GEOTHERMAL RESOURCES OF THE WIND RIVER BASIN, WYOMING

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 ($10^{-6}cal/cm^2sec$)= = 1 heat flow unit (HFU) = 0.013228 British thermal unit per square foot per hour (Btu/ft^2hr) = 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 sixth 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 three maps: a generalized geological map (Plate I), a thermal gradient contour map (Plate III), and a structure contour map (Plate II).

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 Wind River Basin of centeral Wyoming (Figure 1).

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, and by the Wyoming Water Research Center. 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/m^2 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 WIND RIVER BASIN, WYOMING

The Wind River Basin covers approximately 8,000 square miles in central Wyoming (see Figure 1 for location). Most of Fremont County and the eastern one-third of Natrona County are in the Wind River Basin. The basin is bounded by major mountain uplifts on the north (Owl Creek Mountains), west (Wind River Mountains), and south (Granite Mountains). This uplifts are complexly folded and faulted areas for which most or all of the sedimentary rocks have been eroded. Thus, they form distinct hydrologic as well as structural and topographic boundaries. On the east the Wind River Basin is bounded by a gentle uplift, the Casper Arch. Along this broad fold the oldest exposed rocks are of Juarssic and Lower Cretaceous age.

Like other Wyoming basins, the Wind River Basin includes many fold and fault structures superimposed on the overall downwarp of the basin. The background heat flow and ground water circulation patterns control geothermal resource distribution.

The geothermal setting of the Wind River Basin will first be described in the context of heat flow values. Then the relevant stratigraphy will be presented, followed by discussion of the major folds and faults in the basin. The distribution of geothermal gradients will then be analyzed through discussion of areas of anomalously high gradients. A brief discussion of the thermal springs in the basin follows. The major conclusions of the report are then summarized.

HEAT FLOW

Heat flow determinations have been made at five sites in the Wind River Basin (Table 2). These values were derived through precision thermal logging and conductivity determinations of holes into Precambrian basement rocks. They are believed to be free of hydrologic disturbances and representative of regional patters. The heat flow values come from two general localities: the Granite Mountains along the southern margin of the basin, and the Owl Creek Mountains along the northern margin. Values from the Granite Mountains area in the southern part of the Basin vary from 50-70 milliwats per square meter (mW/m^2). Values from the eastern Owl Creek Mountains indicate a a heat flow in the 70-80 mW/m^2 range. The northern values are higher than the moderate heat flows of the southern basin and correspond with a broad zone of moderate to high heat flows across central Wyoming tentatively identified by Muffler (1979) and Decker et al., (1980). The origin of this zone of higher heat flow is not known, and the boundaries are based on rough contouring of the sparse data available. In consideration of the gross structural fabric of the basin, heat flow values are assumed to be most uniform along east-west or northwest-southeast trends. The distribution of the north to south decrease in heat flow cannot be defined without intermediate data points. Analysis of gradient anomalies within the Wind River Basin (see thermal gradient section below) suggests the higher heat flow of the Owl Creek Mountains may extend at least part way into the basin.

Breckenridge and Hinckley (1978) suggest warm springs in the northwestern Wind River Basin may be due to high heat flow associated with the Absaroka volcanic complex. No heat flow determinations have been made for this part of the basin. However, Hinckley et al., (1982) suggests that the Absaroka igneous activity to too old to affect significant modification of present regional heat flow patterns. The effect on the study area of Late Cenozoic volcanism in the Yellowstone-Teton National Parks area immediately northwest of the Wind River Basin is not clearly understood, but this activity is of an age to create local, present-day heat flow anomalies.

Heat flow determinations in the Wind River Basin indicate geothermal conditions similar to the other Wyoming Basins. In a sequence of normal sedimentary rocks, purely conductive thermal gradients generally fall in the 12 to 15°F/1,000ft range; perhaps slightly higher in the northern basin due to somewhat higher heat flow. Such gradients are not usually considered sufficient to provide a useful geothermal resource by themselves, but will lead to the development of high temperatures at depth. Thus, where deeply circulating ground water is brought close to the surface by circulation over folds or up fault systems, highly elevated gradients and attractive energy resources may result.

STRATIGRAPHY - HYDROLOGY

In the Wind River Basin the mass transfer of heat by moving water creates areas of high geothermal gradients. Therefore, it is important to identify those strata with favorable water-bearing characteristics. In addition, the confining strata above and below there aquifers must be considered in terms of their effectiveness in restricting ground water flow patterns.

The stratigraphic chart for the Wind River Basin (Table 3) lists formation thicknesses, lithologies, and general water-bearing characteristics. Much of these data are drawn from Richter (1981) to whom the reader is referred for a thorough discussion of Wind River Basin hydrogeology. Plate I presents the surface distribution of the various strata to be discussed. As a first cut, strata are identified as major confining unit, aquifer, or major aquifer. It should be understood that these division are very general and that in local areas of relatively higher permeability and/or small water demand, any formation listed may constitute a useful "Aquifer".

The youngest deposits in the Wind River Basin are the sands, silts, and gravels deposited along stream channels. Because of their good accessibility, obviously good recharge, and generally high permeabilities, these quaternary deposits form one of the most important aquifers in the basin. Ground water temperature in this aquifer will generally approximate the mean annual air temperature, 43°F for most of the Wind River Basin (Lowers, 1960). Such waters have geothermal potential primarily through the use of ground water heat pumps. These devices can extract heat from any above-freezing waters and are therefore constrained more by general ground water availability than by the distribution of geothermal anomalies.

The Moonstone, Arikarree, and White River Formations are only present locally in the basin. Simiarly to the quaternary deposits, they are unconfined aquifers. This lack of confinement precludes significant ground water circulation upwards from deep zones of these aquifers. They are therefore unlikely to provide waters of elevated temperature. The Wagon Bed, Tepee Trail, and Aycross Formations are poor water producers, are present only in the extreme northwest and southeast parts of the basin, and are therefore of little geothermal interest.

The Wind River Formation constitutes most of the surface of the Wind River Basin. This highly productive aquifer alone accounts for approximately 50 percent of all private domestic wells in the basin. (An additional 30 percent are developed in quaternary deposits (Richter, 1981)). Although the Wind River Formation is mostly unconfined, interbedded low-permeability shale and mudstone layers create artesian conditions locally (Richter, 1981). As with the Quaternary deposits, the Wind River Formation is most geothermally attractive for ground water heat pump applications. It is considerably thicker than the quaternary deposits, however, may be overlain by several thousand feet or younger sediments. Thus, relatively high temperatures may be available in deep wells.

Beneath the Wind River Formation, strata begin to develop significant geothermal potential. With grater depth of burial, higher temperatures will occur under normal gradients. The Fort Union - Lance aquifer, for example, is over 10,000 feet deep in the central basin and has reported temperatures in excess of 200°F. With the incident of major confining units, artesian conditions may be imposed on underlying aquifers and the stage is set for the type of forced convection depicted in Figure 3. Since the geothermal potential of these Mesozoic and Paleozoic-age strata is dependent on local structures, generalization beyond overall aquifer productivity and water quality cannot be made. Aquifers in the lower Cenozoic and Mesozoic sections are generally dependent on sandstone layers for their productivity. Well yields up to several hundred gallons per minute (gpm) are reported from various of these strata though most yields fall in the 10-50 gpm range. Water quality from these units is quite variable, but is generally poor. Chloride and sulphate are the most common anions; sodium is the dominant cation (Richter, 1981).

As the stratigraphic chart indicates (Table 3), there are several major aquifers in the Paleozoic section. Most important of these is the Tensleep Sandstone, which is under significant artesian pressure beneath much of the Wind River Basin. Dana (1962) reports a Tensleep-Madison well near Lander flowing 3,000 gpm and Richter (1981) reports that Tensleep well yields "typically range up to several thousand galls per minute". Richter (1981) reports well yields of up to several hundred gpm for the Park City and Amsden Formations and the Madison Limestone. Richter proposes that these formations, along with the Darby Formation and the Bighorn Dolomite, be grouped with the Tensleep Sandstone as a single "Tensleep aquifer system". This system has generally good quality water except in the deep, interior basin. Cations are mixed, with calcium and magnesium generally greater than sodium. Bicarbonate and sulphate are dominant anions.

At the base of the sedimentary section is the Flathead Sandstone. This unit has been developed as a highly productive aquifer in parts of the Bighorn Basin. It is known to produce moderate quantities of good quality water in the Wind River Basin, but has not been developed to any significant extent.

STRUCTURE

At sufficient depth, high temperature water could be developed from any of the aquifers discussed above. This is due to the simple increase in temperature with depth which occurs in the earth. In the structurally lowest part of the Wind River Basin, for example, the Flathead Sandstone should contain water in excess of 450°F. Even so, water temperatures reflecting only normal, background gradients are not generally considered valuable enough to justify well-drilling costs. Only where these deep heated waters are transfered closer to the surface will a significant geothermal resource exist. That transfer can be accomplished artificially via a drill hole, e.g. one drilled for oil and gas exploration and development, or naturally, structurally as in the schematic fold or fault of Figure 3.

Plate II is a contour map of the top of the Lower-Cretaceous age Cloverly Formation. It is essentially a simplification of maps by Barlow and Haun, 1978) and Keefer (1970). In a general, basin-wide sense, all the sedimentary formations older than Upper-Cretaceous in the Wind River Basin accumulated as a horizontally layered stack. This stack was deformed during the latest Cretaceous and Early Cenozoic to produce the structural relief seen in the Cloverly Formation. Thus this surface in general represents the structural relief of higher and lower strata in the basin. It is representative of other pre-deformation strata in all but the absolute elevations.

During and following this period of deformation, sedimentary material was continually eroded from the uplifts and deposited in the forming basin. This created broad, thickening basinward wedges of the Tertiary sediments. Thus, such aquifers as the Fort Union and Wind River Formations are progressively less deformed than underlying strata and less likely to contain geothermally useful fold and fault systems.

Mesozoic and Paleozoic aquifers receive precipitation and runoff recharge where they are exposed at the surface along the basin-bounding uplifts (see Plate I). Waters then move basinward, escaping upwards where faults or erosion have eliminated confinement. A general circulation for the Cloverly Formation has been proposed by Richter (1981) and is indicated by the arrows on Plate II. Given the similar geometry and recharge patters of most Mesozoic and Paleozoic strata, flow patterns are assumed to be similar.

THERMAL GRADIENTS

Information on thermal gradients in the Wind River Basin comes from two sources: oil and gas well bottom-hole temperatures (BHT's), and precision thermal logging. Tables 4 and 5 present summaries of the 1,733 bottom-hole temperatures and calculated gradients collected for the Wind River Basin. Temperatures range from 65 to 370°F, yielding gradients from 2.6 to 144.4°F/1,000 ft. Shallower than approximately 2,500 feet, all reported temperatures are less than 100°F and, along with their calculated gradients, are therefore subject to considerable error as discussed earlier. Nonetheless, the table lists many gradients in excess of 20°F/1,000 ft which are confidently based on deep holes with high temperatures. Table 6 lists data from the precision thermal logging of wells in the Wind River Basin (data from Heasler et al., 1983). These data are plotted on Plate III.

An alternative view of the BHT data is presented in Figure 7. Figure 7 shows the effect of drilling mud in creating unrealistically high gradients at shallow depths. The divergence of the 100°F mud curve from a significant portion of the data (e.g. the 80th percentile curve) indicates that only below 2,000 to 3,000 feet will bottom-hole temperatures be consistently free of drilling fluid induced increases. Points to the right of the 80th percentile line on this plot are those considered to represent possibly significant geothermal anomalies.

The areal distribution of gradients is presented on Plate III. All available bottom-hole temperature data, thermal logging, thermal spring, thermal well, and heat flow data are plotted on this map and approximate gradient contours are proposed. Where gradients identified as anomalous (based on Table 5 and Figure 7) occur in the same vicinity, an area of anomalous gradient is mapped. Due to the uncertainty of individual gradient points, contours and anomalous areas are generally based on consideration of a group of values for a given area.

Table 7 provides summary information on each of the areas of anomalous gradient identified on Plate III. Even in these areas, however, gradients are not extreme. Nowhere, for example, are there confirmed gradients as high as those for the Thermopolis and Cody areas of the Bighorn Basin (Hinckley et al., 1982; Heasler, 1982). The "approximate depths", "temperatures", and "principle formations" of Table 7 are simply those from which the available gradient data derive. While there is no implication that the anomaly is confined to these brackets, extrapolation to much shallower or much deeper zones must be done cautiously.

Since the basic heat flow into the Wind River Basin is insufficient to create high conductive gradients, geothermal anomalies are primarily a function of convective redistribution of heat. The complex interaction of ground water and geologic structure is the principle geothermal agent. The following pages will discuss what is known or can be deduced about that interaction in the Wind River Basin. General principles will be developed along with individual system specifics through analysis of each of the mapped anomalous areas. Included is consideration of temperatures, depths and general character of the potential geothermal resource, and possible, unverified extensions to the anomalous areas. The discussion begins with Area 2, where there are abundant data and a relatively straightforward geothermal system.

The high gradients of area 2 are perhaps the most well established of any in the Wind River Basin. In addition to abundant oil and gas well bottom-hole temperature data is a confirming thermally logged hole and a major hot spring (see Plate III). Plate II shows the coincidence of the area with a major fault system paralleling nearly the entire length of the Wind River Mountains. In addition, at Area 2 there is a significant fold immediately northeast of the fault system. The indicated ground water flow direction is northeastward and eastward off the flank of the mountains, descending into the Wind River Basin. Subtracting the structure contour elevations (0-1,000 feet) from the approximate surface elevation (6,000 feet) shows the top of the Cloverly to be around 6,000 feet deep adjacent to the fault. Addition of the 2,500 feet of intervening strata (see Table 3) places the Park City (Phosphoria) Formation at 8,500 feet with the Madison Limestone at 9,500 feet. A gradient of only 12°/1,000ft would thus lead to formation and contained ground water temperatures of about 150°F. Displacements across the fault system range from 3,000 to 6,000 feet. In the vicinity of Area 2, strata are uplifted approximately 4,000 feet on the northeast side of the fault. Folding has deformed the strata up an additional 3,000 feet (see Plate II) which means the Cloverly Formation was brought above the present land surface and eroded away at the crest of the fold. Waters in the Paleozoic aquifers remain confined beneath relatively impermeable strata, moving up and over the fault/fold system and delivering deep heated waters to the near surface.

The resource potential of Area 2 can be addressed based on this model. The presence of the generally productive Paleozoic aquifers at relatively shallow depths is advantageous where water quantity and quality are considerations. The depth/gradient aspects of this system indicate around 140°F as the maximum temperature likely to be encountered. This is in reasonable agreement with the 100 to 130°F bottom-hole temperatures reported when allowances are made for moving ground water failing to reach full equilibrium temperatures in the deep portion of the system, and for some cooling as waters ascend to shallower zones.

The major complication in the flow system of Areas 2 and 3 is faulting. Where strata are simply deformed into folds, stratigraphic continuity and ground water flow patterns are generally maintained (although the fracturing attending folding of competent rock layers may greatly enhance permeabilities along steep flexures). The effect of faulting, however, is quite variable. Faulting may create ground water pathways up through normally confining beds. Such zones as these may allow deep heated waters to rise to the near-surface, creating geothermal anomalies in the absence of folding. On the other hand, faulting may produce tight, impermeable zones which seriously restrict ground water movement. Also, the juxtaposition of permeable and impermeable strata across a fault may reduce or eliminate hydraulic continuity. Faults will change in configuration and effect on hydrology at different places, and thus produce effects which may be quite difficult to anticipate. In addition large, deep faults presented on Plate II are somewhat conjectural, based on interpretation of subsurface data, in some cases with little or no surface expression.

At present the effect of large-scale faulting on geothermal systems can best be analyzed emperically. The existence of geothermal anomalies strongly suggests that water is moving up and across the fault system in the vicinity of Areas 2 and 3. Elsewhere along the fault the effect is different. North of Area 2, for example, there are many bottom-hole temperature points, yet no gradient anomaly is indicated. Given the deep syncline just west of the fault along with the 5,000 foot fault displacement, the setting for a major geothermal system is created. Presumably, then, the fault in this area does not permit the free passage of ground water. Such a restriction is also indicated by the ground water flow parallel to the fault system in this area proposed by Richter (1981) (see Plate II).

Between Areas 2 and 3 are few data points to confirm or deny a gradient anomaly. If the general ground water flow directions of Richter (1981) are correct, the explanations of Areas 2 and 3 suggest the anomaly may extend all along the length of the fault (although adjacent folding is most developed in and around Areas 2 and 3). The thermal well southeast of Lander is also on this fault system. It flows 99°F water from a depth of 1,884 feet for a gradient of 30°F/1,000ft. Bottom-hole temperature values between this and Area 3 do not indicate high gradients, but data are sparse. Thus, it is not known whether the well marks an isolated area of anomalous gradient or a continuation of the Area 3 anomaly along the fault.

Area 1 essentially coincides with the Dubois Oil Field. The structure is complicated and not well understood in this area. The thick mantle of volcanic rocks in the area further confuses outcrop/recharge relationships. The depths and temperatures used to define the area are large enough to be reasonably secure. Hydrologic control is assumed to some combination of folding and faulting of undetermined extent.

Area 4 is established by only 2 data points, from approximately 3,000 feet. The area occupies the crest of a major fold, however, and is located so as to receive a component of ground water flow from deep areas to the southwest. Closer examination of the area including thermal logging would be necessary to verify the anomaly.

Area 5 is established by 3 data points. These points range over 6,500 feet of depth. A maximum temperature of 230°F is reported and is considered relatively reliable. The area is located near the top of a fold, the southeast limb of which is faulted as it dips very steeply into the adjacent syncline. Confined ground water arriving at area 5 from the east and southeast rises around

7,000 feet in the last four miles. For the Cloverly Formation this is sufficient to produce a gradient anomaly of 25°F/1,000 ft and temperatures of over 200°F (at a background gradient of 12°F/1,000 ft). For the Tensleep Sandstone, approximately 2,500 feet deeper, around 30°F can be added. Ground water flow from the southwest could produce only normal gradients at Area 5 and is therefore not indicated. Also, it can be inferred that the fault just west of Area 5 does not seriously restrict ground water movement.

Area 6 is in essentially the same configuration as Area 5, except that Area 6 exists on both sides of the fault. This is additional evidence that the fault is not a ground water barrier and that it may actually create a fractured zone of locally increased permeability. Gradients are somewhat lower in Area 6, reflecting the shallower nature of the adjacent syncline. This anomaly may extend all along the fault/fold system between areas 6 and 5. Numerous data northwest of Area 5, however, are consistent in marking a generally normal gradient in that area.

Area 7 coincides with the faulted portion of the Conant Creek anticline. Thermal springs issue from the Park City Formation in this area, where erosion has cut through the confining beds of the Chugwater Formation. Although the Springs flow only 61°F, within a third of a mile is a well (presumably with more direct subsurface access) flowing 70°F (Breckenridge and Hinckley, 1978). The Park City and Tensleep aquifers plunge northward from the spring site, and bottom-hole temperatures are as high as 140°F. Breckenridge and Hinckley (1978) discuss this geothermal system in reference to the springs and present the model of northeastward ground water flow heated in the depths of the syncline between Area 7 and Area 8. Any flow from the west or southwest would be adequate to produce the observed temperatures in the Paleozoic formations beneath Area 7. Richter's (1981) proposal of flow from the southeast would almost certainly be inadequate, and is therefore not indicated. Were it not for the thermal springs and flowing well, the sparse bottom-hole temperature data would probably not be considered sufficient to verify an anomaly in contradiction of the previously proposed flow direction.

Area 8 is defined by numerous and consistent bottom-hole temperatures from deep zones with high temperatures. Although there are no surface flows from this system, thermal logging confirms the bottom-hole temperature derived gradients. Most of the temperature values are from the Tensleep Sandstone which range from 150 to 180°F. The highest temperature reported for this area is 234°F from the Park City Formation at a depth of 5,443 feet. Like most of the anomalous areas discussed so far, Area 8 occupies the top of the fold, adjacent to a large displacement (2,000-3,000 feet) fault and a deep syncline. The Tensleep Sandstone is approximately 12,000 feet deep just west of Area 8, and is around 10,000 feet deep even in the shallower part of the syncline south of the anomaly. This is sufficient to produce temperatures of 180°F even at a 12°F/ 1,000 ft gradient. Ground water flow from the structural depression just northwest of Area 8 could be 230°F at this gradient. Thus, the gradient anomaly is consistent with ground water flow northward and eastward off the flanks of the Wind River Mountains.

As in previous cases, the anomaly at Area 8 requires that the fault not seriously impede ground water movement in that vicinity. Bottom-hole temperatures north and south of Area 8 along the same structural trend are not generally anomalous. A change in the hydrologic effect of the fault is a possible explanation of this distribution.

Area 9, 10, and 11 are weak anomalies. Gradients of 15-20°F/1,000ft are well established by deep wells into a variety of upper Mesozoic and Lower Cenozoic strata. The highest reported temperature in these areas is 348°F, from a depth of 20,853 feet in Area 9. These areas occupy one of the structurally lowest portions of the Wind River Basin, just south of a major and complex fault zone. The north side of this fault system has been uplifted to form the Precambrian cored Owl Creek Mountains. Displacements in excess of 20,000 feet are common; stratigraphic and hydrologic disruption is total. Due to the great depths involved and the very thick Tertiary section in this area, Pre-Cenozoic structure is not well known. As discussed earlier, Plate II is compiled for the Cloverly Formation but corresponds in general geometry to all strata deposited prior to the folding and faulting of the Cloverly Formation. The ages of the formations containing the data which define Areas 9-11 span the time of these deformational events, which further complicates the structural environment of any geothermal system.

Area 9 roughly conforms to the crest of a broad anticline in the Cloverly Formation. Structural mapping by Barlow and Haun, (1978) indicates this fold involves strata as young as the Waltman Shale Member of the Fort Union Formation. Ground water flow regimes are not known for the area, so maximum temperatures and anomaly extent cannot be predicted. Due to the great thickness of overlying Wind River Formation, and the moderate gradients involved, this anomaly probably only represents a useful resource where existing drilling provides access.

The origin of areas 10 and 11 is even less clear, for there does not appear to be the general structural control of folding as at Area 9. Whether there are unrecognized faults and folds controlling the flow of heated ground water in these deep systems is not known. Given the total thickness of sedimentary rocks in these areas, temperatures in excess of 400°F may be generated in the Paleozoic aquifers under normal gradients. If the ground water in these units accessed higher strata, anomalies would be grater than those already discussed.

An alternative explanation for the indicated anomalies in Areas 9-11 is higher heat flow. Measured heat flows just to the north in the Owl Creek Mountains are sufficient to create purely conductive gradients in the range of those observed (depending on formation thermal conductivities). In this case the apparent absence of structural/hydrologic control is no longer a problem for the moderately high gradients could be caused simply by the higher heat flow. Further study of the hydrology and thermal conductivities of the strata in this area may serve to define the geothermal potential and to refine understanding of regional heat flow as well.

Area 12 is on the margin of the Wind River Basin, in a configuration similar to that of Areas 6-8. Major faults dominate the structure, though the area roughly corresponds to the crest of a north-trending anticline. Based on Plate II, ground water circulation in confined aquifers is probably not deep enough to create this anomaly. Thus, vertical migration of ground water along the faults is a more likely mechanism. The thermal gradients of three data points identifying Area 12 are not high, however, and further exploration is needed to verify these gradients.

Area 13 is in a complexly faulted region which is an extension of the basin-bounding fault system of Area 9. In this environment it is highly unlikely that continuous, confined aquifers exist. It is much more difficult to assess the geothermal effects of fault-created zones of vertical permeability than to analyze simple fold systems. With detailed, deep thermal logging and geochemical studies it might be possible to delineate the mechanisms creating anomalies such as this. At the present, we can only infer that waters heated in deeper strata are rising along fault zones to create the gradient anomalies observed in overlying units. In such a case, the anomaly can be expected to decrease with depth.

Area 14 appears to be fold controlled. Waters confined to the Tensleep aquifer and moving into the area from the south and southeast will have passed through depths sufficient to produce the observed temperatures under normal geothermal gradients. Waters in deeper aquifers may be 20-30°F warmer, so the maximum temperature likely to be developed for this area is less than 200°F. In absence of faults and fractures to increase permeability and allow vertical migration of water between aquifers, the observed gradients are probably as high as this system can produce.

THERMAL SPRINGS

Breckenridge and Hinckley (1978) identify 7 thermal spring localities in the Wind River Basin. (see that bulletin for detailed discussion including water temperatures, flows, chemistry, and flora.) Fort Washakie Hot Springs and Conant Creek Springs have been discussed in connection with anomalous gradient Areas 2 and 7 respectively. Although the remaining five localities are definitely geothermally anomalous, they have not been included in the previous discussion due to a lack of subsurface thermal information. All seven thermal spring localitites are shown on Plate III.

In the southeast corner of the basin is 75°F Horse Creek Springs (T.32N., R.86W., sec. 35). According to

Breckenridge and Hinckley (1978) the springs flow from alluvium along the east-west trending north Granite Mountains fault system; both cooling Eocene age Igneous rocks in the area and deep circulation along the fault system are offered as possible heating mechanisms. As discussed above, igneous activity of this area is probably too old to still contribute significant heat. Thus, the fault system becomes the most plausible mechanism for the thermal springs. This suggests a thermal anomaly may extend for some distance east and west from the springs.

Sweetwater Station Springs (T.29N., R.95W., sec. 15), west of Jeffrey City, are also fault controlled (Breckenridge and Hinckley, 1978). That nearby bottom-hole temperatures reflect normal gradients indicates the localized nature of the spring system. This also raises the question of how many more small, fault-controlled geothermal systems exist in the Wind River Basin which have neither surface expression in springs nor the oil producing potential to attract discovery through drilling.

The most enigmatic geothermal phenomena in the basin are the thermal springs near Dubois. From north to south these three spring localities are: Warm Spring Creek Springs (T.42N., R.107W., sec. 32), Little Warm Spring (T.41N., R.107W., sec. 14), and Jakeys Fork Spring (T.41N., R.106W., sec. 29), and flow a total of 700 gpm at an average temperature of 78°F (Breckenridge and Hinckley, 1978). As can be seen on Plate III, these springs define a line parallel to the northeast flank of the Wind River Mountains. All three localities are along the contact of the Park City Formation and the overlying Chugwater Formation. Reflecting this same strong stratigraphic control are extensive travertine deposits running southeast from the springs over 30 miles (Breckenridge and Hinckley, 1978). Gilliland (1959) reports a total sub-

Chugwater sedimentary thickness of 3,000 feet. Mapping by both Gilliland (1959) and Keefer (1970) indicate no significant disruption of the gentle basinward dip of the strata in this area, and nearby bottom-hole temperatures indicate gradients no higher than 15°F/1,000 ft. Thus, circulation of ground water to the lowest strata in the section is necessary to produce the observed temperatures at the indicated granite, yet there is no sign that such a circulation system exists. The possibilities of such mechanisms as previously unrecognized fault systems or local heat flow anomalies cannot be addressed without further study.

SUMMARY AND CONCLUSIONS

Background heat flow in the Wind River Basin is generally insufficient to produce high conductive gradients. Only where hydrologic systems re-distribute heat through mass movement of water will high temperatures occur at shallow depths. Aquifers which may have the confinement and structural characteristics necessary to create such geothermal systems are the Lance/Fort Union, Mesa Verde, Frontier, Muddy, Cloverly, Sundance, Nugget, Park City, Tensleep, Amsden, Madison, Bighorn, and Flathead Formations. Of these, the Tensleep Sandstone and Madison Limestone are the most attractive in terms of both productivity and water quality.

Structural control on hydrology (and hence geothermal systems) occurs through folding and faulting. Where folding is important, oil and gas exploration holes have generally provides sufficient temperature data to evaluate geothermal gradients. Where faulting alone provides the flow patterns necessary to generate a geothermal anomaly, high gradients may be localized and the data used in this report may be insufficient to delineate such an anomaly. Fault systems tentatively identified as anomalous by bottom-hole temperatures and/or the occurrence of thermal springs present useful directions for further study.

Most of the identified geothermal anomalies in the Wind River Basin occur along complex structures in the southwest and south. Large, weakly anomalous areas in the north-central basin area are unexplained and may simply reflect the overall increase in heat flow believed to occur from south to north across the basin. The most attractive geothermal prospects identified are anomalous Areas 2 and 3 north of Lander, Sweetwater Station Springs west of Jeffrey City, and the thermal springs southwest of Dubois, Even in these areas, it is unlikely temperatures in excess of 130 - 150°F can be developed. Geothermal resources elsewhere in the study area are probably best pursued in conjunction with oil and gas production or water development projects. Particularly in the case of the Paleozoic aquifers, the coincidence of oil and gas deposits and useful thermal waters is very likely. This may allow exploitation of more valuable petroleum resource to pay drilling and development costs, with thermal waters being produced as a valuable by-product.

There is also potential in the Wind River Basin for normal temperature geothermal applications such as ground water heat pumps and surface de-icing operations. The extensive surface occurrence of the highly productive Wind River Formation is very favorable in this respect, for small supplies of 40-50°F ground water should be readily available over a large portion of the basin.

Areas in which the geothermal potential could most usefully be studied further are the fault systems previously mentioned and the thermal springs system in the vicinity of Dubois. Not only would such studies help to define potentially significant energy resources, but they may also provide useful data on overall basin hydrology.

References Cited

Barlow and Haun, Incorporated, 1978, Wyoming structure contour map: Petroleum Ownership Map Company, (POMCO), Casper, Wyoming, scale 1:500,000.

Breckenridge, R.M., and Hinckley, B.S., 1978 Thermal springs of Wyoming: Geological Suvey of Wyoming Bulletin 60, 104 p.

Dana, G. F., 1962, Groundwater reconnaissance study of the state of Wyoming; Part 5, Wind River Basin Report: Wyoming Natural Resources Board, Cheyenne.

Decker, E.R., 1973, Geothermal measurements by the University of Wyoming: University of Wyoming Contributions to Geology, v. 12, no. 1, p. 21-24.

Decker, E.R., Baker, K.R., Bucher, G.J. and Heasler, H.P., 1980, Preliminary heat flow and radioactivity studies in Wyoming: Journal of Geophysical Research, v. 85, p. 311-321.

Dunnewald, J. B., 1958, Geology of the Fish Lake Mountain Area, Fremont County, Wyoming: University of Wyoming unpublished M.S. Thesis.

Gilliland, J. D. 1959, Geology of the Whiskey Mountain Area, Fremont County, Wyoming: University of Wyoming unpublished M.S. Thesis, 93 p.

Heasler, H.P., 1982, The Cody hydrothermal system: Wyoming Geological Association 33rd Annual Field Conference Guidebook, Yellowstone National Park, p. 163-174.

Heasler, H.P., Hinckley, B.S., Buelow, K.L., Spencer, S.A., and Decker, E. R., 1983, Map of the geothermal resources of Wyoming: U.S. Department of Energy, scale 1:500,000. [Available from the Geological Survey of Wyoming.]

Hinckely, B.S., Heasler, H.P., and King, J.K., 1982, The Thermopolis hydrothermal system, with an analysis of Hot Springs State Park: Geological Survey of Wyoming Preliminary Report 20, 42 p.

Keefer, W. R., 1970, Structural geolgy of the Wind River Basin, Wyoming: U.S. Geological Survey Professional Paper 495-B, 60 p.

Love, J. D., 1947, The Tertiary stratigraphy and its bearing on oil and gas possibilities in the Jackson Hole Area, Northwestern Wyoming: U.S. Geological Survey Investigations Series Chart 27.

Lowers, A.R., 1960, climate of the United State - Wyoming: U.S. Weather Bureau, Climatography of the United States no. 60-48, p. 1116 and 1128.

Muffler, L. J. P. (editor), 1979, Assessment of Geothermal Resources of the United States--1978: U.S. Geological Survey Circular 790, 163 p.

Richter, H. R. Jr., 1981, Occurrence and Characteristics of Ground water in the Wind River Basin, Wyoming: Water Resources Research Institute, University of Wyoming, 149 p.

Whitcomb, H.A., and Lowry, M.E., 1968, Ground-water resources and geology of the Wind River Basin area, central Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-270, 3 plates with text, scale 1:250,000.

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. Wind River Basin heat flow values[1].

Location (T-R-Sec)	Heat Flow (mW/m^2)	Thermal Conductivity (W/m^oK)
29-90-6	63	3.70
29-90-6	60	3.67
28-92-27	60	2.93
28-92-27	58	2.93
28-92-27	68	2.76
28-92-27	74	2.76
28-92-27	77	2.93
28-89-28	54	2.93
28-92-27	71	2.93
28-92-27	66	2.93
28-92-27	64	2.93
40-92-22	71	3.30
40-92-22	79	3.30
30-90-18	59	2.34
30-90-7	50	2.34

[1] Measurements made by University of Wyoming personnel as described by Decker, 1973. Values primarily from Decker et al., 1980

Table 3. Stratigraphic column for the Wind River Basin[1].

Age	Formation	Thickness (ft.)	Physical Description	Water Bearing Characteristics	Water Quality[2]
Cenozoic					
Quaternary					
Tertiary					
Pliocene	Moonstone Fm.	0-1400	poorly consolidated shale, sandstone, mudstone, tuff, limestone, and conclomgerate	Major Aquifer: yields up to 500 gpm	TDS 100-1000 mg/l
Miocene	Arikaree Fm.	0-900	sandstone with interbedded tuff, limestone, and conglomerate; basal conglomerate	Aquifer: yeilds ≤ 100 gpm Major Aquifer: yields generally up to 300 gpm, 100 gpm not uncommon	TDS <600 mg/l; Ca, Na, HCO_3, SO_4
Oligocene	White River Fm.	0-1000	fine sandstone with interbedded tuff and bentonite	Aquifer: yields 1-300 gpm, max. 850 gpm	
Eocene	Wagon Bed Fm.	0-700	bentonitic sandstone	Confining Unit: yields < 10 gpm	TDS 1500-2500 mg/l
Eocene	Tepec Trail Fm.	0-2000	tuffaceous siltstone, sandstone	Confining Unit: yields < 10 gpm	
Eocene	Aycross Fm.	0-1000	shale, mudstone, conglomerate, volcanics, sandstone	Confining Unit:	
Eocene	Wind River Fm.	250-1000	siltstone, shale, mudstone, and sandstone	Major Aquifer: yeilds up to 1500 gpm, 200 gpm flowing wells	TDS 100-5000 mg/l; HCO_3, SO_4
Eocene	Indian Meadows Fm.	0-700	mudstone, sandstone, limestone	Confining Unit:	
Paleocene	Fort Union Fm.	0-8000	conglomerate, sandstone, shale, siltstone	Aquifer: yields up to 100 gpm, 10 gpm flowing wells. Basal section is a Confining Unit	
Mesozoic					
Cretaceous	Lance Fm.	0-6000	sandstone, shale, pebble conglomerate	Aquifer: yeilds up to 100 gpm	TDS >1000 mg/l; Na, SO_4, Cl, HCO_3
Cretaceous	Meeteetse Fm.	0-1300	sandstone, shale, siltstone, mudstone	Confining Unit	poor
Cretaceous	Mesaverde Fm.	600-2000	upper unit of sandstones; middle unit of shale, siltstone, and sandstone; basal sandstone	Aquifer: yeilds up to 500 gpm, locally artesian	TDS >1500 mg/l; Na, SO_4, HCO_3
Cretaceous	Cody Shale	3000-5500	shale with interbedded thin sandstones	Major Confining Unit	poor
Cretaceous	Frontier Fm.	500-1000	alternating sandstone and shale	Aquifer: yeilds up to 150 gpm, 10-25 gpm flowing wells	TDS <500-3000 mg/l; Na, SO_4, HCO_3, Cl
Cretaceous	Mowry Sh.	400-600	interbedded shale and bentonite	Major Confining Unit	
Cretaceous	Muddy Sst.	20-150	fine to medium sandstone	Aquifer: 10-50 gpm flowing wells	TDS >500 mg/l; Cl, HCO
Cretaceous	Thermopolis Sh.	120-250	shale and mudstone, sandstone lenses	Major Confining Unit	
Cretaceous	Cloverly Fm. and	300 to	sandstone, middle shale unit	Aquifer: yields generally <50 gpm, up to 300 gpm, 1025 gpm flowing wells	TDS <1500 mg/l; Na, HCO_3, SO_4
Jurassic	Morrison Fm.	600	mudstone and shale, sandstone lenses	Confining Unit: yeilds <5 gpm	
Jurassic	Sundance Fm.	150-600	sandstone and stilstone, carbonates at base	Aquifer: 250-50 gpm flowing wells from Sundance-Nugget aquifer	TDS <500-2000 mg/l; Na, Cl, SO_4
Jurassic	Gypsum Spring Fm.	0-230	alternating siltstone, shale, limestone, and gypsum	Confining Unit	poor

Table 3 continued

Age	Formation	Thickness (ft.)	Physical Description	Water Bearing Characteristics	Water Quality[2]
Jurassic	Nugget Sst.	0-400	fine to medium sandstone, siltstone at base	Aquifer: artesian conditions common	generally >1000 mg/l; Na, Cl, SO_4
Triassic	Chugwater Fm.	1000-1300	interbedded siltstone, sandstone, and shale	Major Confining Unit: Sandstone layers locally yield <20 gpm	generally poor, sandstone layers may have TDS <1000 mg/l
Traissic	Dinwoody Fm.	0-250	interbedded siltstone, sandstone, and limestone	Confining Unit	
Paleozoic					
Permian	Park City Fm.	150-300	interbedded limestone, dolomite, siltstone, sandstone increasing shale content eastward.	Aquifer: yields up to 100 gpm	TDS <100 mg/l; Mg, Ca, Na, HCO_3, SO_4
Pennsylvanian	Tensleep Sst.	200-600	massive, fine sandstone	Major Aquifer: up to 3000 gpm flowing wells	TDS <500 mg/l near outcrops; TDS >2000 mg/l in basin interior Mg, Ca, Na, HCO_3 SO_4
Pennsylvanian	Amsden Fm.	0-400	shale, limestone, dolomite; basal sandstone		
Mississippian	Madison Lms.	200-700	limestone, dolomite; cavernous near top	Aquifer: yields 1-300 gpm	TDS <500 mg/l
Devonian	Darby Fm.	0-300	dolomite, siltstone, shale	Confining Unit: yields springs where fractured	
Ordovician	Bighorn Dol.	0-300	dolomite; basal sandstone	Aquifer	
Cambrian	Gallatin Lms.	0-450	limestone, shale, thin sandstone beds	Confining Unit: yeilds <5 gpm	
Cambrian	Gross Ventre Fm.	0-750	limestone and shale	Confining Unit	
Cambrian	Flathead Sst.	50-500	sandstone, basal conglomerate	Aquifer: yields 1-25 gpm	TDS <500 mg/l; Ca, Na,
Precambrian			granite, gniess and schist	small yields where fractured	SO_4, HCO_3, good quality

[1]Data condensed from Richter (1981) with modifications from Whitcomb and Lowry (1968)

[2]The quality of water in any water-bearing strata may significantly deteriorate as the water migrates basin ward.

Table 4. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Wind 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%
0 - 500	10	84	65	72.4	72	75	82	84
500 - 1,000	18	100	60	79.2	80	86	94	95
1,000 - 1,500	76	152	50	83.2	81	90	93	98
1,500 - 2,000	103	117	62	88.8	89	95	99	103
2,000 - 2,500	57	123	62	90.7	90	95	97	113
2,500 - 3,000	82	146	69	96.6	96	102	107	113
3,000 - 3,500	164	172	72	107.9	109	117	121	126
3,500 - 4,000	142	164	79	107.8	105	115	121	126
4,000 - 4,500	83	156	78	107.1	108	111	117	122
4,500 - 5,000	105	171	78	110.2	109	113	120	129
5,000 - 5,500	92	234	61	117.2	116	121	128	131
5,500 - 6,000	63	160	89	122.1	120	126	138	143
6,000 - 6,500	75	163	97	126.9	126	134	143	149
6,500 - 7,000	79	185	95	131.3	129	135	146	152
7,000 - 7,500	75	198	109	142.2	138	152	160	180
7,500 - 8,000	64	212	64	148.9	150	159	164	174
8,000 - 8,500	39	182	122	152.4	156	162	168	175
8,500 - 9,000	46	190	112	150.7	151	160	166	181
9,000 - 9,500	27	195	120	153.2	151	165	171	184
9,500 - 10,000	34	230	68	158.3	160	169	180	205
10,000 - 10,500	34	250	125	175.0	181	189	204	215
10,500 - 11,000	31	214	124	163.8	163	173	184	198
11,000 - 11,500	45	240	134	187.4	192	199	205	211
11,500 - 12,000	43	250	142	196.9	195	202	208	214
12,000 - 12,500	22	260	135	197.0	208	214	217	225
12,500 - 13,000	14	306	170	217.9	212	226	242	265
13,000 - 13,500	12	245	159	207.2	216	238	238	240
13,500 - 14,000	17	267	172	221.2	230	240	255	264
14,000 - 14,500	9	268	218	245.7	256	262	262	268
14,500 - 15,000	6	290	174	246.8	268	281	281	290
15,000 - 15,500	7	284	200	241.4	250	252	265	284
15,500 - 16,000	7	292	216	248.3	252	254	270	292
16,000 - 16,500	11	316	245	294.0	305	309	314	316
16,500 - 17,000	2	278	258	268.0	278	278	278	278
17,000 - 17,500	4	340	317	331.3	338	338	340	340
17,500 - 18,000	8	345	268	315.3	338	340	345	345
18,000 - 18,500	9	345	308	331.2	337	338	344	345
18,500 - 19,000	2	351	338	344.5	351	351	351	351
19,000 - 19,500	5	356	318	331.4	325	340	356	356
19,500 - 20,000	4	343	318	327.3	343	343	343	343
20,000 - 20,500	1	310	310	310.0	310	310	310	310
20,500 - 21,000	3	348	323	338.0	343	348	348	348
21,000 - 21,500	-	-	-	-	-	-	-	-
21,500 - 22,000	2	370	309	339.5	370	370	370	370
22,000 - 22,500	-	-	-	-	-	-	-	-
22,500 - 23,000	1	370	370	370.0	370	370	370	370

Total: 1,733 bottom-hole temperature measurements.

Table 5. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Wind 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%
0 - 500	10	144	48	79.0	67	72	104	144
500 - 1,000	18	81	20	45.9	45	50	55	65
1,000 - 1,500	76	77	5	30.9	30	34	39	43
1,500 - 2,000	103	43	11	26.4	25	28	31	34
2,000 - 2,500	57	37	9	21.4	21	23	24	29
2,500 - 3,000	82	39	8	19.5	19	21	22	24
3,000 - 3,500	164	38	8	19.6	19	21	23	24
3,500 - 4,000	142	30	9	17.5	16	19	21	22
4,000 - 4,500	83	26	8	15.2	14	15	17	18
4,500 - 5,000	105	26	7	14.1	13	14	16	18
5,000 - 5,500	92	35	3	14.1	13	14	15	17
5,500 - 6,000	63	20	7	13.8	13	14	16	17
6,000 - 6,500	75	18	8	13.4	13	14	15	16
6,500 - 7,000	79	20	7	13.0	12	13	15	16
7,000 - 7,500	75	21	9	13.7	12	15	16	18
7,500 - 8,000	64	21	2	13.6	13	14	15	17
8,000 - 8,500	39	17	9	13.3	13	14	15	15
8,500 - 9,000	46	16	7	12.3	12	13	13	15
9,000 - 9,500	27	16	8	11.9	11	13	13	15
9,500 - 10,000	34	19	2	11.8	11	12	13	16
10,000 - 10,500	35	20	7	12.9	12	14	15	16
10,500 - 11,000	31	16	7	11.3	11	12	12	14
11,000 - 11,500	46	17	8	12.8	13	13	14	14
11,500 - 12,000	43	17	8	13.1	12	13	14	14
12,000 - 12,500	24	17	7	12.7	13	13	14	14
12,500 - 13,000	13	17	9	13.2	13	13	14	15
13,000 - 13,500	12	15	8	12.3	12	13	14	14
13,500 - 14,000	19	16	9	12.8	12	14	14	15
14,000 - 14,500	9	15	12	14.3	15	15	15	15
14,500 - 15,000	6	16	8	13.8	15	16	16	16
15,000 - 15,500	6	15	10	13	13	14	14	15
15,500 - 16,000	7	15	10	13.1	13	13	14	15
16,000 - 16,500	12	16	10	15.0	16	16	16	16
16,500 - 17,000	2	14	12	13.5	14	14	14	14
17,000 - 17,500	4	17	15	16.7	17	17	17	17
17,500 - 18,000	9	17	12	15.3	16	16	16	17
18,000 - 18,500	9	16	14	15.8	15	16	16	16
18,500 - 19,000	2	16	15	16.2	16	16	16	16
19,000 - 19,500	5	16	14	15.0	14	15	16	16
19,500 - 20,000	4	15	13	14.3	14	14	15	15
20,000 - 20,500	1	13	13	13.1	13	13	13	13
20,500 - 21,000	3	14	13	14.3	14	14	14	14
21,000 - 21,500	-	-	-	-	-	-	-	-
21,500 - 22,000	2	15	12	13.7	15	15	15	15
22,000 - 22,500	-	-	-	-	-	-	-	-
22,500 - 23,000	1	14	14	14.5	14	14	14	14

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

Table 6. Thermally measured wells in the Wind River Basin[1].

Location		Depth	Bottom-hole Tempreature	Gradient[2]	Interval[3]
Latitude	Longitude	(meters)	(C°)	(°C/km)	(meters)
			FREMONT COUNTY		
43 38.5	109 42.1	67.9	6.606	10.0	40-67
43 37.2	109 38.5	630.0	25.660	31.1	90210
43 31.4	109 2.3	274.0	16.000	29.3	20-274
43 31.3	109 2.2	284.5	18.100	25.8	170-240
43 31.1	109 2.4	208.5	13.802	25.4	100-208
43 24.7	107 54.5	193.5	13.646	23.5	20-193
43 24.6	107 54.8	193.0	13.398	21.3	100-193
43 24.5	107 54.5	197.5	13.426	23.0	110-190
43 24.5	107 52.6	172.2	12.526		
43 24.4	107 55.0	140.7	11.892	20.2	100-140
43 24.4	107 55.0	141.0	11.892	20.2	100-140
43 24.4	107 54.8	190.7	13.739	19.7	80-190
43 24.4	107 53.5	133.2	10.706	4.2	9-133
43 24.4	107 52.9	152.0	13.340	34.4	10-150
43 24.4	107 51.7	99.5	11.030	24.3	50-99
43 24.3	107 52.5	164.3	12.621	5.3	29-164
43 24.2	107 53.4	118.7	11.613	6.8	30-118
43 24.1	107 53.7	84.3	12.177	6.3	9-84
43 20.7	107 51.2	40.0	13.074		
43 20.6	107 51.4	75.0	12.646		
43 20.6	107 51.4	89.0	11.411	20.0	60-89
43 20.3	107 52.0	173.0	15.330		
43 16.3	108 54.2	1,610.0	53.460	30.2	200-1,610
43 7.0	108 53.6	165.0	16.964	60.1	80-163
43 7.0	108 53.4	1,080.0	53.292	36.3	340-1,080
42 54.7	107 35.5	38.0	9.468		
42 54.6	107 32.9	38.0	7.232		
42 54.6	107 32.7	66.0	9.500		
42 54.6	107 32.3	58.0	9.497		
42 54.6	107 31.1	63.0	9.869		
42 54.4	107 33.2	52.0	9.448		
42 52.7	108 7.0	89.0	11.411	20.0	60-89
42 52.2	108 19.4	215.0	14.644	19.2	20-215
42 52.2	108 17.3	120.0	12.900	17.8	30-120
42 50.5	108 17.6	180.6	14.120	19.6	50-180
42 50.5	108 17.3	290.0	15.922	18.1	40-120
42 50.2	108 51.5	60.0	9.512	30.6	10-50
42 50.1	108 52.8	291.0	9.788		
42 46.2	108 9.5	220.0	14.304	25.9	80-220
42 45.4	107 10.4	1,410.0	62.101	39.0	100-1,410
42 45.4	107 40.7	41.0	8.740	11.8	20-41
42 45.4	107 40.7	29.0	8.268		
42 45.4	108 40.7	38.0	8.829		
42 44.6	107 10.7	1,900.0	71.884	33.4	10-1,900
42 44.6	107 35.4	339.0	14.611	27.8	150-210
42 44.5	107 35.3	340.0	14.631	21.5	150-340
42 44.0	107 35.2	232.0	14.918	38.7	20-150
42 41.9	107 48.4	127.0	10.144	20.2	50-127
42 41.8	107 48.5	60.0	9.044	20.8	20-60
42 41.8	107 48.3	96.0	9.976	15.1	40-90
42 40.7	107 46,1	87.0	10.883		
42 40.4	107 48.0	65.0	10.829	45.2	20-65
42 40.4	107 44.3	137.0	11.673	35.1	60-130
42 40.4	107 42.9	126.0	10.269	25.6	50-120
42 40.4	107 42.0	177.0	12.025	31.6	30-170
42 40.4	107 40.5	127.0	10.032	22.4	50-127
42 39.4	107 42.9	203.0	11.980	26.1	40-203
42 39.4	107 41.9	180.0	14.402	54.2	40-130
42 39.4	107 40.6	185.0	13.040	20.4	50-160
42 38.5	107 40.6	216.0	13.653	40.3	90-190
42 35.1	107 40.6	255.0	12.503	26.4	70-190
42 35.0	107 40.0	195.0	12.222	17.5	90-160
42 35.0	107 40.0	180.0	12.212	20.9	80-180
42 35.0	107 40.0	57.0	9.828	13.5	20-57
42 34.3	107 39.5	310.0	13.322	18.4	90-250
42 25.3	107 56.2	1,310.0	59.601	38.7	40-1,310
42 23.4	107 56.4	1,530.0	52.665	28.0	100-1,100

NATRONA COUNTY

42	51.4	106	46.4	670.0	33.435	26.6	200-740
42	51.4	106	4604	380.0	24.356	33.3	20-280

[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.

Table 7. Geothermal gradient anomalies in the Wind River Basin, Wyoming.

Area	Location (TWN-RNG)	Thermal Gradients (°F/1000 ft.)	Approximate Depths feet	Approximate Temperatures (°F)	Principal Formation(s)	Structural Control
1	42,43N-107W	15-30	3000-4000	110-160	Tensleep, Phosphoria	?
2	1,2N-1W,1E	20-40	2000-3500	100-130	Phosphoria, Tenslep Madison	fault/fold
3	25-2E 33N-99W	20-30	≤2000	90-110	Phosphoria	fault/fold
4	1S-5E	24-25	3000	110-120	Ft. Union	fold
5	1S-6E	16-20	2500-9000	170-230	Morrison, Tensleep	fold(?)
6	33,34N-94,95W	15-18	5000-8000	130-170	Shell Cr., Madison, Tensleep, Sundance	fault
7	33N-93,94W	20-25	4000-5000	130-140	Tensleep	fault/fold
8	32N-94,95W	15-19	6000-8000	120-180	Tensleep	fault/fold
9	38,39N-89,90,91W	15-17	7000-19000	140-330	Wind River, Ft. Union, Lance, Shannon, Cody Frontier	fold/fault
10	37N-90-91W	15-20	9000-15000	190-250	Ft. Union, Lance, Meeteetsee	?
11	37,38N-89W	15-17	5000-15000	190-270	Ft. Union, Lance	fold(?)
12	33N-90W	18-28	3000-6000	100-154	Tensleep	fault
13	37N-85, 86W	20-35	2000-4000	100-140	Cody, Frontier, Mowry	fault
14	37,38N-83W	19-22	3500-5000	110-170	Tensleep (?)	fold

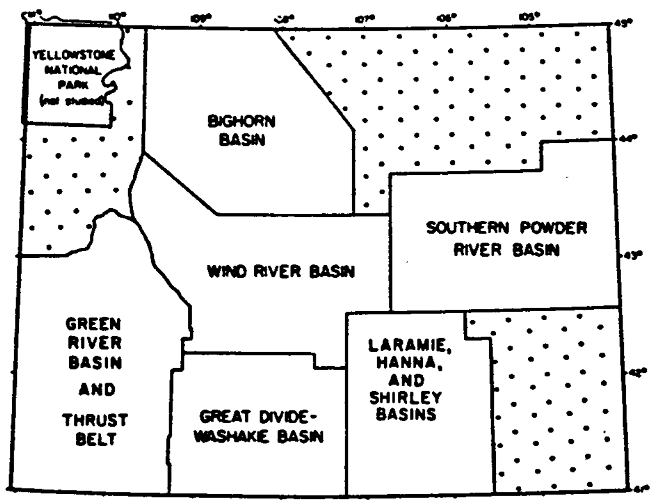


Figure 1. Study areas planned or completed in this series.

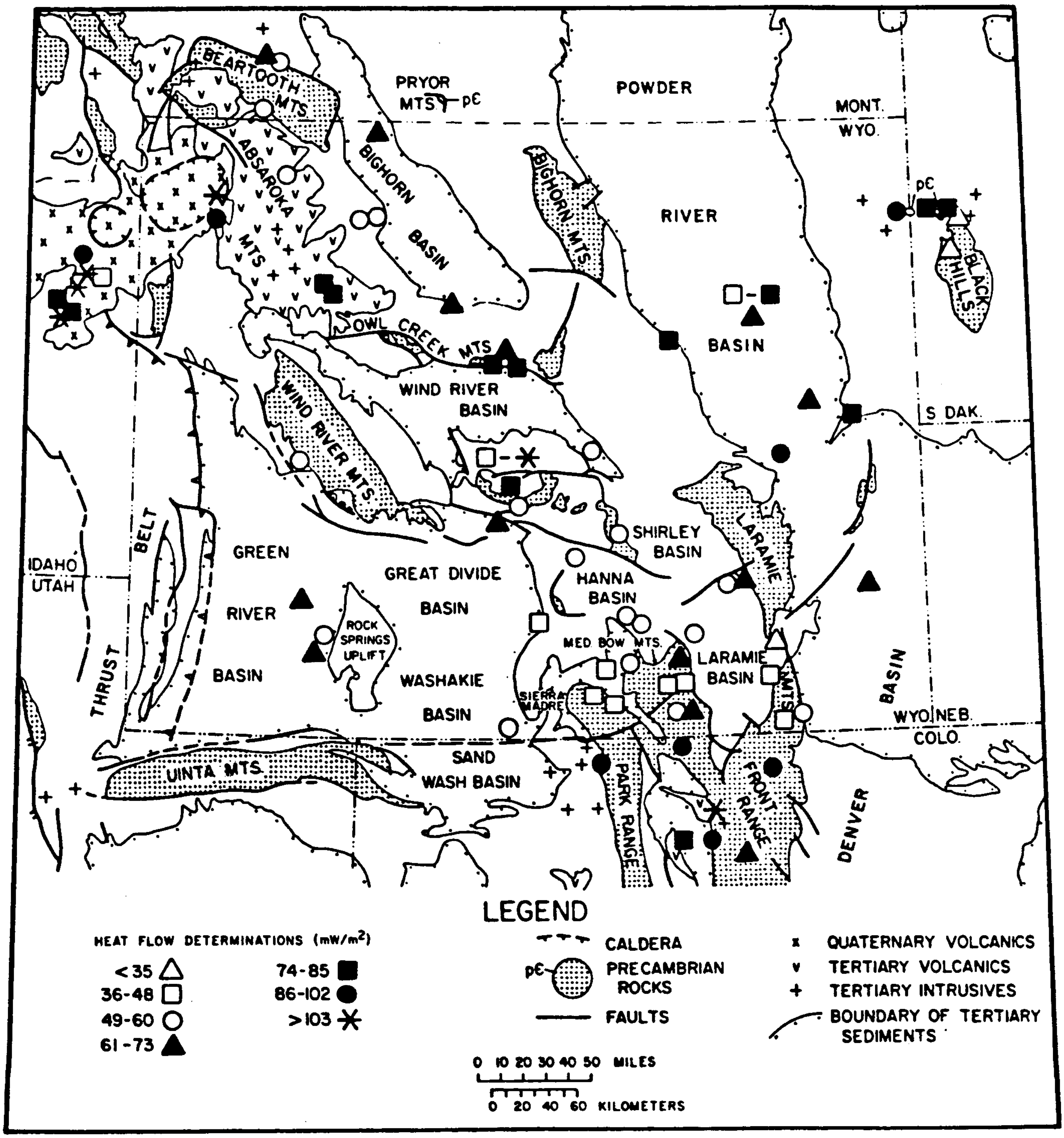


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.

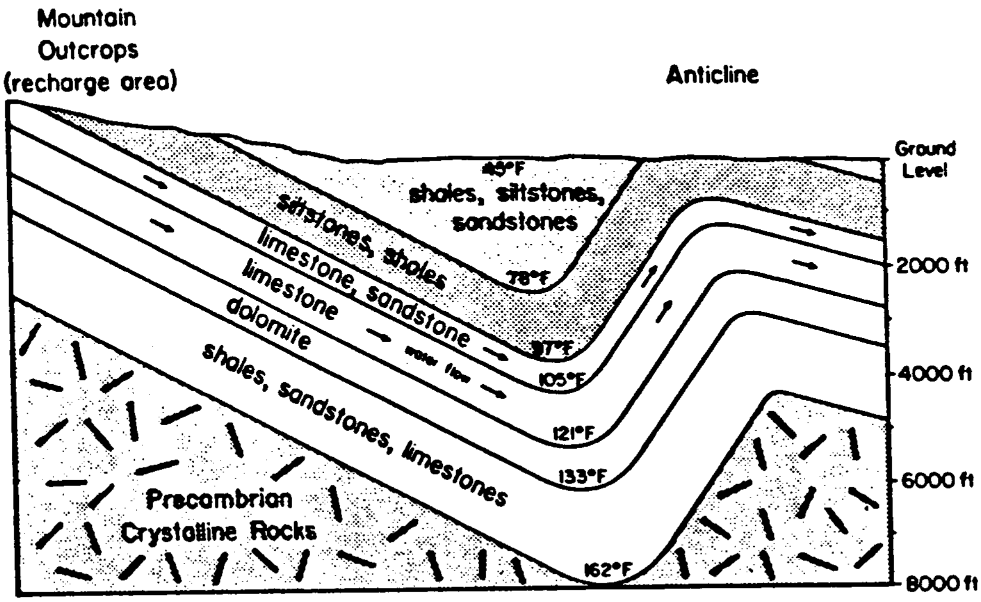


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

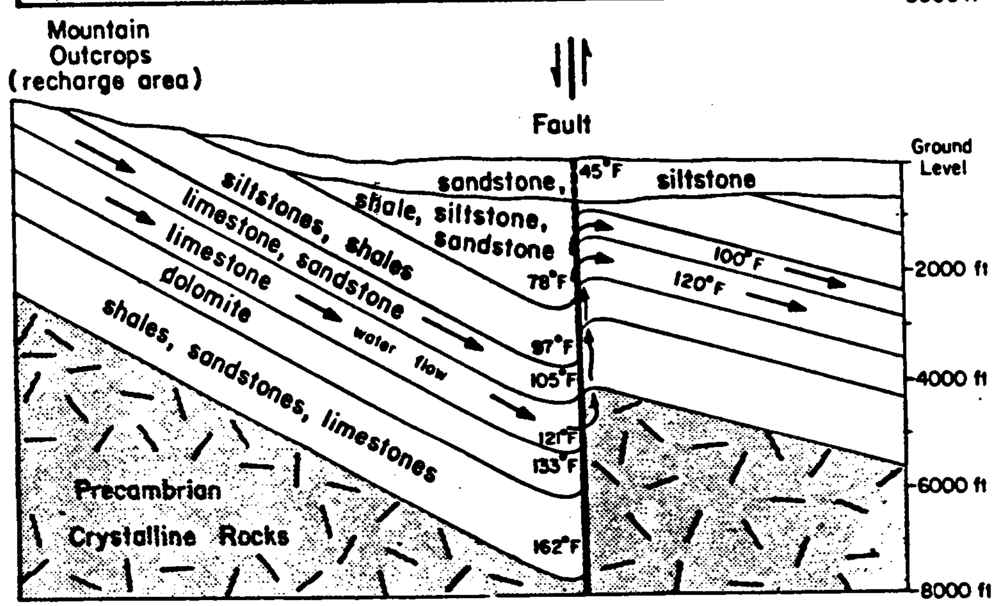


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

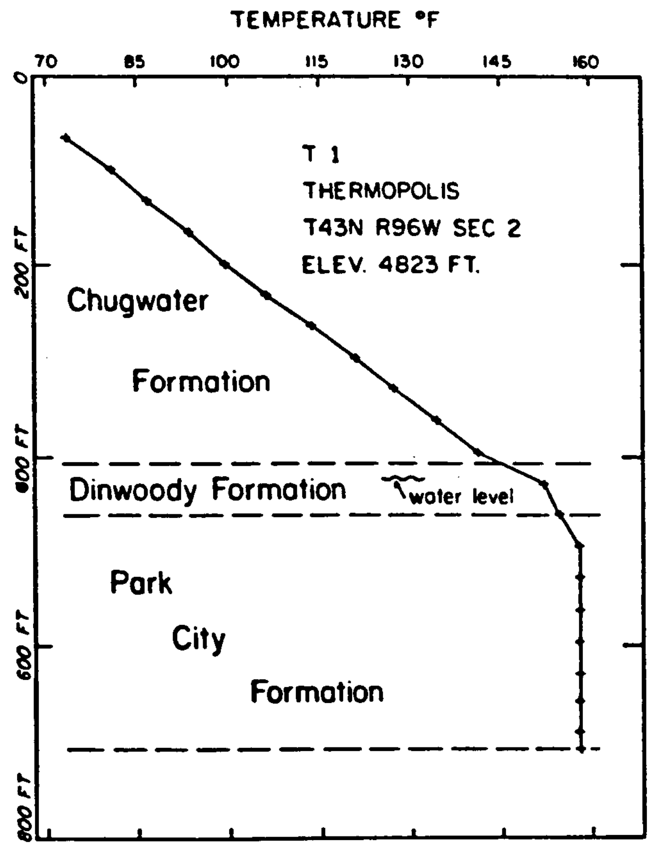


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.

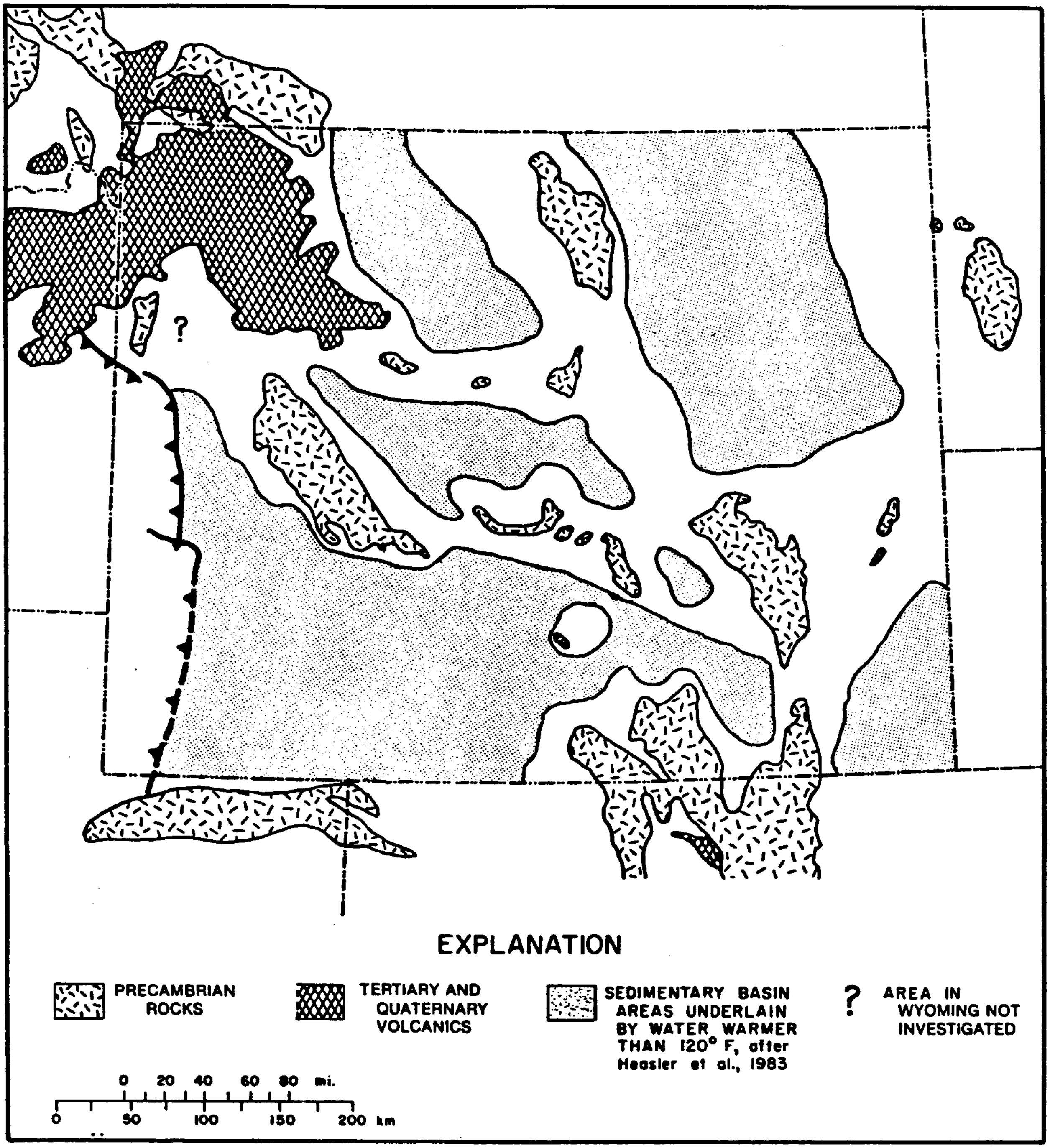


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.

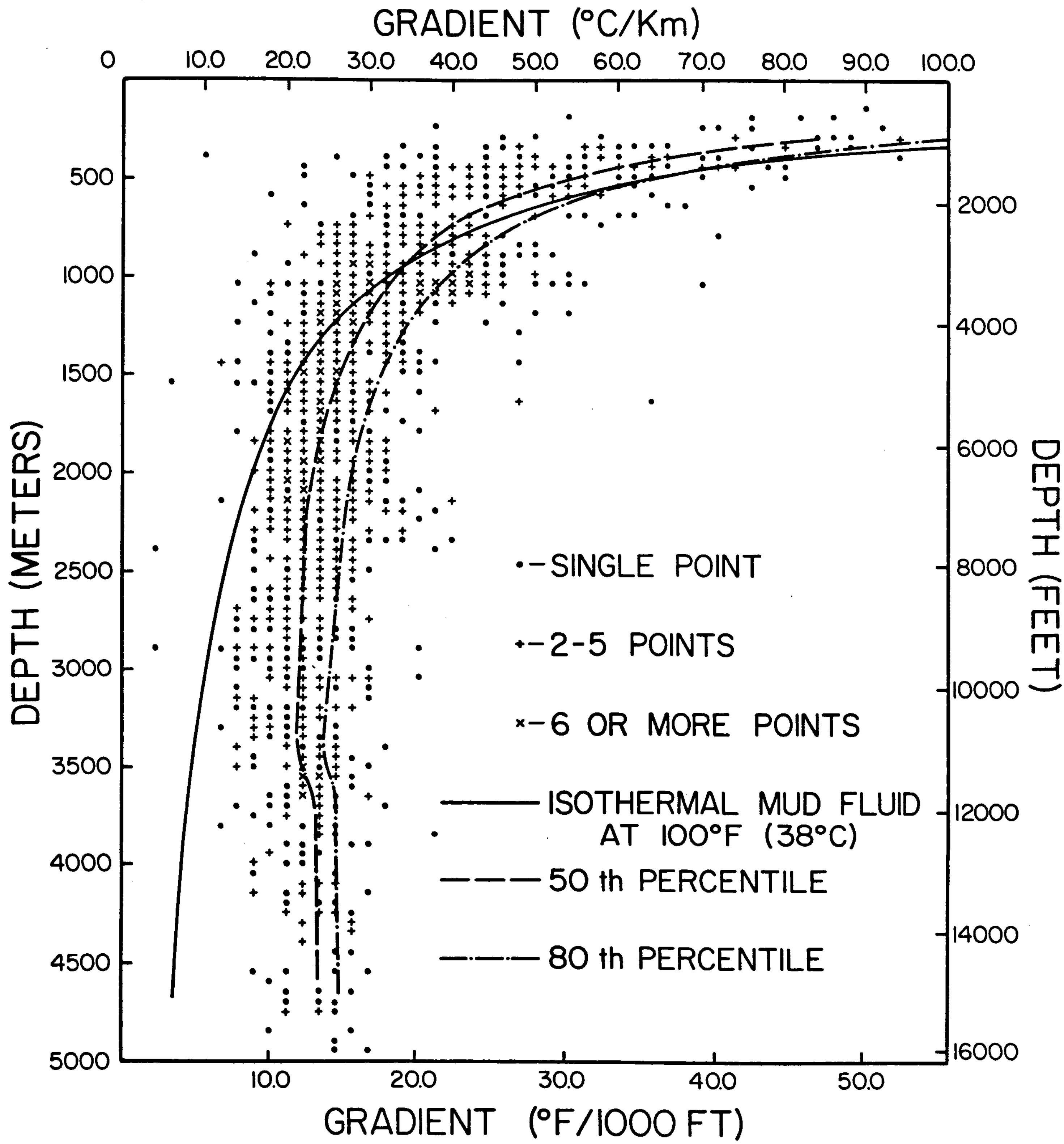
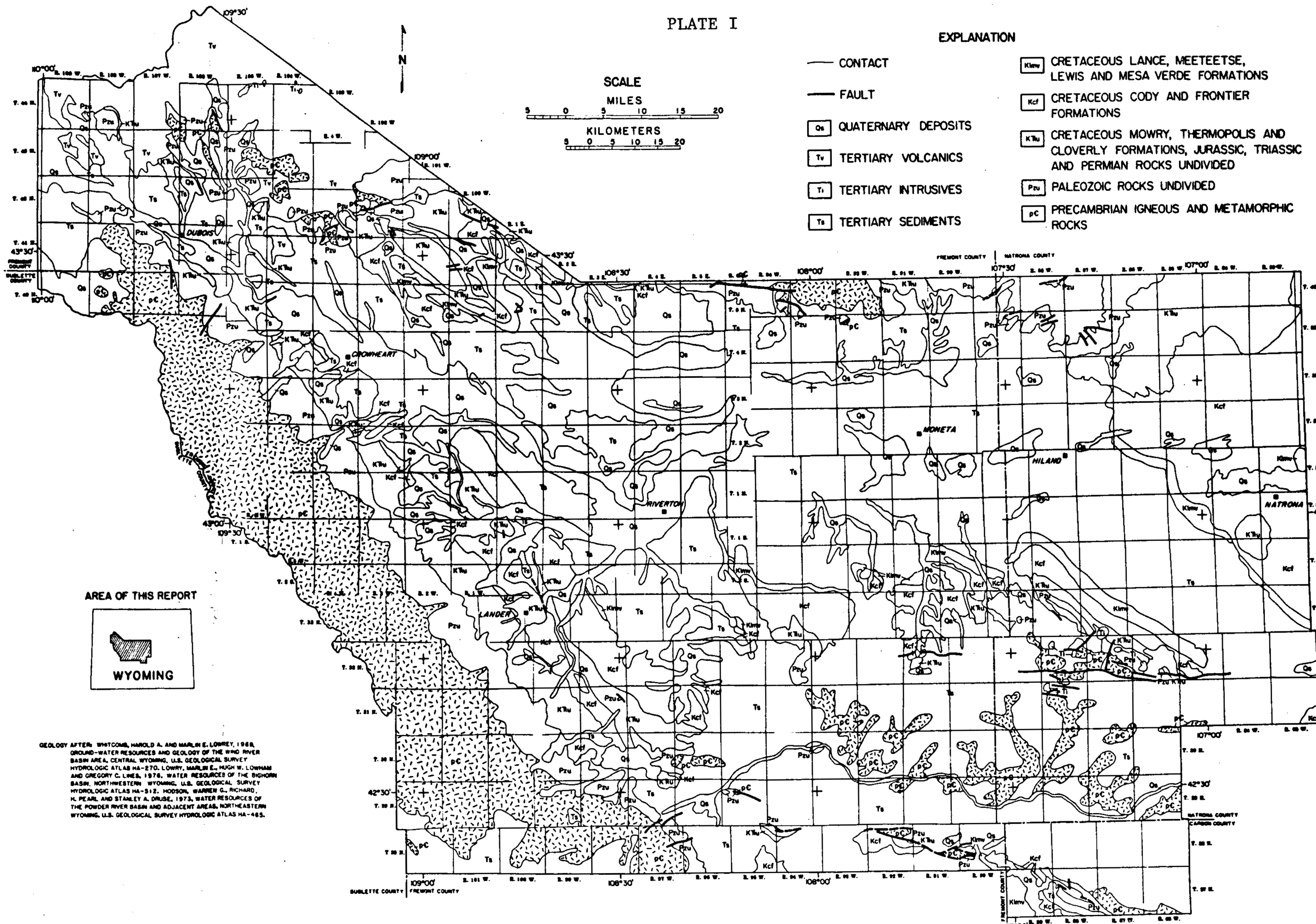


Figure 7. *GRADIENT-DEPTH PROFILE FOR WIND RIVER BASIN, BASED ON 1733 BOTTOM-HOLE TEMPERATURES.*

PLATE I



GENERALIZED GEOLOGIC MAP OF THE WIND RIVER BASIN, WYOMING

PLATE II

GENERALIZED STRUCTURE CONTOUR MAP OF THE CLOVERLY FORMATION, WIND RIVER BASIN, WYOMING

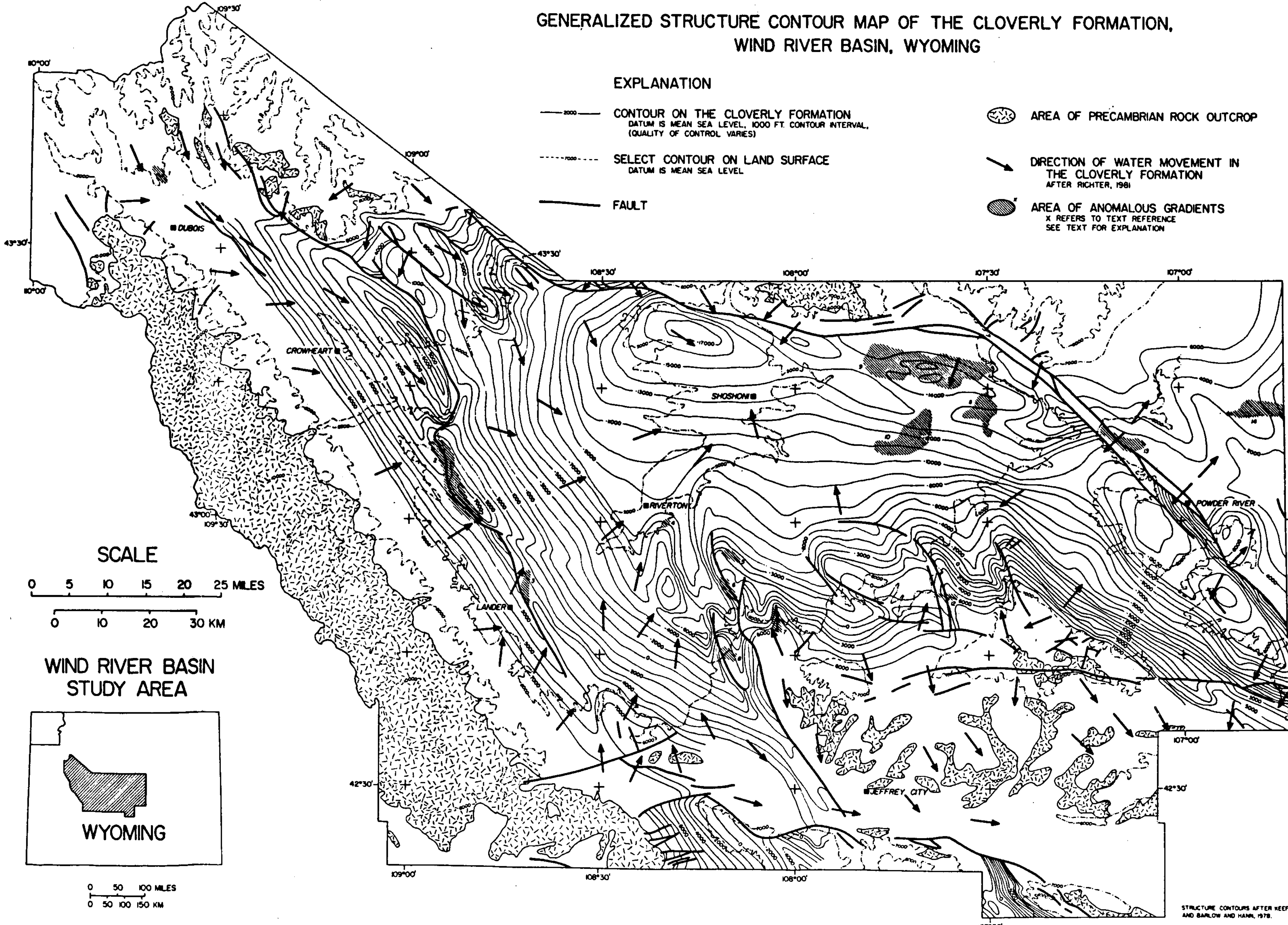


PLATE III

THERMAL GRADIENT CONTOUR MAP OF THE WIND RIVER BASIN, WYOMING