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Geothermal Investigations in Ohio and Pennsylvania

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DISCLAIMER

GEOTHERMAL INVESTIGATIONS

IN

OHIO AND PENNSYLVANIA

by

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ABSTRACT

New values of heat flow were determined for the Appalachian Plateau in eastern Ohio and northwestern Pennsylvania. Corrected values for wells in Washington and Summit Counties, Ohio, are 1.36 and 1.37 heat-flow units (HFU), respectively. Those of 1.84 and 2.00 HFU define a previously unknown heat-flow high in Venango and Clarion counties, Pennsylvania. Thermal conductivity was measured for core samples from 12 wells in Ohio and 6 wells in Pennsylvania. Heat production was determined for 34 core and outcrop samples from Ohio, Pennsylvania, and New Jersey.

INTRODUCTION

This work was undertaken as part of a program to select sites for hot, dry rock geothermal-energy extraction in the eastern United States. In this study, areas having relatively high conductive heat flow associated with radiogenic heat-producing plutons were sought in Ohio and western Pennsylvania. From the geological and geophysical literature, the authors chose areas in which geothermal gradients could be measured in wells, and the thermal conductivity of core samples obtained. From these data they determined the conductive heat flow for four favorable sites.

GEOLOGY

Figure 1 depicts the geometry of the Precambrian basement surface inferred from 120 wells (Owens, 1967; Saylor, 1968). Subsurface depths to Precambrian rocks range from < 0.6 km in western Ohio to > 3.6 km in eastern Ohio and western Pennsylvania.

The Precambrian surface in western Ohio reveals the broad linear Indiana-Ohio platform (Green, 1957), which may be the structural predecessor of the Cincinnati-Findlay Arch. The eastern slope of the basement platform increases eastward from 1 to 20 m/km and forms the western margin of the Appalachian Basin. The surface dips to the east in eastern Ohio, and to the south in northwestern Pennsylvania.

In eastern and central Ohio (Fig. 2), and in northwestern Pennyslvania (Saylor, 1968), samples from the basement comprise quartz-feldspar gneiss, smaller amounts of quartz-mica schist and amphibolite, and minor occurrences of marble and calcsilicate rocks. The western third of Ohio seems to be underlain by Precambrian quartz-feldspar gneiss and granite. Also rhyolite, trachyte, and andesite (McCormick, 1961; Gonterman, 1973) have been identified.

If only the rock in the immediate subcrop is mapped, the underlying rock that may have more geophysical significance is ignored. Although Summerson (1962) maps an area underlying Guernsey County, Ohio, as granitic gneiss, only the upper 3 m are gneiss, whereas the next 81 m are amphibolite (McCormick, 1961). In this study, the dominant lithology is mapped and a single pattern is used for medium to coarse quartzo-feldspathic rocks. The mapped area of some rock types has been decreased around drill-hole sites. A newly identified area of granite (M. F. Schmidt, personal communication) in Morrow County has been added to the Ohio map.

Precambrian rocks crop out only in southeastern Pennsylvania. Granite, diorite, gabbro, and anorthosite are associated with granitic gneiss, paragneiss, and metavolcanic rocks (Gray and Shepps, 1960). Throughout the rest of the state they are identified from cores and cuttings and by interpretation of geophysical data. Rocks in the basement in Ohio and northwestern Pennsylvania are similar to those in Precambrian outcrops in Pennsylvania. However, anorthosite has been reported only in southeastern Pennsylvania.

The basement in Ohio and western Pennsylvania may be an extension of the Grenville belt based on radiometric age determinations (Bass, 1960; Rudman et

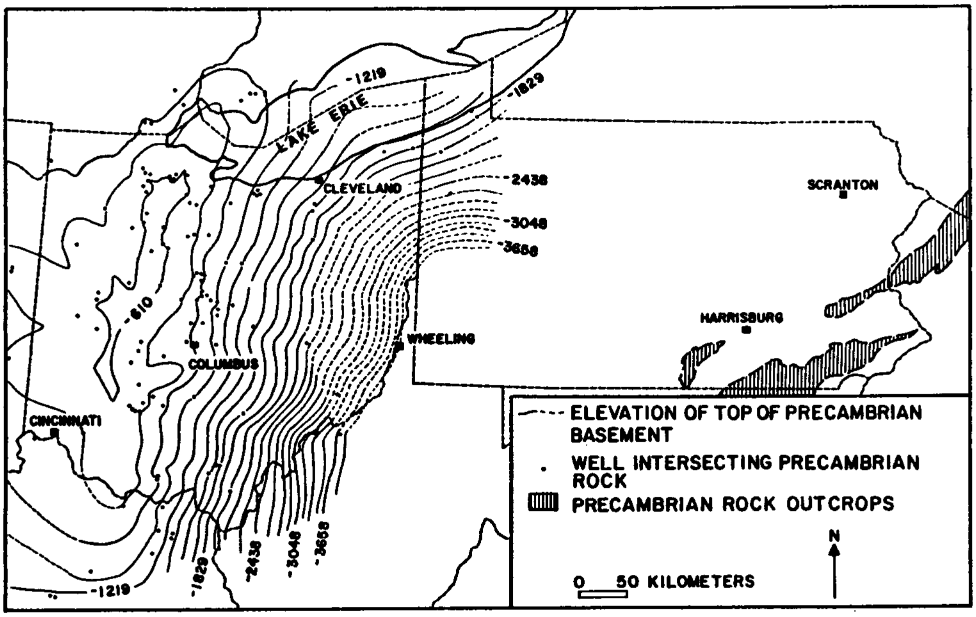

Fig. 1.

Elevation of top of Precambrian basement in Ohio and Pennsylvania (from Owens, 1967 and Saylor, 1968).

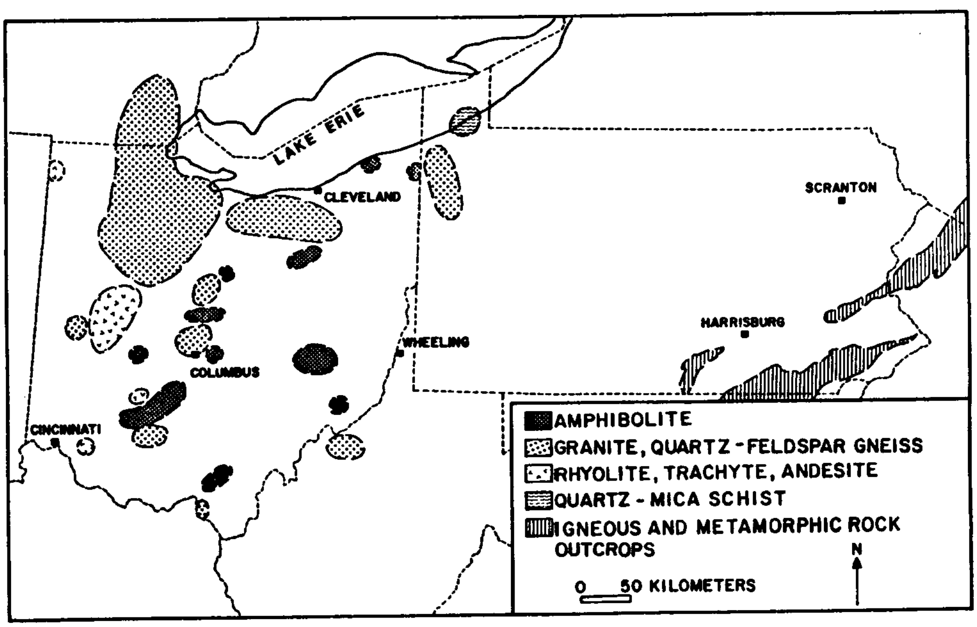

Fig. 2.

Precambrian rock types in Ohio and Pennsylvania (from McCormick, 1961; Summerson, 1962; Saylor, 1969; and Ross, 1972).

al., 1965; Lidiak et al., 1966; Hofmann et al., 1972; Lapham, 1975; Barbis, 1978). Rb-Sr and K-Ar ages determined on biotite and muscovite from such rocks in Ohio and on whole rock samples from Pennsylvania range from 837 to 942 Myr. Exceptions are whole-rock Rb-Sr ages (1242 and 1304 Myr) for two Ohio trachyte and rhyolite samples (Lidiak et al., 1966; Barbis, 1978), and Rb-Sr feldspar ages for four Ohio gneiss and granite samples, which range from 1118 to 1406 Myr (Barbis, 1978).

Barbis (1978) concludes that the Precambrian basement in Ohio was metamorphosed during the Grenville orogeny 1171 $\pm$ 36 Myr ago. The distribution of basement ages rules out an earlier conclusion (Bass, 1960) that the Grenville Front extends southward from Canada through western Ohio. The trachyte and rhyolite dates indicate that volcanism occurred about 1280 Myr ago. All basement rocks in Ohio and western Pennsylvania have Precambrian ages.

The Precambrian basement is overlain by Paleozoic sedimentary rocks that range in thickness from < 0.6 km in western Ohio to > 5.5 km in southeastern Pennsylvania. The Paleozoic stratigraphy is described by Shearrow (1957) and Collins (1979). The dominant rock types are:

System	Lithology
Permian	Sandstone
Pennsylvanian	Sandstone, shale, limestone, coal
Mississippian	Sandstone, siltstone, shale
Devonian	Limestone, shale
Silurian	Sandstone, carbonate rocks, evaporite
Ordovician	Carbonate rocks
Cambrian	Sandstone

Cambrian and Ordovician schist, gneiss, quartzite, and serpentinite crop out in southeastern Pennsylvania. In the same area, Triassic shales and sandstones are intruded by diabase dikes. Pleistocene moraines overlie much of the bed rock in the northern parts of Ohio and Pennsylvania.

In the Plateau structural province, which includes Ohio and western Pennsylvania, flat-lying Paleozoic rocks locally have gentle folds. Low regional dips of the Paleozoic rocks in Ohio are related to the Cincinnati Arch (Fig. 3) where uplift began no earlier than Silurian time (Scotford, 1964).

In the Valley and Ridge Province in central Pennsylvania, the Paleozoic rocks were deformed by intensive folding and thrust faulting. In southeastern Pennsylvania, the structural features in metamorphic rocks of the Piedmont Province are partially obscured by sedimentary and volcanic rocks in Triassic grabens.

GEOPHYSICAL SURVEYS

Sources of gravity data include surveys of Ohio (Heiskanen and Uotila, 1956), Pennsylvania (Diment et al., 1972), and the United States (Woollard and Joesting, 1964). Gravity data for the area are mapped in Fig. 4.

The region has generally negative Bouguer gravity values that are characteristic of continents. In easternmost Ohio and western Pennsylvania there are slight fluctuations in gravity values. Prominent anomalies occur in central and western Ohio and in central and eastern Pennsylvania. The longer wavelengths and more subdued anomalies in eastern Ohio may be related to the increased depth to the basement (Rudman et al., 1965) or to greater homogeneity of the basement rocks (Summerson, 1962). Because the basement in western Ohio has more granite interspersed with metamorphic rocks, density of the terrain is more heterogeneous. Pincus (1960) concluded from an analysis of five major Bouguer anomalies in Ohio that they are caused by density contrasts within the Precambrian basement complex.

Positive anomalies in northwestern Ohio have amplitudes and wavelengths of 40 mgal and 25 km in Sandusky and Seneca Counties, 10 mgal and 25 km in Lucas and Wood Counties, and 30 mgal and 50 km in Auglaize, Shelby, and Miami Counties (Newhart, 1975; Haidarian, 1976; Williams, 1976; and Quick, 1976). A large negative anomaly studied by Haidarian (1976) has an amplitude of 25 mgal and a wavelength of 65 km. The positive anomalies seem to be related to gabbro or amphibolite masses in the crust, whereas the negative anomaly may be related to a deeper granite pluton. However, the petrology deduced from gravity values does not agree with cores of basement rocks (McCormick, 1961; Summerson, 1962). Although the high-amplitude Bouguer anomaly and magnetic anomaly in Sandusky and Seneca Counties are thought to result from mass of amphibolite, a drill hole intercepted granite. However, the bodies outlined

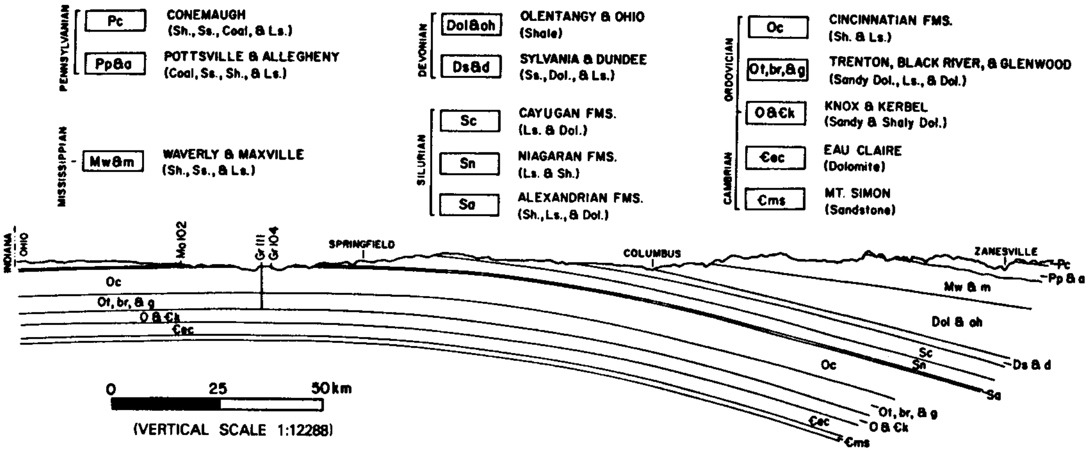

Fig. 3.

Generalized stratigraphic section across the Cincinnati-Findlay Arch in western Ohio.

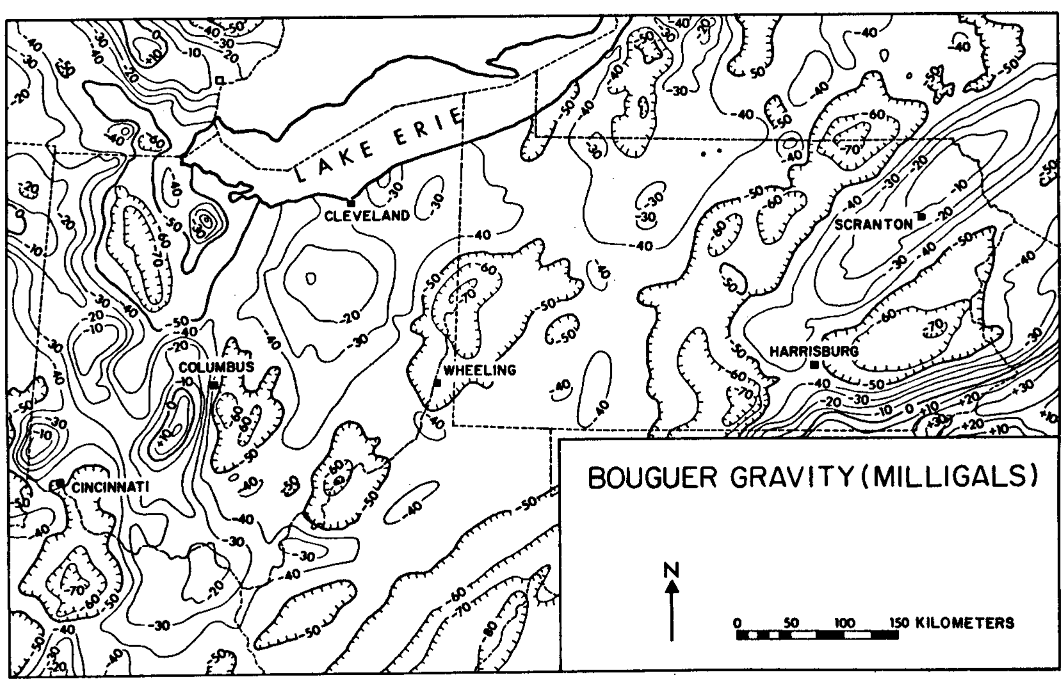

Fig. 4.

Bouguer gravity map of Ohio and Pennsylvania (modified after Heiskanen and Uotila, 1956; Wollard and Joestling, 1964; and Diment et al., 1972).

by the gravity anomalies may be deep within the Precambrian basement. All large-scale anomalies in Fig. 4 indicate density variations in the basement complex. Wallace's (1978) measurement of gravity at 450 stations shows a regional gradient identical to that in northeastern Ohio.

In Pennsylvania, large Bouguer anomalies are related to deep sources as in Ohio (Duecker, 1954; Diment et al., 1972) and to shallow diabase intrusions (Kane, 1961). The anomalies in Fig. 4 are due to sources within the basement, which is deep in much of Pennsylvania. In eastern Pennsylvania, the Scranton gravity high is flanked by negative troughs. The Scranton gravity high may result from an excess mass emplaced within the basement complex in Precambrian time (Diment et al., 1972).

Magnetic anomalies associated with gravity anomalies in Ohio have low relief and low gradients that may result from deep basement sources. In Pennsylvania, magnetic anomaly patterns are smooth over areas underlain by Paleozoic sedimentary rocks, but they have high gradients over areas underlain by Precambrian basement or later intrusions. Interpretations of sources causing such anomalies are consistent with models by Haidarian (1976), Quick (1976), Diment et al., (1972), and Rudman et al., (1965).

Seismic studies in Ohio and Pennsylvania have determined crustal and upper-mantle velocity structures, depths to the Mohorovicic discontinuity, and sub-Moho layering (Woollard, 1972; Diment et al., 1972). Detailed studies are limited and do not show indications of recent magmatic activity.

The seismicity of Ohio and Pennsylvania is illustrated in Fig. 5. Two zones of moderate seismic activity are separated by a zone of quiescence in southeastern Ohio and western Pennsylvania.

Other seismic areas are in western and northern Ohio. The most active part is the Anna earthquake zone near the bifurcation of the Findlay and Kankakee arches (Bradley and Bennett, 1965). The western Ohio earthquake zone is along the trend of the New Madrid fault zone in Missouri and thus may be related to it.

Earthquake activity along Lake Erie in northern Ohio has been related to seismicity in northwestern New York and in the valley of the St. Lawrence River (Bradley and Bennett, 1965; Spall, 1979). Some recent seismicity may result from reactivation of basement faults (York and Oliver, 1976).

Seismic activity in eastern Pennsylvania seems to be a northeastern extension of the seismic zone of the southern Appalachians. It has been

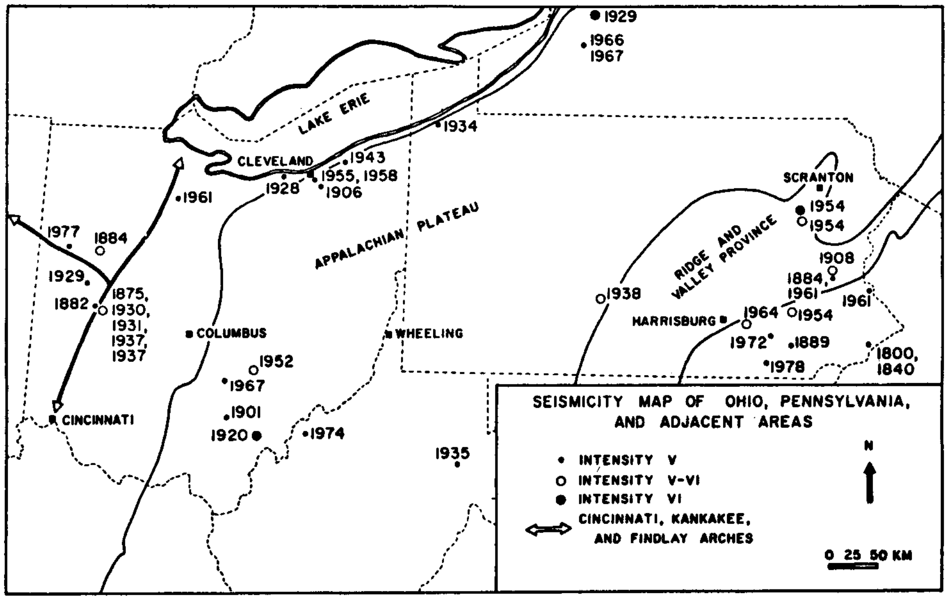

Fig. 5.

Seismicity map of Ohio, Pennsylvania, and adjacent areas.

inferred that slow uplift in the Appalachian region has continued along older faults that have been reactivated (Woollard, 1958; Bollinger, 1973).

GEOTHERMAL REGIME

Research has focused on updating the temperature gradient map of Ohio and Pennsylvania (American Association of Petroleum Geologists and U.S. Geological Survey) and generation of heat-flow data.

The geothermal-gradient map of Ohio (Fig. 6) is based on bottom-hole temperature (BHT) readings from 291 oil and gas production or exploration wells (App. A). The gradient map for Pennsylvania (Fig. 7) is based on BHT readings from 533 wells (App. B). Geothermal gradients were computed by subtracting the temperature of shallow ground water (T_{gw}) (Figs. 8 and 9) (Water Well Journal, 1979) from the BHT readings, assuming a depth of 30.5 m for the T_{gwm}, and dividing the difference by the depth at which BHT readings were taken, reduced by 30.5 m. BHT readings were corrected for the time each reading was taken after drilling-fluid circulation had stopped and for the depth of the reading. The correction is based on an approximation of the graphical solution presented by Kappelmeyer and Haenel (1974). The resulting

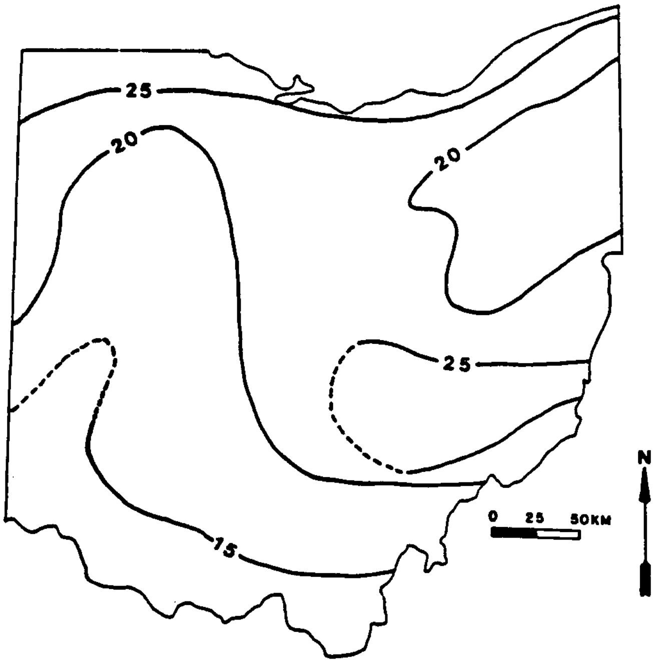

Fig. 6

Geothermal gradient map of Ohio (°C/km).

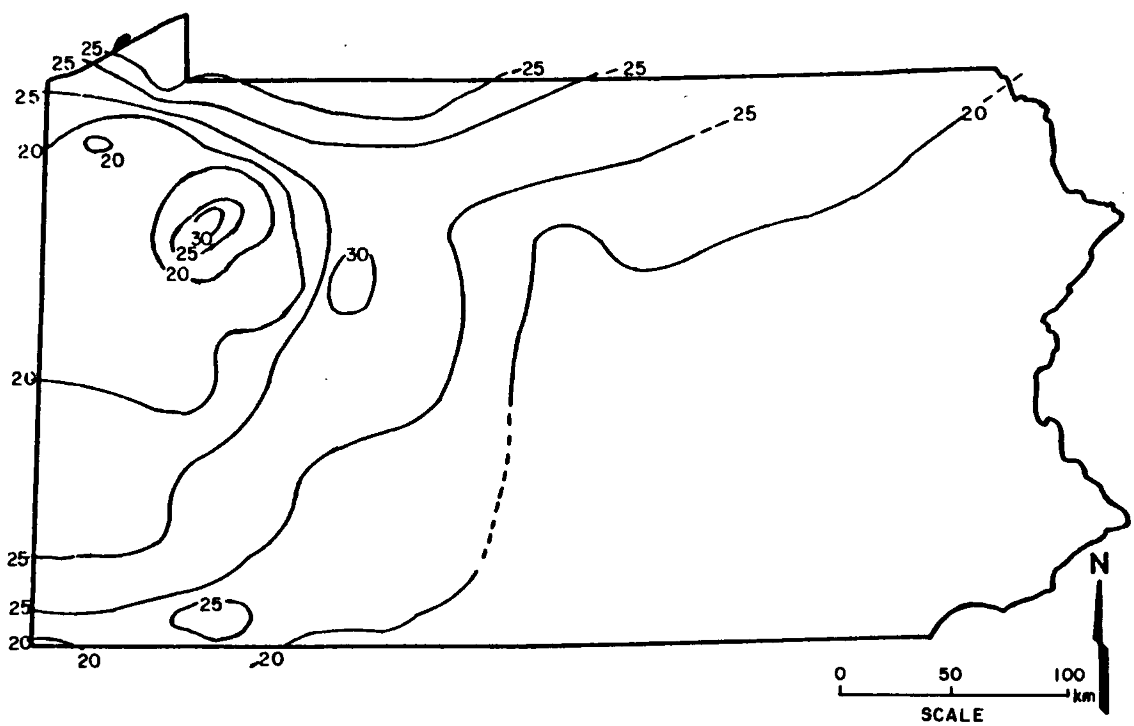

Fig. 7.

Geothermal gradient map of Pennsylvania (°C/km).

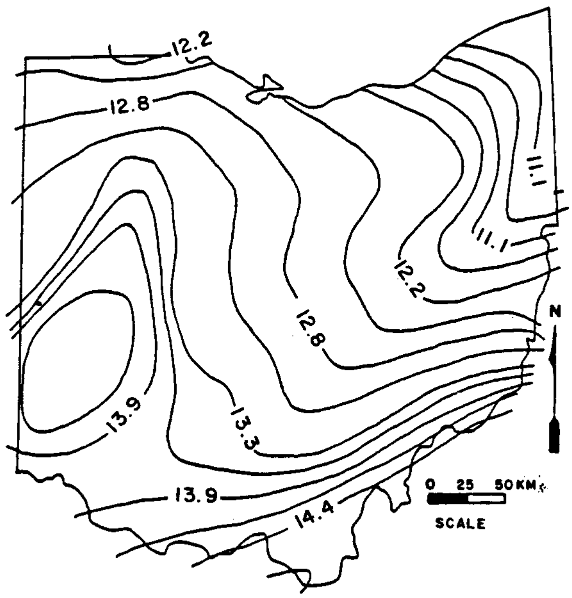

Fig. 8.

Temperatures (°C) of ground water in Ohio at depth of 30.5 m (modified after Water Well Journal, 1979).

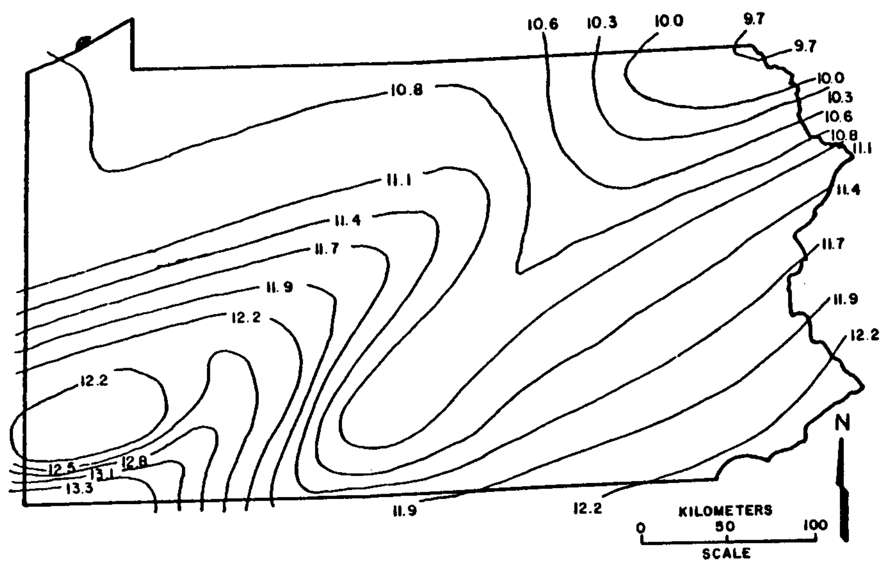

Fig. 9.

Temperatures (°C) of ground water in Pennsylvania at depth of 30.5 m (modified after Water Well Journal, 1979).

corrected gradients may be accurate within ± 2°C/km. This error results primarily from a lack of information concerning the elapsed time between cessation of the mud circulation and temperature logging.

Some differences between the geothermal-gradient and ground-water temperature maps are noted in Ohio and Pennsylvania. Ground-water temperatures in shallow (15-45 m) aquifers are determined by the shallow geothermal gradient and the ground-water recharge system. Convection causes redistribution of the conductive heat flow in both regimes. Its effect is greatest in regions of high relief and intense faulting, where recharge by precipitation at higher altitudes maintains constant ground-water movement toward discharge areas. Where the heat-transfer effects at shallow and moderate depths are greatest, the differences in the geothermal-gradient and ground-water temperatures are largest.

Acquisition of new information on the geothermal gradient was limited by the availability of wells suitable for direct measurements. Depth-temperature profiles obtained from a number of wells that intercepted aquifers in Ordovician dolomites in western Ohio could not be used because some depth intervals have temperature inversions or near-zero temperature gradients, possibly from convective heat transfer. As there has been little past or present drilling in central and eastern Pennsylvania, few wells were available. Temperatures were measured at discrete intervals using a thermistor probe, which was calibrated to $\pm$ 0.02°C.

Corrections

Most heat-flow measurements are made in shallow (2-km) wells that were not drilled for geothermal purposes. Where temperatures have been perturbed near the earth's surface, corrections must be applied to remove the effects of paleoclimatic variations, surface topography, and surface drainage. Because these temperature corrections are cumulative and depth- and time-dependent, the most recent perturbation should be removed first and the oldest last.

The largest temperature correction is the removal of the effects of Quarternary climatic variations. Past long-term changes in mean surface temperature have produced significant changes at depth (Birch, 1948). Pleistocene glacial stages decreased the mean surface temperature whereas interglacial stages increased it. The overall effect has been a decrease in the observed geothermal gradient.

A mathematical model of surface-temperature history may be approximated by a step function that defines the deviation from mean surface temperature with time. The model that best represents paleoclimatic effects in Ohio and Pennsylvania (Table I) is a composite of the step functions proposed by Birch (1948), Urban (1971), Diment et al., (1972), and Cermak (1976). The correction for temperature increase during the Holocene epoch (Cermak, 1976) decreases the paleoclimatic correction below previously reported values (Urban, 1971; Diment et al., 1972; Schlorholtz, 1979). Step changes are considered instantaneous (Birch, 1948). Three values of thermal diffusivity were used to approximate the maximum (κ = 0.016 cm^2/sec), minimum (κ = 0.008 cm^2/sec), and mean (κ = 0.010 cm^2/sec) values expected (Birch, 1948; Urban, 1971).

Surface topography and previous episodes of uplift and erosion may affect near-surface geothermal gradients. The effects of surface topography

TABLE I

STEP FUNCTION DEFINING THE PALEOCLIMATIC MODEL FOR NORTHWESTERN PENNSYLVANIA[a]

Time (yr)	Deviation From Present Mean Surface Temperature (°C)
0 - 20	0.0
20 - 50	+2.5
50 - 100	+2.0
100 - 150	+1.5
150 - 200	0.0
200 - 400	-1.0
400 - 500	-0.5
500 - 600	0.0
600 - 700	+0.5
700 - 800	+1.0
800 - 900	+2.0
900 - 1000	+1.0
1000 - 2000	0.0
2000 - 3000	+0.5
3000 - 4000	+1.25
4000 - 5000	+0.75
5000 - 6000	+2.25
6000 - 7000	+2.5
7000 - 8000	+1.75
8000 - 9000	+1.5
9000 - 10 000	-0.5

Table I (cont)

Time (yr)	Deviation From Present Mean Surface Temperature (°C)
10 000 - 20 000	-5.0
20 000 - 30 000	-10.0
30 000 - 40 000	0.0
40 000 - 60 000	-10.0
60 000 - 80 000	0.0
80 000 - 100 000	-10.0
100 000 - 200 000	+2.0
200 000 - 300 000	-10.0
300 000 - 600 000	+2.0
600 000 - 700 000	-10.0
700 000 - 900 000	+2.0
900 000 -	0.0

[a](Birch, 1948; Urban 1971; Diment et al., 1972; Cermak, 1976)

are removed by adjusting measured temperatures to corrected values below a horizontal datum at the collar of the well. An area within a 20-km radius of each well was integrated in the steady-state topographic correction (Birch, 1950). There have been only minor amounts of uplift and erosion within the study area since early Paleozoic time (Willard, 1962), so no correction was necessary for these factors.

If a river is considered as a line heat source (or sink) of infinite length, the temperature disturbance introduced into shallow strata by a river is defined by

$$T_{(x,y,z)} = \frac{zTo}{2\pi} \int_{-\infty}^{\infty} dx' \int_{-L}^{0} dy' / \left(x - x'\right)^2 + \left(y - y'\right)^2 + z^{2\ 3/2} ,$$

where To is the temperature difference in °C between the mean annual temperature of the river and that of the surrounding soil. L is the width of the river in meters and $1/\left((x - x')^2 + (y - y')^2 + z^2\right)^{3/2}$ is the distance weighting factor (Mongelli, 1970). The mean annual soil temperature was assumed to equal the mean annual air temperature. This approximation is valid for areas of low to moderate elevation (Mongelli, 1970).

Ohio

The most distinctive feature of the Ohio ground-water temperature map (Fig. 9) is the northward-trending high, along the Cincinnati Arch in the western part of the state. However, the geothermal-gradient map has a slight negative correlation coincident with the arch. Because the lithology of the gently dipping Phanerozoic strata is fairly uniform throughout Ohio and western Pennsylvania, shallow subsurface variations in the geothermal regime, cannot readily be attributed to lateral variations in thermal conductivity of the rocks. Moreover, the regional topography is nearly flat. Therefore, the higher temperature of the ground water coincident with the Cincinnati Arch may result from deeper convective ground-water movement along faults and vertical fractures. A similar high ground-water temperature anomaly in southwestern Pennsylvania trends southwestward through West Virginia and into the southernmost counties of Ohio. Cannon et al. (1980) proposed a conceptual model for a convective system generating an anomaly in shallow glacial formations. The general principle of the model may be applied as well to two deep, confined aquifers separated by a fractured lithologic unit having aquiclude characteristics, such as a shale or marl. Convection through the fractures would short-circuit between the two aquifers. A well drilled directly above such a convection current would have an anomalously high temperature gradient. A well drilled into such a convection system away from a rising current would have an anomalously low temperature gradient. An analysis of the depth-temperature profiles and depth-geothermal-gradient profiles calculated on the basis of the distribution of BHT throughout Ohio tends to support the validity of the model. The depth-BHT diagram for wells along the Cincinnati Arch has a wide scatter of points (Fig. 10), whereas similar diagrams for areas east and west of the arch show arrays of points along a fairly consistent slope (Figs. 11-15). Likewise, the depth-geothermal-gradient diagram for wells along the arch has a wide scatter of the points,
particularly in the shallow zones (Fig. 16), whereas the same diagrams for the regions east and west of the arch show a fairly consistent geothermal gradient for most depths, within the range from 15°C/km to 30°C/km (Figs. 17-20).

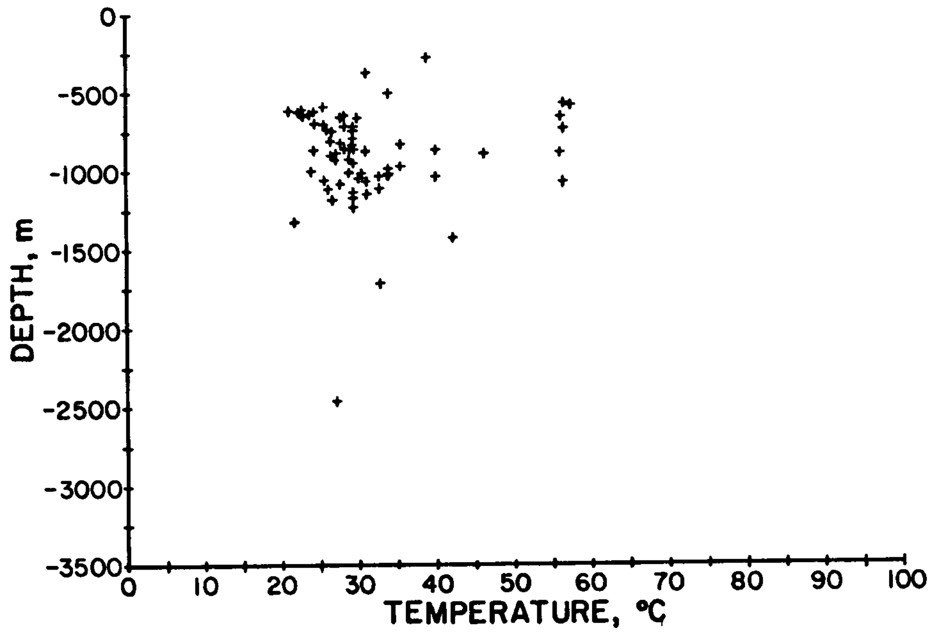

Fig. 10.

BHT in wells along the Cincinnati-Findlay Arch in western Ohio.

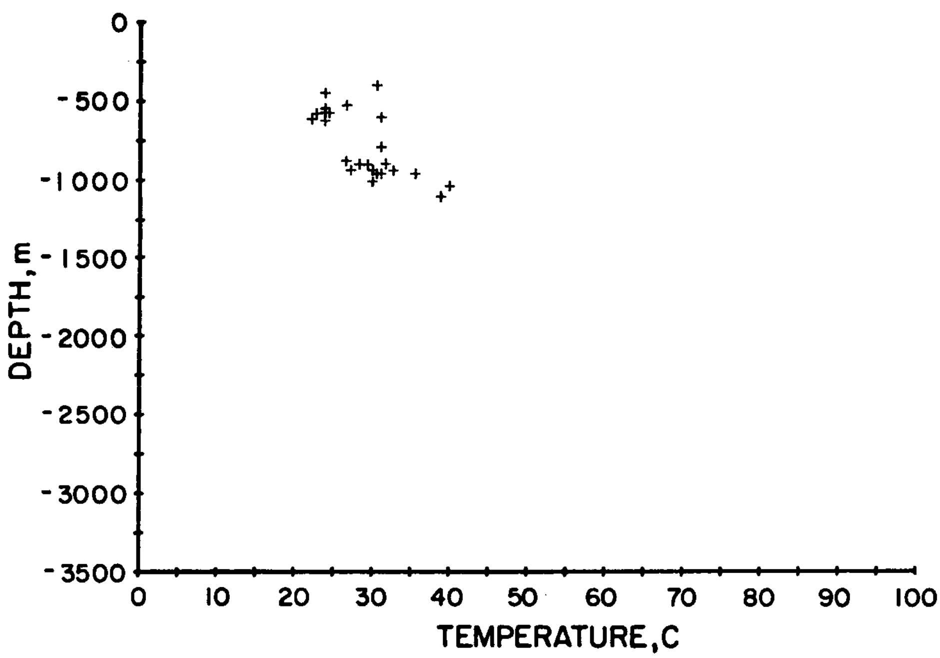

Fig. 11.

BHT in wells on the western flank of the Cincinnati-Findlay Arch in western Ohio.

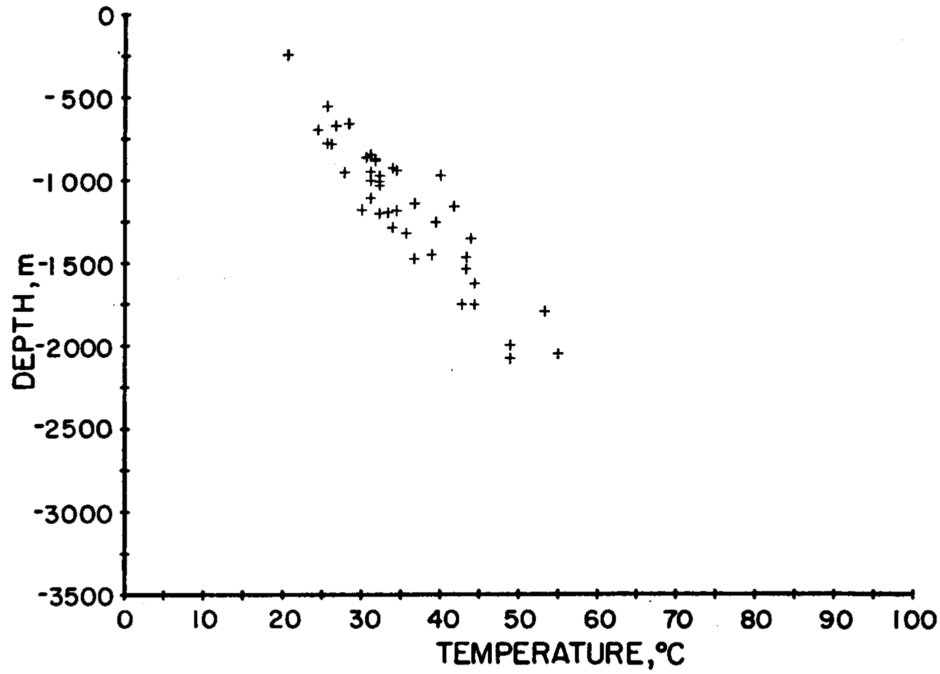

Fig. 12.

BHT in wells on the eastern flank of the Cincinnati-Findlay Arch in central Ohio.

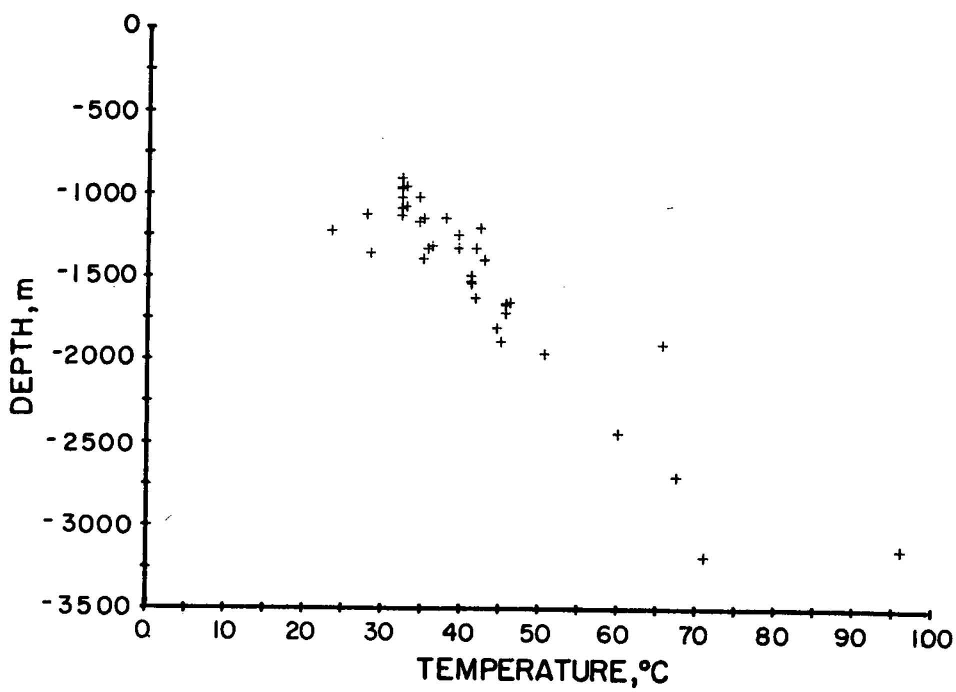

Fig. 13.

BHT in wells in northeastern Ohio.

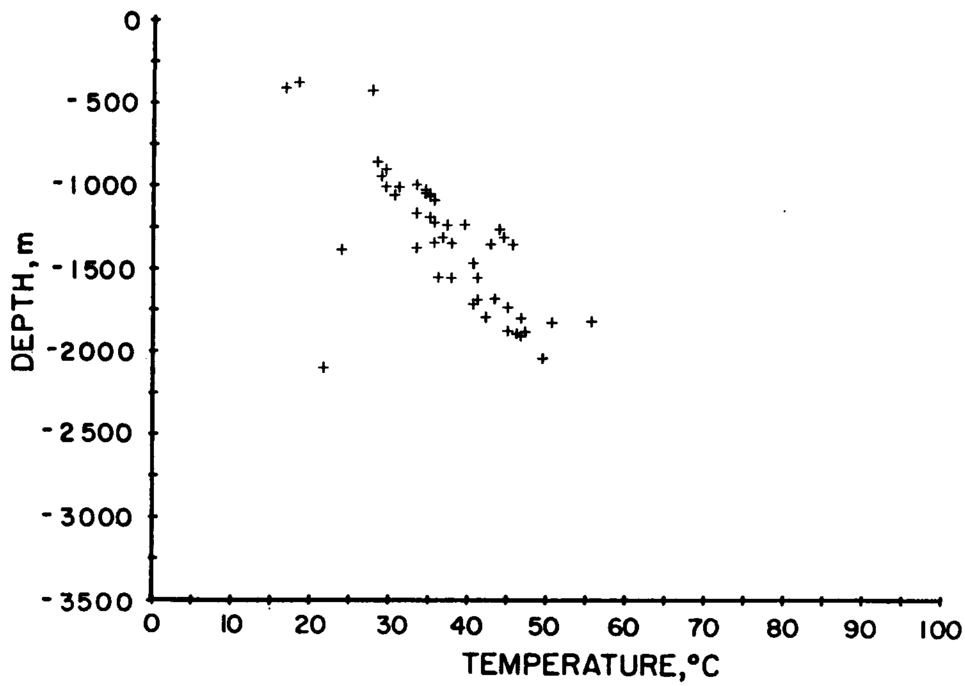

Fig. 14.

BHT in wells in eastern Ohio.

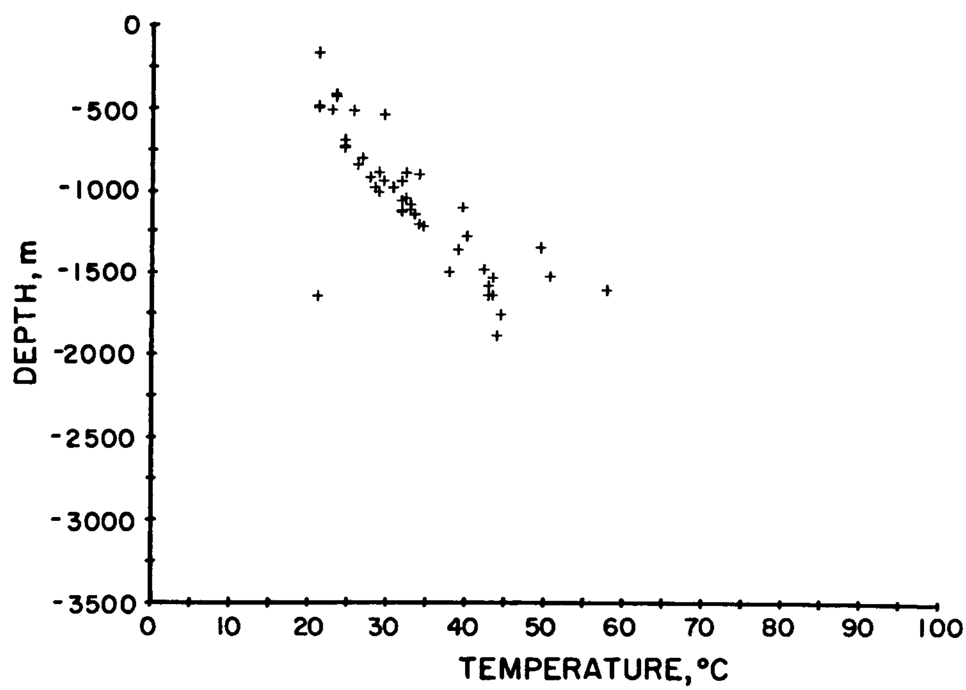

Fig. 15.

BHT in wells in southeastern Ohio.

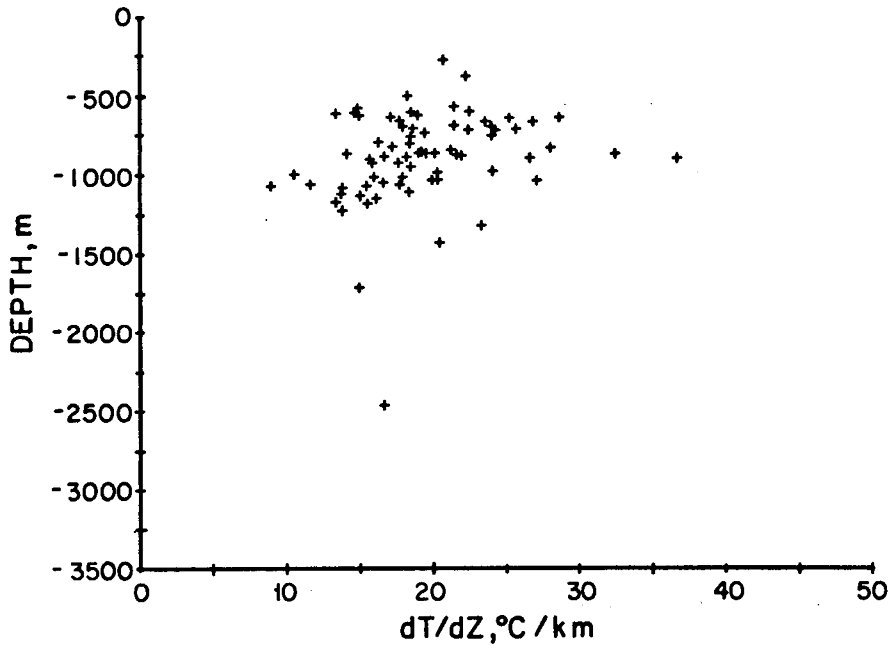

Fig. 16.

Geothermal gradient as a function of depth in wells along the Cincinnati-Findlay Arch in western Ohio.

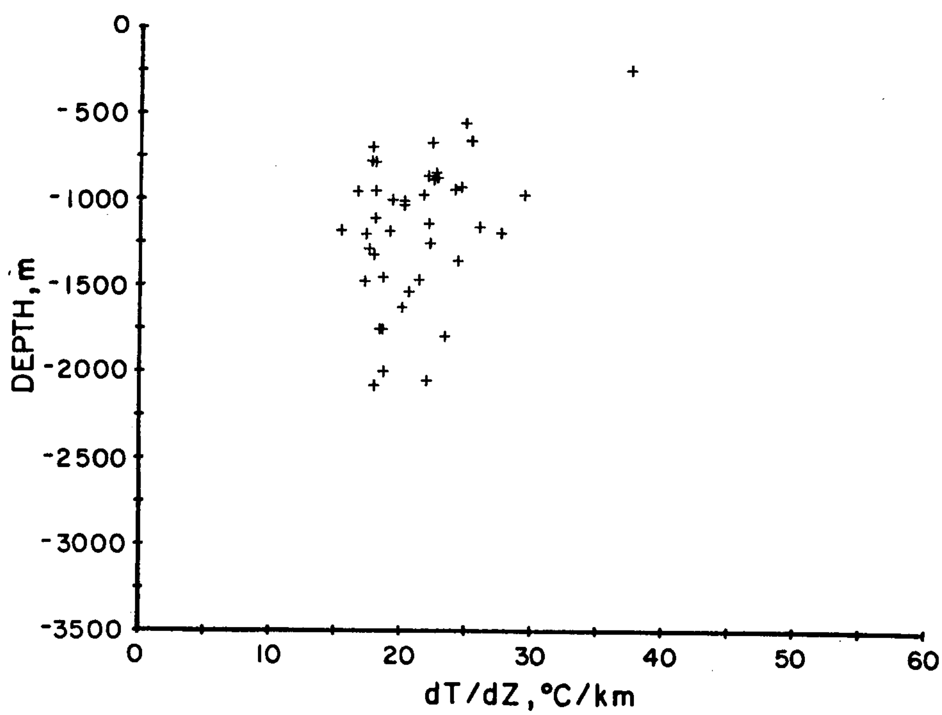

Fig. 17.

Geothermal gradient as a function of depth in wells on the eastern flank of the Cincinnati-Findlay Arch in central Ohio.

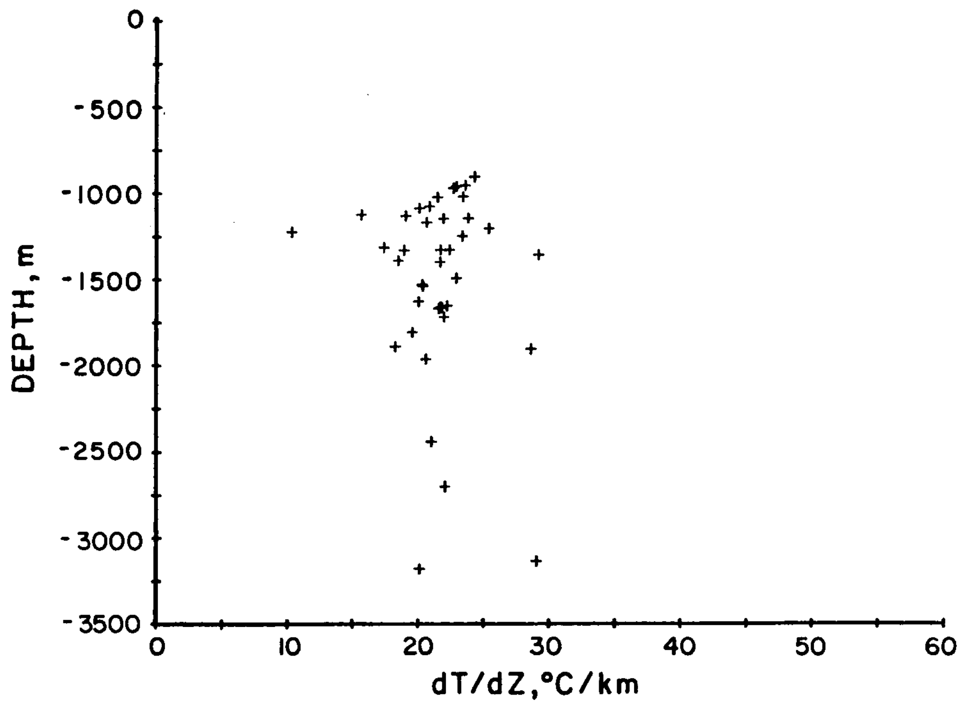

Fig. 18.

Geothermal gradient as a function of depth in wells in northeastern Ohio.

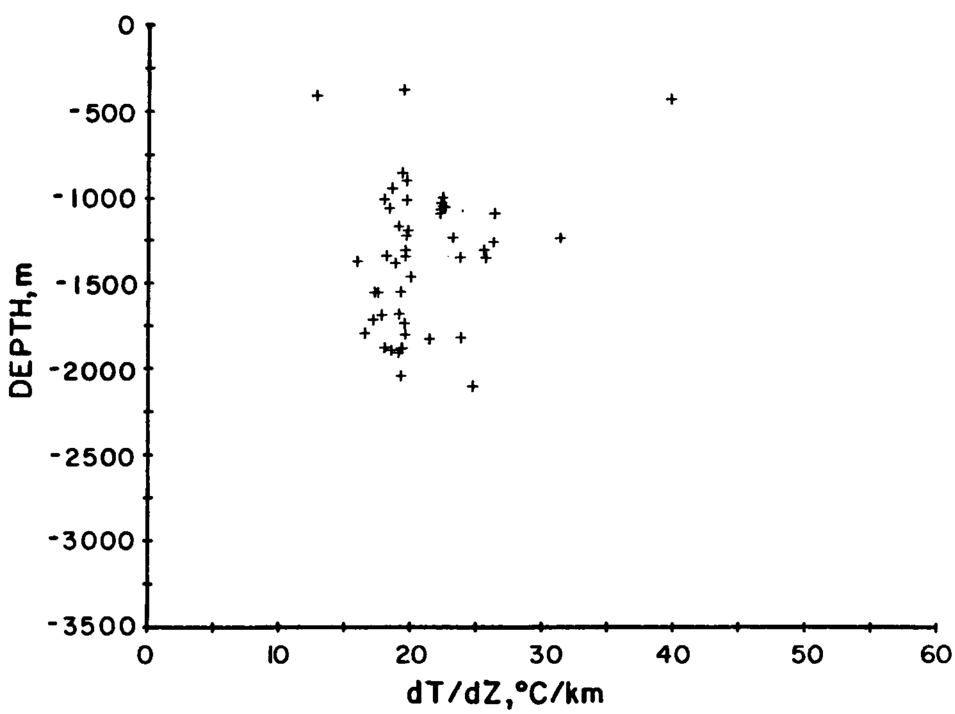

Fig. 19.

Geothermal gradient as a function of depth in wells in eastern Ohio.

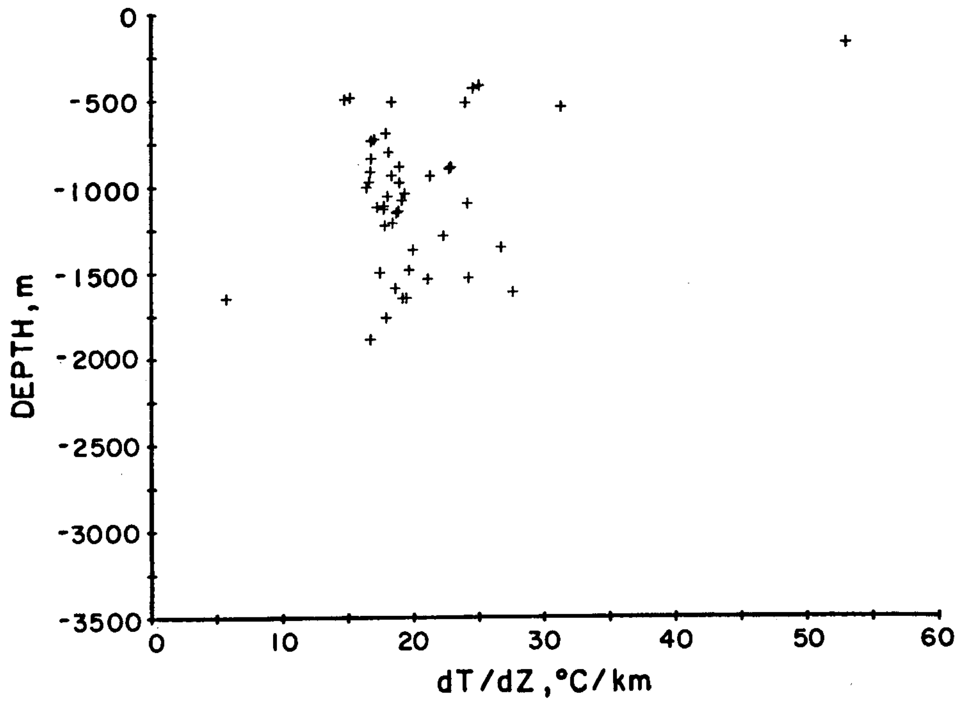

Fig. 20.

Geothermal gradient as a function of depth in wells in southeastern Ohio.

Therefore, terrestrial heat within the sedimentary cover along the Cincinnati Arch may be transferred both by convection and by conduction; in contrast, the uniformity of the geothermal gradient east and west of the arch suggests predominantly conductive heat transfer. Accordingly, efforts to find deep holes for heat-flow measurements were concentrated in eastern Ohio. One suitable well was measured in Washington County (Figs. 21, 22, and App. C), and another in Summit County (Figs. 23, 24, and App. D).

Pennsylvania

The most prominent feature on the geothermal-gradient map of Pennsylvania (Fig. 7) is the northeast-trending anomaly centered on Venango County in the northwestern part of the state. The anomaly maximum exceeds 30°C/km, whereas the gradient for the remainder of Pennsylvania rarely exceeds 25°C/km (Figs. 25-32). An exception is a weak high defined by the 30°C/km contour at the common corners of Jefferson, Clearfield, and Elk Counties east-southeast of the Venango anomaly (Fig. 7). Gradient surveys were made in the Morrison well (Fig. 33) in Venango County and in the Bowser well (Fig. 34) in

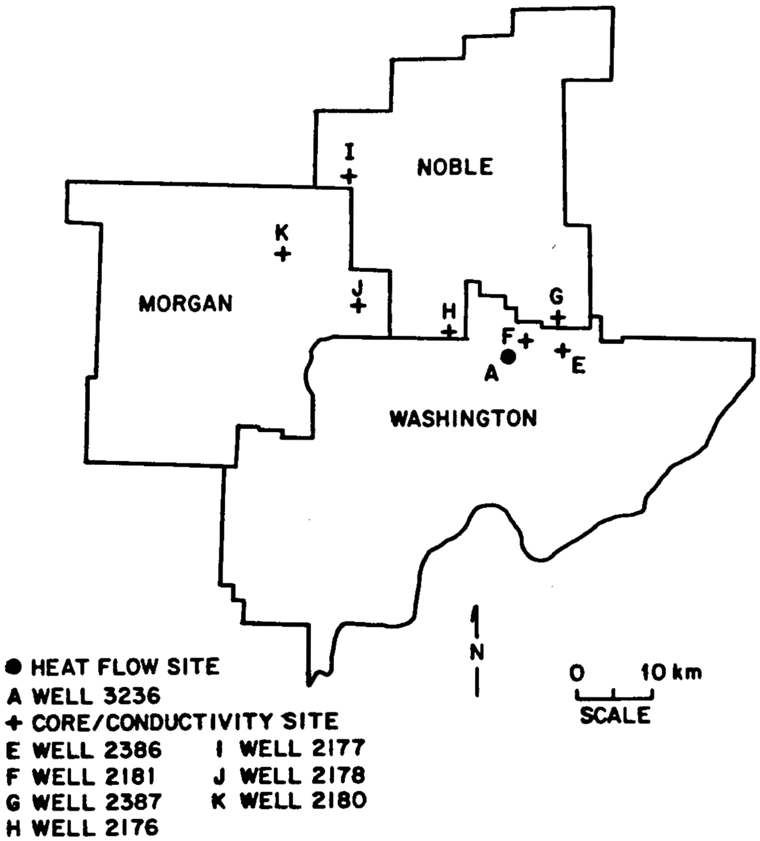

Fig. 21.

Wells in Morgan, Noble, and Washington Counties, Ohio at which heat-flow measurements were made or core was collected for thermal conductivity determinations.

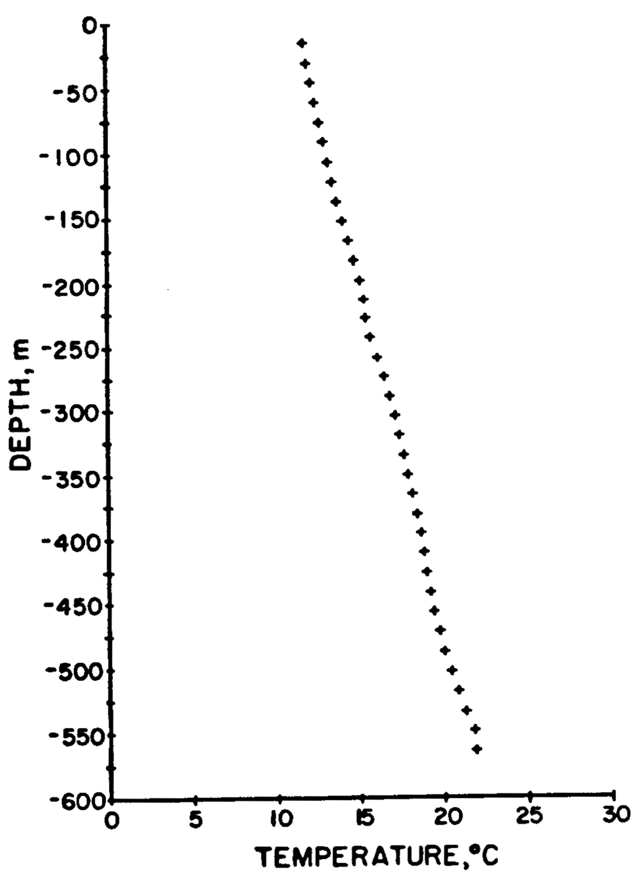

Fig. 22.

Depth/temperature profile in Well 3236 in Washington County, Ohio.

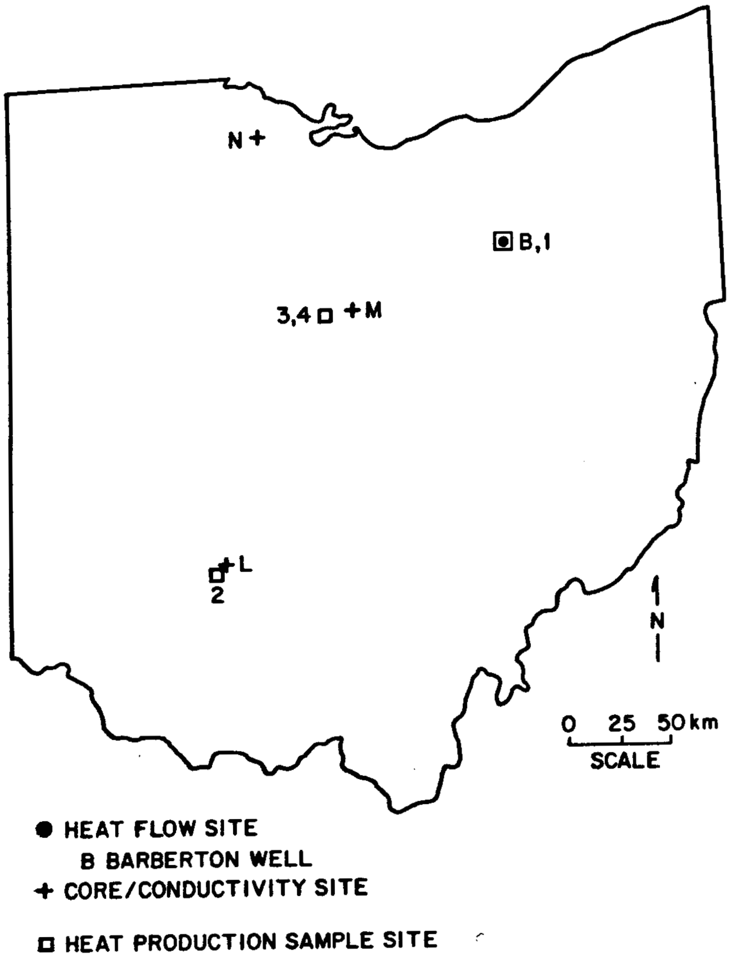

Fig. 23.

Other wells in Ohio at which heat-flow measurements were made, core was collected for thermal conductivity determinations, or samples were collected for heat-production determinations.

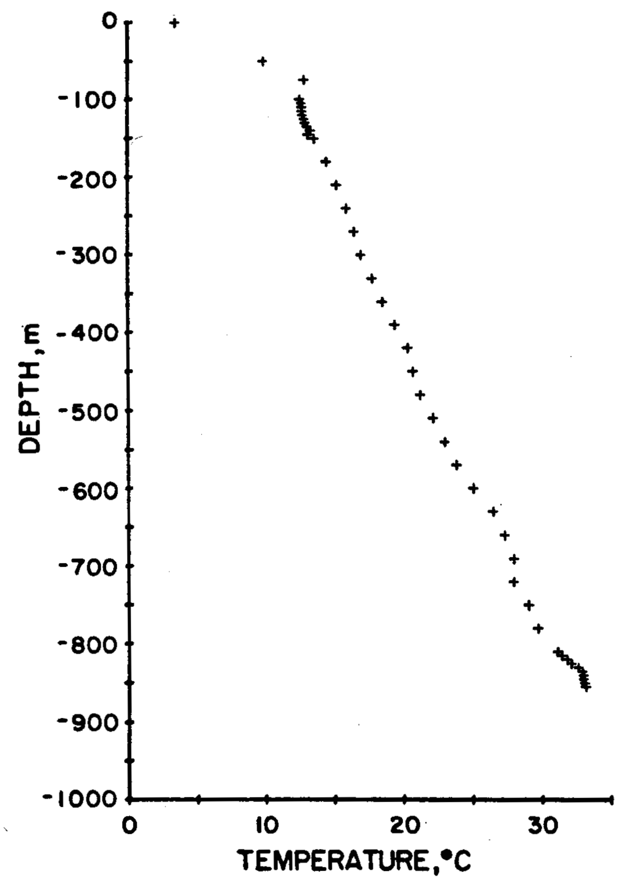

Fig. 24.

Depth/temperature profile in Barberton well in Summit County, Ohio.

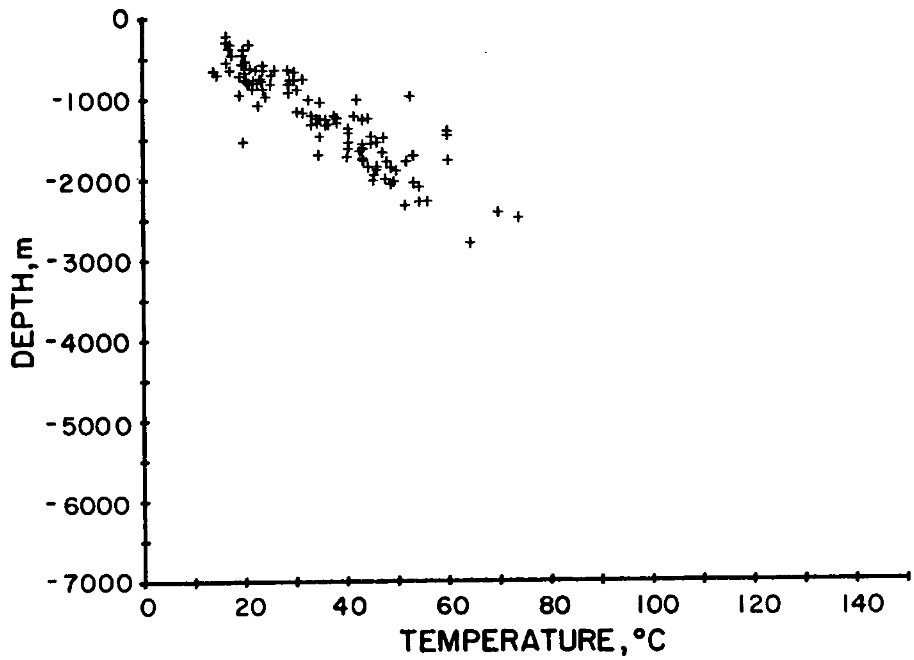

Fig. 25.

BHT in wells in northwestern Pennsylvania.

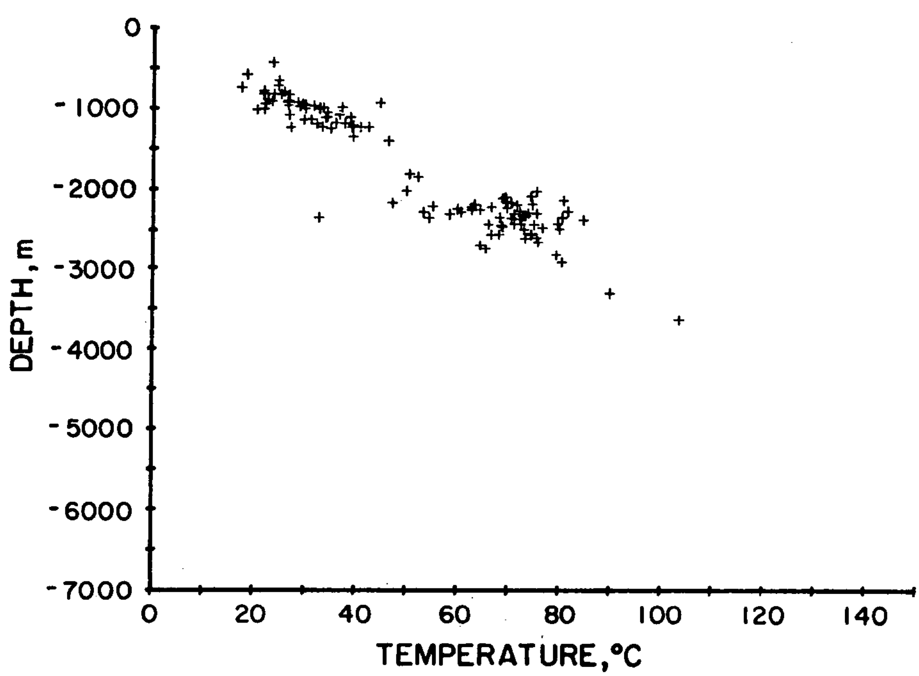

Fig. 26.

BHT in wells in southwestern Pennsylvania.

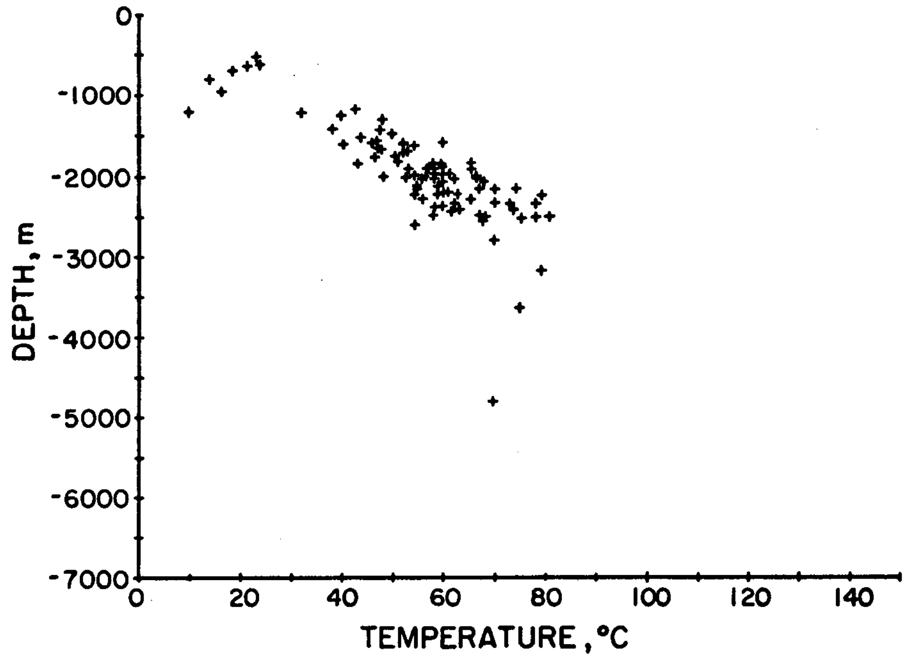

Fig. 27.

BHT in wells in north-central Pennsylvania.

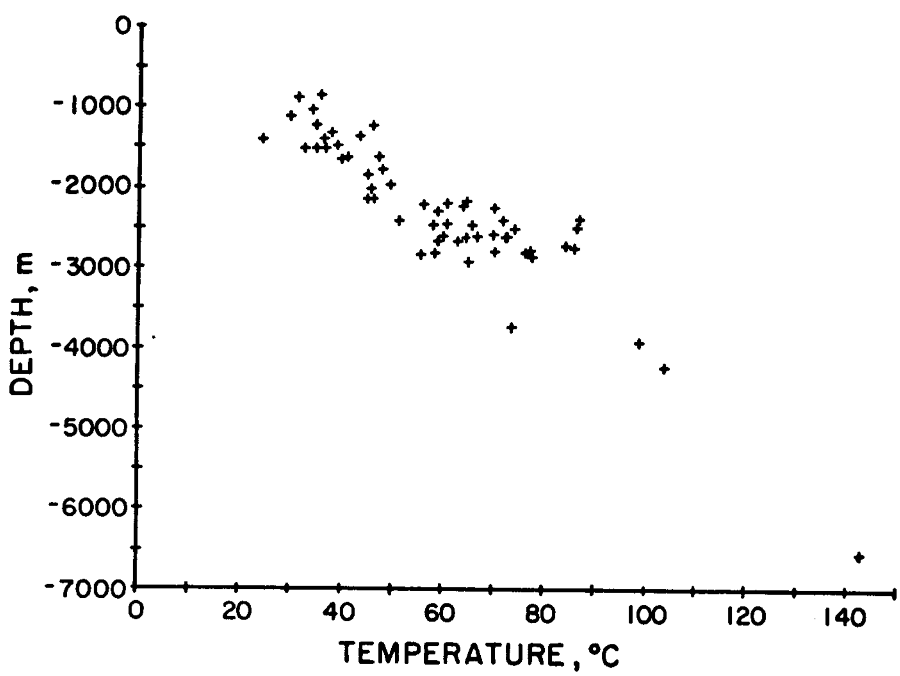

Fig. 28.

BHT in wells in central and northeastern Pennsylvania.

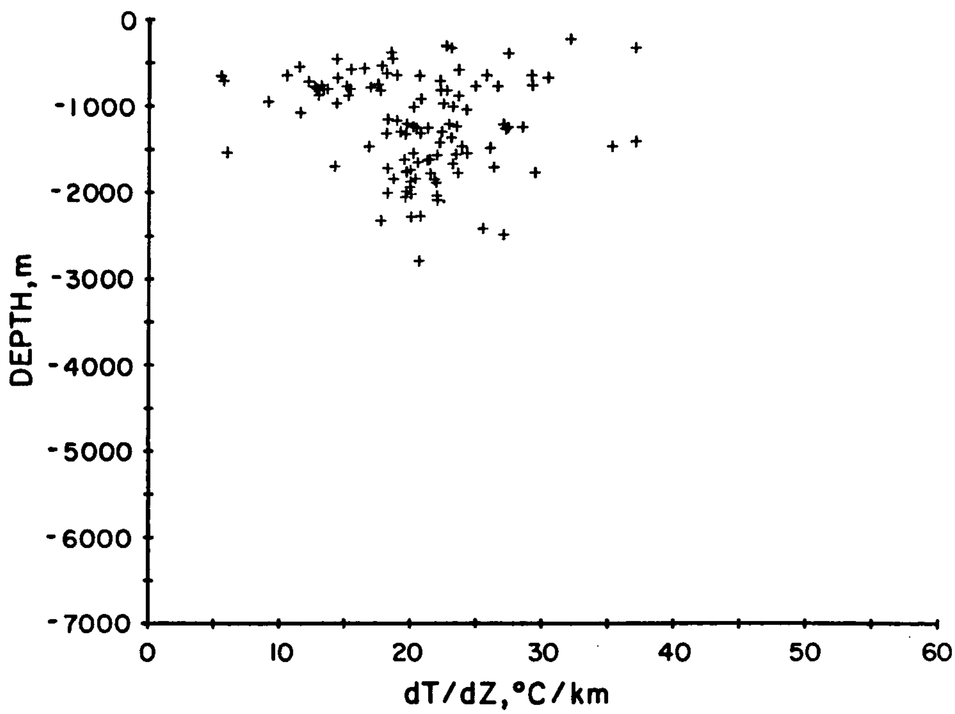

Fig. 29.

Geothermal gradient as a function of depth in wells in northwestern Pennsylvania.

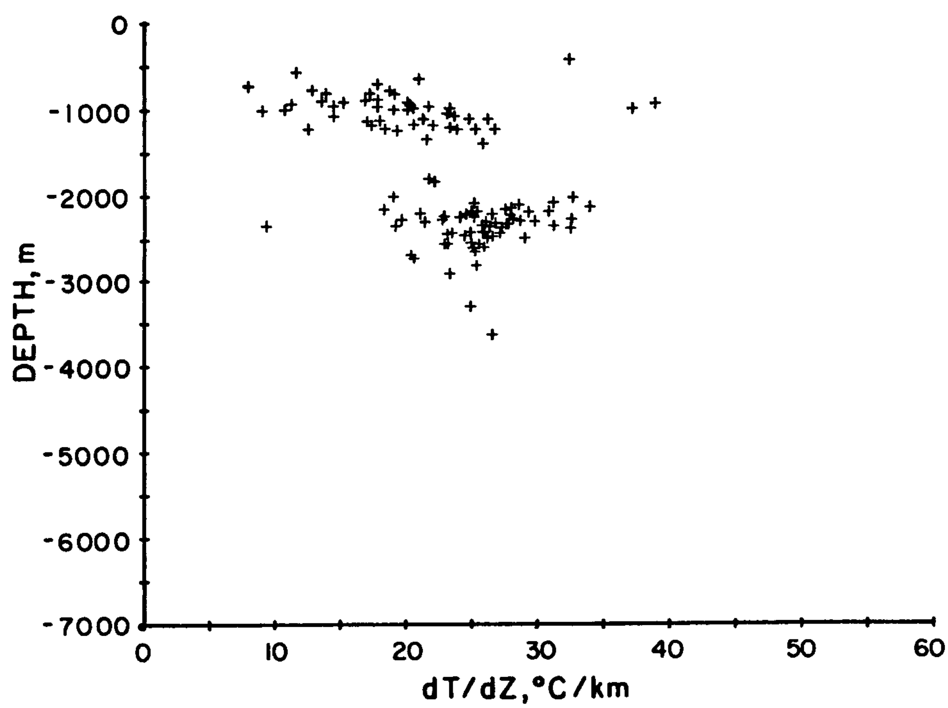

Fig. 30.

Geothermal gradient as a function of depth in wells in southwestern Pennsylvania.

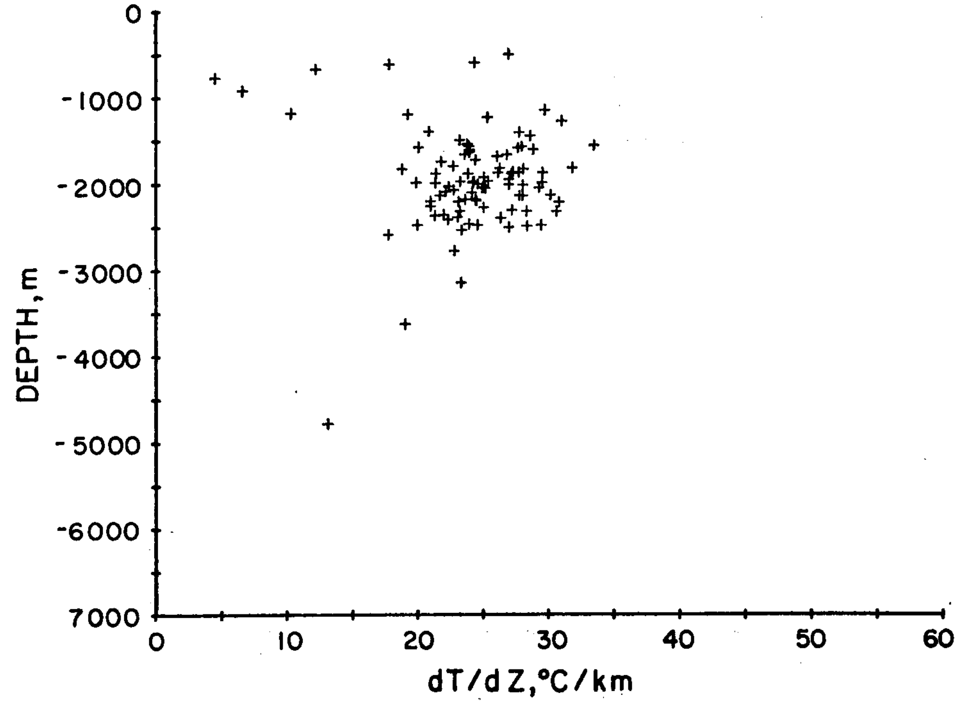

Fig. 31.

Geothermal gradient as a function of depth in wells in north-central Pennsylvania.

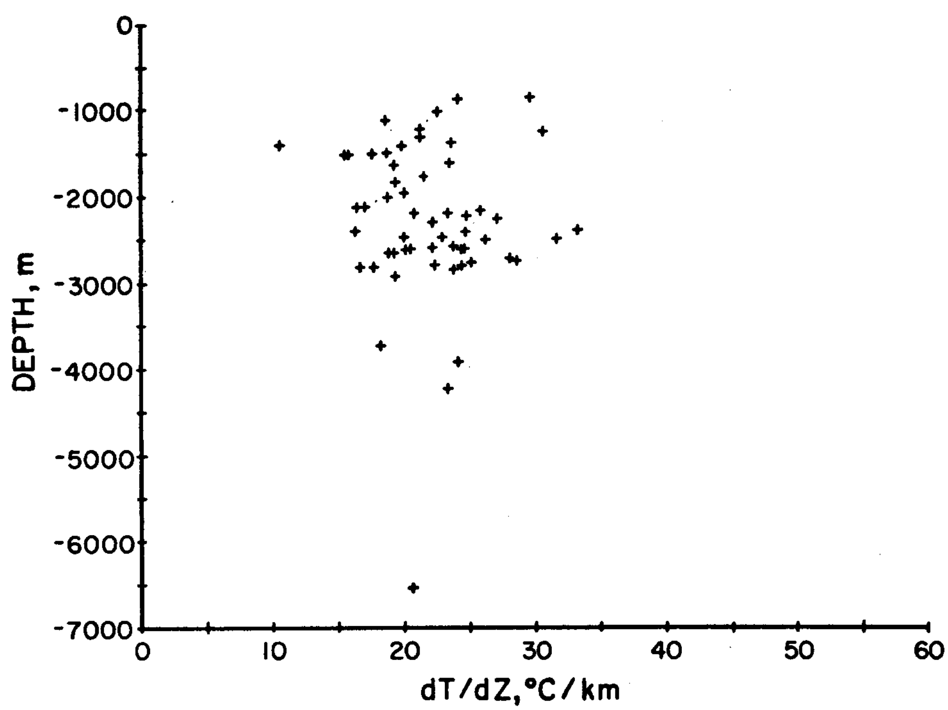

Fig. 32.

Geothermal gradient as a function of depth in wells in central and northeastern Pennsylvania.

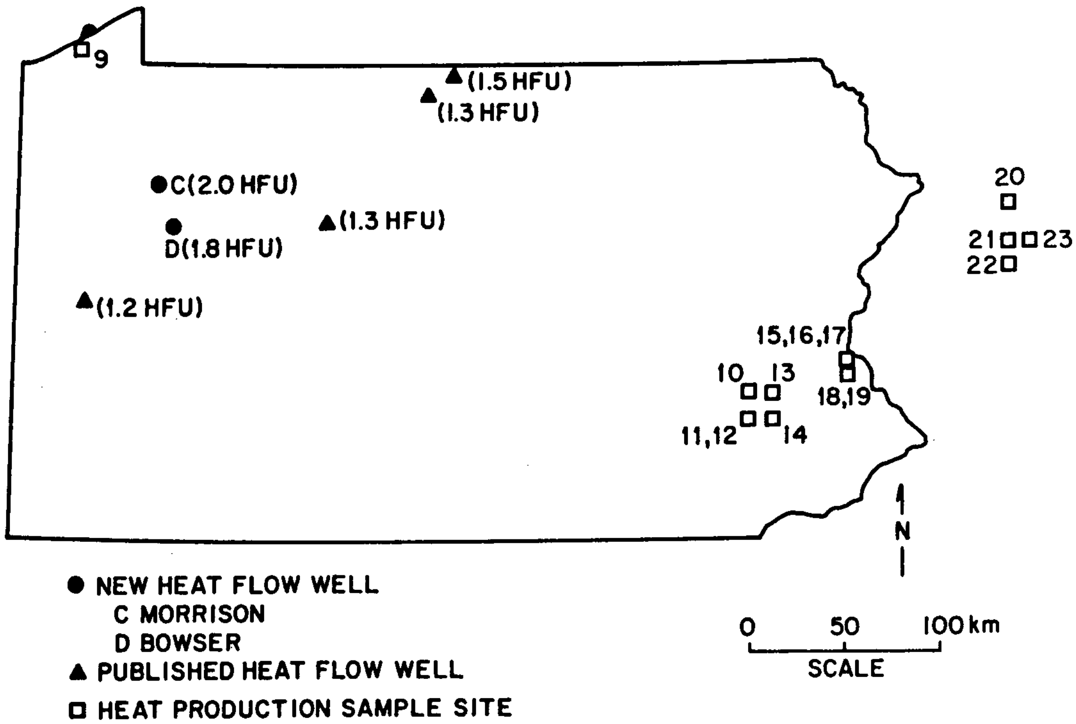

Fig. 33.

Wells and outcrops in Pennsylvania at which heat-flow measurements were made or samples were collected for heat-production determinations.

Clarion County. In addition, core samples from the Bowser well and samples from several wells near the Morrison well were used for measurement of thermal conductivities.

The Morrison well had been drilled to 323.1 m nine months before measurements were made. The Bowser well caved at 458 m in 1969 and is currently producing a small amount of gas from Mississippian sandstones in the uppermost 243 m. Because of gas production, ground-water disturbances and, poor lithologic control, only measurements between depths of 243 m and 353 m were considered reliable. Depth/temperature profiles for the two wells are plotted in Figs. 35 and 36. Basic temperature data and the relevant corrections are included in Apps. E and F. Linear regression of the depth/temperature points within the useful intervals in the Morrison and Bowser wells yields mean uncorrected gradients of 22.63°C/km and 22.53°C/km respectively, and a correlation coefficient of 0.99. Extrapolation of these gradients to a depth of 30.5 m gives values of 6.30°C and 7.36°C. These values differ because of differences in the measured temperatures at depth. They are considerably

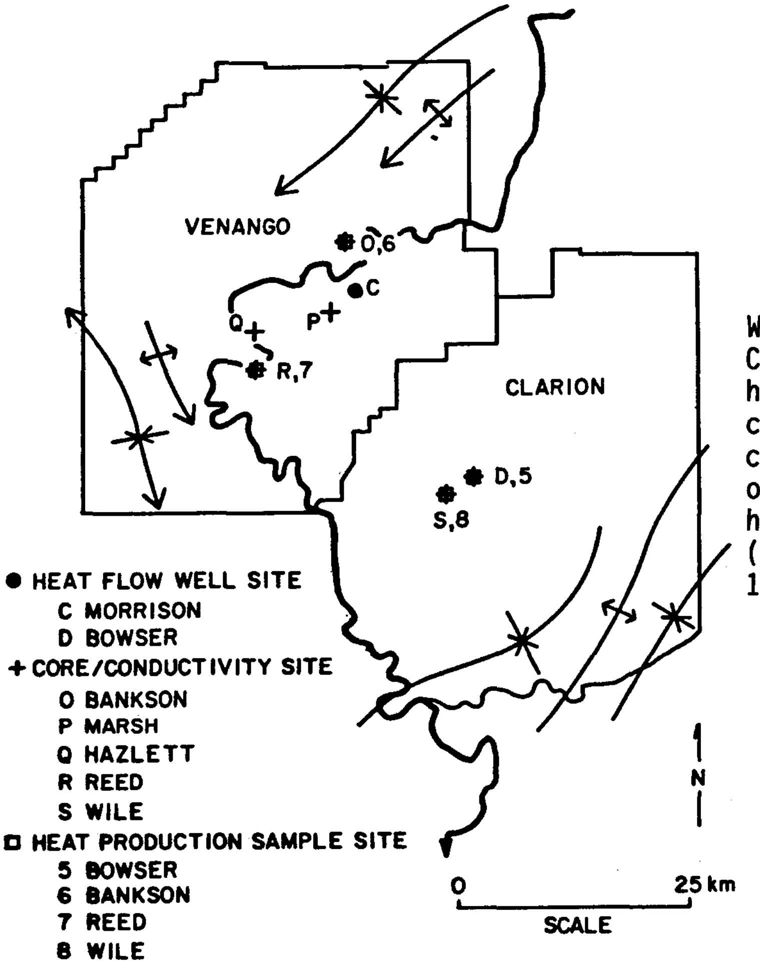

Fig. 34.

Wells in Clarion and Venango Counties, Pennsylvania at which heat-flow measurements were made, core was collected for thermal conductivity determinations, and/or samples were collected for heat-production determinations (from Newport, 1973, and Leggette, 1936).

below the ground-water temperatures of 10.8°C and 11.0°C, respectively. This discrepancy may be due mainly to ground-water heat transport, paleoclimatic effects, and effects of the Allegheny and Clarion Rivers, all of which tend to decrease the geothermal gradient at shallow depths, resulting in shallow temperatures (extrapolated from deeper horizons) lower than those measured. The correction for paleoclimatic effects (Birch, 1948; Urban, 1971; Diment et al., 1972; Cermak, 1976) amounts to an increase to 6.96°C/km and 3.07°C/km in the geothermal gradients in the Morrison and Bowser wells.

Another belt having a relatively higher geothermal gradient, ranging from 25 to 30°C/km, extends from Elmira, New York, through the southwestern corner of Pennsylvania into West Virginia and southeastern Ohio.

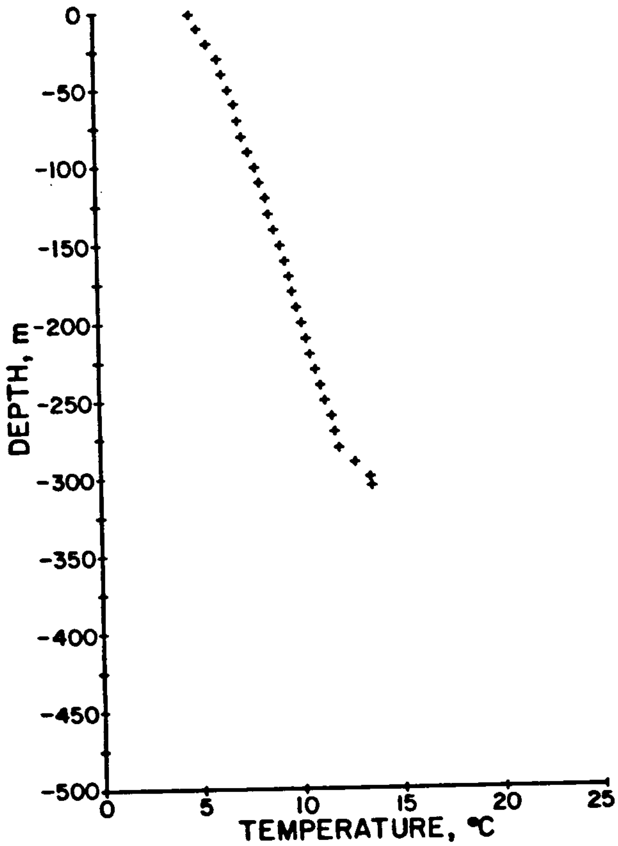

Fig. 35.

Depth/temperature profile in Morrison well in Venango County, Pennsylvania.

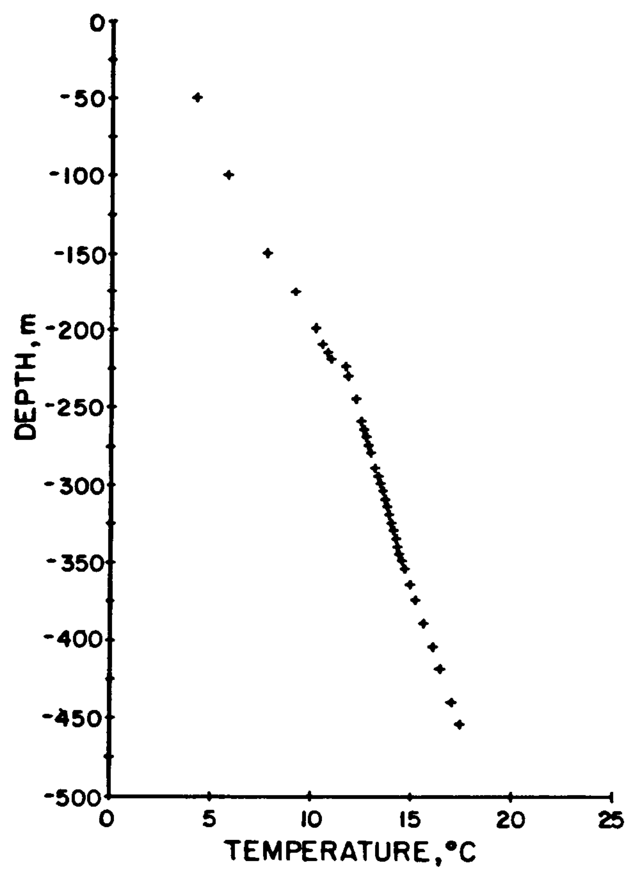

Fig. 36.

Depth/temperature profile in Bowser well in Clarion County, Pennsylvania.

Thermal Conductivity

In practice terrestrial heat flow, q is approximated by

$$q = \overline{K}\ (\Delta T/\Delta z) \quad ,$$

where ΔT is the temperature difference over a finite depth interval Δz comprised of material having a mean thermal conductivity of K.

Thermal conductivity of the rock formations was determined by measurements on core samples using the divided-bar technique (Birch, 1950). The measurements were obtained on machined core-discs, 1.27 to 3.18 cm thick, under an axial pressure of 50 bars that reduced contact resistance to negligible values. Temperatures across the divided bar were measured with thermistors calibrated to $\pm$ 0.02°C with a platinum resistance thermometer. Each core sample was measured for thermal conductivity first "off-the-shelf" and second after saturation with water in a vacuum chamber.

A total of 77 core samples were obtained from wells in Washington, Noble, and Morgan counties in southeastern Ohio (App. G), 29 core samples were taken from the Barberton well (App. H), and 37 other core samples were obtained from wells in southern, central, and northern Ohio (App. I). A total of 64 core samples were taken from wells in Venango and Clarion counties in Pennsylvania (App. J).

Computations of the terrestrial heat flow were done using the interval method. Each well was divided into a series of uniform depth intervals (Δz). The temperature difference (ΔT) for each interval was measured and the mean thermal conductivity (K) was computed. The measured thermal conductivities of representative core samples of each rock unit penetrated were averaged to determine the mean thermal conductivity for each rock type. These means were averaged by weighting the percentage of each lithologic type comprising each depth interval (Δz) in wells from which no core samples were available. The mean heat flow of the evaluated intervals is considered to be the best approximation for the observed terrestrial heat flow. The calculated heat-flow values, with appropriate corrections for each site, are given in Table II.

Three basement samples from Ohio and five from Pennsylvania were analyzed for U(ordinary), ^{232}Th, and K_2O by the Los Alamos National Laboratory. Five samples of shale from Ohio and 11 samples from Pennsylvania also were analyzed at the Los Alamos National Laboratory for U(ordinary) ^{232}Th and K. Analysis of U(ordinary), ^{232}Th, and Ra contents in 34

TABLE II

HEAT-FLOW VALUES

Well Name	Site Location N	W	Q^a ($\mu cal/cm^2 sec$)	Q^b ($\mu cal/cm^2 sec$)	Q^d ($\mu cal/cm^2 sec$)
3236	39°33'30"	81°26'25"	1.14 ± 0.23	1.33 ± 0.23	1.36 ± 0.25
Barberton	41°01'15"	81°37'30"	$1.14 + 0.20$	1.37 ± 0.21	1.37 ± 0.20
Morrison	41°23'52"	79°43'25"	1.44 ± 0.55	1.92 ± 0.75^c	2.00 ± 0.72
Bowser	41°14'00"	79°31'52"	1.73 ± 0.41	1.97 ± 0.47	1.84 ± 0.36

[a]Uncorrected.
[b]Corrected for paleoclimatic changes.
[c]Corrected for Pleistocene glaciation and paleoclimatic changes of rivers.
[d]Corrected for terrain and all other environmental effects.

surface samples of basement rock from the Reading Prong in eastern Pennsylvania and New Jersey were made by A. Drake of the U.S. Geological Survey. Radium content was used because K_2O analyses were not available. The analyses and corresponding heat-production rates are shown in App. K.

DISCUSSION AND CONCLUSIONS

The low-enthalpy convective system associated with the axis of the Cincinnati-Findlay Arch was postulated (Cannon et al., 1980) based on the inverse correlation between the low geothermal gradient and relatively higher ground-water temperatures in the shallow aquifers along the crest of the arch. Cannon et al., (1980) also observed that the warmer ground water in the shallow aquifers contains relatively high concentrations of chloride, total dissolved solids, and silica. The high ionic concentrations in the warmer, shallow ground water may be evidence for the convective model because they result from influx of brackish or saline connate water from deep bed-rock formations into the shallow aquifer through faults and fractures. The distribution of the BHT and of the calculated geothermal gradients (Figs. 10-30) provides additional support for the proposed model (Cannon et al., 1980). Moreover, from Fig. 10 it may be inferred that groundwater at a temperature as high as 60°C may be found along the Cincinnati-Findlay Arch at depths not exceeding 600 m.

The uncorrected heat flow in Clarion County, Pennsylvania is higher than average for the eastern United States (Diment et al., 1972; Sass et al., 1976). When corrected for environmental conditions, the heat flows in Clarion and Venango counties are markedly higher than the mean of 1.34 heat-flow units (HFU) for the eastern United States (Urban, 1971). The values define a local heat-flow high not associated with other reported heat-flow highs in New York (Urban, 1971; Hodge, D. S., 1979, personal communication) nor in other northeastern states (Sass et al., 1980).

The pronounced northeast-trending trough (Fig. 9) on the ground-water temperature map of Pennsylvania and the decreasing hydraulic gradient in northwestern Pennsylvania may result from cold recharge along the Allegheny Mountains and the Allegheny drainage basin, respectively. If so, the geothermal-gradient highs (Fig. 7) mark areas of higher than average conductive heat flow. The area of elevated ground-water temperature (Fig. 9) in southwestern Pennsylvania corresponds roughly with above-average geothermal gradients (Fig. 6).

The Bouguer gravity map of Pennsylvania indicates a southwest-trending gravity low centered at Pittsburgh (Fig. 4). The wavelength of southwest-trending aeromagnetic high centered in Venango County (U. S. Geological Survey, 1979) may indicate that the source of the anomaly is within the upper crust.

Birch et al., (1968), Roy et al., (1968), and Lachenbruch (1968, 1970) observed a linear relation between heat flow (Q) and radiogenic heat production (A):

$$Q = a + bA \quad ,$$

where a is the portion of the observed heat flow originating from the lower crust and mantle. The coefficient corresponding to the thickness of the heat-producing layer of the upper crust is b. The values of a and b are 0.69 and 6.9 respectively for the eastern heat-flow province, according to Costain et al., (1980). For the topographically corrected heat flows of Venango and Clarion counties, the relation would indicate upper crustal heat productions of 11.59 heat-generation units (HGU) and 13.48 HGU respectively, which are much higher values than heat production from the Precambrian basement determined in nearby Erie County (App. K).

Based on a two-layer model, that crustal thickness is approximately 36-45 km (Pakiser and Steinhart, 1964). Assuming a mantle heat flow of 0.4 HFU (Roy et al., 1968) and a lower crustal contribution of 0.95 HFU (Urban, 1971), the upper crustal contribution would be 1.05 HFU for Venango County and 0.89 HFU for Clarion County. This is approximately three times the typical upper crustal contribution for the eastern heat-flow province. Perhaps some excess heat flow is due to the highly radiogenic Pennsylvanian and Mississippian shales (App. K), but the heat production of the shales beneath the Venango anomaly differs little from that of samples below non-anomalous areas in Ohio. Moreover, the Venango anomaly does not coincide with the center of the Appalachian Basin, where the sedimentary cover is thickest (Fig. 1). Therefore, the anomaly may be associated with abnormally high heat production in the upper crust. A more detailed gravimetric survey might provide more information on the nature of the anomaly. If the anomaly is associated with a younger, felsic intrusion, characterized by a high concentration of radiogenic elements, such a survey would help delimit the spatial distribution of the anomaly.

The heat-flow values found elsewhere are well within the commonly expected values characteristic of the Allegheny Plateau, (1.22 to 1.89 HFU) (Joyner, 1960).

SUMMARY AND RECOMMENDATIONS

Two types of geothermal anomalies were encountered during the course of the project. The anomaly in western Ohio is of a convective character, limited to moderate depths within the sedimentary cover. Ground water, at temperatures that may be useful in local agricultural and space-heating projects, seems to convect from deeper formations to shallow zones through the system of faults and fractures associated with the Cincinnati-Findlay Arch. Further research efforts emphasize detailed mapping of the fault and fracture system along the arch and fuller characterization of the hydrothermal phenomena associated with the system. Side-looking airborne radar combined with infrared photography would be useful in mapping the faults and fractures associated with the arch. Ground water should be sampled and analyzed from all available wells.

The heat-flow anomaly in northwestern Pennsylvania seems to be associated with an anomalous heat source within the upper crust. The source probably is within the Precambrian basement, and may be a felsic intrusion having a relatively high concentration of radioactive elements. To determine the validity of this interpretation, a detailed gravimetric survey of the anomalous region and additional heat-flow measurements are recommended. The latter should be determined on at least five cores from wells 500-1000 m deep. Additional heat-flow measurements are recommended in other areas of Pennsylvania where geothermal gradients exceed 30°C/km (Fig. 6).

ACKNOWLEDGMENTS

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APPENDIX A

BOTTOM-HOLE TEMPERATURES IN OIL AND GAS WELLS

IN OHIO

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
Adams	29.40	14.17	1167.8	13.40
Allen	23.89	13.83	619.15	17.10
	22.22	13.58	608.8	14.94
	35.56	13.58	955.6	24.10
	30.56	13.25	995.8	17.93
Ashland	30.56	12.58	864.41	21.92
	33.89	12.58	928.18	24.49
	36.67	12.63	1473.71	17.16
	20.59	12.61	242.93	37.40
	43.89	12.67	1353.62	24.26
Ashtabula	27.78	11.23	1123.49	15.64
	32.22	10.96	969.57	22.64
	32.22	10.96	959.82	22.88
	32.78	11.02	1075.33	20.83
	39.44	11.06	1246.63	23.34
	32.22	11.01	904.34	24.27
	34.44	11.06	1018.34	23.68
	23.33	11.07	1221.64	10.30
	32.78	11.03	954.02	23.55
	34.44	11.02	1167.38	20.60
	50.56	10.83	1962.91	20.56
	•32.22	11.08	1085.09	20.04
	32.22	10.98	1021.69	21.43
	32.22	11.33	1129.59	19.01
	45.00	11.08	1889.76	18.24
	37.78	11.32	1143.61	23.78
Athens	32.78	13.56	1112.52	17.76
	42.02	13.72	1481.33	19.64
	22.78	14.03	508.10	18.31
	31.67	13.22	1054.61	18.01
	23.33	13.56	429.16	24.53
	29.44	13.55	538.58	31.28
	25.56	13.99	513.59	23.94
	34.44	13.22	1223.16	17.79

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
Auglaize	26.67	14.0	521.6	25.8
	23.89	13.28	541.7	37.8
	32.78	13.47	935.4	21.3
Butler	28.30	14.61	895.2	13.30
	30.0	14.5	1004.62	16.53
Carroll	41.11	11.66	1687.07	17.78
	47.22	11.45	1880.01	19.34
	47.22	11.53	1881.84	19.28
	18.33	11.67	373.38	19.43
	40.56	11.72	1713.89	17.13
	45.0	11.75	1734.31	19.51
	43.33	11.81	1680.97	19.10
	46.11	11.67	1891.28	18.51
Champaign	28.33	13.6	686.3	21.40
	27.78	14.28	815.3	17.20
Clarke	26.11	14.53	1111.61	13.71
Clinton	23.9	13.8	993.4	10.5
	33.9	13.	1019.3	20.3
	25.6	13.7	1054.7	11.6
Columbiana	67.50	11.31	2701.14	22.05
	44.44	11.12	1804.42	19.54
	71.11	11.38	3179.67	20.11
	41.67	11.61	1625.19	20.01
	96.11	11.39	3134.87	29.07
	65.56	11.39	1904.70	28.60
	45.56	11.61	1661.77	21.65
Coshocton	30.56	12.34	1056.13	18.36
	46.67	12.31	1905.91	19.07
	42.78	12.29	1351.18	23.73
	37.22	12.25	1234.74	21.35
	49.44	12.21	2042.16	19.25
	39.44	122.38	1232.0	23.18

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
	33.33	12.39	994.56	22.42
	34.44	12.40	1045.16	22.4
	31.11	12.49	1008.58	19.67
Crawford	23.89	13.83	619.15	17.1
	22.22	13.58	608.8	14.94
	35.56	13.58	955.6	24.1
	30.56	13.25	995.8	17.93
Defiance	38.89	12.8	1101.1	23.7
	23.89	2.7	569.1	20.75
	24.44	12.83	569.7	20.4
Delaware	40.0	12.89	1033.6	27.0
	32.8	12.92	1030.6	19.9
	29.4	12.5	946.7	18.4
	40.0	13.0	862.5	32.4
	29.4	12.97	1224.3	13.8
	31.1	12.89	1059.6	17.7
	28.3	13.08	710.3	22.4
	25.6	13.11	702.4	18.6
	29.4	12.89	1132.8	15.0
Erie	34.4	12.5	1182.8	19.0
	25.6	12.69	555.1	24.8
	33.3	12.75	1193.8	27.55
Fairfield	33.33	13.11	1139.95	18.83
	24.44	12.87	736.09	16.75
	26.11	12.84	837.9	16.75
	24.44	12.89	725.42	16.98
	33.33	13.09	1149.71	18.68
	24.44	12.88	691.29	17.87
Fayette	42.2	13.56	1435.0	20.4
Franklin	32.8	13.11	1104.7	18.3
	35.5	13.17	827.8	28.0
	31.1	13.2	1144.7	16.1
Fulton	28.3	12.42	896.4	18.3

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
	31.1	12.47	788.1	24.6
	26.6	13.11	874.7	16.0
Gallia	21.1	14.5	494.08	14.72
	21.11	14.44	484.94	15.13
Geauga	42.22	13.29	1203.05	25.39
	35.00	11.32	1145.13	21.87
	40.00	11.8	1242.3	17.1
Hancock	30.0	13.44	647.8	26.82
	31.1	13.28	855.2	21.6
	28.3	13.3	625.5	25.2
	25.6	13.25	578.3	22.5
	21.1	13.47	600.9	13.4
Hardin	24.4	13.42	606.9	19.0
	27.2	13.25	912.2	15.8
	27.2	13.3	863.7	16.7
	22.8	13.58	622.8	28.6
Harrison	50.6	12.17	1824.5	21.42
	27.7	12.11	422.8	39.74
	16.7	11.86	407.2	12.84
	45.0	11.83	1875.4	18.00
	46.7	12.08	1799.5	19.58
Highland	56.4	13.56	1071.2	8.89
	56.47	13.6	729.6	18.6
Hocking	26.67	13.01	800.1	18.09
	31.67	13.02	938.17	21.24
	32.22	12.96	888.19	22.84
Holmes	36.7	12.28	1141.0	22.0
	48.9	12.28	1998.4	18.6
	53.3	12.39	1794.0	23.2
	31.1	12.42	1003.5	19.2
	39.4	12.36	1253.5	22.1
	48.9	12.22	2078.9	17.9

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
Huron	32.22	12.72	1032.97	20.09
	32.22	2.76	1200.61	17.19
Jackson	33.9	14.25	896.4	22.7
	21.1	13.94	165.9	52.9
Jefferson	51.67	12.06	2100.07	24.72
Knox	28.33	12.72	659.59	25.27
	26.67	12.66	672.29	22.22
	42.78	12.61	1751.08	18.28
	32.22	12.49	974.14	21.59
	33.89	12.71	1284.73	17.43
	24.44	12.68	696.77	17.66
	31.67	12.52	875.08	22.67
	31.67	12.55	885.44	22.36
	31.11	12.72	846.73	22.53
	38.89	12.61	1449.93	18.51
	31.67	12.56	876.6	22.59
	43.33	12.79	1466.09	21.28
	27.78	12.51	954.02	16.54
	27.78	12.51	937.07	16.83
Lawrence	33.89	14.58	982.4	20.28
	46.11	14.67	890.0	36.6
	30.55	14.67	1060.5	15.4
Licking	33.33	12.8	1373.12	15.79
	35.56	12.91	1219.2	19.65
	28.36	12.68	855.27	19.32
	35.0	12.88	1185.98	19.75
	29.44	12.66	899.77	19.65
	37.78	12.64	1552.48	17.24
	40.56	12.72	1462.74	20.0
	44.44	12.66	1309.73	25.54
	37.78	12.83	1344.17	19.57

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
Logan	56.0	13.33	882.7	18.15
	57.4	14.11	577.1	14.8
	56.5	14.17	565.5	21.4
	56.0	13.33	656.1	17.7
Lorain	35.6	12.6	1319.4	17.8
	26.1	12.6	783.2	17.9
Mahoning	41.11	11.7	1537.72	20.33
	46.11	11.56	152.32	22.16
	45.56	11.47	1716.33	21.94
	45.56	11.47	1660.86	21.74
	45.56	11.50	1667.62	21.51
Marion	27.22	12.93	2447.54	16.67
	31.11	13.04	357.1	22.23
Medina	55.00	12.39	2050.69	21.91
	31.11	12.44	1108.25	17.9
	31.11	12.44	949.74	17.9
Meigs	50.6	14.5	1525.0	24.2
	57.8	14.2	1610.1	27.6
Mercer	22.8	13.2	574.6	17.6
	30.56	12.28	396.24	48.07
	31.11	13.24	956.16	19.98
Miami	30.0	14.5	933.91	17.82
	27.22	14.5	932.99	14.7
Morgan	37.78	13.03	1493.82	17.43
	38.89	13.08	1363.98	19.94
	43.33	13.29	1642.87	19.44
	33.89	12.91	1208.44	18.38
	40.0	12.93	1283.21	22.25
	21.11	11.66	1645.62	5.72
	43.33	13.0	1533.14	21.05
	42.78	13.17	1644.09	19.15
Morrow	35.0	12.92	1123.8	20.84
	23.89	14.0	921.72	25.17

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
	35.56	12.82	1211.88	19.84
	34.44	12.83	1264.62	18.07
	31.11	12.86	999.44	18.83
	29.44	12.92	1386.84	12.62
	30.56	12.78	1030.22	18.39
	27.78	12.79	1032.27	15.5
	34.44	12.92	1124.71	20.3
	27.78	11.83	972.3	16.44
	35.0	12.9	1189.94	21.98
Muskingum	35.0	12.72	1048.51	22.57
	45.6	12.47	1353.31	25.69
	41.11	12.68	1552.04	17.49
	43.89	12.43	1261.07	26.26
	33.33	12.43	1161.59	19.07
	36.11	12.6	1548.08	19.23
	36.67	12.37	1309.42	19.57
	35.56	12.49	1085.70	26.33
	23.89	12.44	1383.79	18.81
	34.44	12.57	1025.35	22.68
	28.89	12.56	942.44	18.54
	29.44	12.57	1004.32	17.94
	35.0	12.76	1062.53	22.23
	35.56	12.54	1099.11	22.2
	35.56	12.49	1341.12	18.14
Noble	55.6	13.11	1817.1	23.8
	42.2	13.08	1791.9	16.5
Ottawa	22.8	12.5	586.5	18.5
Paulding	31.1	12.97	597.5	31.98
	23.9	13.02	443.8	26.3
Perry	43.9	12.89	1885.8	16.7
	32.2	12.7	1038.8	19.3
	32.8	12.78	1078.2	19.1
	28.8	12.67	884.8	18.9

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
	29.4	12.86	934.8	18.3
	28.3	12.67	973.6	16.6
	27.7	12.92	914.4	16.7
	31.7	13.05	1117.5	17.2
	28.8	12.89	1002.5	16.4
	31.7	12.92	1127.9	17.7
	30.6	12.72	976.0	18.91
	27.7	13.3	1075.1	13.78
	28.8	13.25	840.3	19.20
Pickaway	28.8	13.11	921.7	17.61
	38.9	13.19	247.6	20.67
Pike	33.89	13.67	494.08	18.24
	26.67	13.64	1176.53	15.47
Portage	41.67	12.67	1325.88	22.36
	35.0	12.04	1387.45	18.47
	36.11	12.17	1311.55	17.36
	42.78	12.0	1396.59	21.64
	41.11	12.24	1492.0	22.88
	35.56	11.98	1328.01	18.89
	28.33	11.79	1354.53	29.18
Ross	26.6	13.36	748.2	18.45
	28.8	13.22	1008.0	15.94
	30.0	13.22	1041.3	16.6
Sandusky	24.4	12.83	677.7	17.9
	28.3	12.89	842.7	18.97
	29.4	12.61	731.1	23.96
	28.3	12.94	671.9	23.95
	29.4	12.58	822.3	21.24
	29.4	12.83	676.5	25.65
	24.4	12.83	848.5	14.14
Scioto	32.78	14.26	1712.06	14.91
	21.67	14.42	1316.74	23.22

County	BHT (°C)	T_{gw} (°C)	Depth (m)	dT/dz
Stark	39.44	12.21	1324.97	21.65
	41.11	12.02	1527.05	20.26
	60.0	11.86	2439.31	20.98
Warren	31.7	14.5	893.0	19.9
	29.4	13.9	898.5	17.9
Washington	444.4	13.5	1758.0	17.9
	23.3	13.7	413.9	25.0
	42.8	13.9	1586.0	18.6
	39.4	13.75	1096.8	24.1
	49.4	13.9	1351.7	26.7
	35.0	13.5	1598.8	13.7
Wayne	32.2	12.5	1008.9	20.1
	44.4	12.6	1752.5	18.5
	44.4	12.6	1625.3	20.0
	41.7	12.4	1159.6	25.9
	43.3	12.4	1534.7	20.5
	25.6	12.4	778.4	17.6
	40.0	12.4	972.9	29.3
	34.4	12.5	942.4	24.0
	30.0	12.6	1179.4	15.3
Wood	31.1	12.9	862.2	21.9
	26.1	12.8	717.0	19.4
	21.1	12.9	595.7	14.6
	29.4	13.0	844.8	20.1
	28.8	12.9	847.9	19.5
	26.6	12.75	784.8	18.4
Wyandot	29.4	13.1	771.6	16.3
	27.7	13.2	642.9	23.6
	26.6	13.2	884.8	15.7
	26.6	13.2	875.0	15.9
	29.4	13.1	703.6	24.2

APPENDIX B

BOTTOM-HOLE TEMPERATURES IN OIL AND GAS WELLS IN PENNSYLVANIA AND ADJACENT AREAS OF MARYLAND AND WEST VIRGINIA

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
Allegheny	18.56	12.33	565.4	11.63	
	31.67	12.19	955.5	21.05	21.73
	71.11	12.22	2407.9	24.77	25.97
	35.00	12.39	1236.0	18.76	19.34
	25.83	12.06	778.5	18.42	18.77
Armstrong	72.78	12.28	2311.6	26.52	27.80
	29.44	11.14	931.5	20.31	
	62.78	12.15	2234.5	22.97	24.11
	32.22	12.23	1175.9	17.36	17.93
	22.00	12.11	992.4	10.29	10.74
	34.28	12.24	1097.3	20.66	21.30
	22.22	12.11	928.1	11.26	c
	30.00	12.00	944.9	19.69	20.34
	30.00	11.69	990.0	19.08	c
	26.67	11.78	879.0	17.55	17.86
	37.22	11.53	975.4	27.19	c
	55.17	11.72	2194.6	20.08	21.09
	47.22	11.56	2051.3	17.65	18.35
Beaver	54.44	11.86	2273.8	18.98	19.95
	49.44	11.28	2014.7	19.23	19.98
	60.83	11.39	1398.4	36.15	37.03
	19.89	11.81	444.7	19.51	
	17.78	11.81	448.1	14.30	
Bedford	86.67	11.86	2389.6	31.71	33.18
	55.56	11.83	2826.4	15.64	16.63
	37.78	11.44	1310.6	20.57	21.26
	47.22	11.54	1615.4	22.51	23.41
	45.00	11.42	1839.2	18.56	19.31
	56.11	11.22	2199.1	20.70	
	45.00	12.09	2128.4	15.69	16.33
	35.56	11.61	853.4	29.10	29.53
	35.56	11.61	1531.6	15.95	16.66
	36.67	11.72	1502.7	16.94	17.44

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
Blair	47.78	11.92	1774.9	20.56	21.38
	58.33	11.94	2822.4	16.62	17.66
	46.11	12.08	2122.6	16.26	16.93
	64.44	12.06	2164.1	24.55	25.76
	34.06	11.78	1020.5	22.50	
Bradford	98.89	10.22	3914.5	22.83	24.10
	58.89	10.17	2288.1	21.58	22.10
	35.00	10.37	1227.1	20.58	21.17
	45.83	10.11	2012.9	18.02	18.71
	36.39	10.01	1402.1	19.23	19.76
Butler	20.44	11.64	527.3	17.72	
	35.00	11.31	1038.5	23.50	24.20
	21.39	11.06	614.2	17.70	18.07
	19.78	11.70	568.5	15.02	15.38
	25.39	11.92	810.2	17.28	17.60
	28.78	11.81	807.7	21.84	22.21
	34.72	11.22	1689.8	14.16	
	51.67	11.25	2316.5	17.68	c
Cambria	65.56	12.36	2468.9	21.82	22.89
	34.72	12.33	1524.0	14.99	15.69
	63.89	12.17	2225.0	23.57	24.73
	84.17	12.39	2718.8	26.70	17.95
	60.56	12.50	2447.8	19.88	
	65.00	12.44	2923.0	18.17	19.29
	66.39	12.39	2593.8	21.07	22.10
	72.50	12.39	2606.0	23.34	24.47
	70.00	12.36	2781.6	20.95	22.22
	73.89	12.11	2503.6	24.98	27.17
	69.72	12.11	2578.6	22.61	23.70
	73.89	12.17	2432.3	25.70	26.93
	86.39	12.17	2489.9	30.18	31.58
Cameron	59.44	11.06	2036.1	24.13	25.02
	43.33	10.97	1822.1	18.06	18.79

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	51.11	11.14	1790.7	22.71	
	50.56	11.15	1872.4	21.39	
	56.56	11.06	1976.3	23.38	24.26
	66.67	11.00	1983.0	28.51	29.53
	59.61	11.06	1823.3	27.08	28.08
	52.78	11.06	1984.6	21.35	c
	60.00	11.00	2048.3	24.28	25.18
	16.50	11.00	914.4	6.22	6.60
	58.33	11.00	1964.4	24.47	25.38
	14.17	11.00	766.3	4.30	
Carbon	44.17	11.39	978.4	34.58	35.51
	41.11	11.42	1644.7	18.40	19.16
Centre	58.06	11.67	2468.9	19.02	19.98
	60.00	11.61	2179.3	22.52	23.64
	70.00	11.33	4773.8	12.37	13.11
Clinton	54.44	11.39	2580.7	16.88	17.74
	21.56	11.28	608.4	17.78	
Clarion	25.56	11.06	696.2	21.78	22.17
	14.78	11.17	693.42	5.45	5.67
	19.67	11.03	557.82	16.37	16.37
	24.44	11.17	960.1	14.28	c
	21.11	11.17	798.0	12.96	13.23
	23.89	11.33	640.1	20.60	
	29.31	11.33	896.1	20.76	
	32.22	11.33	954.6	22.60	
	23.61	11.08	774.2	16.85	c
	22.00	11.22	762.0	14.73	
	16.67	11.04	538.3	11.08	11.41
	19.28	11.28	707.1	11.82	12.11
	23.33	11.17	740.7	17.13	17.46
	23.33	11.17	742.2	17.10	17.42
	25.28	11.17	808.0	18.15	18.47
	28.89	11.22	809.5	22.68	

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	23.89	11.17	869.6	15.16	
	20.83	11.17	789.4	12.74	
	29.17	11.06	758.3	24.88	
	23.89	11.06	574.2	23.60	
	20.56	11.31	765.0	12.58	
	22.50	11.11	634.0	18.87	
	21.81	11.04	865.6	12.89	
	17.36	11.03	636.4	10.45	
	19.28	11.06	939.7	9.04	
	28.75	11.17	634.0	29.14	
	20.56	11.10	752.9	13.09	
	20.00	11.10	1525.8	5.95	
	20.28	11.17	666.0	14.34	
	22.78	11.09	794.3	15.30	
	31.67	11.00	749.2	28.75	29.20
	21.11	10.98	792.5	13.30	13.58
	17.22	10.97	369.7	18.42	
	28.94	10.96	912.3	20.40	20.73
	68.89	11.06	2409.7	24.31	25.47
	60.14	11.06	1760.2	28.38	29.42
	51.94	11.06	1767.8	23.54	c
	53.33	11.06	1699.6	25.33	26.29
	56.11	11.00	2265.6	20.18	20.69
	42.78	11.00	1645.9	19.67	20.47
	52.78	10.94	2966.0	21.61	22.43
Clearfield	67.78	12.11	2529.8	22.27	23.36
	65.56	11.28	1866.9	29.56	
	70.33	11.32	2136.6	28.02	
	73.89	11.67	2392.7	26.34	
	75.56	12.00	2498.4	25.75	26.98
	56.11	11.67	2254.9	19.98	20.99
	63.33	11.67	2380.5	21.99	23.06
	65.56	11.67	2270.8	24.05	25.03

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	62.22	11.67	2313.4	22.14	23.24
	75.56	11.39	2211.3	29.42	30.81
	78.33	11.89	2484.1	27.08	28.36
	67.22	11.78	2461.3	22.81	23.92
	67.22	11.48	2188.6	26.50	27.78
	60.00	11.32	2354.0	20.95	21.99
	78.33	11.44	2316.5	29.26	30.63
	68.11	11.28	2042.2	28.25	29.27
	73.33	11.67	2315.0	26.99	28.28
	70.28	11.30	2301.2	25.97	27.21
	58.33	11.17	1996.4	23.99	24.59
Crawford	33.33	11.03	1200.6	19.06	19.63
	37.78	10.89	1206.7	22.86	
	36.11	10.83	1323.1	19.55	
	38.33	10.91	1233.2	22.80	23.44
	35.00	10.89	1248.5	19.80	20.37
	33.33	10.78	1314.3	17.57	18.09
	36.11	10.92	1250.0	20.66	21.25
	31.67	10.92	1163.1	18.32	18.87
	34.44	10.92	1233.2	19.56	20.13
	43.33	11.00	1242.7	26.67	27.39
	34.44	10.93	1293.6	18.62	18.16
	36.67	10.89	1312.2	20.11	20.68
	38.33	10.91	1294.2	21.70	22.31
	43.33	10.89	1609.6	20.55	21.37
	45.00	10.92	1460.3	23.84	c
	42.22	10.72	1006.7	19.38	20.16
	45.00	10.74	1553.0	22.50	23.39
Elk	59.44	11.11	1874.4	6.21	27.18
	62.94	11.18	2194.6	23.92	24.50
	74.44	11.19	2127.5	30.16	
	48.33	11.06	1978.2	19.14	19.88
	56.78	11.06	1979.3	23.46	24.33

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	66.67	11.22	2008.0	28.04	
	54.44	11.00	1969.0	22.41	23.25
	57.22	10.97	1865.4	25.21	26.14
	18.61	10.89	664.5	12.18	12.18
	23.33	10.89	492.3	26.95	c
	56.44	11.14	1966.9	23.39	24.27
	68.33	11.02	2471.9	23.47	24.59
	59.17	11.04	1859.3	26.32	27.29
	61.11	11.11	2179.3	23.27	24.41
Erie	44.44	10.87	1241.1	27.73	28.46
	30.56	10.83	1148.5	17.64	18.19
	40.56	10.69	1361.8	22.43	23.04
	22.89	10.94	1068.6	11.51	
	30.56	10.94	874.8	23.23	23.59
	32.78	10.94	1001.3	22.49	23.17
	20.00	10.68	378.0	26.81	27.39
	43.33	10.74	1260.3	26.50	27.20
Fayette	39.44	12.19	1197.3	23.35	c
	74.44	13.18	2545.7	24.36	25.54
	27.61	13.33	911.4	16.21	16.52
	37.78	13.33	1173.5	21.39	22.05
	75.56	13.06	2011.7	31.55	32.69
	24.72	13.00	701.0	17.48	17.85
	74.44	13.06	2069.6	30.11	31.20
	69.44	13.06	2380.5	24.00	25.18
	79.44	12.78	2816.7	23.93	25.35
	70.56	12.18	2148.8	27.56	
	33.50	12.19	972.9	22.61	23.32
	27.22	12.85	1219.2	12.09	12.55
	65.56	12.56	2727.4	19.65	20.62
	64.44	12.91	2684.4	19.42	20.39
	23.89	13.33	807.7	13.58	13.89
	68.61	13.18	2427.4	23.13	c

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	90.00	13.24	3291.8	23.53	24.91
	80.56	13.39	2910.8	23.32	c
	72.50	13.33	2407.9	24.89	
	69.44	13.33	2133.6	26.68	28.00
	71.67	13.14	2407.9	24.62	25.82
	103.61	13.24	3627.1	25.13	26.57
	73.33	13.19	2313.4	26.34	27.63
	75.00	13.24	2417.1	25.88	17.14
Forest	14.11	10.89	645.0	5.24	5.47
	46.11	10.83	1837.0	19.53	19.92
	46.11	10.83	1870.6	19.17	19.92
	17.39	10.86	314.2	23.02	c
	54.44	10.89	2086.1	21.19	21.98
Fulton	31.11	11.11	874.8	23.69	24.06
Greene	26.56	13.41	910.1	14.95	15.25
	32.78	13.39	993.6	20.13	
	26.67	13.33	951.0	14.48	
	32.78	13.34	975.7	20.56	c
	32.89	12.59	2331.7	8.77	9.34
	75.83	12.96	2639.6	24.10	25.26
Indiana	35.00	12.36	1164.3	19.97	20.58
	75.56	12.42	2581.7	24.75	25.93
	76.67	12.25	2455.2	26.57	
	80.00	12.27	2471.9	27.74	29.05
	80.83	12.36	2118.4	32.80	33.96
	71.11	12.36	2285.4	26.06	
	52.22	12.33	1828.8	22.18	
	28.89	12.31	960.1	17.84	
	36.67	12.14	1066.8	23.66	
	21.89	12.42	678.1	12.84	
	81.67	12.42	2255.5	31.12	32.59
	58.44	12.44	2286.0	20.39	21.43
	26.83	12.34	1066.8	13.98	14.50

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	54.44	12.35	2334.2	18.27	19.22
	74.44	12.50	2530.1	24.95	
	73.33	12.47	2301.2	26.80	
	20.56	11.78	1001.0	9.04	
	62.78	11.94	2203.7	23.39	24.55
	68.33	11.81	2329.0	24.59	25.78
	68.89	11.88	2097.9	27.58	28.58
	72.22	11.83	2350.0	26.03	27.28
Jefferson	21.83	11.08	804.7	13.89	
	28.56	11.11	911.4	19.80	20.13
	23.72	11.42	417.6	31.79	32.42
	42.50	11.53	1219.2	26.06	26.77
	69.72	11.53	2212.8	26.67	27.94
	63.33	11.46	2171.7	24.23	25.41
	44.72	11.10	917.4	37.91	38.92
	66.67	11.71	2202.2	25.31	26.54
	39.17	11.58	1219.2	23.20	23.86
	40.83	11.58	1219.2	24.61	25.29
	71.67	11.58	2177.8	27.98	29.32
	75.56	11.56	2280.5	28.44	29.79
	38.89	11.60	1100.3	25.51	26.23
	53.33	11.56	2261.6	18.72	19.68
	34.28	11.69	1036.3	22.45	23.13
	33.89	11.67	1103.4	20.71	21.34
	29.72	11.61	1127.8	16.51	17.05
	74.72	11.69	2170.2	29.46	30.85
	64.44	11.53	2234.2	24.01	25.18
Juniata	58.89	10.91	2659.4	18.25	19.15
Lackawanna	40.00	10.14	1648.4	18.46	19.20
Lawrence	60.00	11.04	1453.9	34.39	35.24
	47.78	11.08	1478.3	25.35	26.01
Luzerne	30.00	10.49	1118.6	17.93	18.48
	24.44	10.56	1402.1	10.13	10.48

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
Lycoming	55.56	10.96	2024.5	22.36	
	32.22	10.63	1187.2	18.67	19.23
	61.67	11.08	2407.9	21.28	22.32
	58.89	10.99	2202.8	22.05	23.13
	57.89	11.06	1813.6	26.27	
	59.17	11.03	2098.5	23.28	24.14
	81.11	10.77	2474.4	28.78	29.45
	54.44	11.13	2197.6	19.99	20.99
McKean	48.06	10.72	1264.9	30.24	31.02
	75.28	10.74	3618.0	17.99	19.04
	47.78	10.73	1399.0	27.07	27.77
	50.56	10.79	1720.6	23.53	24.42
	62.22	10.89	2002.5	26.03	26.98
	60.00	10.83	1551.4	32.33	33.51
	50.00	10.71	1438.4	27.91	28.62
	10.11	10.67	1173.5	-0.49	-0.31
	42.78	10.66	1140.0	28.95	29.72
	47.78	10.78	1659.6	22.71	23.59
	40.00	10.67	1219.5	24.67	25.34
	55.56	10.86	2068.1	21.94	22.76
	43.89	10.83	1492.6	22.61	23.21
	24.06	10.79	585.2	23.91	24.34
Mercer	40.56	11.03	1537.7	19.59	20.13
	43.33	11.04	1560.6	21.11	21.96
	50.00	10.96	1882.4	21.07	21.88
	43.33	10.97	1618.5	20.38	21.20
	35.00	11.03	1460.6	16.86	
	47.22	10.89	1661.2	22.28	23.15
	40.28	10.91	1713.9	17.45	18.17
	43.33	10.94	1749.6	18.84	19.60
	43.50	10.92	1757.5	18.87	19.62
	46.11	10.94	1539.2	23.31	24.23
	64.44	10.92	2784.7	19.44	20.61

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	40.56	11.02	1612.1	18.67	19.44
Pike	103.89	10.89	4239.8	22.09	23.33
Potter	56.67	11.00	1920.2	24.17	25.06
	60.83	11.06	1941.6	26.05	27.00
	46.67	10.79	1740.1	20.99	221.80
	46.94	11.04	1539.2	23.79	
	60.00	10.98	1862.3	26.76	27.74
	53.33	10.89	1877.6	22.98	23.85
	58.33	10.93	2363.7	20.32	21.32
	55.00	11.06	2133.0	20.90	21.69
	59.44	11.06	2044.6	24.02	24.91
	52.22	10.83	1566.7	26.94	27.96
	47.78	10.81	1633.7	23.06	23.95
	54.44	10.81	1600.2	27.80	28.84
	47.22	10.78	1608.7	23.09	23.99
	46.11	10.78	1565.1	23.02	23.92
	40.56	10.78	1575.8	19.27	20.06
	55.00	11.06	2088.5	21.35	22.15
Somerset	77.00	12.00	2776.7	23.67	25.07
	71.67	13.00	2407.9	24.68	
	142.78	12.94	6521.0	19.94	20.60
	62.78	12.83	2656.3	19.02	
	64.44	12.58	2612.7	20.08	
	43.33	12.67	1371.0	22.89	23.54
	49.44	12.47	1959.0	19.16	19.93
	72.22	12.50	2608.5	23.17	24.29
	70.00	12.66	2255.5	25.77	27.03
	51.11	12.64	2407.9	16.18	
	38.89	12.44	1493.5	18.07	18.61
	85.72	12.52	2743.2	26.98	28.56
	76.11	12.39	2802.0	22.99	24.36
Sullivan	77.78	10.52	2853.8	23.82	
	60.83	10.52	2192.7	23.27	

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
Susquehanna	60.00	9.89	2601.2	19.49	20.43
Tioga	65.56	10.92	1808.4	30.73	31.84
	53.06	10.89	1661.2	25.86	26.83
	79.44	10.92	3138.5	22.05	23.33
	38.33	10.80	1387.8	20.29	20.85
	52.22	10.81	1584.0	26.66	27.66
	52.22	10.75	1681.0	25.13	26.08
	70.00	10.94	2771.2	21.55	22.82
Venango	48.89	10.89	1845.6	20.94	21.74
	26.17	10.91	634.0	25.29	25.72
	30.00	10.91	760.2	26.16	26.57
	47.78	10.94	1984.2	18.85	19.59
	45.42	10.94	2002.8	17.48	18.17
	53.3	10.98	2033.6	21.14	21.94
	45.56	10.96	1935.5	18.16	18.88
	48.89	10.96	2048.6	18.80	19.52
	21.11	10.89	312.4	36.26	37.01
	16.67	10.86	211.7	32.07	32.07
	30.00	10.89	659.3	30.39	
	16.67	10.79	290.2	22.63	
Warren	40.56	10.73	1418.5	21.56	22.14
	41.67	10.65	1209.1	26.32	27.02
	48.06	10.78	1770.9	21.42	
	44.44	10.78	1837.3	18.63	
	63.89	10.63	2478.0	25.84	26.05
	43.33	10.74	1732.2	19.15	19.91
Washington	73.06	11.97	2475.0	24.99	26.18
	80.56	11.97	2329.9	29.83	31.23
	25.28	12.11	807.7	16.94	17.27
	73.33	12.06	2590.8	23.93	25.08
	17.50	11.97	723.9	7.97	
	33.33	12.17	1216.2	17.85	18.41
	39.44	12.00	1338.1	20.99	21.59

County	BHT (°C)	T_{gw} (°C)[a]	Depth (m)	dT/dz	dT/dz[b]
	50.00	12.36	2004.1	19.07	
	26.67	12.13	890.0	16.91	
	26.83	12.11	813.5	18.80	19.14
	50.56	12.16	1796.8	21.74	
Wayne	73.89	10.13	3733.8	17.22	18.21
	32.78	10.21	1511.8	15.24	15.68
	32.50	10.17	1521.0	14.98	15.42
Westmoreland	23.50	12.00	895.5	13.29	13.57
	60.00	12.13	2225.0	21.81	22.91
	73.89	12.44	2274.1	27.39	28.70
	66.11	12.76	2414.0	22.39	23.49
	72.22	12.47	2255.5	26.85	18.15
	63.33	12.42	2171.7	23.78	24.96
	60.67	12.33	2260.7	21.67	22.76
	46.39	12.25	1386.8	25.17	25.85
	24.83	12.28	640.1	20.60	21.00
	38.89	12.44	1097.3	24.79	
	66.67	12.37	2514.6	21.86	22.93
	70.56	12.50	2340.9	25.13	26.35
	84.72	12.47	2356.9	31.04	32.50
	31.11	12.08	1120.1	17.46	18.03
	68.17	12.75	2539.3	22.09	23.18
	68.89	12.65	2444.5	23.30	24.44
Wyoming	46.11	10.08	1243.0	29.72	30.48
Maryland	34.44	11.76	1380.7	16.80	
	62.78	11.92	2167.1	23.80	
West Virginia	115.00	13.39	5032.9	20.31	
	78.89	11.90	3166.0	21.36	

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[a] Ground water temperature at depth of 30.5 m.

[b] Geothermal gradient correction for the effects of drilling.

Depth (m)		Time Between Drilling Completion and Logging: 0 - 1 day	2 days
0	152.4	-1	0
152.4	304.8	0	0
304.8	914.4	1	0
914.4	1524.0	2	1
1524.0	2133.6	3	2
2133.6	2743.2	4	2
> 2743.2		5	3

[c] Borehole logged three or more days after completion of drilling. No temperature correction was applied.

APPENDIX C

DEPTH/TEMPERATURE RECORD FROM WELL 3236, WASHINGTON COUNTY, OHIO

DEPTH		TEMPERATURE	
Observed (m)	Topography Corrected (m)	Observed (°C)	Climate Corrected (°C)
15.2		11.92	
30.5		12.12	
45.7		12.35	
61.0		12.57	
76.2		12.85	
91.4	76.2	13.08	13.42
106.7		13.33	13.71
121.9	103.6	13.60	14.04
137.2		13.88	14.37
152.4	134.1	14.18	14.73
167.6		14.52	15.12
182.9	161.5	14.86	15.52
198.1		15.21	15.94
213.4	192.0	15.42	16.21
228.6		15.53	16.38
243.8	219.5	15.82	16.72
259.1		16.22	17.18
274.3	249.9	16.64	17.65
289.6		16.95	18.01
304.8	280.4	17.24	18.35
320.0		17.49	18.66
335.3	307.8	17.77	19.00
350.5		17.99	19.27
365.8	338.3	18.25	19.59
381.0		18.51	19.87
396.2	368.8	18.73	20.15
411.5		18.90	20.37
426.7	399.3	19.06	20.58
442.0		19.23	20.81
457.22	426.7	19.49	21.12
472.4		19.79	21.43
487.3	457.2	20.11	21.81

DEPTH		TEMPERATURE	
Observed (m)	Topography Corrected (m)	Observed (°C)	Climate Corrected (°C)
502.9		20.49	22.24
518.2	487.7	20.89	22.69
533.4		21.32	23.18
548.6	518.2	21.79	23.70
563.9		21.88	23.78

APPENDIX D

DEPTH/TEMPERATURE RECORD FROM BARBERTON WELL,

SUMMIT COUNTY, OHIO

Depth (m)	Temperature (°C)	Geothermal Gradient (°C/km)
0	5.42	
		88.40
50	9.83	
		118.40
75	12.79	
		-12.80
100	12.47	
		28.00
105	12.61	
		2.00
110	12.62	
		6.00
115	12.65	
		8.00
120	12.69	
		20.00
124	12.79	
		16.00
130	12.87	
		26.00
135	13.00	
		48.00
140	13.24	
		-36.00
145	13.06	
		88.00
150	13.50	
		30.00
180	14.40	
		24.33
210	15.13	
		23.00
240	15.82	
		19.00
270	16.39	
		16.33
300	16.88	
		27.00
330	17.69	
		24.67
360	18.43	
		30.00
390	19.33	
		31.33
420	20.27	
		12.00
450	20.63	
		18.67
480	21.19	
		32.00

Depth (m)	Temperature (°C)	Geothermal Gradient (°C/km)
510	22.15	29.00
540	23.02	28.00
570	23.86	41.00
600	25.09	47.33
630	26.51	27.33
660	27.33	22.67
690	28.01	23.33
720	28.01	12.33
750	29.08	22.67
780	29.76	47.00
810	31.17	58.00
815	31.46	78.00
820	31.85	58.00
825	32.14	104.00
830	32.66	58.00
835	32.95	14.00
840	33.02	6.00
845	33.05	14.00
850	33.12	14.00
855	33.19	

APPENDIX E

DEPTH/TEMPERATURE RECORD FROM MORRISON WELL,

VENANGO COUNTY, PENNSYLVANIA

DEPTH		TEMPERATURE			GEOTHERMAL GRADIENT			
Ob-served (m)	Topog. (m)	Ob-served (°C)	River (°C)	Climate (°C)	Ob-served °C/km)	River Corr. (°C/km)	River & Climate Corr. (°C/km)	River, Climate, & Topog. Corr. (°C/km)
10.00	0.86	5.23	5.23	5.02				
					44.00	44.00	26.00	28.11
20.00	10.11	5.37	5.68	5.28				
					51.00	53.00	39.00	42.16
30.00	19.36	6.18	6.20	5.67				
					20.00	20.00	14.00	15.10
40.00	28.63	6.38	6.40	5.81				
					31.00	32.00	32.00	34.48
50.00	37.91	6.69	6.72	6.13				
					27.00	27.00	33.00	35.48
60.00	47.21	6.96	6.99	6.46				
					14.00	15.00	24.00	25.72
70.00	56.54	7.10	7.14	6.70				
					20.00	20.00	31.00	33.19
80.00	65.88	7.30	7.34	7.01				
					32.00	33.00	46.00	49.04
90.00	75.26	7.62	7.67	7.47				
					33.00	34.00	46.00	48.94
100.00	84.66	7.95	8.01	7.93				
					19.00	20.00	32.00	33.97
110.00	94.08	8.14	8.21	8.25				
					28.00	28.00	38.00	40.21
120.00	103.53	8.42	8.49	8.63				
					14.00	15.00	25.00	26.37
130.00	113.01	8.56	8.64	8.88				
					25.00	25.00	34.00	35.79
140.00	122.51	8.81	8.90	9.22				
					32.00	34.00	41.00	43.02
150.00	132.04	9.13	9.23	9.63				
					22.00	23.00	29.00	30.33
160.00	141.60	9.35	9.46	9.92				
					18.00	19.00	25.00	26.12
170.00	151.17	9.53	9.65	10.17				
					15.00	16.00	21.00	21.88
180.00	160.77	9.68	9.81	10.38				
					21.00	22.00	26.00	27.03
190.00	170.39	9.89	10.03	10.64				
					22.00	23.00	27.000	28.01
200.00	180.03	10.11	10.26	10.91				
					22.00	23.00	27.00	28.01
210.00	189.67	10.33	10.49	11.18				
					18.00	19.00	22.00	22.70
220.00	199.36	10.51	10.68	11.40				
					26.00	27.00	31.00	31.96
230.00	209.06	10.77	10.95	11.71				
					25.00	27.00	30.00	30.93
240.00	218.76	11.02	11.22	12.01				
					20.00	21.00	24.00	24.67
250.00	228.49	11.22	11.43	12.25				
					29.00	30.00	33.00	33.88
260.00	238.23	11.51	11.73	12.58				
					18.00	19.00	22.00	22.56
270.00	247.98	11.69	11.92	12.80				
					18.00	19.00	22.00	22.54
280.00	257.74	11.87	12.11	13.02				
					78.00	81.00	84.00	85.89
290.00	267.52	12.65	12.92	13.86				
					76.00	79.00	82.00	83.76
300.00	277.31	13.41	13.71	14.68				
					12.00	12.00	14.00	14.31
305.00	282.20	13.47	13.77	14.75				

APPENDIX F

DEPTH/TEMPERATURE RECORD FROM BOWSER WELL,

CLARION COUNTY, PENNSYLVANIA

DEPTH		TEMPERATURE		GEOTHERMAL GRADIENT		
Observed (m)	Topog. Corr. (m)	Observed (°C)	Climate Corr. (°C)	Observed (°C/km)	River & Climate Corr. (°C/km)	River, Climate, & Topog. Corr. (°C/km)
48.73	50.37	4.19	3.60	32.49	42.49	41.95
98.73	102.01	5.81	5.72	38.40	48.00	46.54
148.73	153.56	7.73	8.12	58.80	64.80	62.91
173.73	179.73	9.20	9.74	39.20	43.60	42.36
198.73	205.06	10.18	10.83	34.00	38.00	36.96
208.73	215.34	10.52	11.21	50.00	52.00	50.58
213.73	220.48	10.77	11.47	34.00	38.00	36.96
218.73	225.62	10.94	11.66	148.00	152.00	147.86
223.73	230.76	11.68	12.42	22.00	24.00	23.35
228.73	235.90	11.79	12.54	28.70	32.00	31.17
243.73	251.30	12.22	13.02	17.30	20.00	19.48
258.73	266.70	12.48	13.32	22.00	26.00	25.34
263.73	271.83	12.59	13.45	24.00	26.00	25.34
258.73	276.96	12.71	13.58	22.00	26.00	25.34
273.73	282.09	12.82	13.71	24.00	26.00	25.39
278.73	287.21	12.94	13.84	23.00	26.00	25.34
288.73	297.47	13.17	14.20	26.00	30.00	29.30
293.73	302.59	13.30	14.25	22.00	24.00	23.44
298.73	307.71	13.41	14.37	26.00	30.00	29.24
303.73	312.84	13.54	14.52	24.00	26.00	25.39
308.73	317.96	13.66	14.65	22.00	26.00	25.39
313.73	323.08	13.77	14.78	18.00	20.00	19.53
318.73	328.20	13.86	14.88	22.00	26.00	25.39
323.73	333.32	13.97	15.01	22.00	26.00	25.44

DEPTH		TEMPERATURE		GEOTHERMAL GRADIENT		
Observed (m)	Topog. Corr. (m)	Observed (°C)	Climate Corr. (°C)	Observed (°C/km)	River & Climate Corr. (°C/km)	River, Climate, & Topog. Corr. (°C/km)
328.73	338.43	14.08	15.14			
				27.45	29.40	28.74
333.83	343.65	14.22	15.29			
				16.33	20.40	19.92
338.73	348.67	14.30	15.39			
				14.00	16.00	15.66
343.73	353.78	14.37	15.47			
				28.00	32.00	31.31
348.73	358.89	14.51	15.63			
				30.00	34.00	33.20
353.73	364.01	14.66	15.80			
				28.00	31.00	30.33
363.73	374.23	14.94	16.11			
				27.00	30.00	29.35
373.73	384.45	15.21	16.41			
				28.67	32.00	31.33
388.73	399.77	15.64	16.89			
				30.00	34.00	33.29
403.73	415.09	16.09	17.40			
				26.00	29.30	28.76
418.73	430.39	16.48	17.84			
				27.50	31.00	30.39
438.73	450.79	17.03	18.46			
				28.00	31.30	30.74
453.73	466.08	17.45	18.93			

APPENDIX G

THERMAL CONDUCTIVITY OF CORE SAMPLES FROM WELLS IN WASHINGTON, NOBLE, AND MORGAN COUNTIES, OHIO

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	K(wet)	Porosity (%)
		Well 2386, Washington County, Ohio		
34.1	Ls	5.53	5.73	1.46
108.6	Ss	5.95	7.95	8.54
130.2	Ss	6.44	7.16	3.05
169.5	Sh	2.80	2.88	5.36
175.4	Sh	3.54	3.47	2.86
192.9	Sh	4.22	4.22	2.07
196.0	Ss	8.56	10.41	9.28
196.7	Sh	3.53	3.52	3.34
2-6.3	Ls	5.11	5.22	0.58
234.1	Sltst	4.14	4.01	3.19
250.6	Ls	7.18	7.69	1.04
		Well 2181, Washington County, Ohio		
57.1	Ss	6.64	9.39	8.27
58.6	Ls	4.13	4.98	2.83
64.4	Ss	7.00	8.51	4.15
72.3	Mdst	6.44	6.88	2.09
152.7	Ss	7.85	10.14	3.40
154.2	Sh	3.78	3.83	3.68
158.4	Sh	4.51	4.74	1.86
165.7	Sltst	3.82	4.10	2.48
165.8	Sltst	3.75	4.09	3.46
172.9	Ss	6.98	8.19	2.71
175.8	Sh	4.96	5.19	---
217.3	Coal	0.93	0.98	3.53
217.3	Coal	1.13	1.19	2.58
217.3	Coal	0.77	0.812	3.51
217.5	Mdst	4.82	4.93	2.78
227.0	Sh	3.48	3.53	---

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	K(wet)	Porosity (%)
		Well 2387, Noble County, Ohio		
106.2	Sltst	4.84	5.25	---
129.4	Sltst	5.93	6.29	1.74
		Well 2176, Noble County, Ohio		
53.6	Ls	7.11	7.36	1.94
59.7	Ls	5.65	5.73	0.60
89.3	Sltst	5.00	6.01	6.00
117.9	Ss	4.72	5.40	4.60
127.3	Mdst	3.53	3.42	5.11
139.3	Ss	7.81	10.29	10.65
140.1	Ss	8.23	10.47	9.36
152.7	Ss	7.81	9.85	11.36
163.1	Ss	4.68	5.52	4.15
164.9	Mdst	4.58	4.53	---
165.6	Sltst	5.15	5.54	2.61
171.7	Ss	8.05	10.20	8.68
178.3	Sh	3.62	3.52	4.82
184.4	Sltst	4.38	5.01	4.24
194.1	Sh	4.06	4.16	3.62
229.3	Sh	4.20	4.46	2.22
229.3	Sh	4.31	4.53	2.57
231.2	Ss	8.00	9.02	2.82
		Well 2177, Noble County, Ohio		
100.0	Sh	4.34	4.82	3.77
122.2	Ss	7.06	9.39	10.82
163.4	Ss	5.88	7.23	3.87
183.8	Sltst	5.96	6.28	2.88
219.7	Ss	9.53	11.70	20.24

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	K(wet)	Porosity (%)
		Well 2178, Morgan County, Ohio		
69.4	Sh	5.15	5.95	---
78.6	Sh	4.14	4.40	1.13
124.6	Sh	3.67	3.76	---
155.0	Ss	7.67	9.72	12.14
174.9	Ss	8.09	9.70	10.96
182.9	Mdst	4.30	4.32	3.97
200.2	Sltst	6.20	6.36	1.84
214.1	Sltst	4.77	4.83	3.31
217.9	Ss	7.04	8.11	2.82
242.0	Sh	4.60	4.68	2.51
267.9	Sltst	4.86	4.98	---
		Well 2180, Morgan County, Ohio		
70.7	Mdst	4.19	4.44	3.80
85.6	Sltst	4.42	4.74	5.15
93.6	Ls	5.54	5.50	2.33
104.1	Ss	8.30	9.24	2.72
168.2	Sltst	3.41	3.41	3.77
187.7	Sh	3.15	3.35	---
200.6	Sh	3.78	4.04	2.57
222.4	Sltst	6.02	6.08	4.42
		Well 2182, southeastern Ohio		
232.9	Sh	4.09	4.12	2.40
234.8	Sltst	4.33	4.38	2.42
244.8	Ss	9.25	11.05	10.76
247.2	Mdst	5.92	5.92	2.41
248.3	Sltst	6.80	6.97	2.01
251.2	Mdst	6.12	6.24	2.82

APPENDIX H

THERMAL CONDUCTIVITY OF CORE SAMPLES FROM BARBERTON WELL, SUMMIT COUNTY, OHIO

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	Thermal Conductivity K(wet) (mcal/cmsec°C)	Porosity (%)
113.9	Sh	1.38	---	---
117.4	Sh	3.00	4.43	1.36
118.3	Sh	3.22	3.91	1.09
121.1	Sh	2.25	2.93	1.74
123.5	Sh	2.46	2.94	1.41
126.9	Sh	2.63	---	---
129.6	Sh	2.35	---	---
132.7	Sh	2.83	3.14	1.99
135.7	Sh	2.00	---	---
138.8	Sh	1.37	---	---
142.1	Sh	1.25	---	---
147.6	Sh	1.64	3.40	1.26
782.6	Ls	5.64	5.64	2.03
786.9	Ls	5.45	5.55	21.45
791.8	Ls	6.12	5.90	.74
796.7	Ls	5.24	6.74	.69
801.5	Ls	3.50	5.00	.48
806.1	Ls	5.30	7.10	.78
813.7	Ls	3.84	3.91	5.18
816.2	Ls	4.89	4.73	1.91
820.2	Ls	4.56	4.66	1.66
825.9	Ls	5.46	5.87	.95
830.8	Ls	6.06	6.47	.69
835.7	Ls	5.67	6.02	2.17
840.3	Ls	6.23	6.63	1.62
846.4	Ls	5.33	5.46	1.11
850.3	Ls	5.90	6.15	1.33
855.2	Ls	5.81	6.21	1.42

APPENDIX I

THERMAL CONDUCTIVITY OF CORE SAMPLES

FROM OTHER WELLS IN OHIO

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	K(wet)[a]	Porosity (%)
		Wilson well, Fayette County, Ohio		
394.9	Ls	5.21	7.01	1.90
398.0	Ls	4.75	8.96	2.39
401.1	Ls	4.32	5.06	1.32
550.5	Dol	5.60	9.96	4.13
556.6	Dol	6.82	8.18	9.94
557.2	Dol	7.47	7.59	4.97
838.8	Sh	2.67	3.32	1.33
927.2	Ss	5.31	7.23	10.73
930.3	Ss	3.98	7.83	11.20
930.3	Ss	3.75	7.59	9.30
931.8	Ss	5.45	7.30	10.30
936.4	Ls	7.84	10.24	5.082
		Heston well, Morrow County, Ohio		
1217.6	Ls	8.45	9.16	5.48
1218.5	Ls	7.01	8.17	6.72
1220.0	Ls	8.53	9.72	8.08
1221.2	Ls	6.82	9.03	2.24
1223.1	Ls	6.82	9.03	2.24
1223.1	Ls	6.77	8.07	5.13
1224.6	Ls	7.21	8.92	6.10
1226.1	Ls	6.05	8.20	3.58
1227.6	Ls	8.24	9.42	3.29
1220.2	Ls	8.46	28.76	2.95
1231.0	Ls	7.16	7.22	5.02

Depth (m)	Lithology	Thermal Conductivity K(dry) (mcal/cmsec°C)	Thermal Conductivity K(wet)[a] (mcal/cmsec°C)	Porosity (%)
	U. S. Gypsum well, Ottawa County, Ohio			
37.9	Dol	12.58	13.49	4.84
46.1	Dol	8.84	11.92	5.62
51.5	Dol	9.13	10.55	9.06
61.1	Dol	12.27	13.17	5.88
68.6	Dol	12.02	12.80	3.56
76.3	Dol	10.04	12.26	10.33
82.6	Dol	10.50	12.832	7.86
99.1	Dol	10.37	12.90	9.74
107.1	Dol	9.17	9.70	9.89
113.5	Sh	2.55	---	---
114.1	Sh	2.60	---	---
129.3	Dol	10.77	12.27	5.64
137.6	Dol	10.68	11.60	3.58
143.0	Sh	2.56	---	1.33

[a]Several green shales disaggregated during the vacuum-saturation process. Another was destroyed during pressurized-conductivity measurement. Paraffin bindings did not keep these shales from being destroyed.

APPENDIX J

THERMAL CONDUCTIVITY OF CORE SAMPLES FROM THE WELLS IN CLARION AND VENANGO COUNTIES, PENNSYLVANIA

Depth (m)	Lithology	K(dry)	K(wet) Vacuum satur.	K(wet) 16-day atm. satur.	Porosity[a] Vacuum satur. (%)	Porosity[a] 16-day atm. satur. (%)	Sonic Velocity[b] (m/sec)
		Thermal Conductivity (mcal/cmsec°C)					
			Bankson well, Venango County, Pennsylvania				
241.4	Ss	7.36	8.78		2.75		
244.4	Ss	9.38	10.49		5.98		
247.3	Ss	9.37	10.44		13.95		
250.0	Ss	6.48	7.24		13.95		
351.2	Sh	3.46	---		---		
251.9	Sh	3.42	---		---		
286.7	Ss	8.342	9.28		8.67		
290.3	Cgl	9.50	11.27		10.65		
			Marsh well, Venango County, Pennsylvania				
258.9	Ss	8.77	10.24		7.41		
287.1	Ss	8.44	9.39	9.55	2.78	3.42	4063.9
293.8	Ss	6.94	8.35		15.32		4417.5
298.1	Ss	9.24	10.40		7.93		4354.4
299.3	Ss	7.99	10.07		9.02		4175.5
301.1	Ss	5.78	8.49		6.94		4293.1
			Hazlett well, Venango County, Pennsylvania				
250.5	Ss	8.14	9.60		11.58		4515.6
251.8	Ss	8.45	9.58		10.40		3672.2
253.3	Ss	9.53	10.61		9.36		3650.3
255.1	Ss	6.25	7.43		14.13		3705.8
256.5	Ss	8.14	8.67	8.86	3.68	4.52	3142.2
			Reed well, Venango County, Pennsylvania				
226.3	Cgl	11.58	11.79		4.39		4262.9
248.7	Sh	3.89	4.67		4.28		3907.8
263.9	Sh	4.30	5.25		4.18		4354.4
264.7	Sh	4.94	3.71		2.86		3907.8
267.9	Ss	6.25	7.35		4.58		4532.4

Depth (m)	Lithology	K(dry)	K(wet) Vacuum satur.	K(wet) 16-day atm. satur.	Porosity[a] Vacuum satur. (%)	Porosity[a] 16-day atm. satur. (%)	Sonic Velocity[b] (m/sec)
		Thermal Conductivity (mcal/cmsec°C)					
		Bowser well, Clarion County, Pennsylvania					
219.5	Sh	4.67	4.63	---	1.86	1.94	4063.9
222.8	Cgl	11.14	12.99		6.00		4629.9
224.1	Sgl	10.32	11.29		6.40		4493.4
269.0	Ss	7.92	10.38		7.83		3825.8
271.0	Ss2	7.68	7.77	7.77	0.71	2.41	4313.2
272.0	Ss	5.91	6.84		4.99		4594.9
280.9	Ss	6.60	6.65	---	2.26	---	4063.9
282.1	Sltst	7.57	8.03	---	1.27	1.27	4701.2
283.1	Sltst	5.36	---	---	4.44	---	4618.3
285.1	Sh	3.85	3.83	3.37	3.20	4.69	4313.2
286.2	Sh	3.48	3.52	3.48	1.99	3.92	4375.1
287.4	Ss	7.32	9.27		4.19		4417.5
288.8	Ss	6.59	7.58		2.66		4406.8
290.0	Ss	6.85	8.23		5.53		4375.1
291.4	Ss	5.51	6.40		2.75		4537.9
293.2	Ss	5.32	5.76	5.88	1.77	2.97	4549.1
294.4	Ss	6.37	7.00	7.20	2.09	3.34	4526.6
296.3	Ss	6.58	7.86		4.68		4471.4
308.3	Sltst	8.25	8.59	8.32	0.89	2.31	4375.1
310.0	Cgl	7.85	8.91	---	1.20	1.20	5080.1
323.8	Sh	5.43	5.63	5.71	2.00	3.67	4629.9
326.5	Ss	8.55	10.08	10.06	1.99	3.74	465.3
334.2	Sltst	7.42	8.52		3.30		4665.3
340.2	Sltst	8.21	8.27	8.37	1.70	3.39	4493.4
346.3	Cgl	9.98	11.94		6.58		4812.5
349.3	Sh	4.72	4.82	4.84	0.67	2.85	4460.4
586.2	Sh	3.33	3.31	3.31	3.72	5.42	4174.8
589.2	Sltst	7.48	7.91	7.81	1.69	2.30	4495.5

Depth (m)	Lithology	Thermal Conductivity K(dry)	K(wet) Vacuum satur.	K(wet) 16-day atm. satur.	Porosity[a] Vacuum satur. (%)	16-day atm. satur. (%)	Sonic Velocity[b] (m/sec)
			(mcal/cmsec°C)				
			Bowser well, Clarion County, Pennsylvania (continued)				
			Wile well, Clarion County, Pennsylvania				
257.6	Sltst	8.28	8.72	8.99	0.92	2.24	4293.1
260.9	Ss	8.91	11.17		8.08		4010.6
279.2	Sh	3.53	3.46	3.47	1.15	3.34	4449.8
283.8	Ss	7.56	8.87		3.15		4354.4
294.6	Cgl	10.02	11.40		4.30		5277.9
295.4	Ss	9.63	10.17		2.57		2902.9
291.1	Cgl	7.62	8.35	---	1.22	1.22	2930.7
311.5	Cgl	12.69	12.81		3.24		4827.1
312.7	Cgl	10.78	11.84	11.71	2.10	3.12	4876.8
315.0	Ss	9.92	11.63		5.83		4618.3
334.7	Ss	7.79	8.53	8.56	2.76	3.53	4218.7
337.1	Sh	4.73	4.75	---	5.55	---	4800.0

[a]The cut-off porosity with the vacuum-saturation method is 2.5%. Fourteen of the 18 samples having porosities of less than 2.5% showed a mean increase in porosity of 2.87% when saturated under atmospheric pressure for 16 days.

[b]The mean of the 1-ft and 3-ft spacing values on the sonic-velocity logs was used.

APPENDIX K

RADIOGENIC ELEMENTS AND HEAT PRODUCTION IN CORE AND OUTCROP SAMPLES FROM OHIO, PENNSYLVANIA, AND NEW JERSEY

Map No.	Location County	Location Site	Lithology	Analyst[a]	Ra (ppm)	U (ppm)	Th (ppm)	K (%)	K_2O (%)	Heat Generation (μcal/g/yr)
	OHIO									
1	Summit	Barberton	Shale	1		2.10	11.4	4.98		3.83
			Shale	1		1.00	< 0.9	8.19		< 0.93
			Shale	1		2.58	13.4	5.07		4.58
		Shale	1		2.80	9.8	3.28		4.01	
			Shale	1		1.48	8.5	7.48		2.80
2	Fayette		Amphibolite	1		1.60	1.0		1.46	1.76
3	Morrow	Granite		1		2.11	15.6		5.42	6.12
4	Morrow		Pegmatite	1		3.54	1.06		2.03	3.34
	PENNSYLVANIA									
5	Clarion	Bowser	Shale	1		4.41	16.3	2.23		7.10
			Shale	1		3.75	16.8	2.62		6.81
			Shale	1		2.97	12.3	2.37		5.27
			Shale	1		3.62	14.5	2.79		6.29
			Shale	1		4.01	17.3	3.13		7.23
			Silt			4.52	20.3	2.04		7.91
6	Venango	Bankson	Shale	1		3.67	16.3	2.92		6.73
7		Reed	Shale	1		3.82	14.9	2.82		6.53
			Shale	1		4.10	15.4	2.87		6.85
8	Clarion	Wile	Shale	1		3.73	15.5	2.48		6.49
						3.41	14.5	3.05		6.21
9	Erie		Quartz-mica schist	1		3.55	11.12		8.90	7.22
10	Berks	Fleetwood	Igneous	2	0.97		7.54	3.58		3.18
			Igneous	2	1.63		7.04	1.91		3.11
11		Birdsboro	Igneous	1		1.83	7.63		5.45	4.33
12		Birdsboro	Igneous	2	0.95		1.27	4.57		2.18
			Igneous	2	2.87		2.17	1.47		1.93
			Igneous	2	1.06		0.85	0.47		1.07
13		Boyertown	Igneous	2	0.35		0.32	1.82		0.81
14		Manatowny	Igneous	2	1.78		1.36	4.21		2.71
			Igneous	2	1.09		7.31	3.87		3.30
			Igneous	2	5.38		13.55	0.12		6.67
15	North-ampton	Easton	Igneous	1		4.26	12.2		6.43	7.29
16		Easton	Igneous	1		34.67	15.1		5.84	29.9
17		Easton	Igneous	2	0.93		0.06	0.98		1.08
			Igneous	2	4.01		9.32	2.68		5.51
			Igneous	2	7.92		24.86	6.01		12.38
			Igneous	2	4.28		12.43	4.60		6.85

Map No.	Location County	Location Site	Lithology	Analyst[a]	Ra (ppm)	U (ppm)	Th (ppm)	K (%)	K_2O (%)	Heat Generation (μcal/g/yr)
18	Bucks	Riegels-ville	Igneous	1		0.86	< 1.0		5.84	< 2.38
19		Riegels-ville	Igneous	2	0.67		0.36	3.23		1.43
			Igneous	2	0.30		0.34	1.59		0.72
			Igneous	2	0.22		0.27	3.40		1.13
	New Jersey									
20	Sussex	Franklin	Igneous	2	0.09		0.07	0.7		0.27
				2	2.17		4.54	2.09		3.06
				2	5.51		15.88	3.81		8.23
				2	3.02		4.28	6.34		4.77
				2	1.52		0.97		2.26	1.91
				2	0.89		0.46		4.71	2.01
				2	0.42		0.19		4.50	1.56
21	Morris	Dover	Igneous	2	9.22		28.93	4.44		13.72
22		Mendham	Igneous	2	0.10		0.15	1.51		0.51
23		Boonton	Igneous	2	3.15		14.92	3.86		6.33
			Igneous	2	3.65		26.15	3.25		8.77
			Igneous	2	1.00		9.07	2.38		3.19
			Igneous	2	0.13		3.76	0.84		1.07
			Igneous	2	0.94		1.49	4.91		2.31
		Blue	Igneous	2	0.61		0.45		4.70	1.80
			Igneous	2	3.00		6.89		3.69	4.56
			Igneous	2	1.09		11.66		3.78	4.15
			Igneous	2	0.87		4.24		1.83	1.98

[a]1 = Los Alamos National Laboratory
2 = U. S. Geological Survey

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