GEOTHERMAL ENERGY IN THE EASTERN UNITED STATES: THE RADIOGENIC MODEL

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The geothermal energy resource in the eastern United States is primarily a liquid-dominated, low-temperature system. 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; Muffler and Cataldi, 1979).

The major factors that result in geothermal anomalies in the eastern United States are different than those in the West. For example, heat from radioactive decay is more important in the East. In the eastern United States, known geothermal gradients are in the range of 10° to 50°C/km. Gradients higher than 30°C/km are considered to be anomalously high. The geothermal gradient, $\Delta T/\Delta z$, is a function of both conductive heat flow, q, and thermal conductivity, K, because:

$$\Delta T/\Delta z = q/K.$$

High gradients will therefore be found where the local heat flow has a high value, and where the local thermal conductivity of rocks is low. As discussed below, high heat flow is characteristic of unmetamorphosed granites; low thermal conductivity is characteristic of sediments that blanket these granites. The efficient transfer and use of geothermal energy always requires convective transport of thermal energy by fluids. In all geothermal systems, the most desirable locations are those where the warmest fluids can be extracted from the shallowest depths. These locations are usually, but not always, coincident with regions where the conductive heat flow is highest.

Birch et al. (1968), Lachenbruch (1968), and Roy et al. (1968) showed that the local heat flow in the eastern United States is related to the concentration of uranium and thorium in surface rocks (mostly granite). Costain and Glover (1980) found a similar relationship in the southeastern United States. Isotopes of uranium (U), thorium (Th), and potassium occur in sufficient abundance and have half-lives sufficiently long to be important for heat generation from radioactive decay (Birch, 1954). Decay of a uranium atom produces about four times as much heat as the decay of thorium atom; however, Th/U ratios in many granite rocks are about equal to four so that thorium is usually as important as uranium. The heat generated from uranium and thorium in typical granites is about 85-90% of the total; heat from potassium decay is considerably less important, about 10-15% The immediate implication of this is that the distribution of uranium and thorium in the upper 10 to 15 km of the earth's crust is primarily responsible for the observed lateral variations in surface heat flow in the eastern United States.

Unmetamorphosed granite plutons and batholiths relatively enriched in uranium and thorium are exposed in the Piedmont Province (Fig. A-3). These Piedmont rocks are concealed to the southeast by a seaward-thickening wedge of Atlantic Coastal Plain sediments. Similar granitoids occur in these concealed Piedmont rocks, which are the basement beneath the Atlantic Coastal Plain.

Geothermal resources in the Appalachian Mountain System and the Atlantic Coastal Plain may be grouped into (I) water-saturated sediments of low thermal conductivity overlying radioactive heat-producing granites, (II) areas of normal geothermal gradient, (III) hot and warm springs emanating from fault-fracture zones as a result of leakage from greater depths, (IV) hot dry rock, especially radioactive granites beneath sediments of low thermal conductivity.

Resource I (Fig. A-4) is referred to as the "radiogenic model" (Costain et al., 1980) and has been the principal objective of the geothermal program at Virginia Polytechnic Institute and State University (VPI&SU). Temperature gradients are high in areas where the resource is found because heat-producing granite basement rocks are blanketed with a thick sequence of sediments of relatively low thermal conductivity (Fig. A-5). Large volumes of granite with low concentrations of uranium and thorium will increase the subsurface temperature substantially, and relatively higher temperatures will be found at shallow depths within sediments that overlie such bodies, as indicated in Fig. A-5. An understanding of the distribution of granites and of uranium and thorium in the basement rock is therefore important in order to define locations where the highest temperatures occur at the shallowest depths.

Optimum sites for the development of geothermal energy in the eastern United States probably will be associated with the flat-lying, relatively unconsolidated sediments that underlie the Atlantic Coastal Plain. These sediments have a relatively low thermal conductivity, and there are many

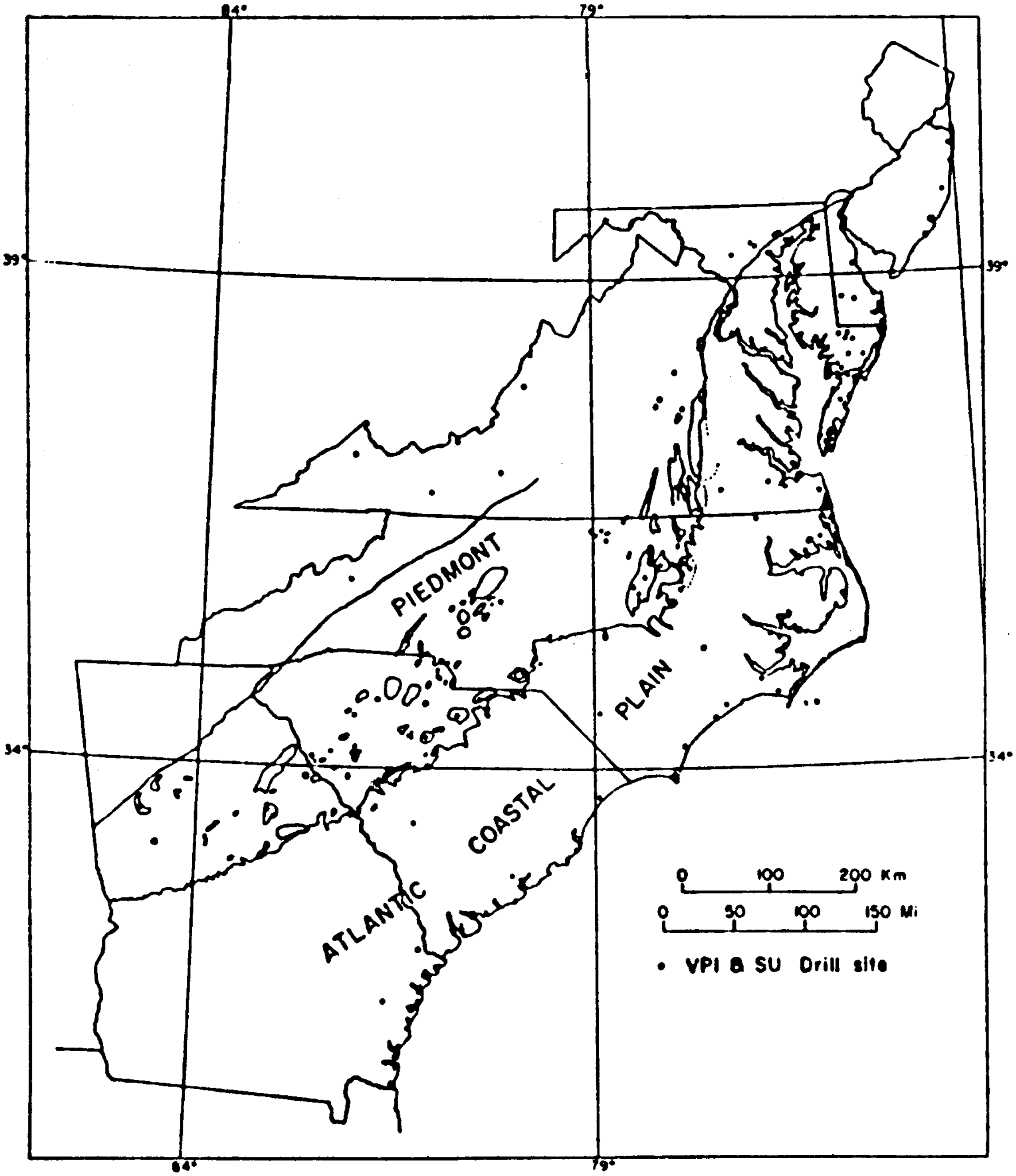

Fig. A-3.
Late Paleozoic syn- and post-Metamorphic granites in the southeastern United States.

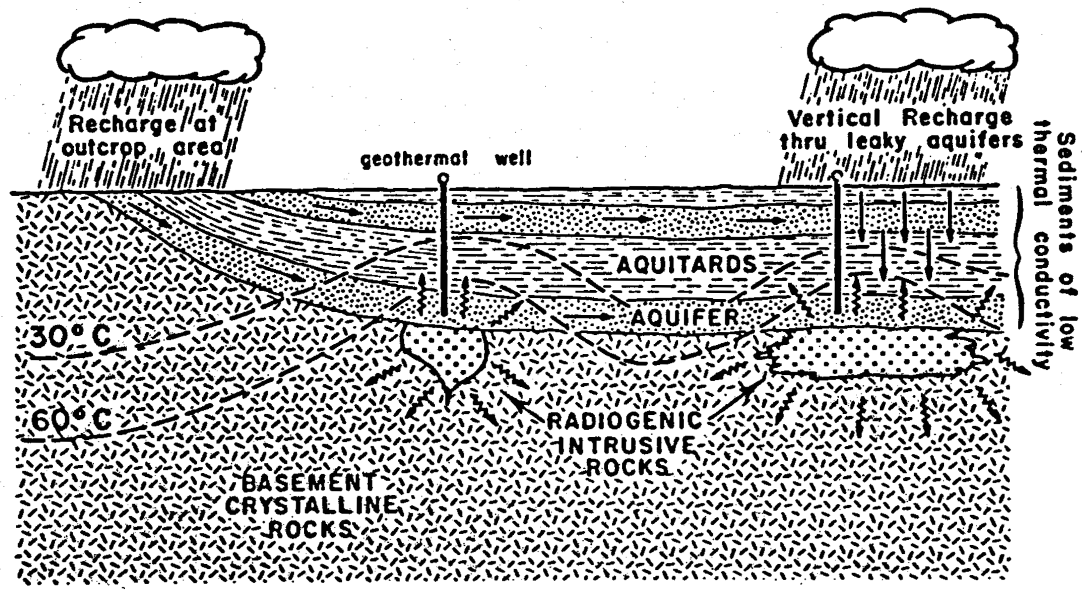

Fig. A-4.
Radiogenic model.

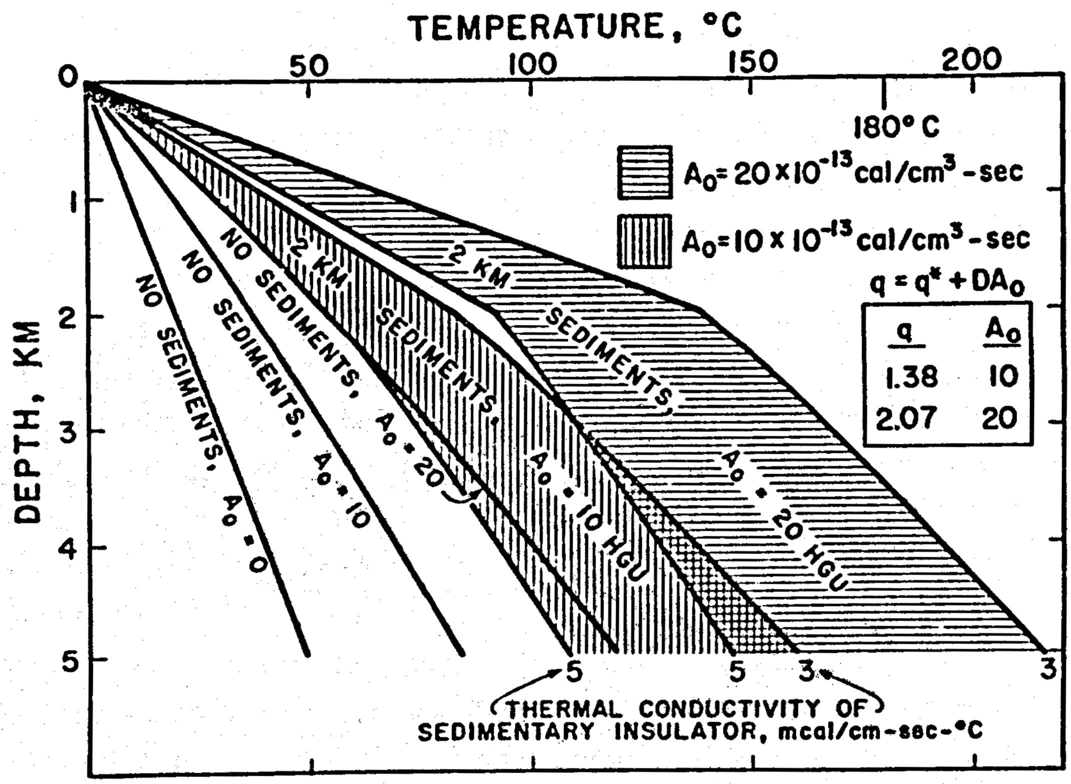

Fig. A-5.
Effect of sediment blanketing.

potential aquifers within the sandy, deeper parts of the sedimentary section that probably contain large quantities of hot water.

Resource II is widely available throughout much of the United States (Sammel, 1979). The entire Atlantic Coastal Plain would fall into this resource category. West of the Blue Ridge, thick sequences of Paleozoic sediments blanket crystalline basement rocks of unknown heat generation. In such areas, thick shales will result in higher geothermal gradients than carbonate rocks or sandstones, even where the heat flow is normal. As noted by Sammel (1979), the low-temperature geothermal waters of the central and eastern United States are known or inferred to be extensive. Their utilization is dependent upon identification of locations where conditions for recovery are economically favorable.

Resource III is found in the northwestern part of Virginia and adjacent parts of West Virginia, where approximately 100 springs have temperatures ranging from 9° to 41°C. The hottest springs are in the Warm Springs anticline in folded sedimentary rock of Paleozoic age in northwestern Virginia. All of the warm springs in the valley are grouped near topographic gaps apparently associated with vertical transverse fracture zones (linears) that cut across adjacent folds to the east and west (Geiser, 1976). Faults and/or joints play an important role in the location of the warm springs, because warm springs are always near gaps that probably have developed along zones of increased fracture or joint density.

There is no known association of warm springs with heat-producing granites. The origin of the warm springs in the Warm Springs Anticline in northwestern Virginia as proposed by Perry et al., (1979) is as follows. Meteoric water enters steeply dipping Silurian quartzites on the northwest limb and permeates to depths sufficient to heat the water in the presence of the normal geothermal gradient (about 10°C/km) near Hot Springs, Virginia. Ground-water flowlines near the surface and midway between the topographic gaps are approximately vertical (and parallel to bedding within the steeply dipping quartzites) because of the boundary condition imposed by the topographic relief between the gaps. At depth, the water moves horizontally and intersects east/west trending, vertical, transverse fracture zones. The temperature of the water issuing from springs located along the transverse fracture zones depends upon the depth reached by the water, and on the degree of its mixing with cooler, shallower water. Implicit in the model is the important requirement that the aquifer have an uninterrupted vertical relief large enough to allow the water to reach depths sufficient to heat it.

The water flow from Boiler Spring (40°C) at Hot Springs, Virginia, is 86,220 gallons/day (Hobba et al., 1979). The flow at Bolar Spring (22°C), about 20 km northeast of Hot Springs, is about 3,000,000 gallons/day. Because the total amount of heat released at the larger but cooler springs is much greater than that released at the smaller but warmer springs (Hobba and others, 1979, Table 3), the geothermal potential of the larger, cooler springs is much higher.

Los Alamos National Laboratory, the leader in the development of hot dry rock resources (Resource IV), predicts large such potential resources in the East. At any given depth, temperatures in hot dry rock in the East will be lower than those in the West. The range of temperatures to be expected in the East can be estimated from Fig. A-5. Of particular relevance to the development of a hot dry rock resource in the eastern United States is the physical significance of the linear relation between heat flow and heat generation. If the slope, D, of the linear relation is directly and simply related to a thickness parameter (Costain and Glover, 1980), then thickness of granite and prediction of subsurface temperature in a hot dry rock environment can be made with a high degree of confidence. The validity of this interpretation of the meaning of D could be constrained by reflection seismic data.

Several kinds of geophysical data have been used by us in our targeting strategy, the most important of which are heat flow determinations used to confirm coincidence of high heat flow and low thermal conductivity; these are the characteristics of the radiogenic model. We have also made extensive use of gravity data in our targeting strategy. Because granite usually is less dense than the country rocks into which it has been emplaced, granite occurrences are commonly revealed by negative Bouguer gravity anomalies.

One of the principal objectives of the geothermal program at VPI&SU has been to locate and study uranium- and thorium-bearing heat-producing granites in the Piedmont (Speer and others, 1980), and to predict the occurrence of such granites beneath the wedge-shaped body of chiefly unconsolidated sediments beneath the Atlantic Coastal Plain. Thickness can reach 3 km. During 1978-79, 49 holes were drilled to a depth of approximately 300 m (1000 ft) on the Atlantic Coastal Plain from New Jersey to North Carolina to determine heat flow. Results from the Coastal Plain have been summarized by Lambiase et al. (1980).

The Portsmouth, Virginia, gravity anomaly (Fig. A-6) is an excellent example of a negative gravity anomaly over a confirmed (by drilling) concealed heat-producing granite beneath 600 m of sediments. The geothermal gradient in the hole over the gravity anomaly is about 42°C/km; the gradient is 27°C/km in a hole drilled nearby (12 km) but off the anomaly in the same sequence of sediments. The heat flow over the granite is about 79 mW/m^2. This is excellent confirmation of the radiogenic pluton model.

One promising area for geothermal development discovered to date in the northern Atlantic Coastal Plain is on the Eastern Shore between Crisfield in southern Maryland and Oak Hall in northern Virginia. A deep hole was drilled at Crisfield, Maryland, because of the known high geothermal gradients there and the moderate depth-to-basement. Upon completion on the Crisfield well, it was discovered that the "basement" seismic reflector marked the top of a poorly known 75-m-thick (locally) indurated, high velocity section of Coastal Plain sediments, and that 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 approximately 58°C. The temperature predicted at the base of the Coastal Plain sediments at Crisfield was about 16% less than the measured temperature because of the uncertainty in estimating the thermal conductivity of Coastal Plain sediments in the lower 78% of the sedimentary sequence.

Three zones in the Crisfield hole were pump tested. Zone No. 1 was perforated between 1262 m and 1285 m. The temperature of the water flowing from the perforated zone was 57.2°C. Water pumped from Zone No. 2 (1187-1227 m) for 48 hours at an average rate of 119 gpm produced a head drawdown of 84 m. The temperature of water at the level of perforation was 56°C and at the surface the discharge temperature was 51°C. Zone No. 3 (1155-1170 m) produced an averaged discharge of 32 gpm for 36 hours, resulting in a static drawdown of 30 m. Downhole water temperature was 54°C and surface discharge temperature reached 35°C.

Limited hydrologic and heat flow data now available make it possible to estimate the thermal lifetime of a geothermal resource (the radiogenic model) beneath the Atlantic Coastal Plain. Laczniak (1980) modeled the response of a leaky aquifer system to a pumping plus injection well (a single dipole) using

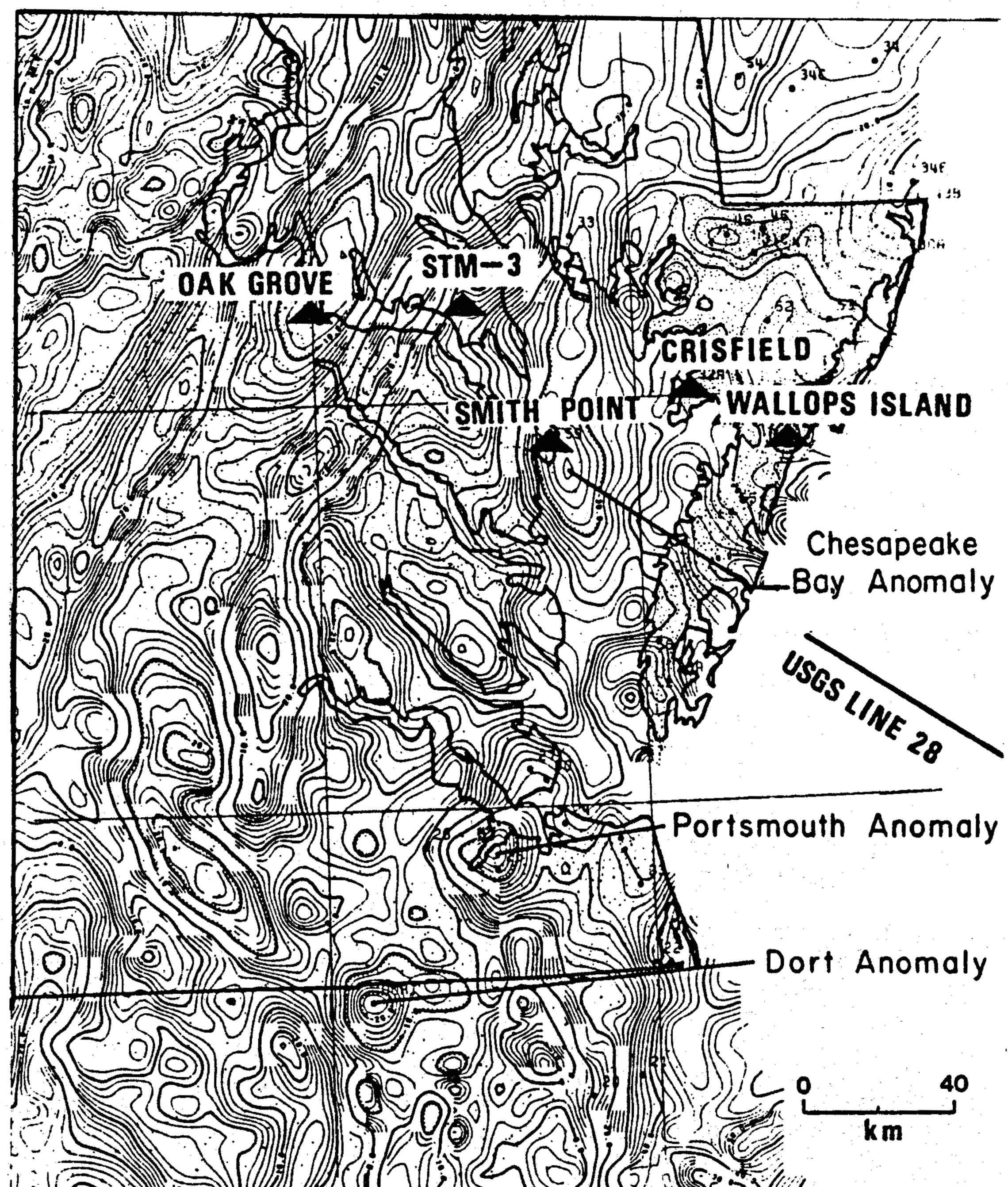

Fig. A-6.
Map showing locations of seismic data in Virginia (Smith Point and Portsmouth).

the integrated finite-difference method. The model was run for a simulated period of 15 years or until steady-state thermal and fluid flow was reached. A doublet system (dipole) with direct injection back into the reservoir was shown to be a feasible method of extracting heat from the low-temperature, liquid-dominated geothermal systems of the Atlantic Coastal Plain.

Important conclusions of Laczniak's study were: a) direct injection back into the reservoir may be necessary to maintain sufficient fluid pressure at the production well for systems with a low permeability; b) temperature distribution within the system is only slightly affected by changes in permeability in the range 10-100 md (millidarcies); c) resting the system for periods of 6 months does not result in a significant recovery; d) a doublet system with thermal and hydrologic conditions similar to those encountered at Crisfield, Maryland, a well spacing of 1000 m, a permeability of 100 md, and a pumping-injection stress of 500 gpm (injection temperature 44°C) could produce 5.5 million Btu's per hour over a period greater than 15 years.

In conclusion, geothermal energy may be an important resource for the eastern United States. Three resource types (the radiogenic model, normal geothermal gradient resources, and hot springs) appear to be favorable for immediate development. Predictions about the thermal longevity of the eastern geothermal resource are favorable.

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