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TID-26985

*Geological - Geophysical Evaluation of the Hot Springs
Area, Bath County, Virginia*
Progress Report

to

Energy Research and Development Administration

Contract No. E-(40-1)-4920

Contract Period: June 1, 1975 - February 29, 1976

Support Ceiling: \$50,000

Report Prepared

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December 1, 1975

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Introduction

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 ($9-12^{\circ}\text{C}$) to about 41°C (105.8°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).

Table I from Reeves (1932, p. 8) shows the number of springs in Virginia grouped according to their temperature. During the month of October, 1975 we obtained a continuous record of the temperature of Boiler Spring at Hot Springs. Boiler Spring is the hottest spring in the region. The recorded deviation from a temperature of 41°C was less than 0.25°C .

The hottest springs are located in the Warm Springs anticline in Bath and Alleghany Counties in Virginia where there are four groups of springs known as the Warm Springs, Hot Springs, Healing Springs, and Falling Springs. Since these are the hottest springs in the region, the present study has focused principally on the region centered around the Warm Springs anticline (fig. 1). Each group of springs in the Warm Springs anticline consists of at least three separate springs in close proximity. The group at

Table 1. Thermal springs in Virginia grouped according to their temperature.

Temperature, °C	Number of Springs
38 - 41	2
32 - 37	8
25 - 30	3
16 - 24	27
13 - 15	45

HOT SPRINGS, VA.

WARM SPRINGS ANTICLINE

FIGURE 1

Warm Springs is made up of three springs within about 30 meters of each other and a fourth about 250 meters to the southwest. At Hot Springs, eight warm springs occur over an area of about 4000 m². Healing Springs consists of three separate springs less than three meters apart. Falling Springs are made up of a number of flows and seepages at a much lower temperature than the other warm springs in the Warm Springs anticline, and with a much greater discharge than any other warm spring in the region.

Purpose of the Investigation

The purpose of this study is to evaluate the geothermal resource potential of the area in the vicinity of the Warm Springs anticline in Bath and Alleghany Counties, Virginia. The Warm Springs anticline is shown on the geologic map of Plate I.

Procedure

Phase I of the study is the compilation of a geologic map based on published maps and supported by reconnaissance and detailed geologic mapping in areas where published maps are not available. Phase II consisted of a regional bipole-dipole electrical resistivity survey made in order to detect the presence of resistivity lows that might be associated with a geothermal system at depth. Phase III will include drilling a single hole to a depth of approximately 300 m (~1000 feet) with the hope of obtaining a heat flow value that is representative of the region.

The above data will be used to arrive at a model which satisfactorily and unambiguously explains the origin of the thermal springs. Additional data other than that discussed above will have to be considered. Topographic maps combined with geologic maps will help to define where the source of the water

that feeds the springs is located. The geochemistry of the spring water will provide data with respect to the origin of the thermal springs.

Previous Investigations

Nearly a century ago, Rogers (1884) noted that the principal warm springs then known in Virginia were located along anticlinal fold axes. This observation has been corroborated by subsequent investigators. The most comprehensive study of the geology of the area was that of Reeves (1939) who reported on the geographic distribution of the springs, the temperature, discharge, chemistry, and gas content of the spring water, and the general geology of the area including topography, structural geology, and stratigraphy. Reeves' study was hampered by lack of complete topographic map coverage, and much of the stratigraphic nomenclature used by him, particularly that relating to the formations from which the springs issue, is now considered inappropriate for the area.

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 depths as the result of anticlinal folding. Rogers proposed that surface water entering the rocks at their outcrop in high anticlinal 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 waters 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), and Reeves (1932) have thus all postulated that the spring waters are of meteoric origin. The chief basis for this conclusion is the similarity in the chemical character of the water from the cold and warm springs, the fact that the dissolved gases appeared to be principally of atmospheric origin (Reeves, 1932, p. 28; 1974), and the observation that the geologic setting in which the springs occur is indeed compatible

with a model of artesian circulation of meteoric water through permeable beds. Additional geochemical studies of the spring waters are now in progress by the U.S. Geological Survey (W. Hobba, personal communication, 1975).

Recognition of albite-felsite sills and dikes of Eocene age in Highland County by Fullagar and Bottino (1969) suggested to Dennison and Johnson (1971) an alternative heat source other than deep circulation of meteoric water. The igneous intrusions are exposed just 30 km north of Hot Springs, Virginia. Dennison and Johnson suggested a causal relationship between the Schooley erosion surface and the known site of igneous activity. The generally accordant and flat profiles of the highest ridges in the Appalachian Plateau and adjacent Ridge and Valley region have been interpreted as an ancient erosion surface known as the Schooley peneplane. The age of this Schooley surface is variously interpreted as Cretaceous or early Tertiary (Wright, 1934, p. 10). The position of maximum uplift of a dome on the Schooley surface with 1000 feet of arching is close to the presumably younger Eocene intrusions in Highland County. Dennison and Johnson (1971, p. 503) proposed that thermal and mechanical energy associated with igneous intrusions at depth could upwarp the erosion surface.

Dennison and Johnson also noted a negative simple Bouguer gravity anomaly with its maximum negative value in western Bath County. Large granitic plutons usually have associated with them

negative density contrasts (Bott and Smithson, 1967). Dennison and Johnson suggested, therefore, that the large negative gravity anomaly is related to a deep felsic pluton that provides heat to the thermal springs centered in Bath County. They suggest that the pluton is either the source of the andesite dikes in Highland County, or possibly represents a later thermal (volcanic) pulse related to the same deep crustal fracture zone. The intrusives of igneous age represent the youngest known igneous activity in the eastern United States. The range of rock types represented is from basalt through andesite to trachytes, all of which can be related to the basalt by a crystal separation, differentiation process (Hall, 1974; Bollinger and Gilbert, 1974); there is no clear correlation, therefore, between these intrusives of shallow origin (Hall, 1974) and a proposed deeper-seated granitic body.

All of these phenomena are located near the apparent termination eastward of the "38th parallel fracture zone" (Snyder and Gerdemann, 1965; Heyl and others, 1965; Zartman and others, 1967). The extent of this fracture zone and its geographic relationship to Bath and Highland Counties are shown in Figure 2. The 38th parallel fracture zone has apparently been a site of sporadic igneous activity from late Precambrian to Eocene time. There is some suggestion that the intrusive activity is older toward the west. Dennison and Johnson (1971, p. 506) conclude that the 38th parallel fracture zone is still a geologically

Tectonic map adapted from the United States, 1962.

Figure 2. 38th parallel fracture zone and relationship to Bath and Highland Counties, Va.

active zone of weakness along which additional activity will probably occur in the geologic future.

Bollinger and Gilbert (1974) reported on a reconnaissance microearthquake survey at six sites in Bath County and one in Highland County. A swarm of 43 microshocks was recorded at Duncan Knob, about 20 km north of Hot Springs; however, the swarm stopped before the other two instruments could be moved into the area. The remaining six stations recorded no definite micro-earthquake activity during the recording program. Since no seismic events were recorded on more than one instrument, it must be concluded that the area is one of low microearthquake activity.

Prior to the present investigation, no detailed geophysical studies have been published in Bath and Highland Counties. This report describes the results of heat flow determinations and a reconnaissance dipole electrical resistivity survey in Bath County. Both of these geophysical approaches must be used to defend the credibility of any model of the origin of the hot springs in western Virginia.

Topography of the Region

Conditions for the generation of springs by deep artesian circulation of meteoric ground water include 1) folded beds, 2) permeability along bedding planes and/or joints extending to depths great enough to heat the water in the presence of the normal geothermal gradient, and 3) a source area of large enough areal extent such that precipitation can enter permeable beds at a relatively high outcrop and be discharged by springs where the same unit is exposed at a lower elevation. The elevations of the hottest springs at Hot Springs vary from 686 to 693 meters above sea level. Plate II shows the extent of surface area in the region above an elevation of 732 meters (2400 feet). It appears that an adequate source area is present to satisfy condition (3) above, and to provide a hydrostatic head sufficient for deep artesian circulation.

Figures 3 and 4 show preliminary structural cross sections across the Warm Springs anticline. It is apparent that condition (1), above, also appears to be satisfied.

Figure 3. Preliminary structure sections across the Warm Springs anticline.

Section D-D', Dunns Gap

Section F-F', Thru Quarry, Hot Springs, Va.

Section E-E', Thru Hot Springs Gap

Sk - Keefer
 Srh - Rose Hill
 St - Clinch ss.
 Oj - Juniata

Omb - Martinsburg
 Ols - Edinburg - Lincolnshire
 Olv - Lurich
 Ob - Beekmantown

Figure 4. Preliminary structure sections across the Warm Springs anticline.

Geothermal Gradient and Heat Flow in Bath County

We have obtained a reliable heat flow value of 1.23 ± 0.20 $\mu\text{cal}/\text{cm}^2\text{-sec}$ from four holes at Back Creek at $38^\circ 13' 45''$ N. Lat. $79^\circ 48' 45''$ W. Long., about 25 km north of Hot Springs, Va. The temperature and gradient profiles are shown in Figure 5. The geothermal gradients over the parts of the holes not affected by moving ground water are approximately $14^\circ\text{C}/\text{km}$. The holes were drilled by others as part of a dam site investigation, and penetrate sandstones and shales of Devonian age.

We have also determined the heat flow at Hot Springs, Va. from a well drilled by the Homestead Corporation to a depth of about 230 meters. The temperature and gradient profiles are shown in Figure 6. The well penetrated limestone and dolomite of probable Middle and Early Ordovician age. No core was obtained from the hole; however, several specimens of limestone were collected from surface outcrops near the hole and thermal conductivity values were determined. The heat flow is $7.6 \mu\text{cal}/\text{cm}^2\text{-sec}$. The geothermal gradient is approximately $100^\circ\text{C}/\text{km}$. This high gradient is probably not representative of the regional geothermal gradient because of the increase in the gradient at the bottom of the hole which appears to be in or probably close to a zone of ground-water circulation. The temperature at the bottom of the hole is approximately 32°C (90°F).

Figure 5. Temperature and geothermal gradient, Bath County, Va.
 The holes are 25 km north of Hot Springs, Va.

Figure 6. Temperature and geothermal gradient at Hot Springs, Va.

Electrical Resistivity Dipole Survey

Electrical methods of geophysical exploration have become a basic tool in prospecting for geothermal reservoirs. Such reservoirs usually have great size compared to the usual targets of electrical prospecting, and for this reason, the conventional electrical techniques have not been used with any degree of success. Rather, new methods of electrical prospecting which can be used on the scale required to examine geothermal reservoirs have had to be developed. Among these new methods are dipole or bipole-dipole and quadripole mapping surveys (Keller et al., 1975).

In bipole-dipole mapping, abbreviated dipole mapping, current flow is established in the earth by using a pair of source electrodes that are not necessarily closely spaced, and so they can be said to form a source "bipole". Current is fed to the ground through two widely separated electrodes. The electric field is then determined at many observation points by observing the voltage drop between two pairs of electrodes oriented approximately at right angles. The current flow pattern will be governed by the spatial variation in resistivity of the ground to a depth comparable to the distance from the source bipole. At each observation point the measured components of the electric field are added vectorially to determine the direction and magnitude of the electric field vector at the observation point. Each component of the electric

field at an observation point is measured using a pair of electrodes separated by a distance ranging from 10 meters to 100 meters. The larger separations are used at the greater distances from the source bipole, where the electric field is low. Signal levels as small as 10 to 20 microvolts are measured with an accuracy of $\pm 5\%$.

With a knowledge of the electric current put into the ground at the source bipole, and the direction and magnitude of the measured electric field vector at the observation site, the data obtained in a dipole mapping survey can be converted to values of apparent resistivity or of apparent conductance for the purpose of presentation and interpretation.

The vector sum of the measured components of the electric field at the observation point is given by:

$$E = \frac{\rho I}{2R_1} \left[1 + \left(\frac{R_1}{R_2} \right)^4 - 2 \left(\frac{R_1}{R_2} \right)^2 \cos d \right]^{1/2} \quad (1)$$

where R_1 , R_2 , and d are defined by the geometry of the source-receiver configuration, I is the known total current flow at the source and ρ is apparent resistivity. The magnitude of the total electric field, E , is obtained from the vector sum of the field components, E_1 and E_2 , measured at the observation point, where

$$E_1 = \frac{\rho I}{2R_1^2}$$

and

$$E_2 = \frac{-\rho I}{2R_2^2}$$

Inversion of equation (1) yields apparent resistivity, ρ , under the assumption of spherical symmetry in current flow for a uniform earth.

For many applications of the bipole mapping method, the distance from the source to an observation point is greater than the depth to crystalline rocks of the basement complex. The basement complex is generally composed of rocks of high electrical resistivity. Such rocks effectively prevent current from penetrating deeper into the earth. For those situations where a relatively conductive sedimentary section overlies rocks in the basement complex of relatively high resistivity, it is inappropriate to assume a spherical symmetry of current flow. Instead, a more meaningful way to present field results is through the use of a formula based on the assumption of cylindrical spreading of current through a thin conductive plate. For a current, I , at the source, the vector sum of the two measured electric field components is given by:

$$E = \frac{1}{2\pi SR_1} \left[1 + \left(\frac{R_1}{R_2} \right)^2 - 2 \left(\frac{R_1}{R_2} \right) \cos D \right]^{1/2}$$

where S is defined as the conductance of the plate, and is the ratio of the thickness, h , of the plate, to its resistivity, ρ .

It is important to note that the apparent values computed for resistivity or conductance are equal to the actual values for a real earth only when the structure of the earth is as simple as that assumed for the derivation of the above formulae. Where

lateral changes in resistivity are present, the computed values of apparent resistivity and apparent conductance may be quite unlike the values actually existing in the ground. Therefore, it is necessary to evaluate the significance of the computed values of apparent resistivity or apparent conductance in order to interpret properly the cause of apparent resistivity patterns which depart from those expected on the basis of simple geometry.

One approach to the interpretation of the field data is to compute resistivity or conductance maps for various simple resistivity distributions for which calculations are possible. Such models include a sequence of horizontal layers, and vertical planes separating regions of different resistivities. Results of computations of apparent resistivity and conductance using such models are given by Keller et al., (1975), and Furgerson and Keller (1975).

Computed apparent resistivity data for Hot Springs for each of three bipole source locations will be included in the Final Report. Examination of these data reveals areas of apparent low resistivity that are not found for all source locations. Such false anomalies commonly occur along the boundary between an area of low resistivity and an area of high resistivity. In order to distinguish between false anomalies arising from the relative positions of the source with respect to resistivity contrasts, coverage of a suspected anomalous area is obtained with current

illumination from several bipole source locations. If the anomaly persists when an area is illuminated from several separate sources, it is probably a real anomaly.

Another approach to minimize the effect of source location and avoid false anomalies is the "rotating-field quadripole method", or more briefly, the "quadripole mapping method". A rotating-field quadripole survey actually consists of two dipole mapping surveys carried out with two bipole sources at the same location, but oriented approximately at right angles to one another. The two source bipoles are energized successively for periods of a few minutes each. Signals from each bipole source are recorded at a receiver site. Thus, apparent resistivity and apparent conductance can be computed either as a function of the direction of the bipole source, or as a function of the direction of the electric field at the receiver. The results of computations using simple models indicate that the most meaningful parameter for the interpretation of the resistivity data is the average of the maximum and minimum values of the apparent resistivity or conductance ellipse. A map of this average minimizes the false anomalies which are present on bipole maps obtained with single coverage.

Plate III shows a composite apparent resistivity map derived from the data used at the three source locations. The composite map was prepared from maps obtained from three rotating-field

quadripole surveys. Resistivity values on each map prepared from a quadripole survey represent the average of the maximum and minimum values of apparent resistivity at each recording location. The composite map is a linear average of the three quadripole maps.

Several resistivity lows are apparent on Plate III. These are significant resistivity anomalies relative to the regions of high resistivity and are undoubtedly due to the presence of water at depth. With the present data, it is not possible to identify with certainty the cause of the resistivity lows evident on Plate III, other than to say that they represent significant relative variations in apparent resistivity. The presence of a low southeast of Hot Springs is not incompatible with a model of deep artesian circulation of meteoric ground water. Further resistivity soundings are proposed to determine the nature and depth of the source of the resistivity low. The resistivity lows might be a manifestation of slow downward percolation of ground water to a southeastward-dipping fault plane, followed by a relatively rapid upward movement of water along the fault plane and cross faults cutting the northwestern limb of the Warm Springs anticline.

Planned Drilling Site for Heat Flow Determination

One hole approximately 1000 feet deep will be drilled in the Warm Springs anticline specifically for the purpose of obtaining a reliable heat flow determination. Drilling will begin during the second week of December. The proposed drilling site is located on the Bowen farm as shown on the Falling Springs, Va. 7-1/2 minute quadrangle (Figure 7).

Several factors entered into the selection of the Bowen farm as the drilling site:

(1) The transverse faults that cut the northwest limb of the Warm Springs anticline (Plate I) are not considered to be of regional tectonic significance; they are interpreted as extension fractures in a rigid, essentially vertical plate of quartzite. Such faults are common in anticlinal folds particularly where the anticlinal axis plunges (DeSitter, 1956, p. 206-211). While not of regional significance, they do appear to be important in controlling the locations of the warmest springs. The hottest springs are located next to the cross-faults and the faults may therefore provide the vertical permeability for the ascending warm water. Drilling sites near cross faults were avoided because convection in such zones might prevent the determination of a representative geothermal gradient.

(2) From the work of Reeves (1939) and from our own field

work, most of the hot and warm springs appear to issue from limestones of Middle Ordovician age. The limestones unconformably overlies the Knox Dolomite of Early Ordovician age. It is generally accepted that limestone develops solution porosity and permeability at a considerably faster rate than dolomite. If bedding plane permeability is preferentially developed in the Middle Ordovician limestones, then drilling in or above this part of the stratigraphic section should be avoided. The selected drilling site begins in the Knox Dolomite of Early Ordovician age and which lies stratigraphically beneath the limestone section. The outcrops of Knox Dolomite at the Bowen farm are the oldest rocks exposed in the Warm Springs anticline. Rocks as old or older are exposed at only one other locality on Plate I, at Bolar, approximately 20 km to the north in the core of another anticline.

(3) The electrical resistivity survey shows the Bowen farm to be an area of high resistivity (Plate III), and therefore hopefully free of significant subsurface water circulation.

Relationship of the 38th Parallel Fracture Zone to Resistivity Anomalies

From the data now available, it cannot be stated unambiguously that the 38th parallel fracture zone has any manifestation

in the study area; however, the resistivity data suggest several east-west trending anomalies as shown on Plate III. Since this trend is certainly not representative of structural trends in the area, but is representative of the trend of the approximately east-west 38th parallel fracture zone, there may be a causal relationship between the fracture zone and the east-west resistivity lows. Figure 2 shows the location of the Warm Springs anticline with respect to the 38th parallel fracture zone. It is noteworthy that the igneous intrusions of Eocene age are directly in line with the projection of the 38th parallel fracture zone. Further deep resistivity studies will help to define the extent of east-west resistivity anomalies to the north in the vicinity of the exposed intrusive rocks of Eocene age, and to the east and west to determine if resistivity anomalies are characteristically found along the projection of the 38th parallel fracture zone.

Results to Date and Plans for Remainder of Contract Term

- 1) A preliminary geologic map and structural cross-sections have been prepared for the Warm Springs anticline and surrounding region. Transverse faults cutting the northwest limb of the Warm Springs anticline are marked by prominent topographic lineaments. These fault zones probably have no important regional tectonic significance; they are interpreted as cross faults commonly found in doubly-plunging anticlines. They do appear, however, to be important in controlling the locations of the groups of warm springs in the Warm Springs anticline.
- 2) A reconnaissance electrical resistivity bipole-dipole survey has been completed. Examination of Plate III shows significant relative differences in apparent resistivity in the area surveyed. Further study of these anomalies is in progress to evaluate the influence of anisotropy on the survey. There may be a causal relationship between the 38th parallel fracture zone and the apparent east-west trend of the resistivity lows. The pronounced low southeast of the Warm Springs anticline may be due to ground-water circulation at depth.
- 3) Heat flow values have been obtained at two locations in Bath County. About 25 km north of Hot Springs the heat flow is

normal with a value of approximately $1.2 \mu\text{cal}/\text{cm}^2\text{-sec}$, and a geothermal gradient of about $14^\circ\text{C}/\text{km}$. At Hot Springs, an apparent heat flow value of $7.6 \mu\text{cal}/\text{cm}^2\text{-sec}$ has been obtained, with an average geothermal gradient of about $100^\circ\text{C}/\text{km}$. These high values are not believed to be representative of the area; ground-water circulation near the bottom of the hole has probably affected the geothermal gradient.

- 4) A drilling site has been chosen in the Warm Springs anticline for the purpose of obtaining a reliable heat flow determination. Drilling will begin about the middle of December. The hole depth will be approximately 305 meters (1000 feet).
- 5) Details will be added to the geologic map of the Warm Springs anticline, with particular emphasis on the cross faults, since the warmest springs appear to be localized near these zones.
- 6) A request has been made to examine available seismic data for the region for the purpose of aiding in an evaluation of a model for deep artesian circulation.
- 7) Heat production measurements will be made on some of the calc-alkaline igneous rocks of Eocene age exposed in Highland County. Calculations are in progress to examine the effect of high uranium and thorium concentrations on the cooling rate of assumed spherical igneous intrusions. Results will be included in the Final Report.
- 8) A proposal for additional studies has been prepared and submitted with this Progress Report.

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Dr. J. K. Costain devoted 45% of his time to this project during the present performance period.

Dr. C. E. Sears devoted 18% of his time to this project during the present performance period.

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PLATE 3

COMPOSITE DIPOLE RESISTIVITY SURVEY

PLATE 4. COMPOSITE DIPOLE RESISTIVITY
MAP, VIRGINIA HOT SPRINGS AREA.

- 4.2 Station location and apparent resistivity, in thousands of ohm metres. Value plotted is mean of means, defined in the text
- Resistivity contour. Contour levels follow a geometric progression.

SS15 Location of Schlumberger sounding

Scale - 1:62 500

0 1 mile

Survey carried out during July and August, 1975. Map compiled by G. V. Keller, September 29, 1975.