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GEOTHERMAL RESOURCES OF THE GREEN RIVER BASIN, WYOMING, INCLUDING THERMAL DATA FOR THE WYOMING PORTION OF THE THRUST BELT

MASTER

by

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CONVERSION FACTORS

Length
1 meter = 3.281 feet (ft) 1 foot = 0.3048 meter (m)
1 kilometer = 0.6214 mile (mi) 1 mile = 1.6093 kilometers (km)

Mass flow
1 gallon per minute = 3.785 liters per minute (lpm)
1 liter per minute = 0.2642 gallon per minute (gpm)

Pressure
1 pound per square inch = 0.07031 kilogram per square centimeter (kg/cm^2)
= 0.06805 atmosphere (atm.)

1 kilogram per square centimeter = 14.22 pounds per square inch (psi)
= 0.9678 atm.

Thermal gradient
1 degree Fahrenheit per thousand feet =
= 1.823 degrees Celsius per kilometer (°C/km)

1 degree Celsius per kilometer = 0.5486° Fahrenheit per thousand feet (°F/1,000 ft)

Thermal conductivity
1 millicalorie per centimeter per second per degree Celsius (10^{-3} cal/cm sec°C) =
= 241.8 British thermal units per foot per hour per degree Fahrenheit (Btu/ft hr°F)
= 0.418 watt per meter per degree Kelvin (W/m°K)

Heat flow
1 microcalorie per square centimeter per second ($10^{-6} cal/cm^2 sec$)=
= 1 heat flow unit (HFU)
= 0.013228 British thermal unit per square foot per hour ($Btu/ft^2 hr$)
= 41.8 milliwatts per square meter ($10^{-3} W/m^2$ or mW/m^2)

Temperature
1 degree Fahrenheit = 0.56 degree Celsius (°C)
1°Celsius = 1.8°Fahrenheit (°F)
°F = 1.8°C + 32 °C = (°F − 32)/1.8

INTRODUCTION

This is the fifth in a series of reports describing the geothermal resources of Wyoming basins (see Figure 1). Each basin report contains a discussion of hydrology as it relates to the movement of heated water, a description and interpretation of the thermal regime, and four maps: a generalized geological map (Plate I), a thermal gradient contour map (Plate II), and a structure contour map and ground-water temperature map (Plates III and IV) for a key formation.

The format of the reports varies, as does the detail of interpretation. This is because the type of geothermal system, the quantity and reliability of thermal data, and the amount of available geologic information vary substantially between basins and between areas within basins.

This introduction contains (1) a general discussion of how geothermal resources occur, (2) a discussion of the temperatures, distribution, and possible applications of geothermal resources in Wyoming and a general description of the State's thermal setting, and (3) a discussion of the methods we used in assessing the geothermal resources. This introduction is followed by a description of the geothermal resources of the Green River Basin of southwestern Wyoming (Figure 1). Also included in this report is a discussion of thermal data available for the Wyoming portion of the Thrust Belt.

Funding for this project was provided by the U. S. Department of Energy to the Wyoming Geothermal Resource Assessment Group under Cooperative Agreement DE-F107-79ID12026 with the University of Wyoming Department of Geology and Geophysics. Compilations of oil-well bottom-hole temperatures can be examined at the office of the Geological Survey of Wyoming in Laramie.

The text uses primarily British units. As outlined in footnotes on the following page, heat flow and thermal conductivity data are generally presented in metric units. A table of conversion factors faces this page.

GEOTHERMAL SYSTEMS AND RESOURCES

By a geothermal resource, we mean heated water close enough to the earth's surface to be useful. Further definition or classification of geothermal resources is not attempted because such definition and classification are based upon changing technological and economic parameters. Rather, we have used geothermal data to describe the thermal regime in each basin. In these descriptions, thermal anomalies have been identified, but we do not try to determine to what degree a given anomaly is a geothermal resource.

Geothermal systems vary from the very-high-temperature, steam-dominated type to warm water being pumped from a drill hole. The type of system depends on how the heat flowing out of the earth is modified by the complex of geologic and hydrologic conditions. Most places in the earth warm up about 14°F for every 1,000 feet of depth (Anderson and Lund, 1979). An attractive geothermal resource may exist where the *thermal gradient** is significantly higher than 14°F/1,000 ft.

Heat flow[†] studies in Wyoming basins (Decker et al., 1980; Heasler et al., 1982) have reported heat flows of about 33 to 80 mW/m^2 (Figure 2). The only exception is in the northwest corner of Wyoming, in Yellowstone National Park, where high-temperature water exists at shallow depth due to very high heat flows of over 105 mW/m^2 (Morgan et al., 1977). By itself, a background heat flow of 33 to 80 mW/m2 would not suggest a significant geothermal resource.

In Wyoming basins, the primary mechanism for the translation of moderate heat flow into above-normal temperature gradients is ground-water flow through geologic structures. Figures 3 and 4 illustrate systems based on two mechanisms. The temperatures listed in the lower portions of the diagrams reflect normal temperature increase with depth. Since the rocks through which the water flows are folded or faulted upwards, water at those same high temperatures rises to much shallower depth at the top of the fold or above the fault. If water proceeds through such a system without major temperature dissipation, a highly elevated thermal gradient is developed. In other words, a fold or fault system provides the "plumbing" to bring deep-heated water to a shallow depth. Any natural or man-made zone through which water can rise, such as an extensive fracture system or deep drill hole, serves the same purpose.

Because warm water is less dense than cold water, deep-heated water tends to rise, a process known as *free convection*. Free convection is relatively weak, and is significant only under conditions of extreme temperature difference or relatively unrestricted flow. Of more importance in Wyoming basins is *forced convection*, in which water moves in a confined aquifer from a high outcrop recharge area at a basin margin to a lower discharge area. Water is forced over folds or up faults, fractures, or wells by the artesian pressure developed within the confined aquifer.

TEMPERATURE, DISTRIBUTION, AND APPLICATION OF RESOURCES

White and Williams (1975) of the U.S. Geological Survey divide geothermal systems into three groups: (1) high-temperature systems, greater than 302°F (150°C); (2) intermediate-temperature systems, 194-302°F (90-150°C); and (3) low-temperature systems, less than 194°F (90°C). While Yellowstone National Park is a high-temperature system, the sedimentary basins of Wyoming fall mostly into the low-temperature and intermediate-temperature groups.

Due to the great depth of many Wyoming basins, ground water at elevated temperature exists beneath vast areas of the State (Heasler et al., 1983). Where a system like those described above (Figures 3 and 4) creates a local area of high gradient, it may be feasible to develop the shallow geothermal resource directly. Outside these scattered areas of high thermal gradient, it is likely that geothermal development will depend upon much deeper drilling, such as that provided by oil and gas exploration.

The geothermal resources in the basins are suited to relatively small-scale, direct-use projects located close by. Energy uses include a wide range of space heating, agricultural, aquacultural, and low-temperature processing applications. (See Anderson and Lund, 1979, for a discussion of direct-use geothermal applications.) Below 100°F, uses are limited to such applications as soil and swimming pool warming, deicing, and fish farming. Through the use of ground-water heat pumps, energy can be extracted from natural waters as cool as 40°F (Gass and Lehr, 1977).

The presently documented thermal springs in the State's basin areas (Breckenridge and Hinckley, 1978; Heasler et al., 1983) release 3.5 trillion British thermal units (Btu's) of heat per year in cooling to ambient temperature. Like the oil springs and seeps that led developers to Wyoming's vast petroleum fields, thermal springs are simply the surface manifestation of the much larger, unseen geothermal resource. For example, Hinckley (1984) has calculated that approximately 24 trillion Btu's of heat would be released per year if all the thermal water produced as a by-product in Wyoming oil fields were cooled to ambient temperature.

METHODS OF ASSESSMENT

The principal purpose of these reports is the documentation and prediction of temperatures in the subsurface. In sections above, we have established a qualitative framework in which higher than-expected thermal gradients occur where deep-heated water is brought to shallow depth. For quantification of temperatures and gradients, a variety of techniques was used.

Sources of subsurface temperature data are (1) thermal logs of wells, (2) oil and gas well bottom-hole temperatures, and (3) surface temperatures of springs and flowing wells.

(1) The most reliable data on subsurface temperatures result from direct measurement under thermally stable conditions. Using thermistor probes precise to ±0.005°C (Decker, 1973), the Wyoming Geothermal Resource Assessment Group has obtained temperature measurements in over 380 holes across Wyoming (Heasler et al., 1983). Temperatures were measured at intervals of 32 feet or less in holes up to 6,500 feet deep. Many of the logged holes had had years to equilibrate, so temperatures of sampled intervals approached true rock temperatures. With these temperature-depth data, least squares statistical analysis was used to determine gradients at depths below the effects of long-term and short-term surface temperature fluctuations. These values are accepted as the most reliable thermal gradients, to which other temperature and gradient information is compared.

Where rock samples from a logged hole were available for testing, laboratory determinations of thermal conductivity were made.* This information was coupled with the measured gradients to calculate the local heat flow. Where stratigraphic relationships or multiple holes with similar heat flow allowed us to rule out hydrologic disturbance, we could determine a purely conductive heat flow. This heat flow was, in turn, applied to all sequences of strata for which thermal conductivities could be estimated to obtain gradient values in the absence of holes that could be logged. Particularly in the deeper portions of Wyoming sedimentary basins, this technique was used as a semiquantitative check on less reliable data.

(2) The most abundant subsurface temperature data are the bottom-hole temperatures (BHT's) reported with logs from oil and gas wells. We used BHT's, because of their abundance, to assess geothermal resources in this study. About 14,000 oil and gas well bottom-hole temperatures were collected for the study areas (Table 1). Thermal gradients were calculated from BHT information using the formula

$$\text{Gradient} = \frac{(\text{BHT}) - (\text{MAAT})}{\text{Depth}}$$

where MAAT is the mean annual air temperature.

Mean annual air temperatures for Wyoming basins are between 40 and 48°F (Lowers, 1960). These values, assumed to approximate mean annual ground temperatures, were used in calculating gradients over fairly large areas under the assumption that variations due to elevation and micro-climatic effects are negligible compared with BHT inaccuracies. The files of the Geological Survey of Wyoming were the principal source of BHT data. (A slightly larger data base is available at the Wyoming Oil and Gas Conservation Commission Office in Casper, Wyoming.)

The use of oil field bottom-hole temperatures in geothermal gradient studies is the subject of some controversy among geothermal researchers. There are problems associated with the thermal effects of drilling and with operator inattention in measuring and reporting BHT's which cast doubt on the accuracy of individual temperature reports. It has been suggested, for example, that in some areas BHT's may correlate with the ambient temperature during drilling and, specifically, that many of the thermometers used in the summer are reading their maximum temperature before they are lowered down the drill hole. Similarly, drilling fluids may transfer heat to the bottom of a drill hole, warming or cooling the rock depending on the drilling fluid temperature and the depth of the hole. The magnitude of a thermal disturbance depends on the temperature difference between the drilling fluid and the rock, the time between the end of fluid circulation and temperature measurement, the type of drilling fluid used, the length of time of fluid circulation, and the degree to which drilling fluids have penetrated the strata.

Theoretical analysis of the deviation of a reported BHT from true formation temperature may be possible on a detailed, well-by-well basis, but is an overwhelming task basin-wide. Therefore, for these studies it was assumed that such factors as time of year, operator error, time since circulation, and drilling fluid characteristics are random disturbances which "average out" because of the large number of BHT's. However, circulation of drilling fluids was considered a systematic effect which depresses temperature more with increasing depth. With sufficient data at all depths, anomalous gradients may be identified despite the fact that they are depressed in value.

The following procedure was used to assess the geothermal resources of a basin from oil and gas well bottom-hole temperatures: First, all available BHT's were compiled and gradients calculated. The gradients were then plotted on a map and contoured for the basin. Thermally logged holes define fixed points in the contouring.

As explained above, temperature gradient values may be lower in deeper holes because of drilling effects. This was taken into account in identifying gradient anomalies by grouping all temperature and gradient data for a basin into 500-foot depth intervals and then calculating the mean value and the 50th, 66th, 80th, and 90th percentile for each interval. These calculations are tabulated in each basin report. The 80th percentile - the value below which 80 percent of the data fall - was chosen arbitrarily as a lower cutoff for the identification of geothermal anomalies.

We calculated a single *background thermal gradient* for each basin (Table 1), based on thermal logs, thermal conductivities of the basin's sedimentary sequence, and heat flow. Although BHT gradients are assumed to be depressed with depth, we do not feel that we can define as anomalous those gradients which are lower than the background thermal gradient. Therefore, thermal gradient values are identified as anomalous only if they fall above the 80th percentile for their depth range *and* above the background thermal gradient for the basin in which they occur. Thus, a gradient of 16°F/1,000 ft, which is considered anomalous at 8,000 feet because it is above both the background thermal gradient and the 80th percentile for the 7,500-8,000-foot depth range, is not considered anomalous at 3,000 feet if it falls below the 80th percentile for the 2,500-3,000-foot depth range.

In these basin studies, a lower BHT cut-off of 100°F was used. In our experience, a temperature gradient based on a temperature lower than 100°F is usually not reliable. Also, sub-100°F water will be of little economic value unless found at very shallow depth.

The final criterion for identification of an area of anomalous gradient is that a group of anomalous points (determined as outlined above) occur in the same area.

Particularly above and within zones of ground-water movement, gradients defined from bottom-hole temperatures may not completely reflect the character of a geothermal resource. For example, Figure 5 shows the effect of ground-water movement homogenizing temperatures in the lower portion of a hole at the top of the Thermopolis Anticline. A gradient calculated from a single BHT at 800 feet would miss the very high gradients and temperatures in the top part of the hole. Conversely, a gradient calculated from a BHT at 400 feet would give a seriously erroneous temperature at 600 feet. These effects illustrate the importance of thermal logging in areas of suspected hydrologic disturbance*. As a general check on the downward projection of thermal gradients, we know from heat flow and rock thermal conductivity considerations that gradients below levels of hydrologic disturbance are similar throughout Wyoming.

An additional constraint on the use of gradient data to evaluate geothermal resources is that ground water must be present to transport the heat. Therefore, we have identified for each basin a productive, basin-wide aquifer which is deep enough to contain water at useful temperatures and for which thermal and hydrologic data are available. A map of temperatures within that aquifer, on which BHT's of that formation are plotted and contoured, is included in each basin report. As with the temperature gradient maps, verification is provided by the much sparser thermal logging data. No attempt was made to correct BHT's for drilling effects, so a certain degree of underestimation of temperatures may be expected in the deeper zones, as described above. Although the deviation of BHT's from true formation temperatures is not known, a tempering effect is that a drill hole in an aquifer with active circulation should equilibrate to undisturbed temperatures relatively quickly.

(3) The third source of subsurface temperature data is measurements in springs and flowing wells. The amount that these waters cool before they reach the surface is generally unknown; therefore, they provide only a minimum temperature check on BHT data. There is also commonly some uncertainty about the depth and source of flow. One can assume that all flow is from the bottom of a flowing well to obtain a minimum

gradient. The most useful subsurface temperature data from springs and wells come from those whose source aquifer can be determined.

The most important aspect of any geothermal resource is the temperature and flow that can be delivered to the surface. In this sense, flowing wells and springs give excellent data, leaving no need for prediction. Selected locations where thermal water (greater than 70°F) discharges at the surface are indicated on the thermal gradient maps.

SUMMARY

The authors have investigated the geothermal resources of several Wyoming sedimentary basins. Oil-well bottom-hole temperatures, thermal logs of wells, and heat flow data have been interpreted within a framework of geologic and hydrologic constraints. Basic thermal data, which includes the background thermal gradient and the highest recorded temperature and corresponding depth for each basin, is tabulated in Table 1.

These investigations of the geothermal resources of Wyoming sedimentary basins have resulted in two main conclusions.

(1) Large areas in Wyoming are underlain by water at temperatures greater than 120°F (Figure 6). Although much of this water is too deep to be economically tapped solely for geothermal use, oil and gas wells presently provide access to this significant geothermal resource.

(2) Isolated areas with high temperature gradients exist within each basin. These areas -- many revealed by hot springs -- represent geothermal systems which might presently be developed economically.

GEOTHERMAL RESOURCES OF THE GREEN RIVER BASIN, WYOMING, INCLUDING THERMAL DATA FOR THE WYOMING PORTION OF THE THRUST BELT

Study Area

The Green River Basin is located in southwestern Wyoming (see Figure 1), and includes all of Sublette County and parts of Uinta, Lincoln, and Sweetwater Counties. It is approximately 180 miles long and 90 miles in width near the southern end. Major uplifts border the basin on all sides reaching elevations of over 13,000 feet in the Wind River Range. The basin floor ranges in elevation from 6000-7500 feet.

The climate in the area varies with altitude. Most of the basin receives less than eight inches of precipitation per year while the surrounding mountains often receive greater than 50 inches per year (Ahern et al., 1981). The mean annual surface air temperature for the Green River Basin is approximately 42°F (Lowers, 1960).

Stratigraphy

The sedimentary rocks in the Green River Basin range in age from Cambrian to Recent and unconformably overlie the Precambrian igneous-metamorphic basement. Figure 7 is a stratigraphic column indicating the general lithologies and thicknesses for the formations present in the basin. The greatest total sedimentary thickness (about 30,000 feet) occurs in the deep syncline which parallels the Wind River Mountains (Krueger, 1968). Surface outcrops in the basin are primarily Tertiary and Quarternary in age (see Plate I).

The Paleozoic rocks of the Green River Basin consist mainly of marine shelf deposits with maximum aggregate thickness of 4500 feet. The western edge of the basin bordering the Thrust Belt marks the eastern edge of the Rocky Mountain geosyncline where much thicker sections of Paleozoic and early Mesozoic rocks were deposited (Ralston et al., 1981). These rocks generally consist of calcareous crystalline limestones and dolomites which grade upward into interbedded mudstones, siltstones and shales.

The Mesozoic stratigraphic section is essentially composed of clastic material deposited in marine shelf and continental environments (Ahern, et al., 1981). The Triassic and Jurassic rocks are approximately 3000 feet thick while those of Cretaceous age have an aggregate thickness of up to 15,000 feet. The Mesaverde Group, a thick sequence of sandstones and shales with interbedded coals and conglomerates, is much thicker and more distinctive in the eastern portion of the basin, where it is divided into four members. It thins significantly to the west and is absent (due to nondeposition or erosion) on the Moxa Arch (Hale, 1955). The Lewis Shale and Lance Formation are also truncated in the western portion of the basin.

The lower Paleocene Fort Union Formation is similar to the underlying shales, sandstones and siltstones of the Mesaverde Group except that it contains more coal sequences. It is equivalent to the Hoback Formation in the northwest part of the basin which reaches a thickness of 16,000 feet (Dorr, et al., 1977).

The late Paleocene and Eocene deposits of the Green River Basin are composed of a complex intertongueing of fluvial and lacustrine sediments of the Wasatch, Green River and Bridger Formations. The aggregate thickness of the sediments is more than 12,000 feet in the south central basin but averages about 6000 feet over most of the area (Ahern et al., 1981).

Sediments of Miocene and Pliocene age are primarily conglomerates, claystones and sandstones with a maximum thickness of 4000 feet in the southeast portion of the basin (Ahern et al., 1981). Quaternary sediments consist of unconsolidated silt, sand, clay and gravel usually less than 100 feet in thickness.

Structure

The Green River Basin is a north-south elongated intermontane basin formed during the Laramide Orogeny. According to Berg (1971) tectonic activity has resulted in approximately 35,000 feet of structural relief in the syncline parallel to the Wind River Mountains (see Figure 8) where the top of the Precambrian is believed to be about 27,000 feet below sea level. In general, the basin is structurally simple, with a few major north to northeast trending folds occurring beneath the unconformable Eocene strata (Blackstone, 1955).

Figure 8 shows the major tectonic features surrounding and within the Green River Basin. To the north and northeast are the Gros Ventre and Wind River Mountains, respectively. The Gros Ventre Range has a small granitic core area flanked by Mesozoic and Paleozoic sediments which apparently have been thrust southwest (Krueger, 1968). The southwest flank of the northwest-southeast trending Wind River Mountains is overlapped by Eocene sediments which cover the structural details of the area. However, several small outcrops of steeply dipping Paleozoic rocks as well as seismic data indicate a major thrust fault at the base of the southwest flank of these mountains (Berg, 1971). According to Berg (1971) a Precambrian wedge of the Wind River Mountains has been thrust over the deep basin syncline resulting in a wedge underlain by Paleozoic sediments and overlain by Eocene rocks.

Further to the south the basin rises gradually to the Rock Springs uplift, a north-south trending asymmetric anticline which bounds the Green River Basin on the east. The core of the uplift is eroded into the Cretaceous Baxter Shale. A series of east-west trending faults occur along the stucture. The southern margin of the Green River Basin is the Uinta Mountain uplift which has been thrust northward into the basin

(Krueger, 1968). The northern flank of the Uintas has been partially covered by the Eocene lacustrine Green River Formation, the Bishop Conglomerate, and the Browns Park Formation.

The north-south trending Thrust Belt forms the western boundary of the Green River Basin (see Figure 8 and Plate I). The Thrust Belt consists of a very thick series of Paleozoic and Mesozoic miogeosynclinal sediments which have been thrust eastward onto a much thinner shelf sequence (Krueger, 1968). The Darby Thrust is the easternmost fault of the Wyoming Thrust Belt, forming the western boundary of the Green River Basin.

In the northwestern portion of the area is a small sub-basin known as the Hoback Basin (see Figure 8). Although the Hoback Basin is physiographically a continuation of the Green River Basin, the two basins are separated by a continuous topographic divide called The Rim. Surface drainage of the former is to the north. The Hoback Basin is overridden on the southwest and northeast by the Thrust Belt and Gros Ventre Range respectively (Dorr et al., 1977). The Hoback Basin contains at least 15,000 feet and possibly as much as 30,000 feet of lower Tertiary clastic sediments shed from the adjacent uplift (Ahern et al., 1981).

An east-west profile through the central part of the Green River Basin has the configuration of a broad, gentle syncline with the east flank rising at a very low angle to the Rock Springs uplift while the west flank is cut abruptly by the Thrust Belt. The Moxa Arch is a north-south trending feature which extends from the Bridger Lake area on the Wyoming-Utah border 120 miles north to the LaBarge platform where it swings to the northwest under the Darby-Prospect Fault (Wach, 1977). Although the arch is a very gentle anticline with a maximum relief of 2000 feet (Krueger, 1968), its geometry is slightly asymmetric, with the steep side to the east.

The east flank is reported to have high angle reverse faults displacing Paleozoic and Mesozoic rocks with Tertiary strata left undeformed. Numerous closures have been seismically located along the arch, giving rise to a number of oil and gas fields including Church Buttes, Opal, Moxa, and Emmigrant Springs.

A general structure contour map of the Green River Basin indicates the elevation of the top of the Dakota Sandstone (Plate II). Because most of the tectonic activity in the basin occurred in late Mesozoic and early Cenozoic time the structural configuration of sediments deposited prior to that activity is roughly similar. The Dakota Sandstone was chosen as a datum for contouring because it is known to be a regional aquifer and a large data base exists for it compared to other stratigraphic units.

Hydrology

Very few data are available for pre-Tertiary aquifers in the Green River Basin. Most of the material for the following discussion is taken from Ahern et al., 1981, the only comprehensive report attempting to deal with basinwide hydrology.

Due to the lack of available data, the water-bearing properties of the pre-Tertiary formations have in some cases been inferred from lithologic properties in outcrop and from hydrologic data obtained from other Wyoming basins (Ahern et al., 1981). However, water production and transmissivities in the central portion of the basin may be less than reported due to a possible reduction in permeabiltiy of 20-60% with the increase of overburden pressure (Fatt and Davis, 1952; Fatt, 1953; Wyble, 1958). A further restriction on pre-Tertiary formation groundwater in the Green River Basin is that thrusting along the margins of the basin severely inhibits recharge of these aquifers due to extensive fault displacement.

The stratigraphic column in Figure 7 includes the general water bearing properties for each formation. Ahern et al. (1981) have assigned eight division to the water-bearing rocks in the Green River Basin-Thrust Belt area:

(1) The Precambrian aquifer is highly fractured and weathered in outcrop near the Gros Ventre and Wind River Mountains producing zones of high permeability. A few wells and springs produce water from the aquifer along the flank of the Wind River Mountains although no flow data are available.

(2) The Flathead aquifer (composed of the Flathead Sandstone), is considered to be a good potential source of water because it is known to contain lenses of permeable sandstone, has a conglomeratic base, and good secondary permeability, (Lines and Glass, 1975). However, except on the LaBarge Platform it is buried too deeply to be within economic reach.

(3) The Paleozoic aquifer includes the Bighorn Dolomite, Darby Formation, Madison Limestone, Tensleep Sandstone and Phosphoria Formation. Because these formations are primarily carbonates the greatest permeability exists where solution openings and fractures occur. Although few data are available for the Madison Limestone in the Green River Basin due to lack of outcrop and great depth of burial, this aquifer exhibits excellent porosity and great yield throughout Wyoming.

(4) The Nugget aquifer includes the Thaynes Limestone, Nugget Sandstone, and Twin Creek Limestone. This aquifer yields 20-900 gpm in springs just west of the LaBarge Platform. However, there is a notable decrease in measured transmissivity and porosity values from the Thrust Belt to the Green River Basin, although there is no change in lithology. The difference may be due to increased

lithostatic pressure and decreased fracture occurrence in the Green River Basin (Ahern et al., 1981).

(5) The Upper Jurassic-Lower Cretaceous aquifer is comprised of a series of vertically and areally discontinuous aquifers. The low permeability and general absence of springs is probably due to the large amounts of shales, siltsones and mudstones present in these units (Ahern et. al., 1981).

(6) The Frontier aquifer, composed solely of the Frontier Formation, produces moderate amounts of water (Ahern et al. 1981). Permeability is highly dependent on cementation of the sandstone.

(7) The Mesaverde aquifer outcrops along the Rock Springs uplift, which provides a favorable recharge zone. Seven wells north of the uplift yield 15-200 gpm from the Rock Springs and Ericson Formations. Farther to the west this aquifer has been partially truncated by an erosional unconformity on the Moxa Arch.

(8) The Tertiary aquifer is by far the best understood and most productive in the Green River Basin (Ahern et al., 1981; Welder 1968). The Wasatch Formation, the Laney Member of the Green River Formation and the Bridger Formation are the major water producers in this aquifer. The Wasatch Formation is most productive along the basin flanks in the northern and central portion of the basin as well as in the southwest corner. Impermeable shales and marlstones of the Green River Formation intertongue with the Wasatch in the basin center creating a hydrologic barrier. Water-bearing sand lenses in the Laney Member of the Green River Formation are utilized along the eastern margin of the basin. The permeable sands of the Bridger Formation, overlying the Green River and Wasatch Formations

produce water in the south-cenral part of basin (Ahern et al., 1981).

In general, circulation in the Paleozoic and Mesozoic aquifers is highly restricted due to deep burial of the sediments as well as lack of recharge areas (Ahern et al., 1981). Due to the large stratigraphic displacement of the Pre-Tertiary sediments of the eastern margin of the Thrust Belt against the Baxter-Hilliard aquitard, any water entering the basin from the outcrop area must transfer down through this thick sequence of shales (Ahern et al., 1981). Flat potentiometric gradients and very saline water within these aquifers (Ahern et al., 1981) further indicate that the amount of flow in the basin is small and circulation is restricted.

Based on drill stem test data on the periphery of the basin, ground water flow in the Mesozoic and Paleozoic aquifers appears to come from recharge areas along the LaBarge Platform. Water then flows southeast towards the southern part of the basin. Additional flow may come from the Great Divide and Washakie Basins to the east (Collentine et al., 1981).

Groundwater movement in the post Baxter-Hilliard strata is better understood due to more data, little structural disturbance of the sediments and good stratigraphic control. Recharge for these aquifers is generally along the flanks of the uplifts but impermeable zones within the Green River Formation prevent downward movement of groundwater (Ahern, et al., 1981).

Circulation in the Tertiary strata is from foothill outcrops toward the center of the basin and then southward. In the southwest part of the basin recharge comes from the north flank of the Uinta Mountains and movement is from south to north (Ahern et al., 1981).

Groundwater quality in the Green River Basin ranges from very poor to excellent, showing a general tendency to become more mineralized with increasing depth (Welder, 1968). Total dissolved solids (TDS) concentrations frequently exceed 10,000 mg/l in the Precambrian to Upper Cretaceous aquifers. Total Dissolved Solids (TDS) in most Tertiary aquifers frequently falls in the 500 to 3000 mg/l range (Ahern et al., 1981). Table 2 is a compilation of pre-Tertiary water quality data in the Green River Basin along with select groundwater analyses from Tertiary aquifers.

Heat Flow and Thermal Modeling

The conductive thermal modeling of an area incorporates stratigraphic, structural, and hydrologic data. These are parameters which set limits on the thermal conductivity of rocks, thermal gradients, and depths to aquifers. Also a regional heat flow value must be determined. Published heat flow values in the Green River Basin range from 46 to 67 milliwatts per square meter (mW/m^2) (Sass et al., 1971, Heasler et al., 1982). These values indicate the most reliable value for a regional heat flow is 54 mW/m^2. This value and an upper value of 67 mW/m^2 were used in Table 3 for the modeling of temperatures. To model the temperature at a given depth the following equation is used:

$$T_A = T_0 + (Q/K_1)dx_1, + (Q/K_2)dx_2 + \ldots.$$

where T_A is the temperature in a certain aquifer, T_o is the mean annual surface temperature, Q is the regional heat flow, K_1 and dx_1 are the thermal conductivity and thickness of the lithologic unit closest to the ground surface, K_2 and dx_2 are the thermal conductivity and thickness of the lithologic unit below unit 1, and so on until the desired depth is reached.

Thermal conductivity values used for formations in the Green River Basin were taken from a variety of sources. Values for the Green River Basin from Sass et al., (1971), Decker and Bucher (1979), and Heasler et al. (1982) were used in addition to thermal conductivities measured for other Wyoming basins (see Decker et al., 1980; Decker and Bucher, 1979; Heasler and Hinckley, 1985; and Heasler, 1978). Where no thermal conductivity measurements have been made on a formation, a value was estimated using the approximate lithologies for the formation.

There are two basic structural models which have been utilized in the thermal modeling of the Green River Basin. These models are: 1) a deep sedimentary basin, and 2) an anticline-syncline geothermal system (see Figure 3). Conductive thermal modeling techniques were used to estimate subsurface temperatures in each case.

As a whole, the Green River Basin is a deep sedimentary basin, and could be considered to contain a moderate (194°F-302°F) to high (>302°F) geothermal resource simply due to the earth's normal increase in temperature with depth. In the Green River Basin the average thermal gradient is approximately 13°F/1000 feet.

By using conductive thermal modeling techniques for the central portions of the basin (characterized by Pacific Creek in Table 3) it is evident that a depth of approximately 10,000 to 12,500 feet must be reached to attain a temperature of 200°F. The structure contour map (Plate II) shows that in more than half the basin the Dakota Sandstone lies beneath at least 13,000 feet of sediments. A maximum temperature at the base of the sedimentary section in that area would probably exceed 350°F at a depth of approximately 27,000 feet. Relative depths and temperatures can be estimated for other formations above and below the Dakota Sandstone using the thicknesses shown in Figure 7.

While such temperatures (greater than 200°F) theoretically seem promising as potential geothermal resources, the great depth and poor quality of the waters associated with such depths place a severe constraint on the practical use of the resource. An additional problem with this particular model is the lack of knowledge concerning quantities of water at these depths. However, many of the deeply buried aquifers are being drilled in search of oil and gas. These holes may provide feasible access to geothermal resources.

The second type of geothermal system evaluated by conductive thermal modeling was the syncline-anticline system near the Church Buttes oil field on the southern portion of the Moxa Arch. Available data indicates that a high gradient area, shown as a hachured enclosure on the gradient contour map (Plate III), exists on the anticline. However, there is little information for the synclinal axis located to the west of the Arch. Conductive thermal modeling was used to estimate temperatures in the syncline to determine if upward movement of water could cause the high temperatures. From Table 3 it can be seen that conductive thermal modeling predicts temperatures in the Dakota Sandstone of 250°F - 300°F (for 54 to 67 mW/m^2). Thermal modeling for the anticline portion of the system predicts temperatures of 219°F to 260°F. The actual measured temperatures in the anticline range from 228°F to 278°F. Thus the temperature anomaly may be the result of local hydrologic conditions, i.e. flowing water heated in the syncline moving up over the anticline.

In order for such a thermal model to be applicable in terms of geothermal resource development a number of conditions must be met: 1) the aquifer must bring heated water close to the surface (generally within 5,000 feet) for the resource to be considered economical, 2) the water in the aquifer must be flowing rapidly enough so that there is no significant heat loss. Generally, the anticlines in the Green River Basin do not meet these criteria. The few structures that exist in the basin are buried under a minimum of 9,000 feet of

Tertiary sediments except on the LaBarge platform. In addition, recharge to the deeper, potentially warmer aquifers is essentially unknown; their water flow rates cannot be estimated. As previously mentioned circulation is probably very poor in these aquifers.

Additional high gradient areas have been located on the Moxa Arch in the vicinity of the LaBarge Platform (see Plate III). Because the Darby - Prospect Thrust overides the Moxa Arch in this area, the syncline-anticline model cannot be applied. The structure contour map (Plate II) indicates that the arch has been broken by faults in this area and thus any groundwater flow has probably been severely disturbed.

Gradient Contours

Plate III shows thermal gradient contours for the Green River Basin. Most of the data used for the map were obtained from oil and gas well bottom hole temperatures (BHT's). There are approximately 1500 BHT's for this basin, most of which are concentrated along the Moxa Arch, the site of greatest known oil and gas potential. Thermal logs of drill holes, shown as +'s on the map and in Table 4; were also used in contouring.

Using BHT's and thermal logs, the average thermal gradient for the Green River Basin is approximately 13°F/1000 feet. This value has been substantiated by conductive modeling from the land surface to the base of the Morrison Formation (See Table 3). The conductive model yields a gradient of 12.9°F/1,000 feet.

Table 5 and 6 list the statistical distribution of the BHT's and BHT-derived gradients in 500 foot depth intervals with the mean BHT and gradient and the 50th, 66th, 80th and 90th percentile for each interval. From Table 6 it is evident that in general the shallow holes (<4,500 feet deep) have higher gradients, while those deeper than 4,500 feet tend to have lower gradients (see also Figure 9). Thus shallow gradients tend to be higher than the average gradient while gradients from deep holes may be slightly lower than the average.

The gradients obtained from thermally logged holes correspond closely with those of BHT's obtained from deeper holes. The statistical analyses in Table 5 and 6 may be used in addition with data from thermally logged holes to obtain reliable temperature information as discussed in the introduction.

The gradient contour (Plate III) map has been contoured on 2.5°F/1,000ft intervals. In many areas there has been generalization, e.g. the odd values in a specific area have not been contoured. (In such cases the gradient is listed beside the hole location on Plate III). In most areas of the Green River Basin except the Moxa Arch, BHT data are sparse. In these areas of little data the gradient contours are approximate and may not reflect high gradient areas if such areas exist. For example, from flowing well information, a high gradient area may be present in the southeast portion of the basin near Flaming Gorge but there is insufficient BHT data to substantiate this. The Moxa Arch has been explored and drilled extensively, thus creating a degree of bias regarding density of data in the area. As mentioned previously, a syncline-anticline system is one of the most likely places to find a geothermal resource. Thus, the present distribution of data should be sufficient for locating most of the larger anomalous areas.

The hachured areas on Plates II, III, and IV delineate groupings of anomalously high gradients. These high gradient areas were determined by the following characteristics: 1) gradients of at least 16°F/ 1,000 ft, 2) 80th percentile group for their depth range (see Table 3), 3) BHT of at least 100°F.

Horizontal hachures identify thermal gradient anomalies of less than 4,500 feet in depth while vertical hachures indicate anomalies at depths greater than 4,500 feet. A cutoff point of 4,500 feet was used because, as seen in Table 5, there appears to be a natural break between gradients at 4,000 and 4,500 foot depth ranges.

There are a few cases in which a potential geothermal resource may not show up as an anomalous gradient area. One such instance would be existing drill holes which have reached warm or hot water. Using the average basin gradient of 13°F/1,000 ft, a depth of 4,500 feet should produce water of 100°F. If such water is under great enough pressure to produce artesian flow, a viable geothermal resource may exist at that particular area even through it is not indicated as a high gradient area. Locations of three flowing thermal wells (temperatures greater than 70°F) are given in Table 7.

Warm springs are a second instance where a potential resource may not be indicated on the gradient map. Two springs flowing water warmer than 70°F (Steele Hot Springs and Kendall Warm Springs) have been located on the gradient contour map (Plate III). Locations, flows, and other pertinent information for these springs are given in Table 7.

The Steele Hot Springs issue from the corner of Fremont Butte on the southwest flank of the Wind River Mountains. According to Breckenridge and Hinckley (1978), basement faults in the area provide a conduit for convectively rising thermal waters from a source in the underlying granite. Kendall Warm Springs are located in the northernmost part of the Green River Basin, occurring on the western flank of the Wind River Mountains which is cut by many major thrust faults. This thrusting has moved the Precambrian crystalline rocks over the Paleozoic section causing numerous faults and tight folds to form parallel to the trend of the range (Breckenridge and Hinckley, 1978). The Kendall Warm Springs occur where the Phosphoria Formation crops out in the center of one such anticline. An adjacent syncline lies east of the springs with a minimum depth of approximately 4,200 feet. According to Breckenridge and Hinckley (1978) recharge occurs at nearly 9,000 feet in elevation on the flank of the mountains where the Phosphoria outcrops. Since the elevation of the springs is 7,800 feet, artesian flow can be expected in the system. In addition, the depth of the syncline should be more than sufficient to produce the 85°F temperature of the springs.

Temperature Contours

The temperature contour map (Plate IV) was compiled from oil and gas well BHT's from the Dakota Sandstone and Morrison Formation. These BHT's are depicted by a solid dot on Plate IV. Additional data were obtained from BHT's in the Frontier Formation which were extrapolated to the Dakota Sandstone using the average gradient of the hole. These values are shown as open circles on Plate IV and were used only as a means of further defining the Dakota temperature contours.

Temperature differences within a formation are a function of depth of burial, the regional heat flow, changes in thermal conductivity within the formation, convective (water flow) heat transfer, and BHT measurement inaccuracies.

Since the Paleozoic and Mesozoic strata have very similar structural configurations in the Green River Basin it is possible to estimate temperatures above and below the Dakota Sandstone from the temperature contour map. The thicknesses shown in Figure 7 can be used in conjunction with an average basin gradient of 13°F/1,000 ft to adjust mapped Dakota Sandstone temperatures to greater or lesser depths.

Because there is a minimum of 5,000 feet of strata below the Dakota Sandstone, the highest temperatures likely to be produced from any sediments in the basin are probably at least 65°F higher than those shown on Plate IV.

The deepest portions of the basin in the east and northeast have not been contoured due to the lack of data in those areas. No wells in the area have been drilled deep enough to reach the Dakota Sandstone. The highest Dakota temperature reported was in a well near Farson with a temperature of 288°F at a depth of 17,007 feet. Temperatures in the area can be estimated using the previously described method.

As stated earlier, deeply circulating water is an essential ingredient of low-temperature geothermal resources in other basins in Wyoming. Unfortunately, very few data are available on the deeply buried Paleozoic and Mesozoic aquifers in the Green River Basin, consequently, hypothesis concerning potential geothermal resources in these aquifers cannot address the imporant question of the amount of water available.

Virtually all available hydrologic data for the Green River Basin is from the Upper Cretaceous and Tertiary sediments. All available hydrologic sources indicate that these formations constitute the principle water resources for the basin (Ahern et al., 1981; Welder, 1968; Robinove and Cummings, 1963). Referring to the gradient contour map (Plate III), it is evident that some of the anomalously high gradient areas are located in shallow (less than 4,500 feet) depth ranges. In almost any area of the basin such a depth occurs within the relatively flat-lying Tertiary sediments. The BHT's for these shallow anomalous area are as high as 130°F for a depth of 4,500 feet making them areas of potential geothermal use. However, much additional research needs to be undertaken in order to delineate such areas.

Thermal Data for the Wyoming Portion of the Thrust Belt

The Thrust Belt of Wyoming is an area of complex geology with unknown geothermal potential. Thermal data were gathered for the region west of the Green River Basin and east of the Wyoming border in Lincoln and Uinta Counties. Scant thermal data exist in this region. No heat flow values nor thermal conductivity studies have been published. Oil well BHT's were available for only 51 wells in Wyoming. Temperature-depth and gradient-depth plots of this data are shown in Figures 10 and 11, respectively. Since so few oil well BHT's were available, no statistical analysis of the data set was attempted. Twelve oil and gas exploration holes in Idaho (Ralston, et al., 1981) and 51 in Wyoming have thermal gradients ranging from 19 to 86°C/km. Maximum reported temperatures for these wells are 210°C at 3,810 meters in Idaho and 132°C at 4,122 meters in Wyoming.

Table 8 lists data for 38 thermally measured wells in the general area of the Thrust Belt. Measured thermal gradients are variable, ranging from 9.2 to 39.1°C/km. Due to the lack of thermal data and complex geology, no thermal gradient maps nor temperature contour maps were constructed.

Thermal springs as hot as 140°F occur both in Idaho (Ralston, et al., 1981) and Wyoming portions of the Thrust Belt (Breckenridge and Hinckley, 1978). The spring systems are commonly associated with deep, high angle faults (Ralston, et al., 1981). The most productive deep aquifers are the Madison Limestone and Bighorn Dolomite, from which spring flows of up to 40,000 gpm are reported (Lines and Glass, 1975).

Two hot springs of interest exist in the northern Green River Basin - Thrust Belt area. Auburn Hot Springs are located in T.33N., R.119W., sec. 20 in northern Lincoln County. Several areas of travertine cones, terraces, warm pools, small springs, and seeps are located in the area. Surface discharge temperatures for the springs range from 61 to 144°F (Breckenridge and Hinckley, 1978). Geochemical thermometry indicates subsurface temperatures of 162 to 216°F (Muffler, 1979). The springs are located at the crest of a tightly folded anticline near the intersections of several faults. Faults and folds generally trend north-northwest, coincident with the alignment of travertine deposits that extend 13 miles north-northwest of the springs (Breckenridge and Hinckley, 1978). These hot springs may be the result of local deep circulation along major faults although the existence of an anomalous heat source can not be excluded due to the sparse thermal data.

The other springs of interest are Granite Hot Springs. These springs are located in T.39N., R.113W., sec. 6 in the southeastern corner of Teton County and flow 300 gpm at a temperature of 106°F (Breckenridge and Hinckley, 1978) They are in the Gros Ventre Mountains at the northern end of the Green River Basin adjacent to the Thrust Belt. Geochemical thermometry indicates the subsurface temperature of Granite Hot Springs may be as high as 199°F (Muffler, 1979). The springs are apparently the result of deep water circulation along a high angle, large displacement fault (Breckenridge and Hinckley, 1978) although existing data does not exclude the existence of an anomalous heat source.

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Table 1. Summary of geothermal data on Wyoming sedimentary basins.

Basin:	Bighorn	Great Divide and Washakie	Green River	Laramie, Hanna, and Shirley	Southern Powder River	Wind River
Number of bottom-hole temperatures analyzed	2,035	1,880	1,530	445	6,100	1,740
Number of wells thermally logged	70	68	47	57	60	67
Background thermal gradient in °F/1,000 ft (°C/km)	16 (29)	15 (27)	13 (24)	12-15 (22-28)	14 (25)	15 (28)
Highest recorded temperature and corresponding depth	306°F at 23,000 ft (152°C at 7,035 m)	376°F at 24,000 ft (191°C at 7,300 m)	306°F at 21,200 ft (152°C at 6,453 m)	223°F at 12,000 ft (106°C at 3,600 m)	275°F at 16,000 ft (135°C at 4,900 m)	370°F at 21,500 ft (188°C at 6,555 m)
Basin depth in feet (km)	26,000 (8.0)	28,000 (8.5)	30,200 (9.2)	12,000; 39,000; 8,200 (3.7; 12.0; 2.5)	16,400 (5.0)	25,800 (7.6)

Table 2. Ground water chemistry data for the Green River Basin.

TERITARY AQUIFER SYSTEM

Location SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
15	108	28		0.1	720	2.6	1,720	2.2	94	1,690	a
15	109	10	49.0	12.0	2,496	10	402	528	3,340	6,564	b
16	114	30	13.0	2	552	1	274	512	296	1,512	b
23	110	13	1.2	.4	292	.8	605	1.8	85	704	a
16	107	22	7	1	436	2	701	115	42	1,016	b
30	111	31	8	1	217	1	317	142	16	490	b
23	107	30	0.0	6.8	338	4.0	567	93	39	883	a
24	109	9	.0	.0	330	.8	519	.0	62	777	a
26	106	3	.0	.6	218	3.1	115	84.2	66	592	a
					Na + K						
13	111	26	174	79	7,321		305	3,325	9,200	20,249	c
27	113	25	18	17	119		317	95	12	418	c
28	112	19	7	8	2,471		1,732	5	2,766	6,191	c
26	112	9	23	12	2,803		1,354	0	3,600	7,143	c
27	113	2	20	13	2,662		1,598	8	3,140	6,753	c
28	112	29	6	20	2,709		4,209	60	1,660	6,661	c
25	110	7	186	42	4,346		378	47	6,900	11,707	c
31	108	29	290	35	4,369		610		7,000	11,994	c

TERTIARY AQUIFER (UNDIVVDED)

SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
18	116	6					885	26	323	1,470	a
26	114	1	46	16	1.2	0.4	197	19	.8	186	a
32	107	8	2.1	0	92	.9	0	11	83	300	f
38	110	22	215	52	4.0	2.7	120	650	3.2	1,000	a
39	111	22	68	6	11		165	80	0	246	a
13	120	25	83.8	23.9			352.2	24.0	10.0	326	b
17	120	6	33.9	37.8	24.3	4.6	257.4	42.0	31.0	315	b
24	115	32	65.8	15.9	54.3	1.7	275.4	75.8	31.0	397	b
19	105	33	120	87			424.8	929	40.0	1,740	b

Table 2 continued.

Location											
SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
18	110	27	28	10	4,894		4,660	0	4,550	12,089	c
27	113	23	174	88	4,205		1,208	24	6,200	11,212	c
28	113	32	67	62	5,045		1,903	4	6,900	13,076	c
29	113	25	26	9	3,853		7,088	256	1,510	9,252	c
32	114	29	158	116	3,750		3,001	280	4,450	10,232	c
19	113	25	132	10	4,304		1,453		6,000	11,230	c
16	106	12	76	50	41,786						c
17	108	26	31	27	11,242		6,076	150	14,000	28,620	c
27	113	17	84	36	3,949		630		5,978	10,357	d
-9	116	18	518.8	179.8	126.9	14.0	259.6	20,985	140	3,340	b
FRONTIER AQUIFER SYSTEM											
16	118	25	119.8	64.0	155.2	19.0	431	470	55.1	1,110	b
17	118	13	120	47.0	54.3	19.0	2,812	340	450	776	b
18	117	13	130	63.9			336.6	420	55	939	b
18	116	6			592.5		870.3	26	323.4	1,467	b
23	115	6	60.8	11.0	42.6	2.9	275.3	58.9	13.0	341	b
23	112	2	124	29	5,359		1,147	48	8,000	14,258	c
26	113	17	50	5	2,364		2,001	7	2,580	5,992	c
27	114	4	37	28	2,853		1,793	142	3,400	7,343	c
28	113	30	202	27	4,913		490	40	7,700	13,123	c
30	113	32					500	1,506	5,000	10,859	e
29	114	19					1,525	716	2,520	6,522	e
28	115	14					1,793	309	4,320	9,119	e
28	113	13					573	39	7,000	11,903	e
28	113	30					490	40	7,700	13,123	e
27	113	4					2,070	0	4,040	8,439	e
27	114	12					1,501	40	5,600	10,578	e
27	114	24					1,305	127	1,360	3,550	e
27	113	3					4	220	560	1,108	e
27	113	3					110	8	900	1,579	e
27	113	10					317	15	544	1,184	e
27	113	15					805	190	3,830	7,528	e
27	113	19					365	5	1,560	2,878	e
26	113	14					927	136	33,000	55,095	e
26	113	17					2,001	7	2,580	5,992	e
26	112	26					1,070	53	4,280	8,041	e

Table 2. continued

Location											
SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
UPPER JURASSIC-LOWER CRETACEOUS AQUIFER SYSTEM											
22	115	8	50.9	12.0	71.8	.7	309.6	56.0	16.0	9,383	b
25	115	14	67.8	12.0	16.5	2.3	216.3	56.9	8.4	283	b
25	115	14	1,196	22.2	3.2	2.7	277.2	169.9	16.0	505	b
					Na + K						
27	113	14	1,539	104	8,088		329	7	16,300	25,200	c
26	113	11	697	133	6,281		525	5	11,000	18,375	c
26	113	2					268	5	14,300	23,482	e
26	113	4					281	5	5,400	9,021	e
26	113	4					573	5	10,700	17,967	e
26	113	10					403	10	13,800	22,968	e
26	113	11					525	5	11,000	18,375	e
17	104	2					4,260	0	4,032	10,309	e
27	113	33					403	5	8,100	13,569	e
27	113	33					207		5,000	8,343	e
27	113	35					317		12,600	20,814	e
20	114	19					1,405	35	5,400	10,149	e
29	114	11					865	417	1,100	19,599	e
29	114	12					855	395	10,300	18,251	e
17	112	22					889	35	6,500	11,493	e
17	112	22					1,220		6,100	11,138	e
16	113	13					1,061	370	6,600	12,346	e
16	112	4					905		6,200	10,983	
					Na + K						
17	112	6	139	29	4,352		815	35	6,500	11,493	d
16	113	13	25	2	4,825		795	270	6,600	12,346	c
28	114	12	182	30	6,923		855	395	10,300	18,251	c
NUGGET AQUIFER SYSTEM											
16	112	17	1,475	139	28,670		990	216	46,500	77,487	c
26	115	26	63.8	5.9	3.7	0.9	226.2	4.9	2.7	209	b
26	115	15	50.8	11.0	4.2	.6	2,064	5.1	3.2	198	b

Table 2 continued.

Location											
SEC	RNG	TNP	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	Reference
					Na + K						
27	113	14	2,112	107	36,830		364	881	60,000	1,000,110	c
28	114	11	2,489	357	33,799		500	936	56,600	94,426	c
28	115	14	777	113	16,400		380	2,416	25,000	44,893	c
17	116	8	1,696	1,260	7,066		1,584	4,815	13,100	28,717	c
27	115	22	63.8	250	10.7	.8	1,839	190	1.9	390	b
PALEOZOIC AQUIFER SYSTEM											
38	110	2	2,146	520	3.9	2.7	118.0	649.4	3.2	1,000	b
16	117	33	820	568	4,740		3,540	4,021	5,400	17,297	c
18	113	19	247	110	7,282		1,806	13,341	1,100	22,969	c
26	114	1	503.8	16.0	1.2	.4	193.8	19.0	.8	185	b
26	113	7	45.9	25.0	5.8	.7	216.3	22.0	7.7	227	b
26	113	7	48.8	30.0	6.7	1.3	275.3	33.0	10.0	287	b

a Welder, 1968
b Ahern, et al., 1981
c Crawford, 1963?
d Biggs and Espach, 1960
e Crawford and Davis, 1962
f Breckenridge and Hinckley, 1978

Table 3. Conductive thermal models for the Green River Basin.

Formation	Conductivity (10^{-3}cal/ cm sec°C)	Formation Gradient[1] 1.3 HFU	1.6 HFU	Depth Feet	Thickness feet (meters)	Temperature (°C) at base of formation[1,2] 1.3 HFU	1.6 HFU
				CHURCH BUTTE			
Browns Park	5.5	23.6	29.1	1,300	1,300(396)	14.4	16.5
Bridger	5.5	23.6	29.1	3,200	1,900(674)	36.3	43.5
Green River	4.0	32.5	40.0	5,325	2,125(648)	50.3	60.7
Wasatch	6.0	21.7	26.7	8,675	3,350(1,021)	69.3	84.0
Fort Union	7.0	18.6	22.9				
Lance	4.5	28.9	35.6				
Lewis	6.0	21.7	26.7	9,475	800(244)	74.6	90.5
Mesaverde	6.0	21.8	26.7	12,325	2,850(869)	99.7	121.3
Baxter	4.5	28.9	35.6	12.425	100(31)	100.3	122.1
Frontier	6.5	20.0	24.6	12.750	325(99)	102.9	125.3
Mowry	5.0	26.0	32.0	13,000	250(76)	104.0	126.7
Dakota	8.7	14.9	18.4	13,650	650(198)	108.5	132.3
Morrison	5.7	22.8	28.1	13,900	250(76)	109.8	133.9
Stump	7.4	17.6	21.6	14,500	600(183)	112.8	137.6
Twin Creek	8.0	16.3	20.0	15,275	775(236)	117.0	142.7
Nugget	7.4	17.6	21.6				
Woodside Thaynes Ankareh	7.2	18.1	22.2	16,850	1,575(400)	125.7	153.4
Dinwoody	2.8	46.4	57.1	16,925	75(23)	126.8	154.7
Phosphoria	9.6	13.5	16.7	17,300	375(114)	128.3	156.6
Tensleep	10.4	12.5	15.4	17,825	525(160)	130.3	159.9
Amsden	8.0	16.3	20.0	18,275	450(137)	132.5	161.8
Madison	9.6	13.5	16.7				
Darby	8.2	15.9	19.5				
Bighorn	11.0	11.8	14.5				
Gallatin	7.4	17.6	21.6				
Gros Ventre	6.0	21.7	26.7				
Flathead	8.5	15.3	18.8				
Precambrian	7.0	18.6	22.9				
				PACIFIC CREEK			
Wasatch	6.0	21.7	26.7	7,600	7,600(2,316)	56.1	66.8
Fort Union	7.0	18.6	22.9	7,600	1,725(526)	65.9	78.9
Lance	4.5	28.9	35.6	9,325	900(274)	73.8	88.6
Lewis	6.0	21.7	26.7	10,225	900(274)	79.7	96.0
Mesaverde	6.0	21.8	26.7	12,470	2,245(684)	94.5	114.2
Baxter	4.5	28.9	35.6	15,760	4,395(1,340	133.2	161.9
Frontier	6.5	20.0	24.6	20,155	612(187)	136.9	166.5
Mowry	5.0	26.0	32.0	20,767	393(120)	140.0	170.4
Dakota	8.7	14.9	18.4	21,160	329(100)	142.5	172.2
Morrison	5.7	22.8	28.1	21,489	361(110)	144.0	175.3
Stump	7.4	17.6	21.6	21,850	250(76)	145.4	176.9
Twin Creek	8.0	16.3	20.0	22,100	248(76)	146.6	178.5
Nugget	7.4	17.6	21.6	22,348	338(103)	148.4	180.7
Woodside Thaynes Ankareh	7.2	18.1	22.2	22,686	1,379(420)	156.0	190.0
Dinwoody	2.8	46.4	57.1	24,065	25(8)	156.4	190.5
Phosphoria	9.6	13.5	16.7	24,090	320(98)	157.7	192.1
Tensleep	10.4	12.5	15.4	24,410	665(203)	160.2	195.2
Amsden	8.0	16.3	20.0	25,075	345(105)	161.9	197.3
Madison	9.6	13.5	16.7	25,420	500(152)	164.0	199.9
Darby	8.2	15.9	19.5	25,920	350(107)	165.7	201.9
Bighorn	11.0	11.8	14.5	26,270	300(91)	166.8	203.3
Gallatin	7.4	17.6	21.6	26,570	100(30)	167.3	203.9
Gros Ventre	6.0	21.7	26.7	26,670	500(152)	170.6	208.0
Flathead	8.5	15.3	18.8	27,170	150(46)	171.3	208.8
Precambrian	7.0	18.6	22.9	27,320			

[1] Calculated for heat flow values of 1.3 HFU (54 mW/m^2) and 1.6 HFU (67 mW/m^2), One HFU = 10^{-6} cal/cm^2 sec.

[2] Assuming a 41°F (5°C) mean annual air temperature.

Table 4. Thermally measured wells in the Green River Basin.[1]

	Location		Depth		Bottom-Hole Temperature		Gradient[2]		Interval[3]
Hole	West Longitude	North Latitude	Meters	Feet	°C	°F	°C/km	°F/1,000 ft	(M)
LINCOLN COUNTY									
East LaBarge 37-4	110 09.6	42 15.7	650	2,133	24.9	76.8	23.0	12.6	280-650
Green River 79-12	110 12.6	42 15.2	1,770	5,807	60.4	140.8	28.6	15.7	160-1,770
Wilson Ranch 8	110 04.9	41 38.4	1,900	6,234	70.9	159.5	25.3	13.9	10-1,900
SUBLETTE COUNTY									
Wagon Wheel 1	109 44.7	42 36.0	748	2,454	28.0	82.4	27.7	15.2	240-690
Wagon Wheel 2	109 44.9	42 35.9	1,480	4,856	50.7	123.2	30.4	16.7	120-1,480
Belco C-217	110 19.7	42 35.4	1,229	4,032	42.7	108.8	29.1	16.0	10-1,220
Belco S33-28	110 18.8	42 33.4	991	3,252	33.0	91.4	25.6	14.1	20-980
Belco S32-33	110 18.1	42 32.4	931	3,055	33.7	92.7	26.3	14.5	20-931
SWEETWATER COUNTY									
BLM Dodge Pass 1	110 02.1	41 55.8	230	755	15.3	59.5	37.3	20.5	70-180
7 Mile Gulch #2	110 00.3	41 45.2	1,910	6,267	71.3	160.3	24.8	13.6	10-1.910
Little America	109 52.4	41 32.4	445	1,460	23.4	74.2	20.0	11.0	10-445
BLM Horn 1-A	109 49.5	41 58.0	497	1,630	22.4	72.3			

[1] Measured by University of Wyoming personnel following the method of Decker, 1973.

[2] Gradient represents a linear least square fit of the temperature-depth data over the most thermally stable portion of the hole.

[3] Interval refers to the depth range in meters over which the least squares gradient was calculated.

Table 5. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Green River Basin. A temperature under a percentile is the temperature below which that percent of the BHT's fall. For a depth interval for which very few BHT's have been measured, the percentile temperatures have little meaning.

Depth interval (feet)	Number	Temperature (°F)						
		high	low	mean	50%	66%	80%	90%
500 - 1,000	6	99	72	85.8	85	97	97	99
1,000 - 1,500	5	94	60	79.4	80	93	94	94
1,500 - 2,000	10	117	74	89.1	87	92	105	117
2,000 - 2,500	26	120	64	86.9	86	88	94	104
2,500 - 3,000	50	110	78	90.3	90	93	102	102
3,000 - 3,500	108	126	70	94.4	94	97	102	107
3,500 - 4,000	121	152	81	97.1	96	99	103	110
4,000 - 4,500	61	130	87	101.6	102	104	107	109
4,500 - 5,000	55	150	85	106.6	104	109	112	126
5,000 - 5,500	29	146	95	109.9	108	112	115	122
5,500 - 6,000	32	134	96	115.8	117	119	126	131
6,000 - 6,500	23	139	110	122.0	121	125	129	138
6,500 - 7,000	38	162	108	127.2	129	131	132	140
7,000 - 7,500	136	190	108	137.7	138	143	148	153
7,500 - 8,000	152	176	112	140.1	142	147	151	155
8,000 - 8,500	105	240	117	145.3	146	151	154	160
8,500 - 9,000	74	191	98	150.7	153	157	162	172
9,000 - 9,500	43	235	124	155.0	159	162	167	174
9,500 - 10,000	49	258	122	168.0	168	176	178	190
10,000 - 10,500	34	235	149	175.7	176	180	186	191
10,500 - 11,000	64	208	135	169.0	168	177	181	196
11,000 - 11,500	79	220	138	181.7	184	189	193	199
11,500 - 12,000	60	249	162	188.8	188	196	200	206
12,000 - 12,500	26	265	168	199.4	196	206	210	218
12,500 - 13,000	41	320	166	210.2	207	212	216	232
13,000 - 13,500	25	278	160	204.0	204	209	214	220
13,500 - 14,000	15	236	162	195.2	192	208	212	219
14,000 - 14,500	2	248	176	212.0	248	248	248	248
14,500 - 15,000	19	258	168	227.4	235	241	244	258
15,000 - 15,500	5	260	201	226.8	218	250	260	260
15,500 - 16,000	7	255	205	226.6	223	240	248	255
16,000 - 16,500	5	248	195	232.0	246	248	248	248
16,500 - 17,000	5	280	212	250.8	256	280	280	280
17,000 - 17,500	7	288	190	241.0	230	256	288	288
17,500 - 18,000	3	274	210	252.0	272	274	274	274
18,000 - 18,500	4	300	213	263.3	282	282	300	300
18,500 - 19,000	6	292	202	268.7	281	287	287	292
19,000 - 19,500	4	313	161	261.5	296	296	313	313
19,500 - 20,000	2	304	255	279.5	304	304	304	304
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	1	305	305	305.5	305	305	305	305
21,000 - 21,500	0	-	-	-	-	-	-	-

Total: 1,529 bottom-hole temperature measurements.

Table 6. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Green River Basin. A gradient under a percentile is the gradient below which that percent of the gradients fall. For a depth interval for which very few BHT's have been measured, the percentile gradients have little meaning.

Depth interval (feet)	Number	Gradient (°F/1,000ft)						
		high	low	mean	50%	66%	80%	90%
500 - 1,000	6	63	32	49.5	48	59	59	63
1,000 - 1,500	5	45	13	30.0	28	41	45	45
1,500 - 2,000	10	41	16	26.1	24	27	41	41
2,000 - 2,500	26	33	9	19.4	17	20	23	27
2,500 - 3,000	50	24	12	17.3	16	18	19	22
3,000 - 3,500	108	25	9	15.9	15	16	17	19
3,500 - 4,000	121	27	10	14.8	14	15	16	18
4,000 - 4,500	61	20	10	14.1	14	14	15	15
4,500 - 5,000	55	21	9	13.5	13	13	14	15
5,000 - 5,500	29	20	10	13.1	12	13	14	15
5,500 - 6,000	32	15	9	12.8	12	13	14	15
6,000 - 6,500	23	15	10	12.8	12	13	13	14
6,500 - 7,000	38	17	9	12.7	12	13	13	14
7,000 - 7,500	136	20	9	13.1	13	13	14	15
7,500 - 8,000	152	17	8	12.7	12	13	14	14
8,000 - 8,500	105	24	8	12.6	12	13	13	14
8,500 - 9,000	74	17	6	12.4	12	13	13	14
9,000 - 9,500	43	20	8	12.2	12	12	13	14
9,500 - 10,000	49	22	8	12.9	12	13	14	15
10,000 - 10,500	34	18	10	13.1	13	13	14	14
10,500 - 11,000	64	15	8	11.8	11	12	12	14
11,000 - 11,500	79	16	8	12.4	12	12	13	13
11,500 - 12,000	60	18	10	12.5	12	13	13	14
12,000 - 12,500	26	18	10	12.8	12	13	13	14
12,500 - 13,000	41	21	9	13.2	12	13	13	14
13,000 - 13,500	25	18	8	12.3	12	12	13	13
13,500 - 14,000	15	14	8	11.1	10	12	12	13
14,000 - 14,500	2	14	9	12.1	14	14	14	14
14,500 - 15,000	11	14	8	12.6	13	13	13	13
15,000 - 15,500	5	14	10	12.1	11	13	14	14
15,500 - 16,000	7	13	10	11.7	11	12	13	13
16,000 - 16,500	5	12	9	11.7	12	12	12	12
16,500 - 17,000	5	14	10	12.5	12	12	14	14
17,000 - 17,500	4	14	8	11.6	10	12	14	14
17,500 - 18,000	3	13	9	11.8	12	13	13	13
18,000 - 18,500	4	14	9	12.1	13	13	14	14
18,500 - 19,000	6	13	8	12.1	12	13	13	13
19,000 - 19,500	4	13	6	11.4	13	13	13	13
19,500 - 20,000	2	13	10	12.1	13	13	13	13
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	0	-	-	-	-	-	-	-
21,000 - 21,500	1	12	12	12.3	12	12	12	12

$$\text{Gradient} = \frac{\text{Bottom-hole temperature} - \text{Mean annual surface temperature}}{\text{Depth}} \times 1{,}000$$

Table 7. Green River Basin thermal wells and springs.

Flowing Thermal Wells (>70°F)

Plate 3 Reference Number	Location (TNP-RGE-SEC)	Formation	Depth(ft)	Yield	Temp	Reference
1	15-108-28	Wasatch	2218	42 gpm	79°F	a
2	15-109-10	Wasatch	2420	20 gpm	77°F	a
3	23-110-13	Wasatch	1725	420 gpm	71°F	a

Thermal Springs

	Name and Location	Formation	Yield	Temp.	Reference
4	Steele Hot Springs 32-107-16	Precambrian?	20 gpm	96°F	b
		Precambrian?	5 gpm	102°F	b
5	Kendall Warm Springs 38-110-2	Phosphoria?	3,600 gpm	85°F	b

[a] Welder, 1968

[b] Breckenridge and Hinckley, 1978

Table 8. Thermally measured wells in the Thrust Belt[1].

Location		Depth	Bottom-Hole Temperature	Gradient[2]	Interval[3]
Latitude	Longitude	(meters)	(°C)	(°C/km)	(meters)
42 58.8	111 0.7	83.0	10.496	27.9	20-83
42 49.8	110 56.8	195.0	11.188	25.6	120-195
42 47.2	111 2.4	44.0	7.336	21.4	10-44
42 46.8	110 55.1	60.0	11.338	18.6	20-60
41 51.8	110 34.8	130.0	28.499		
41 51.5	110 35.9	262.0	33.366	30.1	40-260
41 50.7	110 36.0	161.0	21.312		
41 50.7	110 35.6	61.0	21.640		
41 50.7	110 31.0	42.0	18.104		
41 50.2	110 36.2	168.0	23.646	30.7	110-160
41 50.1	110 30.8	86.0	22.342		
41 49.7	110 36.7	96.0	32.160	39.1	50-96
41 49.4	110 36.1	61.0	31.115		
41 41.6	110 37.9	153.0	10.694	22.6	80-150
41 41.6	110 37.9	152.0	10.478	26.3	80-140
41 41.6	110 37.8	52.0	8.175		
41 41.4	110 37.7	125.0	10.123	37.9	90-120
41 41.3	110 37.9	125.0	9.979	23.2	50-120
41 41.3	220 37.8	102.0	8.553		
41 41.0	110 37.8	96.0	9.363	26.3	50-90
41 41.0	110 37.5	174.0	11.526	15.5	50-174
41 41.0	110 37.5	80.0	8.317		
41 40.9	110 36.9	60.0	8.472	12.2	40-60
41 40.8	110 37.7	174.0	11.050	20.2	9-130
41 40.8	110 37.7	142.0	9.582	13.4	70-140
41 40.8	110 37.7	176.0	12.604	18.5	60-176
41 40.8	110 37.7	176.0	10.232	19.1	90-140
41 40.8	110 37.7	86.0	8.684		
41 40.8	110 37.7	166.0	10.630	20.0	80-160
41 40.2	110 36.9	101.0	9.145	9.2	50-101
41 17.7	110 40.1	75.0	9.197	15.6	50-75
41 16.9	110 40.9	110.0	9.082	17.1	40-110
41 16.8	110 40.9	218.0	12.899	26.6	120-218
41 16.5	110 41.0	98.0	8.277	11.1	30-98
41 9.9	110 47.9	270.0	13.688	28.0	50-240

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[1] Measured by University of Wyoming personnel following the method of Decker, 1973.

[2] Gradient represents a linear least squares fit of the temperature-depth data over the most thermally stable portion of the hole.

[3] Interval refers to the depth range in meters over which the least squares gradient was calculated.

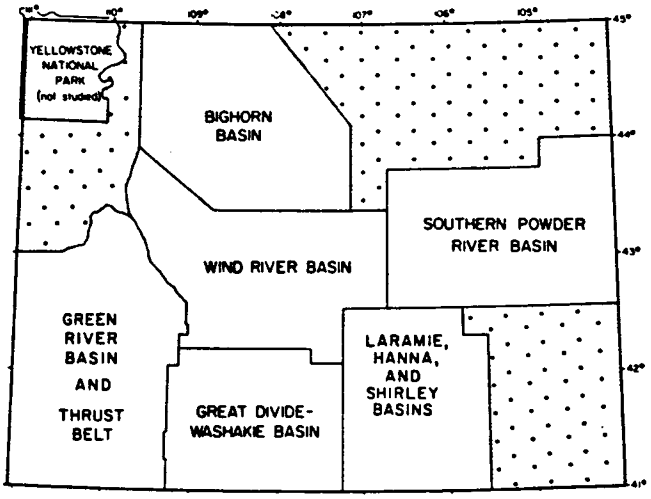


Figure 1. Study areas planned or completed in this series.

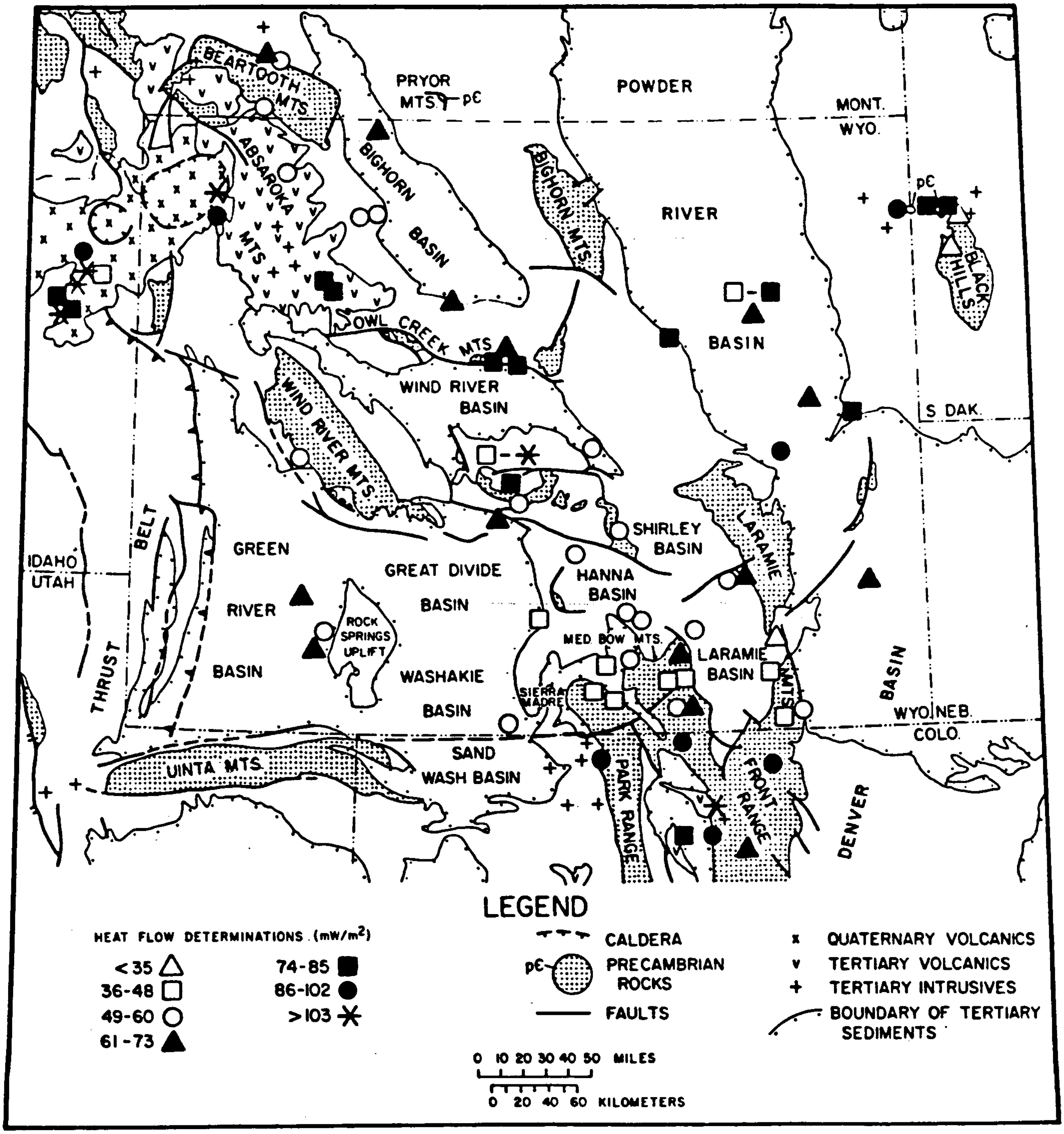


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.

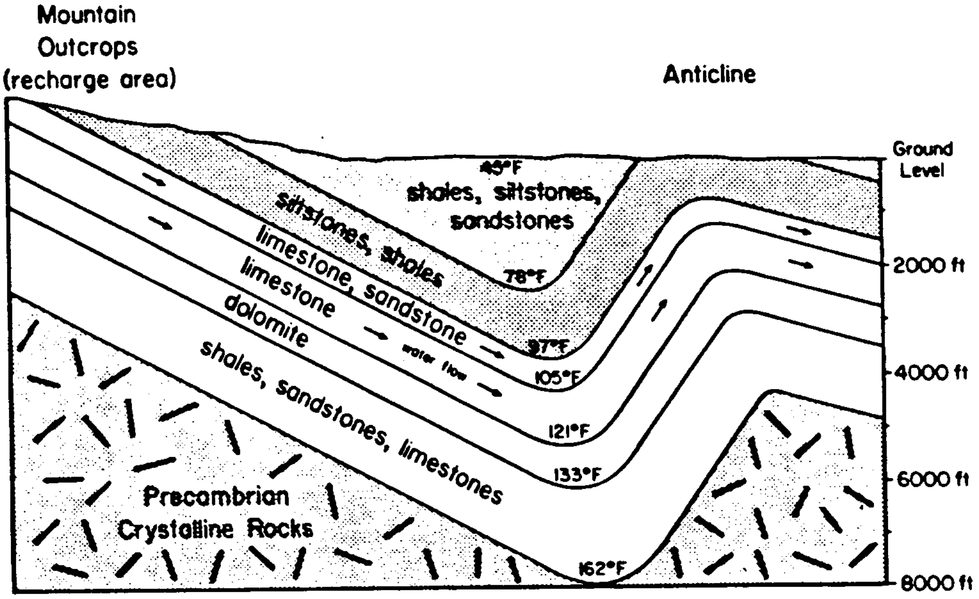


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

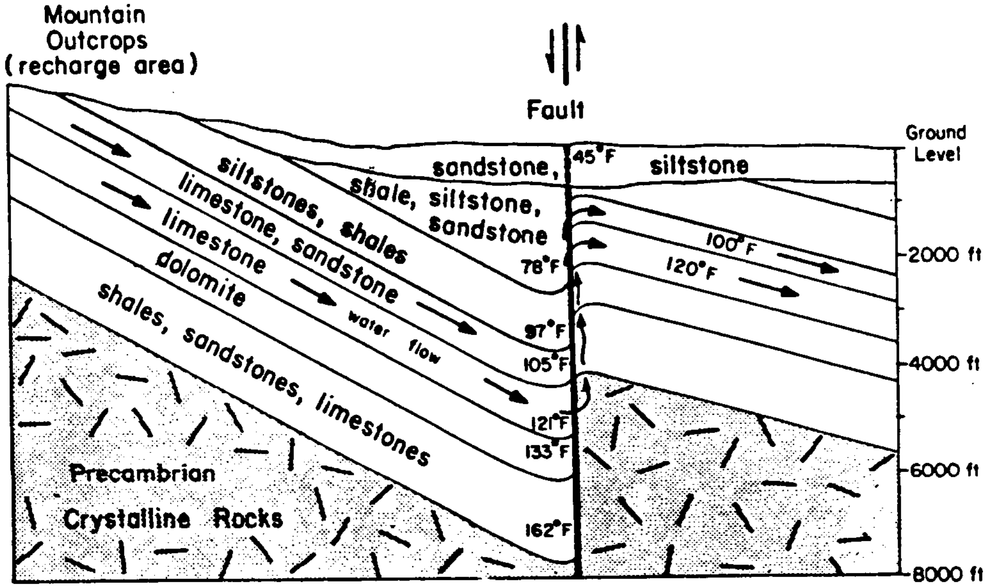


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

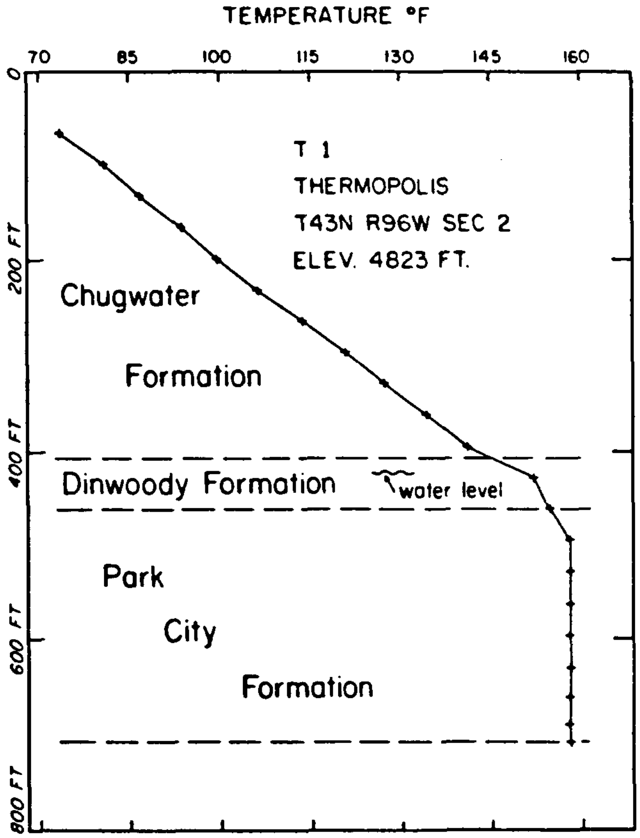


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.

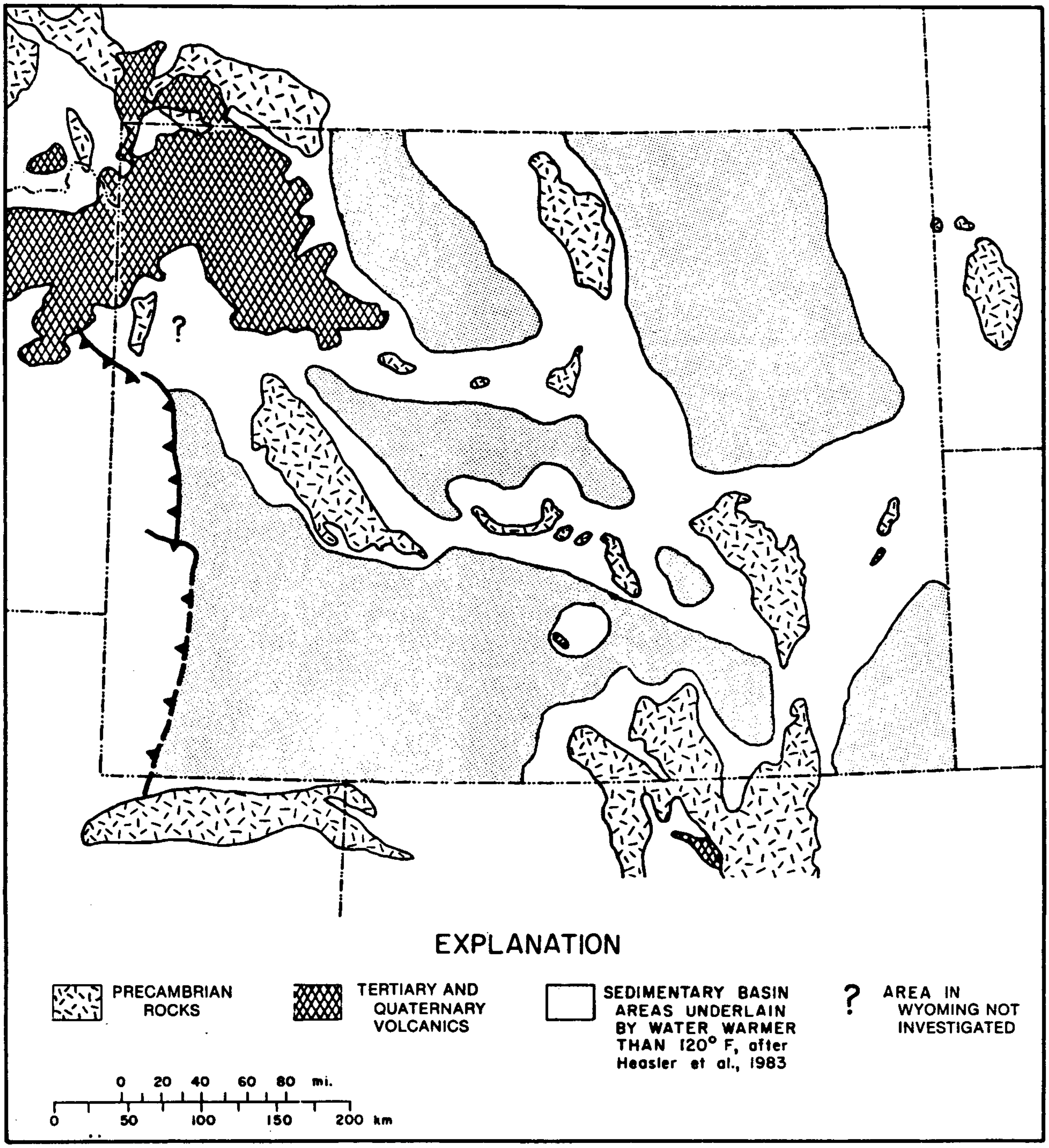
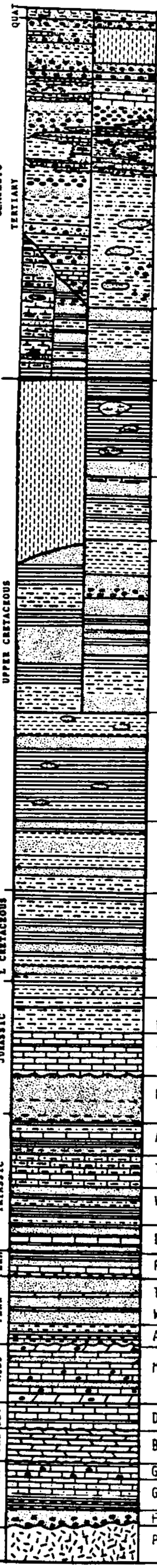


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.

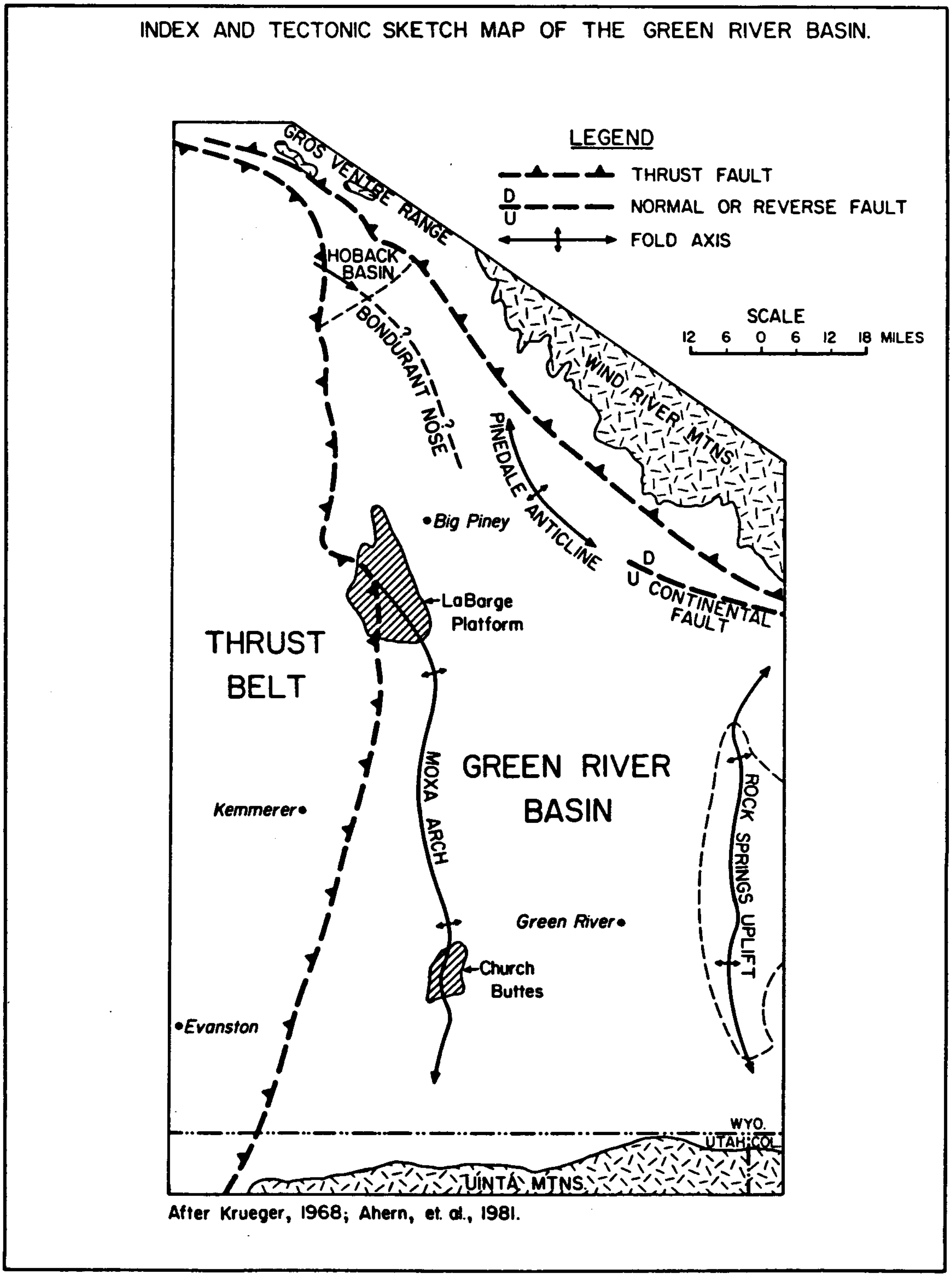


		GEOLOGIC FORMATION		THICKNESS (FT)[a]	LITHOLOGIC DESCRIPTION[b]	WATER-BEARING PROPERTIES[b]
CENOZOIC	QUAT	QUATERNARY DEPOSITS		100	Unconsolidated sand, gravel, silt, and clay	Productive water-bearing deposits yielding 50-500 gpm ..
	TERTIARY	CAMP DAVIS FM BROWNS PARK FM	SOUTH PARK FM	0-5200	Conglomerate, limestone, sandstone and tuffaceous mudstone	Major aquifer - well yields 10-120 gpm
		BISHOP CONGLOMERATE		0-200		
		BRIDGER FORMATION		0-2300	Tuffaceous lacustrine and flood plain deposits, becoming locally conglomeratic near the Uinta Mountains	Major aquifer in south - yields 2-100 gpm
		GREEN RIVER AND WASATCH FORMATIONS		0-2800	Green River Fm - lacustrine claystone, marlstone, oil shale and saline deposits with discontinuous lenses of fine-grained sandstone in the Laney and Tipton shale members; trona deposits in the Wilkins Peak Member Wasatch Fm - Newfork tongue (west) consists of mudstone, sandy with many lenses of fine-to course- grained sandstone; Cathedral Bluffs tongue consists of mudstone and sandstone	Major aquifer in east - sandstone lenses in Laney and Tipton yield 3-100 gpm to wells and springs, vertical permeability low due to heterogeneous lithology
		WASATCH FORMATION (MAIN BODY)		2500-7200	Silty to sandy claystone, lenticular beds of fine- to medium- grained sandstone becoming conglomeratic to the south and west	Major aquifer - well yields 1-1300 gpm in permeable sandstone and conglomeratic lenses
		(LEFT)HOBACK FM (NW) (RIGHT)FT UNION FM (SW)	FT UNION FM	0-2500+	Hoback Formation - interbedded sandstone and calcareous shale with thick conglomeratic lenses (8000-16,000 feet thick) Ft. Union Formation - fine- to medium- grained silty sandstone, lignitic mudstone with coal; coarsens near mountains, major coal seams in lower portion	Minor aquifer - locally utilized
MESOZOIC	UPPER CRETACEOUS		LANCE FORMATION	0-4500	Very fine- to fine- grained, lenticular, clayey, calcareous, dark shale, coal and lignite	Minor aquifer probably capable of yielding small quantities of water from fine-grained sands and conglomeratic sandstones at base
			LEWIS SHALE	0-2700	Calcareous to non-calcareous shale with beds of siltstone and very fine-grained sandstone	Regional aquitard
		MESAVERDE FORMATION	ALMOND FM	0-1000	Sandstone, siltstone, shale and coal	Major aquifer; Ericson sandstone capable of large yields in 7 wells east of basin boundary ranging from 15-200 gpm
			ERICSON FM	400-700	Sandstone, fine-grained to conglomeratic; middle siltstone and shale unit	
			ROCK SPRINGS FM	900-1700	Sandstone, fine- to medium- grained with interbedded shale and coal	
			BLAIR FORMATION	900-1800	Shale interbedded with siltstone and sandstone	
		BAXTER SHALE (CODY SHALE-NE)		2700-4500	Sandy shale with interbedded mudstone and shaley sandstone	Major regional confining unit
		FRONTIER FORMATION		50-2700	Lenticular sandstone, fine- to medium- grained; interbedded mudstone, claystone, siltstone, minor coal	Minor aquifer - irregular occurrence of high transmissivity due to variable cementation and lenticularity of beds; spring yields in west 1-100 gpm
	L CRETACEOUS	MOWRY SHALE		100-1000	Shale, hard, fissile with silty streaks, siliceous bentonite beds	Discontinuous aquifers - moderate water-bearing capabilties in Dakota and Muddy sandstones well yields 30-100 gpm in thrust belt
		DAKOTA SANDSTONE MORRISON FORMATION		400-600+	Sandstone with interbedded shale, clay and lignite	
	JURASSIC	STUMP SANDSTONE PREUSS REDBEDS (NW)		270-460	Interbedded sandstone, siltstone, mudstone, and limestone (Curtis Formation - Entrada Sandstone in southeast)	Aquitard
		TWIN CREEK LIMESTONE (NORTH,EAST)		150-725	Limestone, calcareous shale, gypsum and anhydrite (upper) Gypsum and anhydrite, red shale, siltstone, and dolomite (lower) (Gypsum Spring and Carmel Formations in southeast)	Minor aquifer -spring yields in west 75-300 gpm
		NUGGET SANDSTONE		400-700+	Sandstone, fine- to medium- grained, well sorted, minor amounts of cross-bedded clay and silt increasing with depth	Major Mesozoic aquifer - thrust belt springs yield up to 2000 gpm
	TRIASSIC	ANKAREH FORMATION		330-500+	Shale, interbedded siltstone, fine-grained sandstone, locally limestone in the middle portion	Minor regional aquifer -locally confining; spring in northwest yields 200 gpm
		THAYNES LIMESTONE		0-500+	Silty limestone with siltstone and shale in upper part	Major aquifer - most productive where solution openings and fractures exist
		WOODSIDE FORMATION		500-600	Anhydritic siltstone and mudstone with some fine-grained sandstone	Regional aquitard
		DINWOODY FORMATION		50-450	Siltstone, shale, dolomite;interbedded anhydrite in upper part	
PALEOZOIC	PERM	PHOSPHORIA FORMATION		200-400	Phosphatic carbonate, cherty shale, sandstone (northwest) Carbonate with sandstone (southeast)	Minor aquifer - locally confining
	PENN	TENSLEEP SANDSTONE (NORTH,EAST) WEBER SANDSTONE (SOUTH,WEST)		350-700	Fine-grained well-sorted sandstone with quartzite and thinly layered siliceous dolomitic limestone	Major aquifer - excellent secondary permeability where fractured; springs in thrust belt yield up to 2000 gpm
		AMSDEN FORMATION		300-600	Mudstone, siltstone, sandstone with cherty limestone	Minor aquifer - locally confining
	MISS	MADISON LIMESTONE		300-900	Limestone, thin-bedded to massive, brecciated and partly cherty; dolomite, thick-bedded to massive	Major regional aquifer - permeability dependent on degree of fracturing; spring in west yields 4000 gpm
	DEV	DARBY FORMATION		330-400	Limestone and dolomite, thin-bedded to massive, siltstone	
	ORD	BIGHORN DOLOMITE		150-500	Massive dolomite and dolomitic limestone	
	CAMBRIAN	GALLATIN LIMESTONE		0-200	Interbedded limestone, siltstone, and thin shale	Minor aquifer - potentially productive
		GROS VENTRE FORMATION		500-1000	Shale, with some sandstone and limestone beds	Regional aquitard
		FLATHEAD SANDSTONE		0-200 ?	Quartzite, fine-grained with coarse-grained sandstone lenses	Minor aquifer
	PREC	PRECAMBRIAN UNDIVIDED		?	Gneissic granite with schist, granite and pegmatite	Locally utilized aquifer near outcrop areas; spring yields 2000 gpm in northwest

[a] Thicknesses from Ahern, et al., 1981; Welder, 1968; and Petroleum Information Cards

[b] Lithologic descriptions and water-bearing properties from Ahern, et al., 1981; Welder, 1968, Collentine et al., 1981

Figure 7. Stratigraphic column for the Green River Basin.



After Krueger, 1968; Ahern, et. al., 1981.

Figure 8. Index and tectonic sketch map of the Green River Basin.

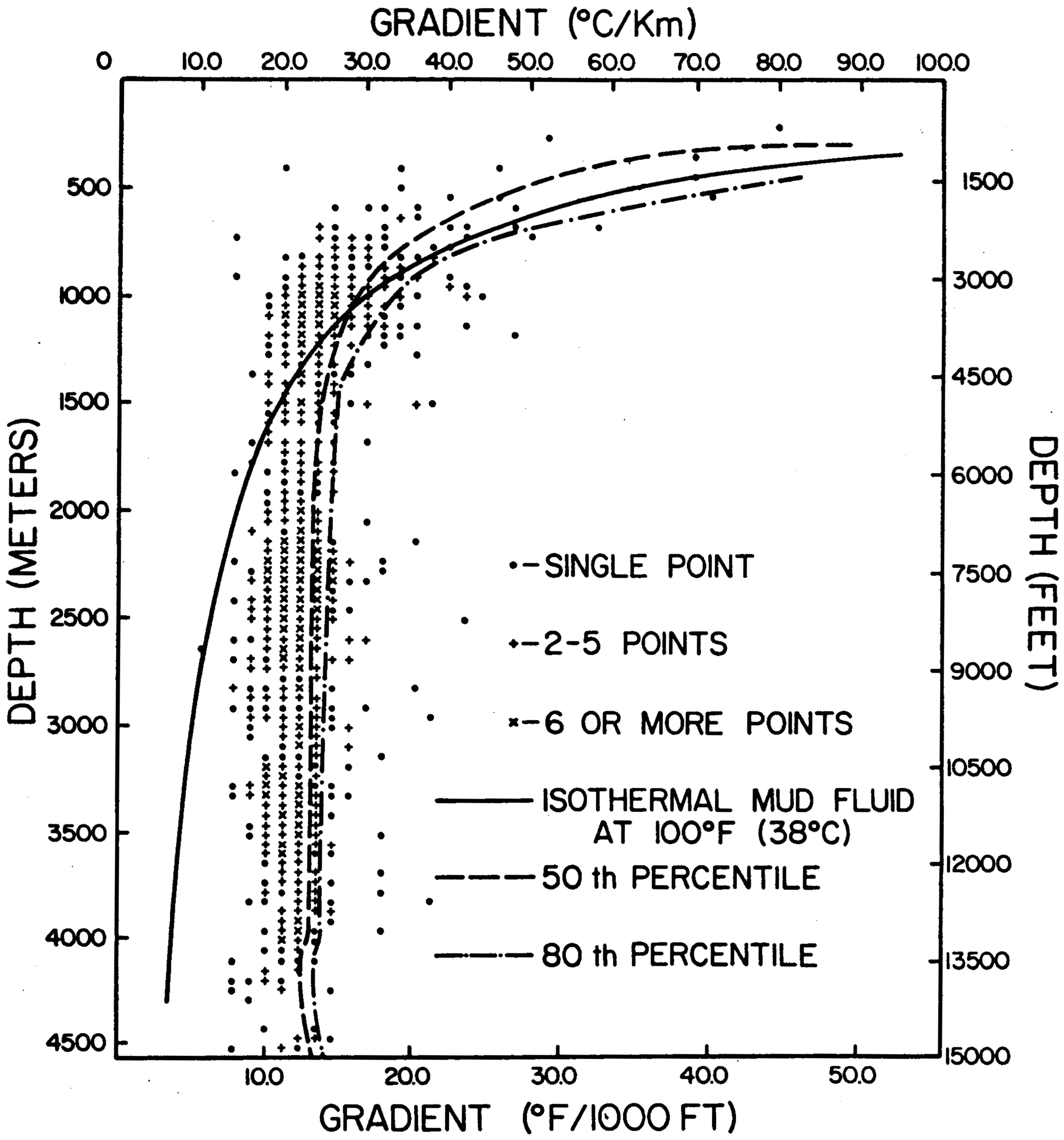


Figure 9. *GRADIENT-DEPTH PROFILE FOR GREEN RIVER BASIN, BASED ON 1529 BOTTOM-HOLE TEMPERATURES.*

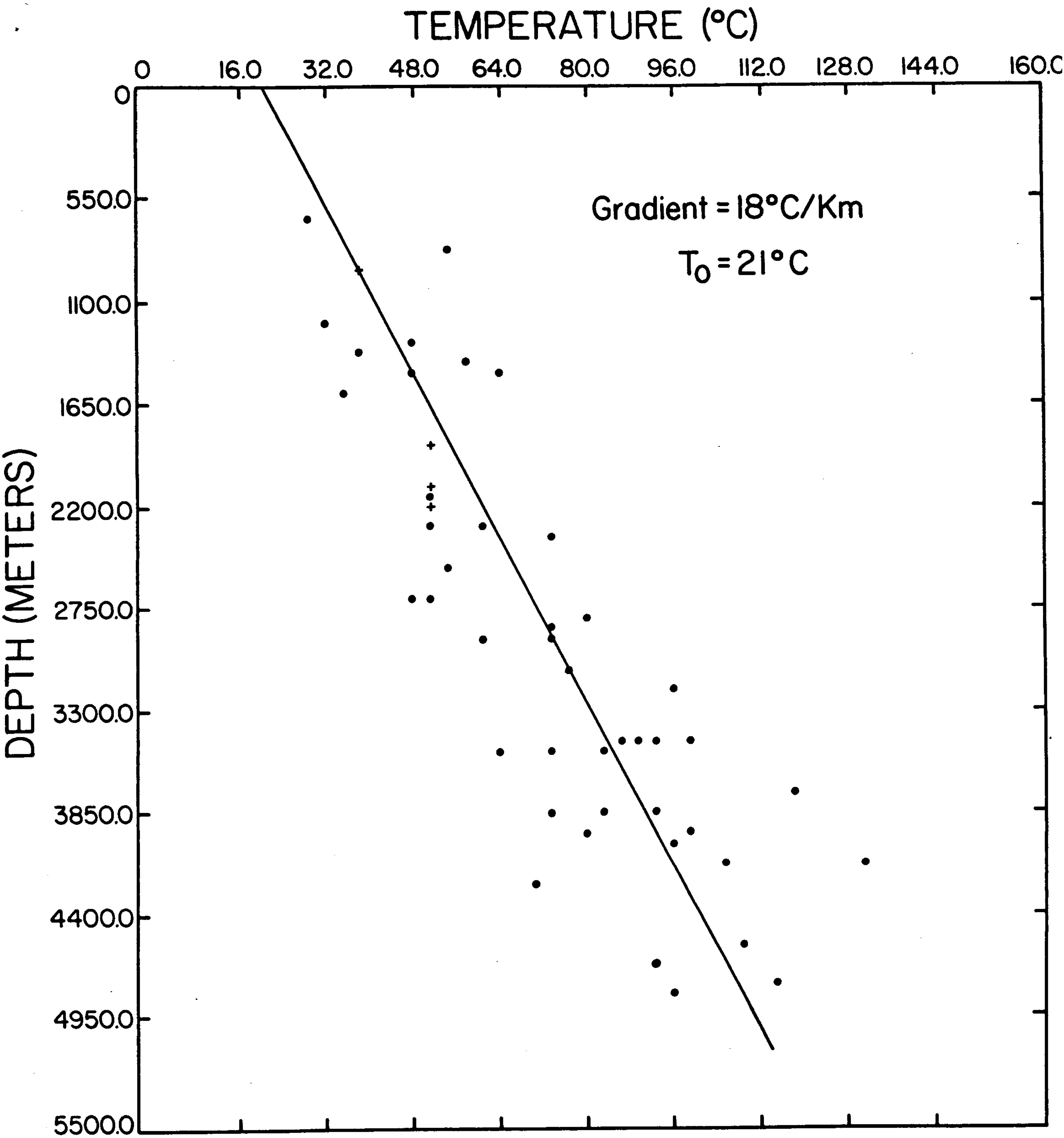


Figure 10. *TEMPERATURE-DEPTH PROFILE FOR THE THRUST BELT*

(based on 51 data values)

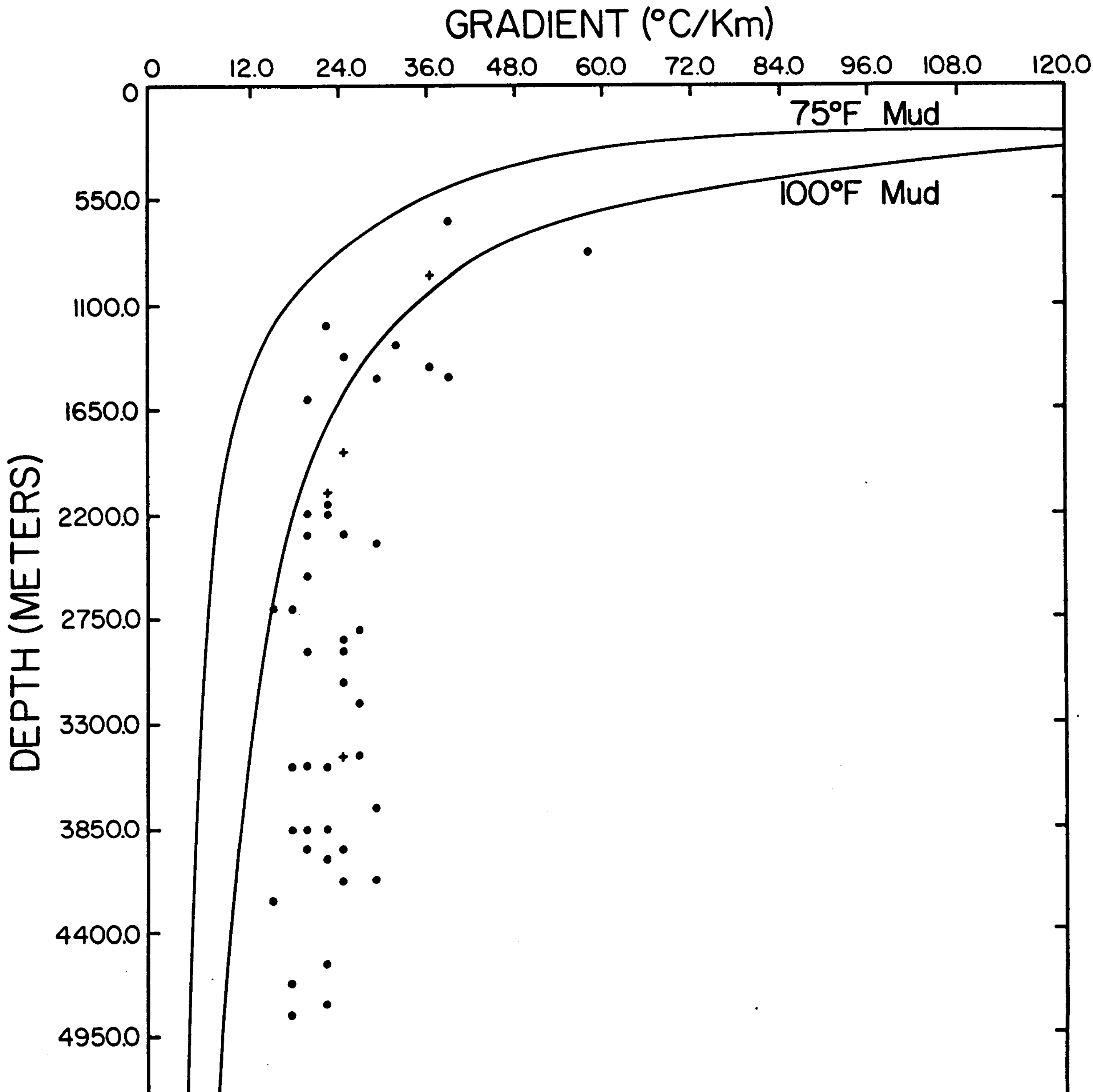
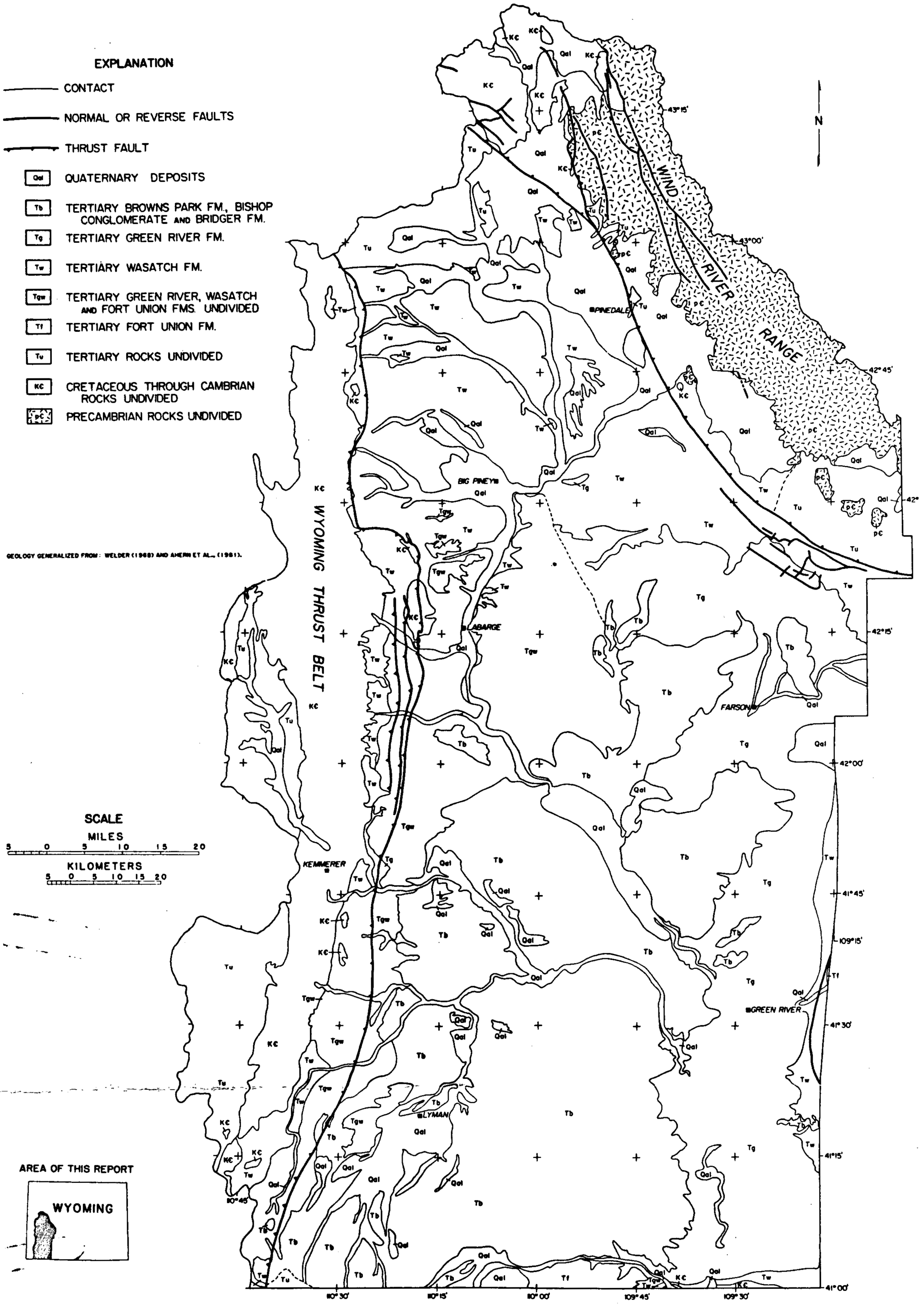


Figure 11. *GRADIENT-DEPTH PROFILE FOR THE THRUST BELT*

(based on 51 data values)

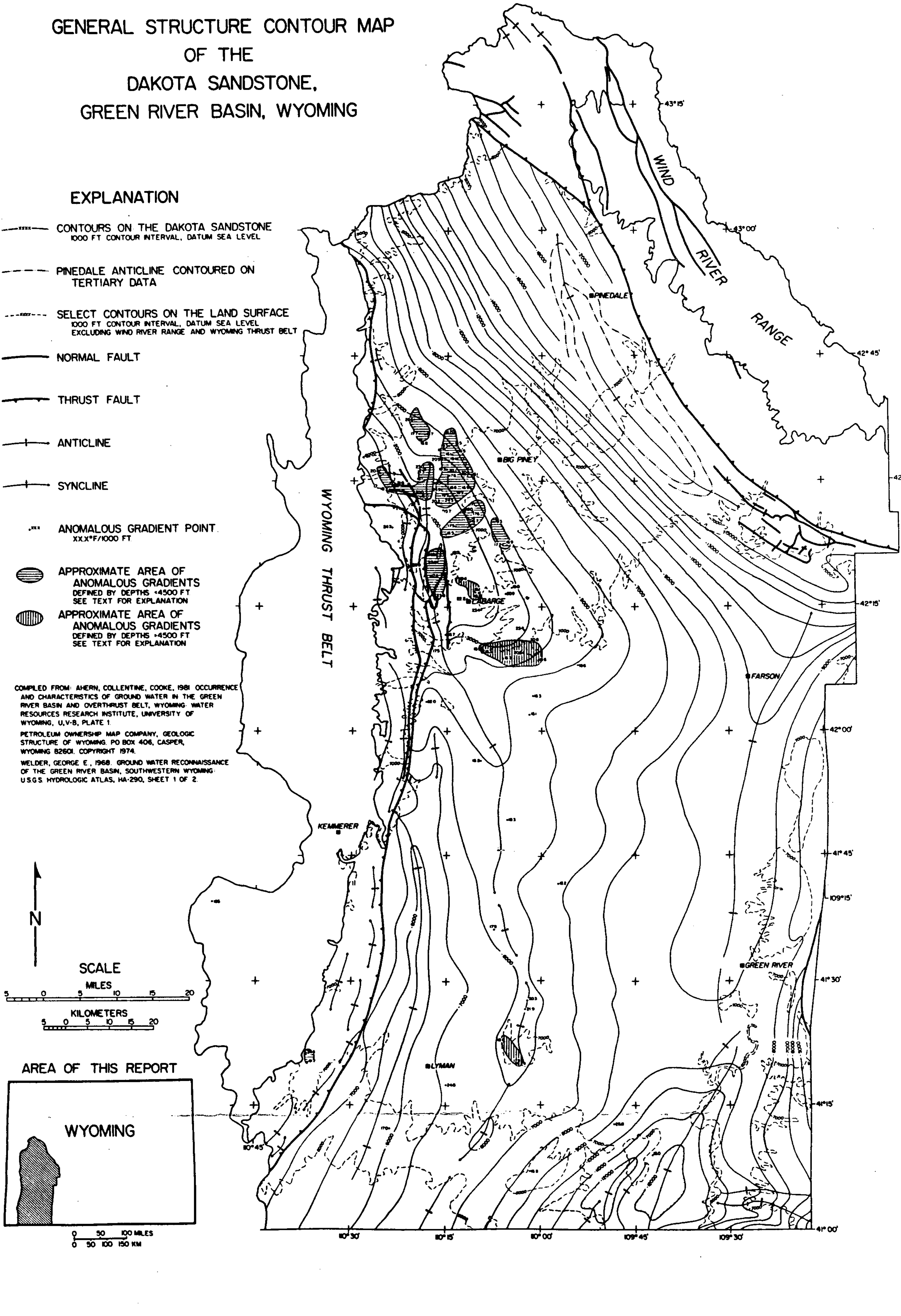
PLATE I



GENERALIZED GEOLOGIC MAP OF THE GREEN RIVER BASIN, WYOMING

PLATE II

GENERAL STRUCTURE CONTOUR MAP OF THE DAKOTA SANDSTONE, GREEN RIVER BASIN, WYOMING



COMPILED FROM: AHERN, COLLENTINE, COOKE, 1981 OCCURRENCE AND CHARACTERISTICS OF GROUND WATER IN THE GREEN RIVER BASIN AND OVERTHRUST BELT, WYOMING. WATER RESOURCES RESEARCH INSTITUTE, UNIVERSITY OF WYOMING, U,V-B, PLATE 1.

PETROLEUM OWNERSHIP MAP COMPANY, GEOLOGIC STRUCTURE OF WYOMING. PO BOX 406, CASPER, WYOMING 82601. COPYRIGHT 1974.

WELDER, GEORGE E., 1968. GROUND WATER RECONNAISSANCE OF THE GREEN RIVER BASIN, SOUTHWESTERN WYOMING: U.S.G.S. HYDROLOGIC ATLAS, HA-290, SHEET 1 OF 2.

PLATE III

THERMAL GRADIENT CONTOUR MAP OF THE GREEN RIVER BASIN, WYOMING

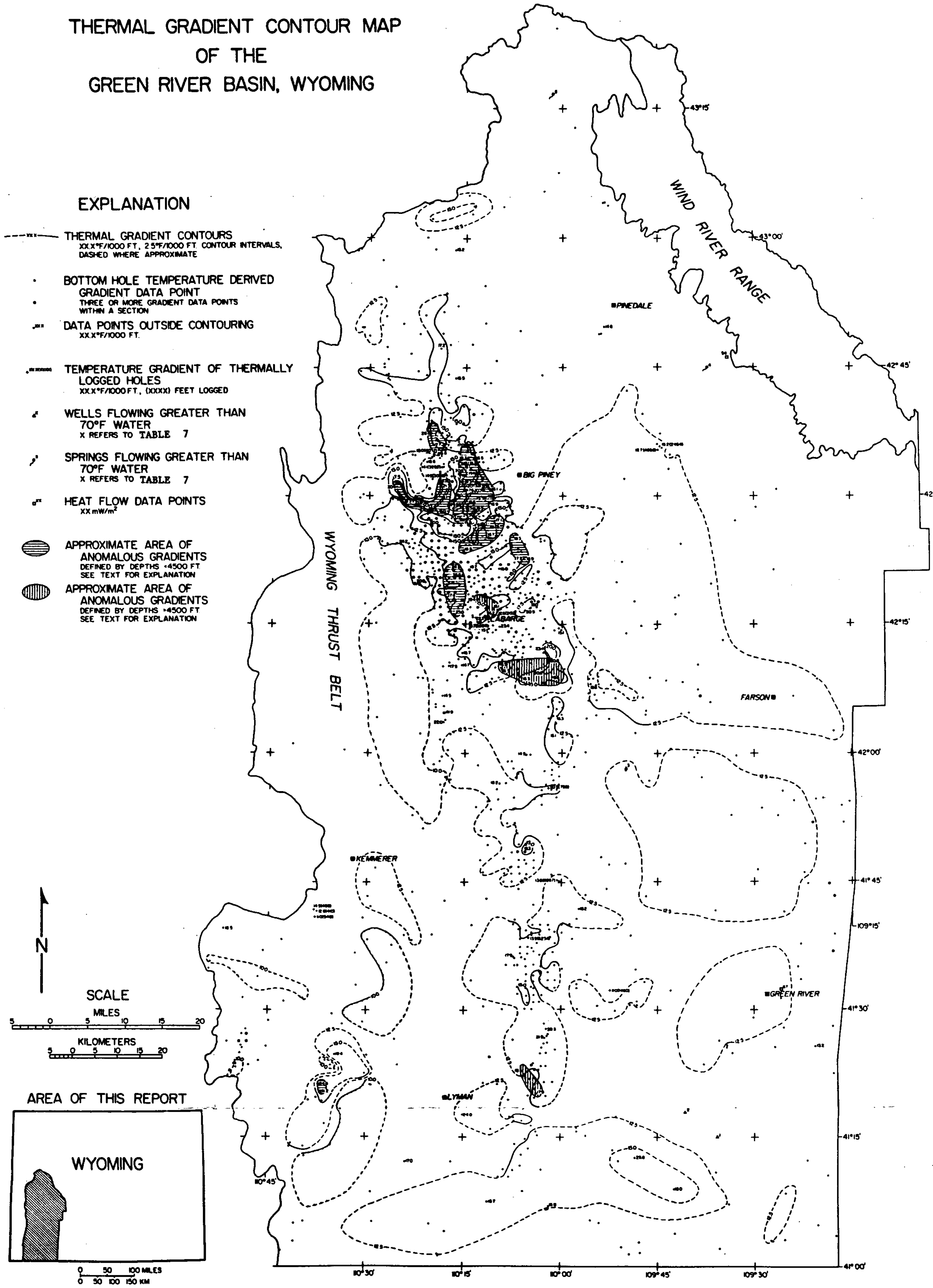
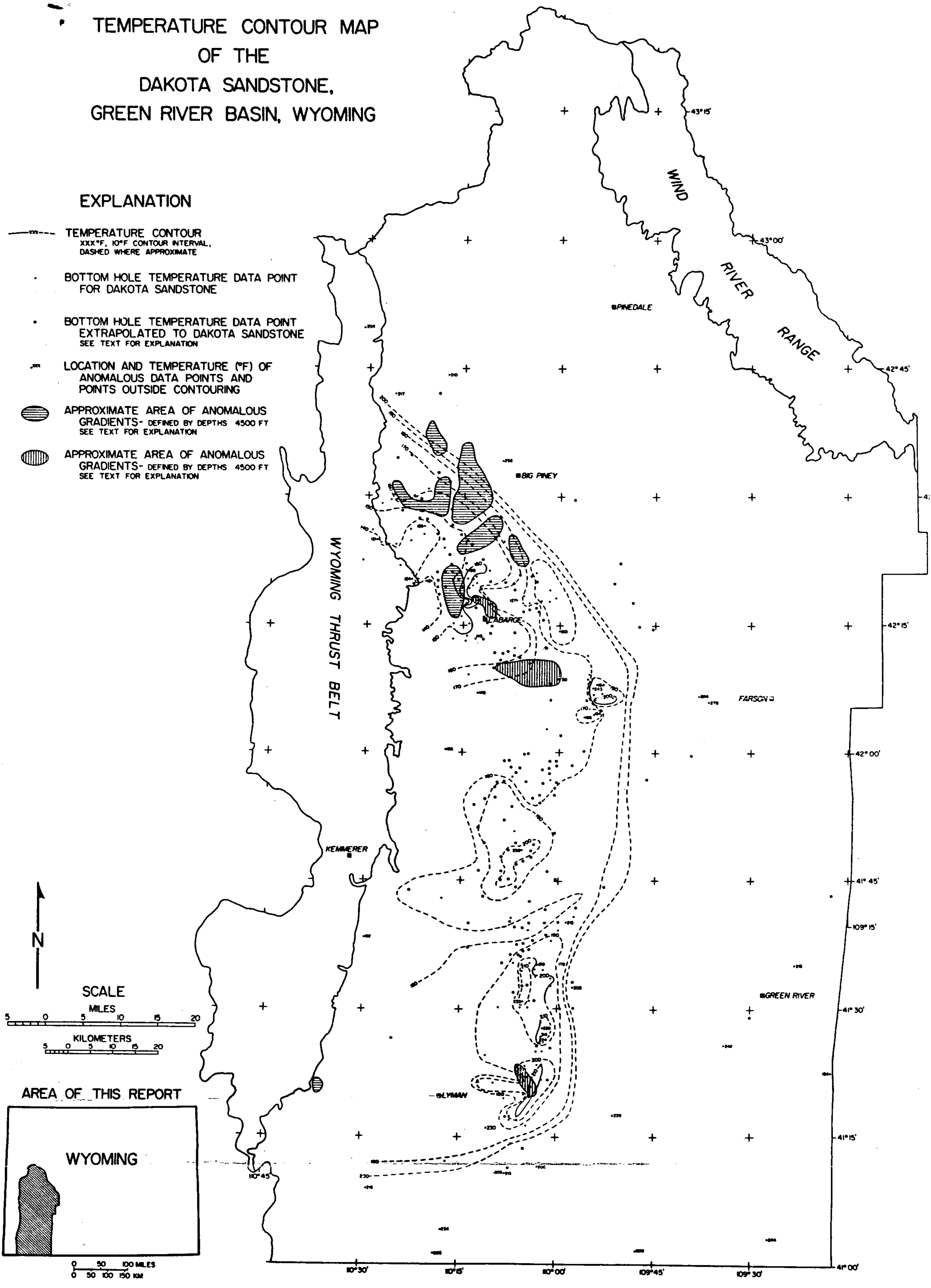


PLATE IV



TEMPERATURE CONTOUR MAP OF THE DAKOTA SANDSTONE, GREEN RIVER BASIN, WYOMING