GEOTHERMAL EXPLORATION METHODS AND RESULTS
ATLANTIC COASTAL PLAIN

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Optimum sites for the development of geothermal energy resources in the eastern United States will probably be associated with the sediments of the Atlantic Coastal Plain. These sediments have a relatively low thermal conductivity resulting in, even for a normal heat flow, relatively high geothermal gradients. If such sediments blanket a radiogenic, heat-producing granite in the basement crystalline rocks, isotherms will be warped upward and higher temperatures will occur at shallower depths. Approximately 50 shallow (300 m; 1000 ft) holes were drilled on the Atlantic Coastal Plain by the Department of Energy during 1978-79 to investigate the distribution of heat flow and the geothermal gradient. To date, the area with the most promising potential appears to be a region between Crisfield, Maryland, and Oak Hall, Virginia. Gradients here are in excess of 40 °C/Km and the thickness of the sedimentary insulator is greater than about 1.2 Km.

Introduction

The first systematic effort to estimate the geothermal resources of the entire United States was made by the U.S. Geological Survey in 1975 and published as USGS Circular 726 (White and Williams, 1975). This study has been updated by a second assessment and published as USGS Circular 790 (Muffler, 1979). Muffler and Cataldi (1979) proposed the use of a consistent terminology for geothermal resource assessment. The "geothermal resource base" is defined as all of the thermal energy in the earth's crust under a given area, measured from the mean annual temperature. The "accessible resource base" is that part of the resource base which is shallow enough to be tapped by production drilling, and is divided into "useful" and "residual" components. The "useful" component is defined as thermal energy that could be extracted at costs competitive with other forms of energy at some specified future time. This useful component is defined as the "geothermal resource". Much exploration remains to be done before the nature and extent of the geothermal resource in the eastern United States can be adequately defined.

Exploration for geothermal resources in the eastern United States takes place in a geologic environment quite unlike that of the west where generation of electric power from geothermal energy is well documented. Use of geothermal energy in the east will probably first be oriented toward non-electric applications using relatively low-temperature fluids as a source of energy for space heating and industrial processes and systems.

This paper briefly discusses the geophysical techniques we have used to investigate the geologic framework of potential geothermal resources of parts of the eastern United States. Geothermal resources in the Appalachian Mountain system and the Atlantic Coastal Plain can be grouped into four types:

I) Radiogenic heat-producing granite buried beneath a thick blanket of sediments of low thermal conductivity,
II) Normal geothermal gradient resources,
III) Warm water emanating from fault zones,
IV) Hot-dry-rock in regions of abnormal geothermal gradient,

Resource I is the principal subject of this paper. Resource II is widely available throughout much of the United States and is discussed by Sammel (1979). Resource III has been recognized in the eastern United States since before 1884 (Rogers, 1884). Resource IV is described by Pettitt (this Symposium).

Optimum sites for the development of geothermal energy in the eastern United States will probably be associated with the flat-lying, relatively unconsolidated sediments that underlie the Atlantic Coastal Plain (Figure 1). In many locations, these sediments are known to yield large quantities of water. The water in these sediments at any given depth is hotter in some locations than in others and depends on the local value of the geothermal gradient. The gradient depends on the heat flow through the rocks and on the thermal conductivity of the rocks. In a series of extremely important papers, Birch et al. (1968), Lachenbruch (1968), and Roy et al. (1968) showed that the local heat flow has a well-defined relationship to the concentration of uranium (U) and thorium (Th) in fresh, unweathered samples of granite collected from the surface of the earth. The immediate implication of their observation is that the distribution of U and Th in the upper 10 to 20 km (33,000 to 66,000 ft) of the earth's crust is primarily responsible for the observed lateral variations in surface heat flow in the eastern United States.

One of the principal objectives of the geothermal program at Virginia Polytechnic Institute and State University is to locate relatively young (330 million years old and younger) U- and Th-bearing granite in the basement rocks beneath the sediments of the Atlantic Coastal Plain. The targeting procedure integrates the disciplines of geology, geochemistry, and geophysics. Geologic and geochemical techniques are being applied to the rocks in the Piedmont in an effort to understand the ages, chemistry, and areal distribution of exposed granite plutons (see paper by Glover, this Symposium). Geophysical techniques include the interpretation of gravity and magnetic potential field data, as well as seismic data, and are being applied to both the Piedmont and the Coastal Plain.

Warm water emanating from fracture zones (Resource III) is not the principal focus of this Symposium. Nevertheless, it is appropriate to mention this known resource. The origin of the hot springs in the eastern United States has been discussed by several authors (Rogers, 1884; Reeves, 1932; Hewett and Crickmay, 1937; Stose and Stose, 1947; Dennison and Johnson, 1971; Lowell, 1975; Costain et al., 1976; Geiser, 1976; Hobba et al., 1977; Hobba et al., 1978). Perry et al. (1979) proposed a model for the hot springs in Virginia that we believe applies to most of the hot springs in the eastern United States. Before discussing the geologic framework for the hot springs in Virginia, it will be useful to review selected geophysical methods we have used to date in the eastern United States for the exploration of geothermal resources.

Geophysical Exploration of Geothermal Resources in the Eastern United States

It is beyond the scope of this paper to discuss in detail the various geophysical, geochemical, and geological techniques that are commonly used to evaluate geothermal resources. The exploration methods used are dependent upon the nature of the geothermal resource. Many of the conventional geophysical methods of exploration are discussed by Dobrin (1977) and are, of course, not restricted to geothermal applications. We have used several kinds of geophysical data during the course of our geothermal program. They are discussed briefly below before summarizing the results of our studies on the Atlantic Coastal Plain.

Heat flow. The most important geophysical data for the exploration of geothermal resources in the east consist of values of regional and local heat flow flowing towards the surface of the earth. Heat flow, q, is described by the conduction equation

$$q = K\,G$$

where the units of q are calories per square cm per sec, K is thermal conductivity (millicalories per cm-sec-°C), and G is the geothermal gradient in °C/Km ($1^{\circ}F/100$ ft = 18.23 °C/Km). This equation applies only to the transport of heat by conduction. Heat transport by fluid convection (hot water) is much more efficient. Any successful geothermal system must incorporate both conduction and convection. A hole drilled to a depth of, say, 300 m (1000 ft) will usually encounter different rock types, each with a different thermal conductivity, K. Because q is constant at any depth in the hole, then as K decreases the geothermal gradient, G, will increase to keep the product KG constant. Simply stated, this means that for any given heat flow, the highest temperature gradients occur in rocks with the lowest thermal conductivities. Shales in the Valley and Ridge province of the Appalachian Mountain System will have temperature gradients that are much higher than those found in holes drilled into dolomite, $CaMg(CO_3)_2$. For the same value of the heat flow, q, higher temperatures will be reached at shallower depths if holes are drilled into thick sequences of shale rather than into dolomite. Shale is a better insulator. The unconsolidated sediments of the Atlantic Coastal Plain have an even lower thermal conductivity.

A major unresolved problem in geology and geophysics is why regional and local variations in surface heat flow occur. For the development of a geothermal resource, it is apparent that the combination of high heat flow and low thermal conductivity will result in the highest subsurface temperatures at the shallowest depths. It is beyond the scope of this paper to speculate on the many hypotheses advanced to explain lateral variations in surface heat flow. One undisputed explanation, however, is that variations in lateral and vertical concentrations of U and Th in basement rocks will result in substantial variations in heat flow (Birch et al., 1968).

The generation of heat by the process of radioactive decay is one of conversion of mass to energy according to Einstein's equation, $E=mc^2$. Only three elements have isotopes with long enough halflives to be important for radioactive heat generation in rocks. These are isotopes of U, Th, and potassium (K). Radioactive isotopes of these elements have halflives of the order of 1 billion years or more. The heat contribution, H, in calories/gram per year from the radioactive decay of these isotopes is given by the equation

$$H = 0.72U + 0.20Th + 0.27K$$

where U is in parts per million (ppm) uranium, Th is in ppm thorium, and K is in per cent potassium (Birch, 1954). The constants in this equation have been revised slightly by Rybach (1976).

Thorium is usually more abundant than uranium in granite, the Th/U ratio falling between 3 and 4. Most of the heat produced comes from U and Th; only about 10 - 15% comes from K. The U, Th, and K concentrations of the Cuffytown Creek pluton in South Carolina are about 10 ppm U, 33 ppm Th, and 3.7% K. Thus this granite generates about 15 calories per gram per year. The density of the granite is about 2.67 grams per cubic centimeter. The granite therefore generates about 12 x 10^{-13} calories per cubic cm per sec, or about 20,000 watts per cubic mile. In fact, most of the heat flowing towards the surface in the Cuffytown Creek granite comes from the heat generated by the radioactive decay of isotopes of U, Th, and K.

Granitic rocks relatively enriched in U and Th (concentrations as high or higher (?) than the Cuffytown Creek) occur locally in the basement rocks beneath the sediments of the Atlantic Coastal Plain. The concentrations of U and Th in the granites are low, a few parts per million, but these concentrations are higher than those in adjacent rocks in the basement. In spite of these low concentrations, large volumes of granite with U and Th will increase substantially the subsurface temperature. Thus, higher temperatures will be found at shallower depths within the overlying sediments. Radiogenic heat is in addition to the normal heat flow around and beneath the granite plutons and can be greater by more than a factor of 2 than the background heat flow that constitutes the normal heat leaving the earth. In some parts of New England, for example, radiogenic heat from granite constitutes two-thirds of the total heat flow leaving the earth in that area (Birch et al., 1968). An understanding of the distribution of granites and of U and Th in the basement rocks is therefore important to define locations where the highest temperatures will occur at the shallowest depths.

Granite plutons are exposed in the Piedmont Province northwest of the Atlantic Coastal Plain (Figure 1). These exposed basement rocks are concealed to the southeast by a seaward-thickening wedge of sediments beneath the Atlantic Coastal Plain. Few holes have been drilled through the sediments to basement, but the sediment thickness is known to be about 3 km (9900 ft) at Cape Hatteras, NC.

Figure 3 illustrates the effect on subsurface temperature where basement rocks are covered with a thick sequence of sediments of relatively low thermal conductivity. Moderate amounts of heat-producing elements occur in the basement rocks, concentrated primarily in granite. The concentrations assumed are not unreasonable. Heat generations of 15 HGU (1 HGU = 10^{-13} cal/cm^3 per sec) have been determined by us in granite plutons exposed in the Piedmont. In New England, exposed granite plutons locally have heat productions of 24 HGU (Birch et al., 1968). The leftmost curve in Figure 2 is the temperature-depth profile in basement crystalline rocks that contain no heat-producing elements, and are not overlain by sediments. As U and Th are added to produce first 10 HGU and then 20 HGU, the subsurface temperature (and therefore the geothermal gradient) increases. Finally, if U- and Th-bearing granite is blanketed by sediments that have a relatively low thermal conductivity, the subsurface temperature is increased further. The relatively unconsolidated sediments of the Atlantic Coastal Plain that overlie granite plutons in the basement is the geologic environment of high geothermal resource potential in the east. Heat flow and the geothermal gradient should be higher over these granites if the granites contain modest concentrations of U and Th. Locations of shallow (300 m) holes drilled by the Department of Energy on the Atlantic Coastal Plain during 1978-79 to determine the geothermal gradient and heat flow were based primarily on the interpretation of gravity and magnetic potential field data.

Gravity data. The magnitude of the gravitational field at any location on the surface of the earth depends locally on the different rock types at depth. Different rock types have different densities. Some rocks weigh more than others. Granite is the least dense of the igneous intrusive rocks that occur in large volumes. Since granite is less dense than the country rocks into which it has been emplaced, a negative gravity anomaly results (Figure 2). If, however, granite was emplaced in country rock that was also granitic in chemical composition, then the gravity field will not be well-defined over the granite and additional geophysical and/or geological techniques must be used.

An important consideration in the targeting of concealed radiogenic granites beneath the sediments of the Atlantic Coastal Plain is an understanding of the regional geologic framework (see paper by Glover, this volume). In the absence of a gravity or magnetic anomaly, an understanding of the regional geology and the possible nature of concealed basement trends is important. Relatively few holes have sampled the basement to date.

Magnetic data. The normal (approximately symmetrical) magnetic dipole field of the earth is distorted by the presence of magnetic minerals in rocks, the most important of which is magnetite. Granite plutons usually contain a small percentage of magnetite. The first step in the interpretation of aeromagnetic data is to subtract the earth's dipole field and examine the "magnetic anomalies" that remain (see Costain, 1979 for a general summary of the description and interpretation of magnetic anomalies). An excellent magnetic anomaly associated with a granite exposed in the Piedmont is shown in Figure 4. Similar granite bodies concealed beneath the sediments of the Atlantic Coastal Plain might be detected by their magnetic signatures if the depth of burial is not too great and if metamorphism has not destroyed the magnetic properties of the mineral assemblages. Examination of existing magnetic data obtained over the Coastal Plain suggests that granitic plutons occur in the basement.

Seismic data. Standard techniques of reflection seismology are essential to define the subsurface geometry of a potential geothermal resource in the eastern United States. In general, reflection seismology offers the highest resolution of any geophysical method used to investigate subsurface geology. In particular, reflection seismology is appropriate to

1) determine depth to crystalline basement,
2) define faults in the basement and/or overlying sediments,
3) examine lateral and vertical changes in velocity in the sedimentary section which can then be correlated with lateral changes in thermal conductivity or changes in thickness of potential deep aquifers.

Figure 5 shows a reflection seismic section recently obtained (February, 1979) near Salisbury, MD. The reflection that originates from the basement is well-defined as are several other reflections from within the overlying sedimentary section.

Excellent reflection seismic data can be obtained on the Atlantic Coastal Plain. Proper recording procedures are essential in order to assure that the desired reflections are not obscured by multiple reflections (Dobrin, 1976, p. 89).

Origin of the Hot Springs in Virginia

In the northwestern part of Virginia and adjacent parts of West Virginia, there are approximately 100 springs that have temperatures ranging from slightly above the mean annual air temperature (9-12 °C; 48-54 °F) to about 41 °C (106 °F). In Virginia, nearly all of the warm springs appear to issue from limestone formations of Middle Ordovician age where these formations are brought to the surface by anticlinal folding. The geographic distribution of the springs has been described by Reeves (1932) and summarized by Sammel (1979).

The hottest springs are located in the Warm Springs anticline in Bath and Alleghany Counties in Virginia where four groups of springs known as the Warm Springs, Hot Springs, Healing Springs, and Falling Springs occur. Each group of springs consists of at least three separate springs in close proximity. The group at Warm Springs is made up of three springs within about 30 m (100 ft) of each other and a fourth about 250 m (820 ft) to the southwest. At Hot Springs, eight warm springs occur over an area of about 4000 square m (6 square miles). Healing Springs consists of three separate springs less than 3 m apart. Falling Springs are made up of a number of flows and seepages at a generally lower temperature (25 °C; 77 °F max) than the other warm springs in the Warm Springs anticline, and with a much greater discharge (250 L/sec= 3960 gpm = 5,700,000 gpd) than any other warm springs in the region. The flow rate of Hot Springs is 63 L/sec (=998 gpm = 1,438,000 gpd) at a maximum temperature of 41 °C (106 °F). At Bolar Spring, the flow rate is 130 L/sec (=2060 gpm = 2,900,000 gpd) at a maximum temperature of 22 °C (72 °F). Flow rates are taken from Sammel (1979).

Rogers (1884) and Reeves (1932) both concluded that the warm and moderately warm springs issue from rocks of Cambrian and Ordovician age where these formations rise from considerable depth as the result of anticlinal folding of sedimentary rocks. Rogers proposed that surface water entering the rocks at their outcrop in high ridges sinks to considerable depths along joints and fissures until it reaches a permeable bed, and then rises along the dip of this bed to its outcrop in an adjacent valley. According to Reeves (1932, p. 26), however, some of the anticlines are broken by thrust faults, but he states that there is no positive evidence that any of the warm springs are along faults. Reeves further concluded that most of the springs of the region undoubtedly are not so located, and that few of the springs are probably fed by water rising along fault planes or through fissures bordering fault planes. Reeves (1932, p. 28) concluded that the springs are produced by meteoric (rain) water entering a permeable bed along its outcrop at a relatively high altitude on the crest or limb of one anticline and rising to the surface where the same bed crops out at a lower altitude in another anticline, the temperature of the waters being an expression of the normal earth temperature in the deep synclinal basins through which the water circulates. Reeves' hypothesis is similar to Rogers' in that it attributes the temperature of the springs to normal earth temperatures. It differs from Rogers' hypothesis in that it predicts movement through permeable beds from one anticline to another rather than movement through joints and fissures from an anticlinal ridge to adjacent valleys.

Rogers (1884), Watson (1924), Reeves (1932) and Hobba et al. (1977) all concluded that the spring waters are of meteoric origin. The occurrence of igneous sills and dikes in Highland County, Virginia suggested to Dennison and Johnson (1971) an alternative heat source other than deep circulation of meteoric water. Igneous intrusions are exposed just 30 km (20 miles) north of Hot Springs, Virginia. They suggested that a deep still-cooling pluton provides heat to the thermal springs centered in Bath County, and that the pluton is either the source of the dikes in Highland County, or possibly represents a later thermal pulse related to the 38th parallel fracture zone, which has been an east-west zone of sporadic igneous activity from late Precambrian to Eocene time.

A hole approximately 305 m (1000 ft) in depth was drilled into the Beekmantown dolomite in the Warm Springs anticline about 8 km southwest of the Hot Springs, Virginia specifically for the purpose of obtaining a reliable heat flow determination (Costain et al., 1976). The geothermal gradient in the hole was 9.3 °C/Km (0.5 °F/100 ft). The thermal conductivity of the Beekmantown dolomite was 12.4 mcal/cm-sec-°C. The heat flow is therefore about 1.2 HFU (1 HFU = 10^{-6}cal/cm^2-sec). This is a representative heat flow value for the region and does not support the hypothesis of a still-cooling pluton at depth.

The gradient within the core of the Warm Springs anticline is about 10 °C/Km in the Beekmantown Dolomite. If this low gradient is maintained to greater depths, water would have to circulate to a depth of only approximately 3 km (10,000 ft) to be heated to the temperatures observed at the surface. Since the thickness of sediments in the area is greater than 4 km (13,000 ft), deep circulation of meteoric water completely within the sedimentary section is possible. It then remains to identify the ground water recharge area for the springs and the factors that control locations where the springs discharge. Perry et al. (1979) proposed the following model.

All of the warm springs in the valley are grouped near topographic gaps associated with vertical transverse fracture zones (linears). The limited data available suggest that faults and/or joints play an important role in the location of the springs, since gaps have developed only along these zones. The Warm Springs anticline is a doubly-plunging anticline with a near-vertical to overturned northwestern limb. The resistant Silurian quartzites are responsible for the high relief in the area. It is postulated that meteoric water enters the Silurian quartzites and possibly adjacent carbonate units along steep to vertical bedding planes on the northwest limb of the anticline, extends to depths sufficient to heat the water, and then rises rapidly along the essentially east-west transverse fracture zones which intersect the bedding-plane permeability at depth. A cross section of this model oriented approximately at right angles to the transverse fracture zones is shown in Figure 6. In this model, ground-water flow lines are shown with an essentially vertical orientation beneath the recharge areas. They diverge at depth and intersect the transverse fracture zones. The temperature of the water issuing from springs located along the transverse fracture zones depends to a large extent on the degree of mixing that has taken place as the meteoric water rises rapidly to the surface along the relatively permeable fracture zone.

In support of this model, there appears to be a correlation between the coincidence of water gaps, the occurrence of warm springs, and the presence of nearby steeply-dipping to vertical quartzite units in areas other than the Warm Springs anticline. The warm spring (22 °C; 72 °F) at Bolar occurs in the same geologic setting.

Geothermal Exploration of the Atlantic Coastal Plain

During 1978-79, 49 holes were drilled to a depth of approximately 300 m (1000 ft) on the Atlantic Coastal Plain. The geographic distribution of the holes is shown in Figure 1. The locations of the drill sites were chosen on the basis of:

1) gravity data,
2) magnetic data,
3) known thickness of Coastal Plain sediments,
4) apparent thermal anomalies based on geothermal gradients determined in existing holes,
5) much of the available basement core data,
6) suitable sites for the evaluation of the radiogenic pluton model,
7) proximity to energy markets.

The sediments of the Atlantic Coastal Plain include a number of semi-confined "leaky" aquifers. These aquifers are separated by relatively impermeable sediments. The water present in the pore space of each semi-confined aquifer may have a different "energy per unit weight", otherwise defined as "hydraulic head", h. Three quantities determine the value of h at any point in an aquifer: the elevation of the point above an arbitrary reference level (basement), the pressure energy (the higher the fluid pressure the greater the pressure energy), and the kinetic energy (speed at which water moves through the pore space of the aquifer). If there were no confining beds, the value of the hydraulic head, h, would be approximately the same anywhere in the sediments above basement (except for small differences associated with variations in ground-water velocity).

The fundamental equation of ground-water flow is governed by Darcy's Law,

$$V = P(dh/dl)$$

where V is the "Darcy velocity" of ground-water flow. The actual velocity of water through the pore space is given by V/n where n is the porosity of the aquifer. P is the permeability of the aquifer; the "hydraulic gradient" is dh/dl. The equation simply states that water flows from a higher energy state (hydraulic head, h) to a lower energy state, always. The difference in energy states is accounted for by energy lost due to friction as the water moves through the pore space of the aquifer. The presence of confining beds causes different values of h to occur in different aquifers. A hole drilled into the sediments of the Coastal Plain will encounter different values of h, which would result in upward (or downward) flow in the hole and prevent the determination of an accurate geothermal gradient. For this reason, each hole was cased to its total depth and cemented to prevent circulation between aquifers. Convection in or near a hole can result in an unreliable geothermal gradient determined in a shallow (300 m) hole.

Temperatures were measured at intervals of 2.5 m (8 ft) in each hole. Average gradients, G, were determined in each hole by the least-squares fit of a straight line over the entire interval of the hole below a depth of about 50 m (160 ft). An attempt was made to recover two sediment core samples, each 8 m (25 ft) in length from each hole. Core recovery was variable because of the unconsolidated nature of the sediments. Thermal conductivity, K, was determined in the laboratory using needle probe techniques.

Temperature profiles, geothermal gradients, and thermal conductivities are reported in a series of progress reports (Costain et. al., 1977, 1978, 1979).

Because the difference in concentrations of U and Th in basement rocks affects the geothermal gradient in the overlying sediments, it was important to site several holes both on and off potential field anomalies. The Portsmouth gravity anomaly (Figure 2) is an excellent example of a negative gravity anomaly over a presumed buried granite pluton. A magnetic anomaly is also present. The sediments here are about 600 m (1900 ft) in thickness. A hole was drilled that encountered granite at a depth of about 600 m, and 90 m (300 ft) of continuous granite core (BQ) are now being recovered. Determinations of heat generation, age, and chemistry will be made on the core. A heat flow value will also be determined over the 90-m interval in the granite to confirm the value of heat flow determined in the overlying sediments. The geothermal gradient in the hole over the gravity anomaly is about 42 °C/Km; the gradient in a hole drilled nearby (12 km) but off the anomaly in the same lithologic sequence of sediments is 27 °C/Km. We regard this as excellent confirmation of the radiogenic pluton model.

Lambiase et al. (1979) discuss in detail the distribution and values of the geothermal gradients obtained in the holes drilled on the Atlantic Coastal Plain. The most promising area to date appears to be between Crisfield, Maryland, and Oak Hall, Virginia, in southern Maryland and northern Virginia on the Eastern Shore (Figure 1). Higher gradients (48 °C/Km) were found elsewhere, for example, within the large negative gravity anomaly in the vicinity of Chesapeake Bay, but the depth to basement there is less.

References

Bell, H., III, and P. Popenoe, 1976, Gravity studies in the Carolina slate belt near the Haile and Brewer Mines, north-central South Carolina. Journ. Res. U.S. Geol. Survey, v. 4, 667-682.

Birch, F., 1954, Heat from radioactivity, In Nuclear Geology, H. Faul, editor, John Wiley and Sons, New York, p. 148-174.

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, J. B. Hadley, and J.B. Thompson, Jr., editors, Interscience, New York, p. 437-451.

Costain, J. K., G. V. Keller, and R. A. Crewdson, 1976, Geological and geophysical study of the origin of the warm springs in Bath County, Virginia. Report prepared for the Department of Energy under Contract E-(40-1)-4920. Available from National Technical Information Service, Springfield, VA, 22161, 184 p.

Costain, J. K., L. Glover, III, and A. K. Sinha, 1977, -78, -79, Evaluation and targeting of geothermal energy resources in the southeastern United States. Series of Progress Reports VPI&SU-5103, and VPI&SU-5648, prepared for the Department of Energy. Available from the National Technical Information Service, Springfield, VA, 22161, 184 p.

Costain, J. K., 1979, Computation of anomalous magnetic fields from point-pole source distributions, in press, J. Mathematical Geology.

Dennison, J. J. and R. W. Johnson, Jr., 1971, Tertiary intrusions and associated phenomena near the thirty-eighth parallel fracture zone in Virginia and West Virginia, Geol. Soc. Amer. Bull., v. 82, 501.

Dobrin, M. B., 1976, Introduction to Geophysical Prospecting, McGraw-Hill, Inc., 630 p.

Geiser, P. A., 1976, Structural mapping in the Warm Springs Anticline, northwestern Virginia. In evaluation and targeting of geothermal energy resources in the southeastern United States, Progress Reports VPI&SU-2, prepared for the Department of Energy under Contract E-(40-1)-5103, p. 116-164.

Hewett, D. F., and Crickmay, G. W., 1937, The warm springs of Georgia, their geologic relations and origin: U.S. Geological Survey Water-Supply Paper 819, 40 p.

Hobba, W. A., Jr., Chemerys, J. C., Fisher, D. W., and Pearson, F. J., Jr., 1977, Geochemical and hydrologic data for wells and springs in thermal-spring areas of the Appalachians: U. S. Geological Survey Water-Resources Investigations Report 77-25, 36 p.

Hobba, W. A., Jr., Fisher, D. W., Pearson, F. J., Jr., and Chemerys, J. C., 1978, Hydrology and geochemistry of thermal springs of the Appalachians: U.S. Geological Survey Professional Paper 1044 (in press).

Lachenbruch, A. H., 1968, Preliminary geothermal model for the Sierra Nevada, Journ. Geophys. Res., v. 73, 6977-6989.

Lambiase, J. J., Dashevsky, S. S., Costain, J. K., and R. J. Gleason, 1979, Geothermal resource potential of the northern Atlantic Coastal Plain, submitted for publication.

Lowell, R. P., 1975, Circulation in fractures, hot springs, and convective heat transport on mid-ocean ridge crests, Geophys. J. Roy, Astr. Soc., v. 40, 351-365.

Muffler, L. J. P., ed., 1979, Assessment of geothermal resources of the United States--1978, U. S. Geological Survey Circular 790, 163 p.

Muffler, L. J. P., and Cataldi, R., 1979, Methods for regional assessment of geothermal resources: Geothermics, v. 7, no. 2-4 (in press).

Nettleton, L. L., 1971, Elementary gravity and magnetics for geologists and seismologists, Society of Exploration Geophysicists, P. O. Box 3098, Tulsa, Oklahoma 74101, 121 p.

Perry, L. D., J. K. Costain, and P. A. Geiser, 1979, Heat flow in western Virginia and a model for the origin of thermal springs in the folded Appalachians, in press, J. Geophys. Res.

Reeves, F., 1932, Thermal springs of Virginia: Virginia Geological Survey Bulletin 36, 56 p.

Rogers, W. B., 1884, On the connection of thermal springs in Virginia with anticlinal axes and faults, Assoc. Am. Geologists and Naturalists, Report of 1st, 2nd, and 3rd meetings, p. 328-330, 1840-1842. A reprint: Geology of the Virginias, p. 577-597, New York.

Roy, R. F., D. D. Blackwell, and F. Birch, 1968, Heat generation of plutonic rocks and continental heat flow provinces, Earth Planet.

Sci. Letters, v. 5, 1-12.

Rybach, L., 1976, Radioactive heat production in rocks and its relation to other petrophysical parameters, Pageoph., v. 114, Birkhauser Verlag, Basel.

Sammel, E. A., 1979, Occurrence of low-temperature geothermal waters in the United States, In Assessment of Geothermal Resources of the United States -- 1978, L. J. P. Muffler, ed., U. S. Geological Survey Circular 790.

Stose, G. W., and Stose, A. J., 1947, Origin of the hot springs at Hot Springs, North Carolina: American Journal of Science, v. 245, no. 10, p. 624-644.

U. S. Geological Survey Open-file Report, 1970, Aeromagnetic map of the Camden-Kershaw area, north-central South Carolina.

Watson, T. L., 1924, Thermal springs of the south: east Atlantic States, Journ. Geology, v. 32, no. 5.

White, D. E., and Williams, D. L., eds., 1975, Assessment of geothermal resources of the United States -- 1975; U. S. Geological Survey Circular 726, 155 p.

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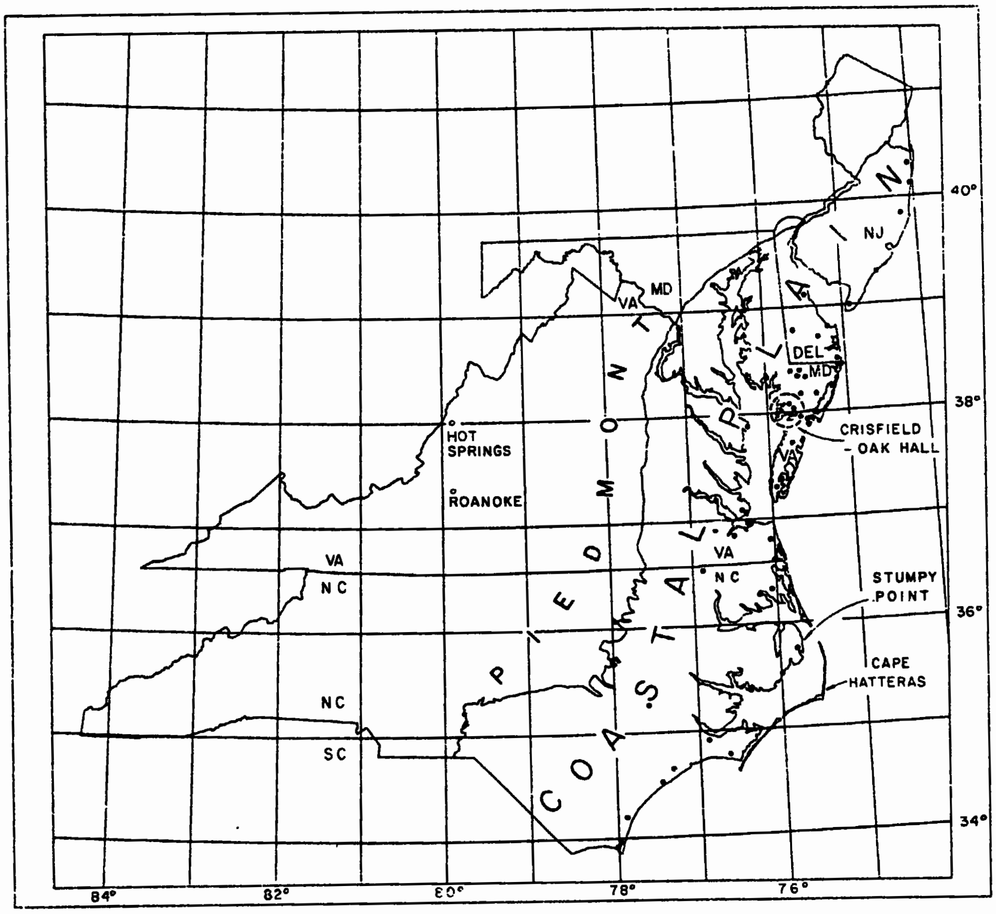

Figure 1. Locations of shallow (300 m) heat flow holes drilled on Atlantic Coastal Plain are shown as small dots.

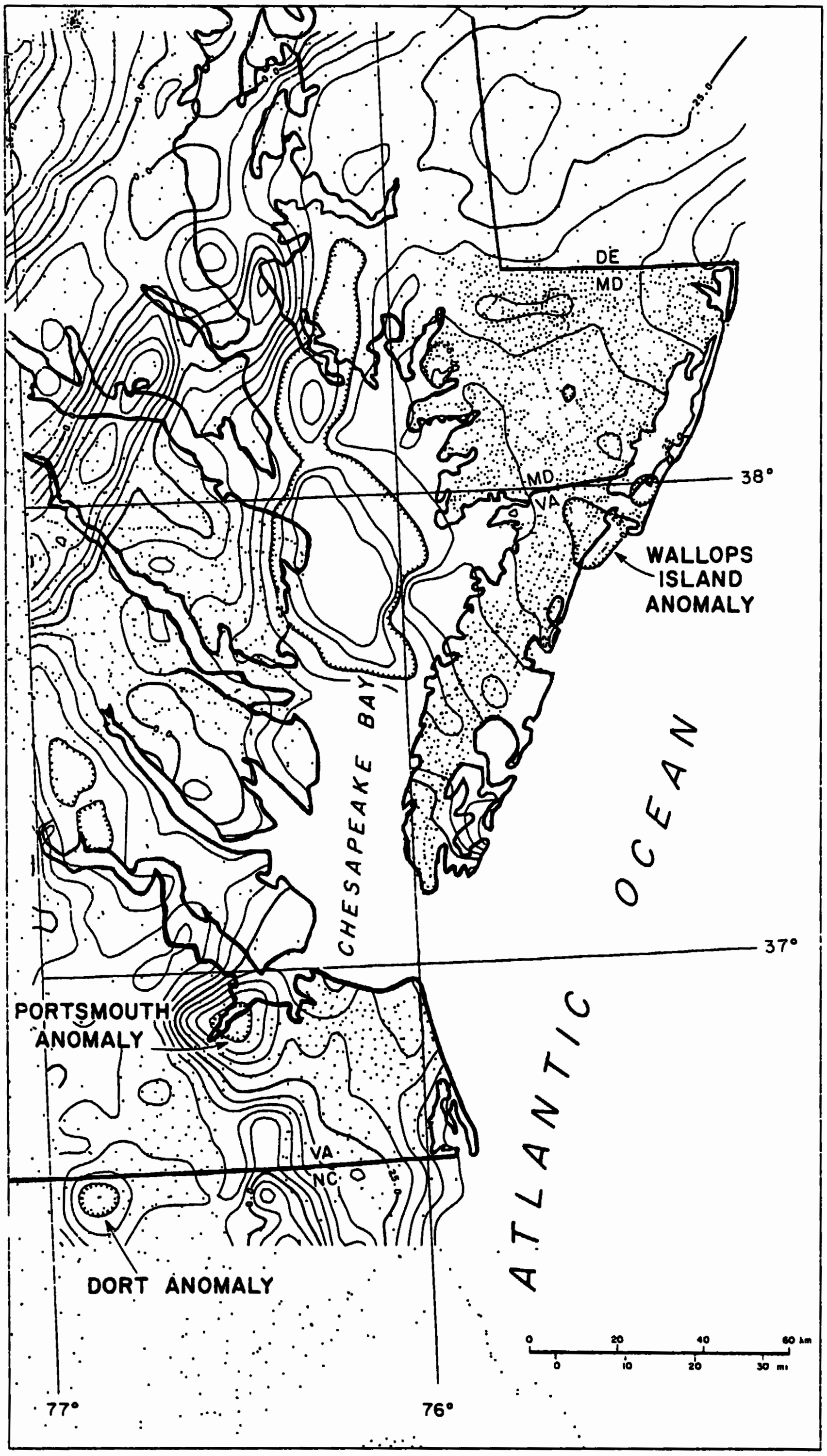

Figure 2. Gravity map of parts of Delaware, Maryland, and North Carolina. Contour interval is 5 milligals. Gravity stations indicated by small dots.

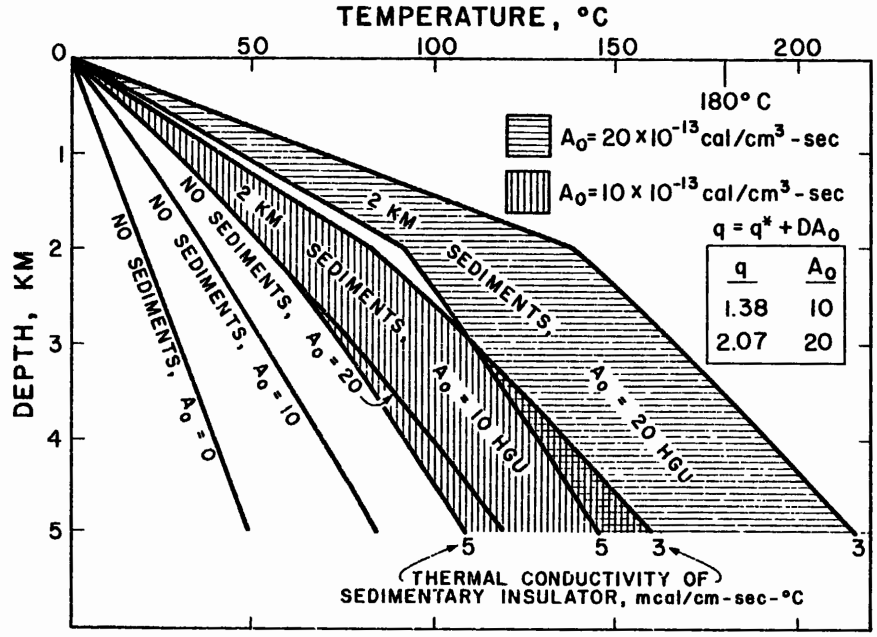

Figure 3. Effect on subsurface temperatures of insulating blanket of sediments of low thermal conductivity.

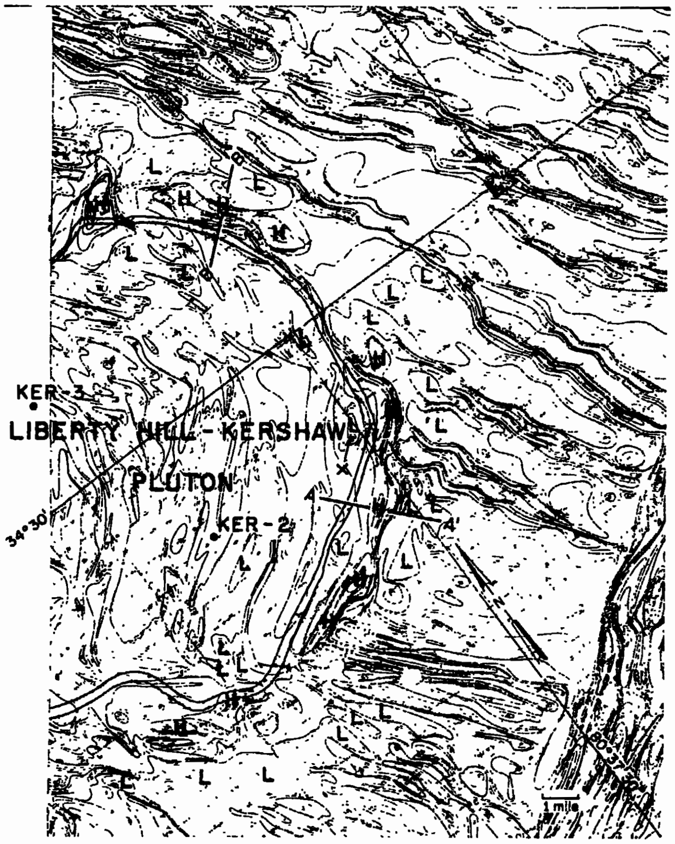

Figure 4. Circular magnetic anomaly associated with the Liberty Hill-Kershaw granite pluton. Northwest-trending linear anomalies are Triassic dikes.

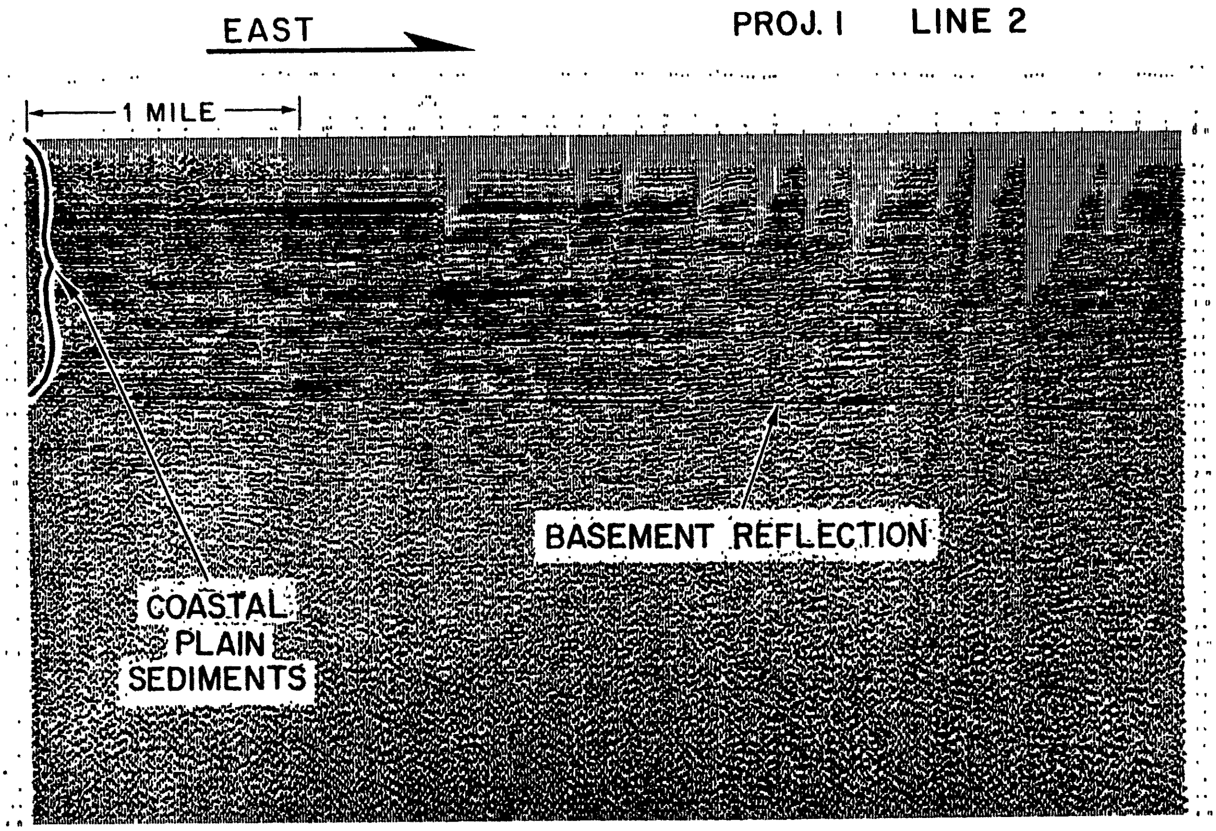

Figure 5. Reflection seismic section (24-fold) obtained near Salisbury, Maryland.

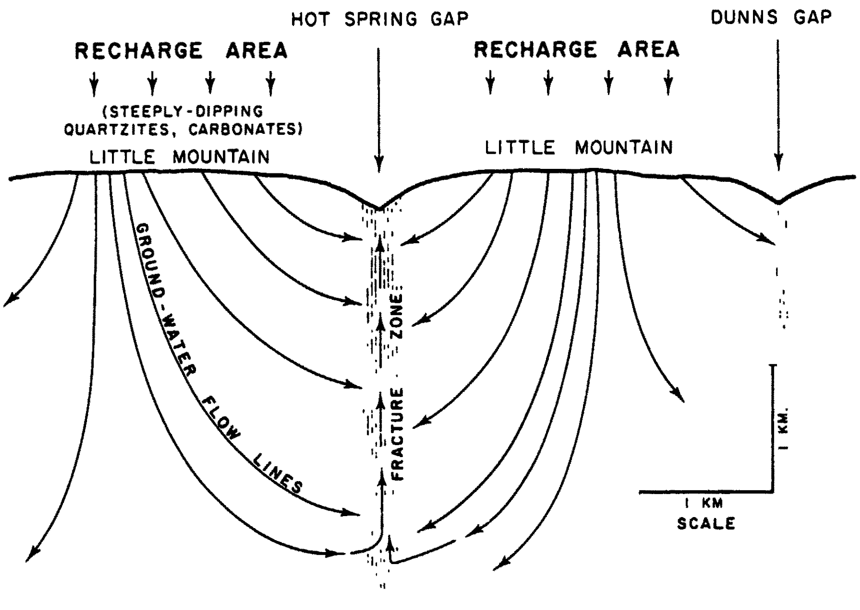

Figure 6. Hypothetical vertical cross section at Hot Springs, Virginia. Section is oriented at approximately right angles to transverse fracture zones.