5387

# GEOTHERMAL EXPLORATION METHODOLOGY IN THE EASTERN U. S. AND RESULTS OF FIRST DEEP TEST ON THE ATLANTIC COASTAL PLAIN AT CRISFIELD, MARYLAND

John K. Costain

Geothermal Program, Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

## INTRODUCTION

This paper includes a brief discussion of the geological and geophysical techniques we have used to investigate the geologic framework of geothermal resources on the Atlantic Coastal Plain. Results of the recent geothermal test well at Crisfield, Maryland are discussed.

Systematic efforts to estimate the geothermal resources of the entire United States have been made by the U. S. Geological Survey (White and Williams, 1975; Muffler, 1979; Sammel, 1979). Much exploration remains to be done before the extent of the geothermal resource in the eastern United States can be adequately defined. Costain, Glover, and Sinha (1980) discuss the geologic model upon which exploration in the eastern United States on the Atlantic Coastal Plain is based.

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 water as a source of energy for space heating and industrial processes and systems.

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. In many locations, shallow aquifers in these sediments are known to yield large quantities of water. Until the deep geothermal test at Crisfield, Md. was completed, not much was known about the yield of the deeper aquifers.

The water in the aquifers of the Atlantic Coastal Plain 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 over the entire 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 order to understand the ages, chemistry, heat production, and areal distribution of exposed granite plutons. Geophysical techniques include the interpretation of gravity and magnetic potential field data, as well as seismic data, and are being used in both the Piedmont and the Coastal Plain.

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. The nature and distribution of geothermal energy are discussed by Muffler et al. (in press). We have used several kinds of geophysical data during the course of our geothermal program (Costain, 1979). 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 °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 Appalacian Mountain System will have temperature gradients that are much higher than those found in holes drilled into dolomite. 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 and therefore act as even better insulators. 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 crystalline basement rocks will result in substantial variations in heat flow (Birch et al., 1968).

Granitic rocks relatively enriched in U and Th 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 sediments overlying the granitic rocks, relative to surrounding areas. Radiogenic heat is independent of normal heat flow around and beneath the granite plutons and can be more than twice 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. These exposed basement rocks are concealed to the southeast by a seaward-thickening wedge of sediments beneath the Atlantic Coastal Plain (Speer and others, 1979). The sediment thickness is known to reach a maximum of 3 km (9900 ft) at Cape Hatteras, N.C.

The effect on subsurface temperature where basement rocks are covered with a thick sequence of sediments of relatively low thermal conductivity is discussed by Costain et al. (1980). 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/cm3 per sec) have been measured during VPI&SU studies of granite plutons exposed in the Piedmont. In New England, exposed granite plutons locally have heat productions of 24 HGU (Birch et al., 1968). If U- and Th-bearing granite is blanketed by sediments that have a relatively low thermal conductivity, the subsurface temperature is increased . 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 th geothermal gradient and heat flow were based primarily on the interpretation of gravity and magnetic potential field data. Summaries of the results to date of this program are given in a series of progress reports entitled Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States (1979).

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. Granite is the least dense of the igneous intrusive rocks that occur in large volumes. Since granite is generally less dense than the country rocks into which it has been emplaced, a negative gravity anomaly results (See, for example, Costain, 1979, p. 20). If, however, granite was emplaced in country rock that was <u>also</u> 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 (Glover, 1979 ). 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, and magnetic minerals can be formed in a contact aureole in the host rocks into which the pluton is intruded (Speer, 1979). A good example of a magnetic anomaly associated with a granite exposed in the Piedmont is shown on the aeromagnetic map of the Camden-Kershaw area in the Piedmont of north-central South Carolina (U.S.G.S., 1970). 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 also suggests that granitic plutons do 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 important 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,

4) examine the spatial continuity of deep acquifers.

## 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 and the results of the drilling program are given in a series of reports to the Department of Energy (VPI&SU-5648-5 and VPI&SU-78ET-27001-7) and are available from the National Technical Information Service, Springfield, Maryland 22161. 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.

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 (Costain, 1979, p. 20) 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) was recovered. Determinations of heat generation, age, and chemistry have been made on the core. A heat flow value was 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 drill 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. A hole 100 m into basement has just been completed at the off-anomaly drill site confirming that the basement rocks are not granitic.

Lambiase et al. (1979) discuss in detail the distibution 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, Md., and Oak Hall, Va. in southern Maryland and northern Virginia on the Eastern Shore. 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.

## Summary of Results of Deep Geothermal Test at Crisfield, Maryland

A Site Selection Meeting was held at Blacksburg, Va. on January 16-17, 1979. During this meeting possible drill sites were discussed for which:

a) the geothermal gradient was known to be relatively high as a result of the VPI&SU shallow (300 m) drilling program on the Atlantic Coastal Plain in New Jersey, Delaware, Maryland, and North Carolina,

b) the thickness of Coastal Plain sediments was not excessive and depths could be reached that would result in a cost-effective drilling program.

No hard data were available with regard to well yields of any deep aquifers in the areas discussed, and the final selection of a site was therefore not prejudiced by the occurrence of known or suspected aquifers.

Maximum temperatures predicted at the base of the sediments by VPI&SU were determined by assuming that the average geothermal gradient in a cased, cemented 300 m hole remained constant to the base of the sediments. Temperatures predicted by this method would therefore be maximum expectable temperatures because it was felt unlikely that, for the areas under consideration, the thermal conductivity of the sediments would decrease with depth. Our basement temperature predictions are considered maxima because they are based on data from the upper 305 m where thermal conductivities might be expected to be somewhat low in the northern part of the Atlantic Coastal Plain.

At the time of the Site Selection Meeting in Blacksburg, an accurate estimate of the depth to basement at Crisfield was not available. A depth was therefore computed using the nearest wells that penetrated basement, under the assumption that the slope of the basement surface was approximately constant between these wells. Subsequent reflection seismic data (obtained before the drilling began) indicated that our initial assumption was incorrect, and that the depth to the 'basement' reflector was approximately 1.30 km, about 16% less than the depth stated at the Site Selection Meeting in January; the maximum predicted temperature would therefore also be less by about the same amount. (The final depth and temperature estimate were made by VPI&SU more than two months before the drilling at Crisfield began; the revised estimates are incorporated into our Progress Report VPI&SU-5648-5, p. A-79 and C-24). In light of this new seismic data, it was nevertheless the recommendation of VPI&SU that the site not be changed because it was clear that the Crisfield site was consistent with program objectives.

Upon completion of the Crisfield well it was discovered that the 'basement' reflector marked the top of a poorly known 75-m thick (locally) indurated high-velocity section of Coastal Plain sediments, and that true crystalline basement was at the base of this indurated sequence at a depth of 1.36 km. Temperature at the top of crystalline basement was found to be about 58°C (137°F). Thus, the predicted temperature was within 16% of the actual temperature, and the difference was due to the uncertainty in estimating the thermal conductivity of Coastal Plain sediments in the lower 80% of the sedimentary sequence.

The drill site at Crisfield, Md. is located off but near the flank of a major negative gravity anomaly that underlies the Chesapeake Bay. We have named this gravity minimum the 'Chesapeake Bay Gravity Low' (CBGL). The highest gradient we have determined to date in the eastern United States was determined in one of our shallow (300 m) heat flow sites at Smith Point, Va. The Smith Point site is on the western flank of the CBGL. Based on our growing data base and confirmation of the radiogenic model (Costain, Glover, and Sinha, 1980) at Portsmouth, Va., we speculate that the CBGL may represent a large radiogenic granite in the basement. The depth to basement at Smith Point is approximately 0.92 - 0.96 km. Although the geothermal gradient at Smith Point is higher than that at and near Crisfield, the sediment thickness is greater at Crisfield; the Crisfield site is as close as possible to the CBGL on the Delmarva Penninsula without drilling on Smith Island in the Chesapeake Bay (an attractive possibility because of the potential geothermal energy resource on Smith Island and the demonstrated need there).

Drilling began at Crisfield, Md., on May 13 and was completed on June 14, 1979. Drilling was done under contract to Gruy Federal, Inc. Total depth reached (including basement penetration) was 1693 m. Analysis of drill cuttings of basement rock (Gleason, 1979) indicates a relatively uniform lithology over the 331 m of basement penetrated. The basement is a metavolcanic rock. For a more complete description, see Gleason (1979).

Overlying crystalline basement at a depth of 1362 m is a 75-m thick, well-indurated unit which is an excellent seismic reflector. From drill cuttings, this unit appears to be a lithologically heterogeneous composite of buff, blue-gray, brown, and red shale clasts, and gradually downward-increasing amounts of subrounded to subangular sand-sized gray-green metavolcanic fragments. For a more complete discussion refer to Svetlichny and Lambiase (1979). Drill cuttings from overlying Coastal Plain sediments were sampled every 3 m by VPI&SU staff, and ten 10-meter core attempts were made at selected intervals in the Coastal Plain sediments. Core intervals, recoveries, and lithologic descriptions of drill cuttings are given by Svetlichny and Lambiase (1979). Lithologies encountered in the sediments above basement include thick sand layers interbedded with thin layers of variegated shale (Patuxent Formation); dark-colored clay, shale and sandy shale (Arundel); fine to medium sands intercalated with variegated shale and clay (Raritan); and fine-to-medium white and buff quartz sand with minor stringers of carbonaceous clay and lignite (Magothy?). Sands and silts overlie the Magothy.

The Crisfield hole was not intended to be completed as a production well. Limited pump tests were run to determine potential fluid production by perforating the casing. Three zones in the coastal Plain sediments were perforated. The following results of temperature logging and aquifer testing are taken from Dashevsky and McClung (1979).

Zone No. 1 was perforated between 1262m and 1285m (4142 ft - 4217 ft). A down-hole centrifugal pump set at 180m (600 ft) lowered the piezometric surface to a depth of 180m below the ground surface in 8 min at a rate of 150 gpm. It is not clear whether or not all perforations in this zone were effective in allowing water to enter the well. A smaller pump capable of maintaining 10 gpm was then set at 180m and pumped for 24 hours at an average rate of 14 gpm. The static drawdown at this discharge was approximately 4.6m (15 ft). The temperature of the water flowing from the perforated zone was 57.2 °C (135 °F) at the level of perforation.

Zone No. 2 was perforated from 1187m to 1227m (3895 ft - 4026 ft) and the large volume pump was set at a depth of 210m (700 ft). This second zone was indicated by logs and cuttings to be a cleaner sand than Zone No. 1. Water was pumped from this zone for 48 hours at an average rate of 119 gpm drawing the static head down 84m (275 ft). The temperature of water at the level of perforation was 56 °C (133 °F) and at the surface the discharge temperature was 51 °C (124 °F). During each pump test, surface temperature was seen to rise continually. Under high production for an extended period of time it is expected that the difference between the well head and perforation temperature would be less.

Following tests of Zone No. 2, a cement retainer was set at 1181m (3874 ft) and the perforations of Zones 1 and 2 were squeezed with cement.

Zone No. 3 was perforated between 1155m and 1170m (3792 ft - 3840 ft). Logs and cuttings indicated this zone to be a clean sand within a thick shale horizon. The small low-volume pump was set at a depth of 125m (410 ft) and produced at an average discharge of 32 gpm. for 36 hours, resulting in a static drawdown of 30m (98 ft). Down-hole water temperature was 54 °C (129 °F). A preliminary estimate of permeability of #Zone 2 is 110 md (Paddison, 1979). Estimates made by Gruy Federal, Inc., however, are 75 md.

## Conclusions

Results of the first deep geothermal test in the sediments beneath the Atlantic Coastal Plain are encouraging. Electric logs run in the Crisfield hole indicated the presence of aquifers at depth. The limited amount of aquifer testing that was possible indicated the presence of aquifers of potentially adequate production for many low temperature geothermal applications. The scope and variety of applications of geothermal energy on the Atlantic Coastal Plain are now being investigated by the Applied Physics Laboratory of Johns Hopkins University (Dr. A. W. Stone, personal communication, 1980).

## Acknowledgements

This work was sponsored by the Department of Energy under Contract Number DE-AC05-78ET27001 to principal investigators J.K. Costain and L. Glover, III.

## 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., 1979, Geothermal exploration methods and results: Atlantic Coastal Plain, in A Symposium of Geothermal Energy and its Direct Uses in the Eastern United States, Special Report No. 5, Geothermal Resources Council, Davis, CA 95616.

Costain, J. K., L. Glover, III, and A. K. Sinha, 1980, Low-temperature geothermal resources in the Eastern United States, EOS Transactions, Amer. Geophy. Union. (This paper contains some editorial errors that involve figure captions and an omitted figure. For a corrected reprint, write the authors.)

Dashevsky, S. and W. McClung, 1979, Summary of temperature logging of Crisfield, Maryland geothermal test hole, in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, edited by J. K. Costain and L. Glover, III, Progress Report VPI&SU-78ET-27001-7 to the Department of Energy; available from the National Technical Information Service (NTIS), Springfield, Virginia, 22161.

Evaluation and targeting of geothermal energy resources in the southeastern United States, 1979. Series of Progress Reports VPI&SU-5103, and VPI&SU-5648, edited by J. K. Costain, L. Glover, III, and A. K. Sinha, and VPI&SU-78ET-27001-7, edited by J. K. Costain and L. Glover, III; prepared for the Department of Energy. Available from National Technical Information Service, Springfield, VA, 22161, 184 p.

Gleason, R. J., 1979, Description of basement rocks from Crisfield, Md. deep geothermal test hole, in Evaluation and Targeting of Geothermal Energy Resources in the Southeastern United States, Progress Report VPI&SU-78ET-27001-7 to the Department of Energy; available from National Technical Information Services (NTIS), Springfield, Maryland, 22161.

Glover, III L., 1979, General geology of the east coast with emphasis on potential geothermal energy regions: A detailed summary, in A Symposium of Geothermal Energy and its Direct Uses in the Eastern United States, Special Report No. 5, Geothermal Resources Council, Davis, CA 95616.

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.

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).

Muffler, L. J. P., J. K. Costain, D. Foley, E. A. Sammel, and W. Youngquist, in press, The nature and distribution of geothermal energy, in Direct Utilization of Geothermal Energy: Development of Four Educational Reports, published by Geothermal Resources Council, Davis, CA, 95616.

Paddison, F., 1979, Geothermal heating for the Crisfield, Maryland High School, in Geothermal Energy and The Eastern U.S., Minutes, Johns Hopkins University, Applied Physics Laboratory, p. XV-1 - XV-16.

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.

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

Speer, J. A., 1979, Magnetic anomalies coinciding with metamorphic isograds in the Liberty Hill aureole, South Carolina, Geological Society of America, Abstracts with Programs, March, 1979.

Speer, J. A., S. W. Becker, and S. S. Farrar, 1979, Field relations and petrology of the postmetamorphic, coarse-grained granitoids and associated rocks of the southern Appalachian Piedmont, in The Caledonides in the U.S.A., IGCP Project 27: Caledonide Orogen, Dept. of Geol. Sic., VPI&SU, Blacksburg, VA, 24061.

Svetlichny, M. and J. L. Lambiase, 1979, Coastal Plain stratigraphy at DGT-1, Crisfield, Maryland, in Evaluation and Targeting of Geothermal Resources in the Southeastern United States, edited by J. K. Costain and L. Glover, III, Progress Report VPI&SU-78ET27001-7 to the Department of Energy. Available from NTIS, Springfield, MD 22161.

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

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.