.

Meyer, F., 1974. Evolution of Hydraulic Characteristics of a Deep Artesian Aquifer From Natural Water-Level Fluctuation, Miami; Florida Bureau of Geology, 32 pp.

Miller, J. A., 1979. Potential Subsurface Zones for Liquid-Waste Storage in Florida, Florida Bureau of Geology and Florida Dept. of Environmental Regulation Map Series 94, scale 100 miles per 3 inches.

Milton, C., 1972. Igneous and Metamorphic Basement Rocks of Florida, Florida Bureau of Geology Bull. 55, 125 pp.

Milton, C., and R. Grasty, 1969. "'Basement' Rocks of Florida and Georgia," Am. Assoc. Petrol. Geol. Bull., Vol. 53, No. 12, pp. 2483-93.

Narasimhan, T. N., 1975. A Unified Numerical Model for Saturated-Unsaturated Groundwater Flow, PhD dissertation, University of California, Berkeley, Calif.

Narasimhan, T. N., and P. A. Witherspoon, 1976. "An Integrated Finite-Difference Method for Analyzing Fluid Flow in a Porous Media," Water Resources Research, 12, No. 1.

Narasimhan, T. N., P. A. Witherspoon, and A. L. Edwards, 1978. "Numerical Model for Saturated-Unsaturated Flow in a Deformable Porous Media: The Algorithm," Water Resources Research, 14.

Naval Facilities Engineering Command, 1981. Energy Conservation Seminar and Workshop, NAVFACENGCOM, Southern Division, Charleston, S.C.

Naval Weapons Center, 1983. Potential Geothermal Energy Use at East Coast Naval Facilities, by R. W. Newman, JHU/APL; China Lake, Calif., NWC, April 1983; NWC TP 6423.

Neiss, R. C., 1979. "Utilization of Geothermal Energy With an Emphasis on Heat Pumps," in A Symposium of Geothermal Energy and Its Direct Uses in the Eastern United States, Geothermal Resources Council, Davis, Calif.

Oglesby, W. R., M. M. Ball, and S. J. Chaki, 1973. Bouguer Anomaly Map of the Florida Peninsula and the Adjoining Continental Shelves, Florida Bureau of Geology Map Series No. 57, scale 1:1,000,000.

Paddison, F. C., C. S. Leffel, Jr., W. J. Toth, and R. S. P. Weissbrod, 1978. Direct Applications of Geothermal Energy in the Eastern United States and Estimates of Life Cycle Costs; Applied Physics Laboratory, Johns Hopkins University, Laurel, Md.

Perry, L. D., 1979. "Heat Flow in the Atlantic Coastal Plain," in Evaluation and Targeting of Geothermal Energy Resources in the United States; J. K. Costain, L. Glover, III, and A. K. Sinha, eds.; NTIS Progress Report VPI&SU-5648-5, prepared for DOE under Contract No. ET-78-C-05-5648.

Phillips, J. D., 1977. "Magnetic Basement Near Charleston, S.C.--A Preliminary Report," in Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report, D. Rankin, ed., USGS Prof. Paper 1028, pp. 119-37.

Popenoe, P., and I. Zietz, 1977. The Nature of the Geophysical Basement Beneath the Coastal Plain of South Carolina and Northeastern Georgia, USGS Prof. Paper 1028-I.

Pratt, T., in press. "Structure and Emplacement of a Buried Alleghanian Granitoid--Geophysical Evidence From Lumberton, N.C.," submitted to Bull. Geol. Soc. Amer.

Prowell, D. C., 1983. Index of Faults of Cretaceous and Cenozoic Age in the Eastern United States, USGS Miscellaneous Field Studies Map MF-1269, 2 sheets.

Rankin, D., ed., 1977. Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report, USGS Prof. Paper 1028, 204 pp.

Richards, H. G., 1954. Subsurface Triassic in Eastern North Carolina, Amer. Assoc. Petrol. Geol. Bull. 38, pp. 2564-65.

Robertson, J. D., 1983. "Carbonate Porosity From S/P Traveltime Ratios," Soc. Expl. Geophys. Expanded Abstracts, 53rd Annual Meeting, Las Vegas, Nevada, pp. 356-58.

Robertson, J. D., and W. C. Pritchett, 1983. "Bright Spot Validation Using Comparative P-wave and S-wave Seismic Sections," Soc. Expl. Geophys. Expanded Abstracts, 53rd Annual Meeting, Las Vegas, Nevada, pp. 355-56.

Russell, G. S., and C. W. Russell, 1980. Rb-Sr Isotropic Study of Granitic Core From Portsmouth, Virginia; VPI&SU, DOE Progress Report No. 78-ET-27001-8, pp. A64-68.

Russell, G. S., J. A. Speer, and C. W. Russell, in press. The Portsmouth Granite, a 263 Ma Postmetamorphic Biotite Granite Beneath the Atlantic Coastal Plain, Suffolk, Virginia.

Sass, J. H., and others, 1971. In J. Geophys. Res., Vol. 76, p. 6383.

Sass, J. H., and J. P. Ziagos, 1977. "Heat Flow From a Corehole Near Charleston, South Carolina," in Studies Related to the Charleston, South Carolina, Earthquake of 1886--A Preliminary Report, D. Rankin, ed.; USGS Prof. Paper 1028, pp. 115-17.

Sengbush, R. L., P. L. Lawrence, and F. J. McDonal, 1961. "Interpretation of Synthetic Seismograms," Geophysics, Vol. 26, pp. 138-57.

Smith, D. L., and G. M. Griffin, eds., 1977. The Geothermal Nature of the Floridian Plateau, Florida Bureau of Geology Special Publication 21, 161 pp.

Smith, D. L., and W. R. Fuller, 1977. "Terrestrial Heat Flow Values in Florida and the Thermal Effects of the Aquifer System," in The Geothermal Nature of the Floridian Plateau, D. L. Smith and G. M. Griffin, eds.; Florida Bureau of Geology Special Publication 21, pp. 91-130.

Smith, D. L., R. G. Gregory, and J. W. Emhof, 1981. "Geothermal Measurements in the Southern Appalachian Mountains and Southeastern Coastal Plains," Amer. J. Sci., Vol. 281, pp. 282-98.

Smith, D. L., and S. S. Shannon, Jr., 1982. Heat Flow Reconnaissance of the Gulf Coastal Plain, Los Alamos National Laboratory, LA-9222-HDR.

Smith, M. C., and G. M. Ponder, 1982. Hot Dry Rock Geothermal Energy Development Program, Los Alamos National Laboratory, LA-9287-HDR, April 1982.

Sorey, M. L., 1975. Modeling of Liquid Geothermal Systems, PhD dissertation, University of California, Berkeley, Calif.

Speer, J. A., S. W. Becker, and S. S. Farrar, 1980. "Field Relations and Petrology of the Postmetamorphic, Coarse-Grained Granitoids and Associated Rocks of the Southern Appalachian Piedmont," in The Caleonides in the U.S.A., D. R. Wones, ed.; Department of Geological Sciences, VPI&SU, Memoir No. 2, pp. 137-48.

Speer, J. A., T. N. Solberg, and S. W. Becker, 1981. "Petrography of the Uranium-Bearing Minerals of the Liberty Hill Pluton, South Carolina: Phase Assemblages and Migration of Uranium in Granitoid Rocks," Economic Geology 76, pp. 2162-75.

Speer, J. A., 1982a. "Description of the Basement Granitoid Rocks of Drill Hole C25A, Near Portsmouth, Virginia," in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Final Report to DOE, VPI&SU-78-ET-27001-12, pp. 79-98.

Speer, J. A., 1982b. "Descriptions of the Granitoid Rocks Associated With Two Gravity Minima in Aiken and Barnwell Counties, South Carolina," Geology 26, pp. 15-24.

Streckeisen, A., 1976. "To Each Plutonic Rock Its Proper Name," Earth Science Reviews, Vol. 12, pp. 1-33.

Stringfield, V. T., 1936. Artesian Water in the Florida Peninsula, USGS Water-Supply Paper 773-C, pp. 115-95.

Stringfield, V. T., 1964. Relation of Surface-Water Hydrology to the Principal Artesian Aquifer in Florida and Southeastern Georgia, USGS Prof. Paper 501-C, pp. C164-169.

Todd, D. K., 1959. Ground Water Hydrology, New York, John Wiley.

Toth, W. J. "Geothermal Energy Market Assessment, Atlantic Coastal Plain," in Geothermal Energy and the Eastern U.S., Ch. XIX.

Tyson, H., and E. M. Weber, 1964. "Groundwater Management for the Nations of the Future Computer Simulation of Groundwater Basins," J. Hydraul. Div., ASCE, 90(HY4).

U.S. Department of Energy, 1982. "Geothermal Progress Monitor," Proceedings of the Geothermal Program Review, October 25-26, 1982, Conf.-8210125, October 1982.

U.S. Geological Survey, 1964. The Yield of Sedimentary Aquifers of the Coastal Plain of SE River Basins, USGS Water Supply Paper 1699-W, pp. W1-W56.

U.S. Geological Survey, 1964. Cone of Depression Near Savannah Area, USGS Water Supply Paper 1613-D.

U.S. Geological Survey, 1967. The Status of Groundwater Resources 1967; Nansemond County and Isle of Wight County, Virginia; Geraghty and Miller, Consulting Groundwater Geologists.

U.S. Geological Survey, 1978. Aeromagnetic Map of Northern Florida, USGS Open-File Report 78-761, 1 pl.

Vernon, R. O., 1973. Top of the Floridian Artesian Aquifer, Florida Bureau of Geology Map Series 56.

White, D. E., 1973. "Characteristics of Geothermal Resources," in Geothermal Energy, P. Kruger and C. Otte, eds., Stanford University Press, pp. 69-93.

White, D. E., and D. L. Williams, 1975. "Assessment of Geothermal Resources of the United States, 1975," Introduction, USGS Circular 726.

Wicker, R. A., and D. L. Smith, 1978. "Reevaluating the Florida Basement," Gulf Coast Association of Geological Societies Transactions, Vol. 28, Pt. 2, pp. 681-87.

Yantis, B. R., J. K. Costain, and H. D. Ackermann, 1983. "A Reflection Seismic Study Near Charleston, S.C.," in Studies Related to the Charleston, South Carolina, Earthquake of 1886--Tectonics and Seismicity, G. S. Gohn, ed.: USGS Prof. Paper 1313, pp. G1-G20.

Ziagos, J. P., J. H. Sass, and R. J. Munroe, 1976. Heat Flow Near Charleston, South Carolina, USGS Open-File Report 76-148.

Zietz, I., J. Calver, S. S. Johnson, and J. R. Kirby, 1967. Aeromagnetic Map of Virginia, USGS Geophysical Investigations Map GP-915.

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