THE GEOLOGICAL SURVEY OF WYOMING

Gary B. Glass, State Geologist

REPORT OF INVESTIGATIONS NO. 29

GEOTHERMAL RESOURCES OF THE BIGHORN BASIN, WYOMING

by Henry P. Heasler and Bern S. Hinckley

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CONTENTS

ILLUSTRATIONS

Figures

Plates (in pocket)

TABLES

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 second 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 Bighorn Basin of northwestern 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.

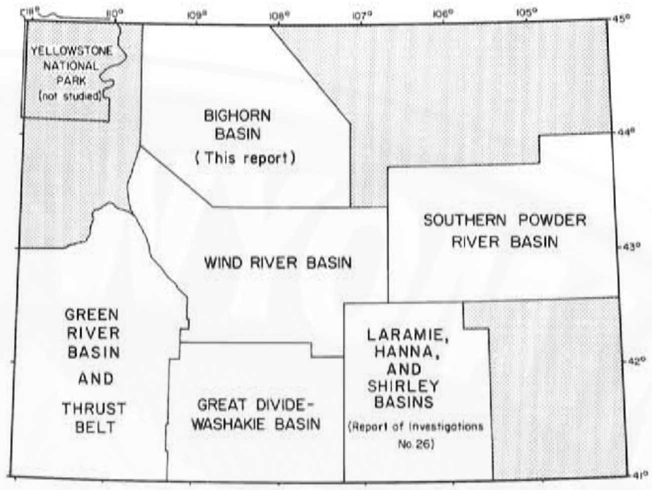

Figure 1. Study areas planned or completed in this series.

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

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*Thermal gradient units can be expressed as millidegrees Kelvin per meter (m°K/m), degrees Celsius per kilometer (°C/km), or, as in this report, degrees Fahrenheit per thousand feet (°F/1,000ft).

†Heat flow units are milliwatts per square meter. The world average is 59 mW/m^2 (Chapman and Pollack, 1975). Thermal conductivity units are watts per meter per degree Kelvin. Measured thermal conductivities in Wyoming range from 1 to 5 W/m°K (Heasler, 1978). Thermal gradient is related to heat flow and thermal conductivity by the formula:

$$G = H/C$$

or,

$$\text{Thermal gradient} = \frac{\text{heat flow}}{\text{Thermal conductivity}}$$

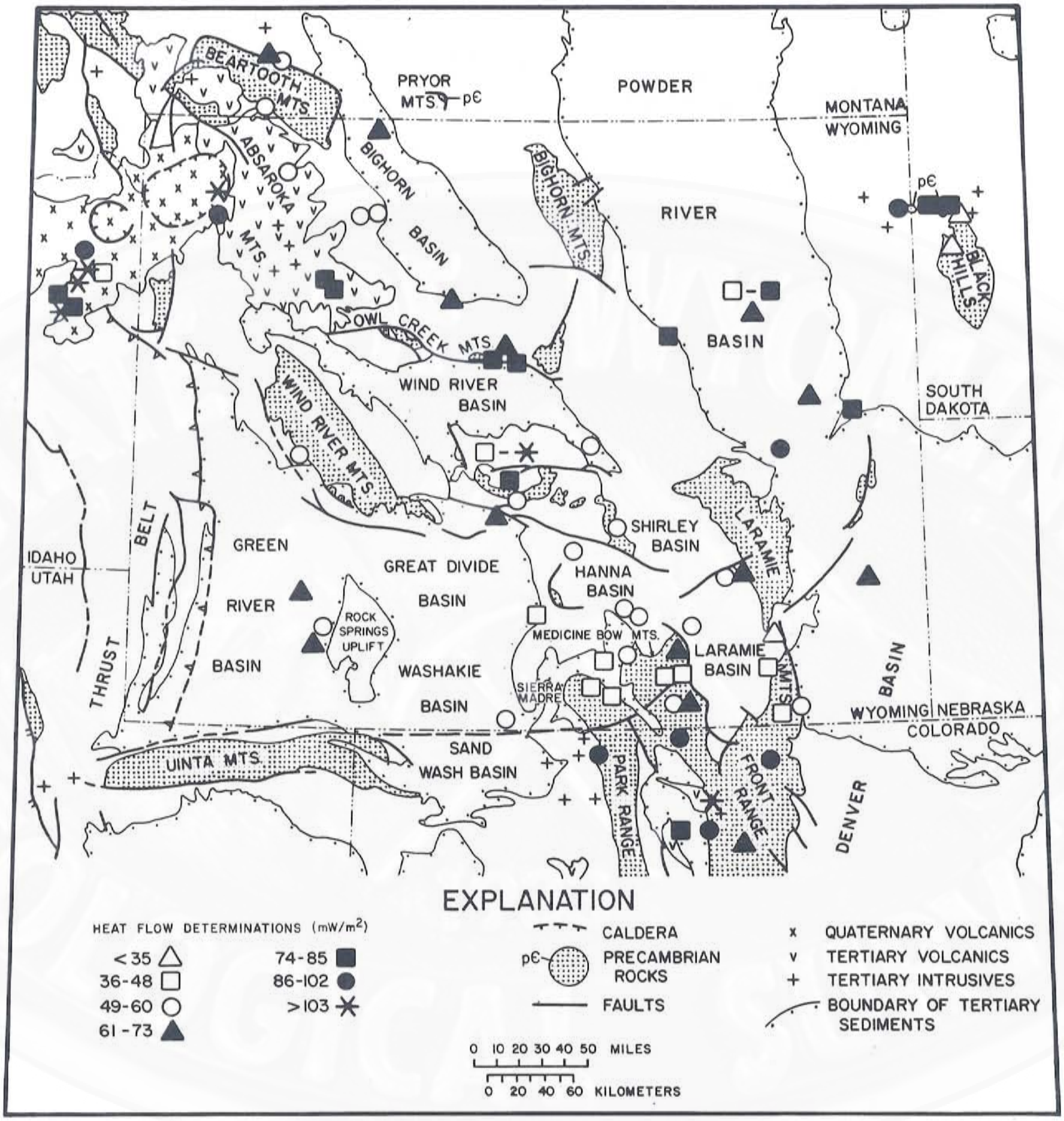

Figure 2. Generalized geology and generalized heat flow of Wyoming and adjacent areas. From Heasler et al., 1982.

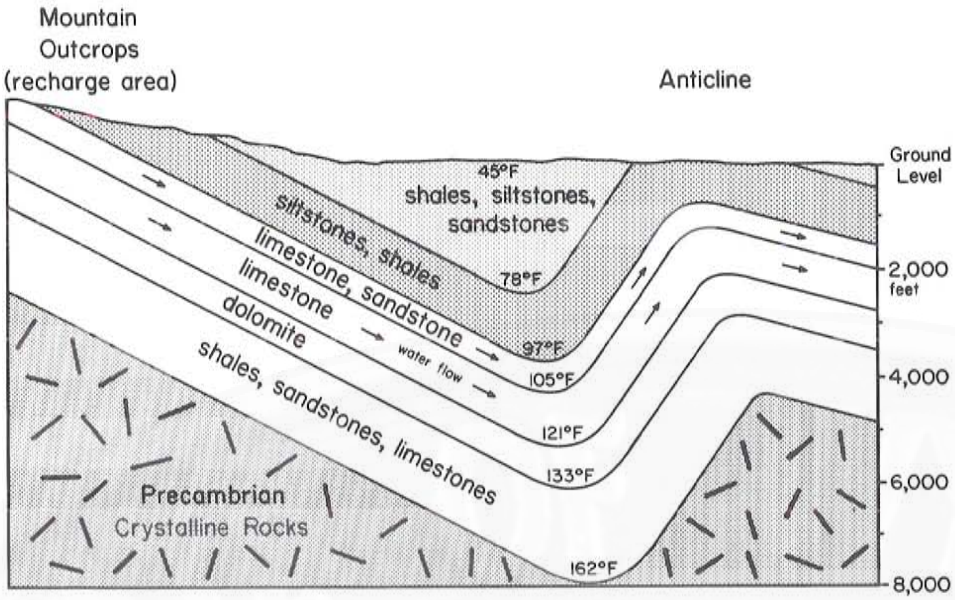

Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

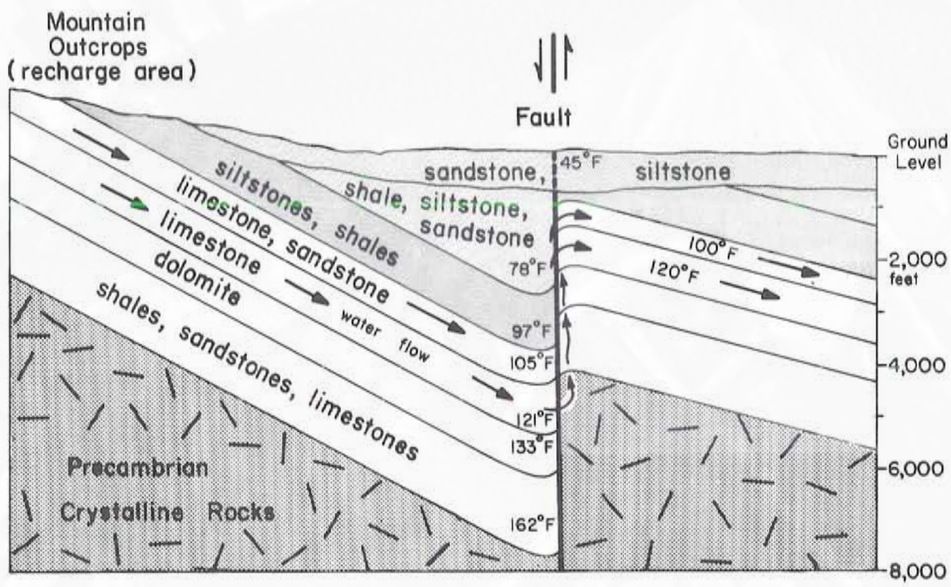

Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

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.)

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*See Decker (1973) for a discussion of the laboratory techniques of thermal conductivity determination.

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)

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

*Heasler et al., 1983, provide a list and map of holes thermally logged by the Wyoming Geothermal Resources Assessment Group.

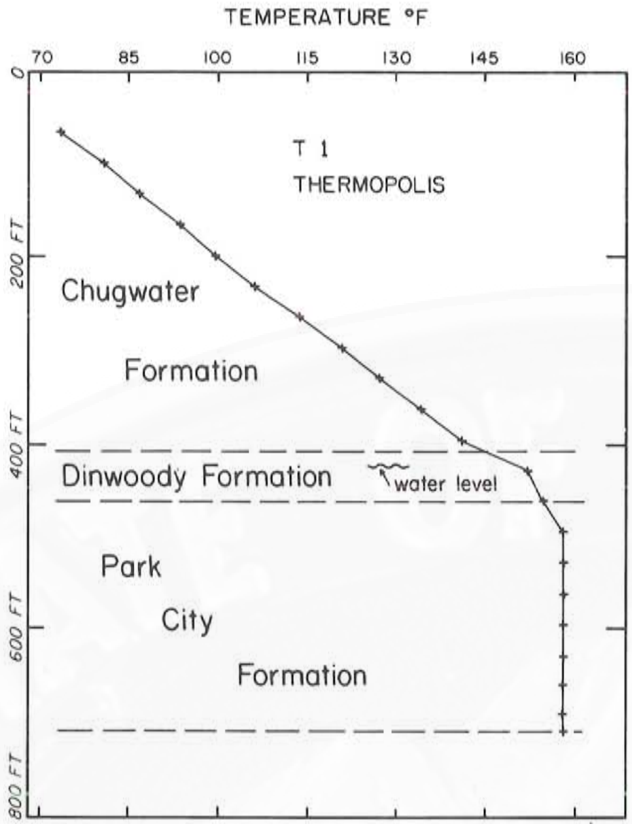


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. Modified from Hinckley et al., 1982.

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.

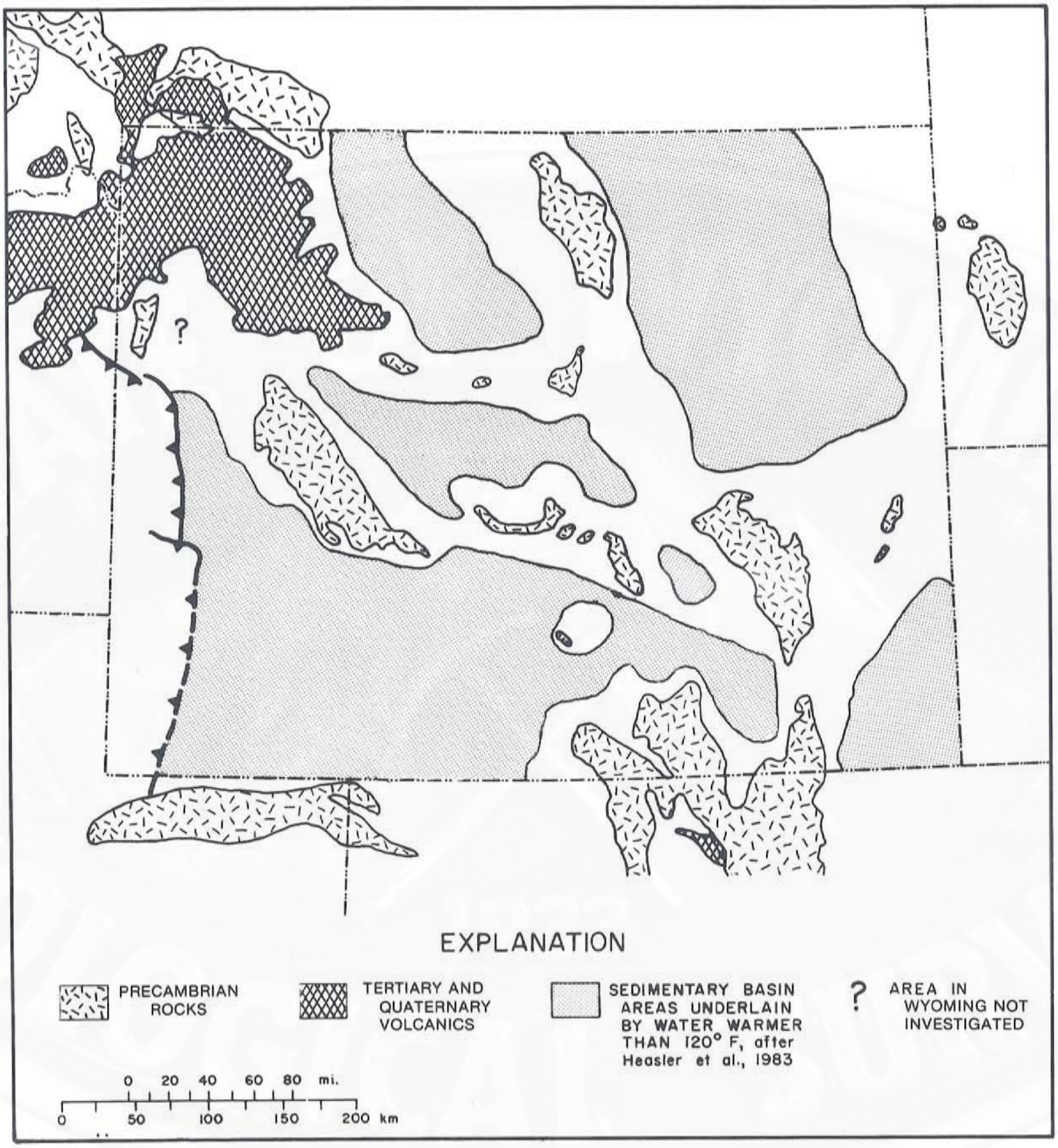


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.

GEOTHERMAL RESOURCES OF THE BIGHORN BASIN

STUDY AREA

The Bighorn Basin covers approximately 1,200 square miles in northwest Wyoming (see Figure 1). Parts of Park, Big Horn, Washakie, and Hot Springs Counties are included in the Bighorn Basin. The basin is bounded by major mountain uplifts: the Beartooth Mountains on the northwest, the Pryor Mountains on the north, the Bighorn Mountains on the east, and the Owl Creek Mountains on the south. These uplifts expose Precambrian crystalline rocks in their cores, and so create structural and stratigraphic boundaries. On the west, the basin is bounded by the volcanic complex forming the Absaroka Mountains. Many of the basin structural elements extend beneath this volcanic mass; on the west, then, the basin margin is defined more topographically than structurally.

In this report, we first discuss the stratigraphy of the Bighorn Basin. Because of the importance of ground water as a mechanism for the transfer of geothermal heat, we discuss the distribution and general water-bearing properties of potential aquifers. Next, the deformation of these strata is discussed, and here the focus is on structures suitable for the creation of geothermal anomalies. After presenting the stratigraphy and structure of the basin, we discuss the magnitude and distribution of measured thermal gradients. Finally, the ground-water temperature of the most productive aquifer in the Bighorn Basin, the Tensleep Sandstone, is evaluated.

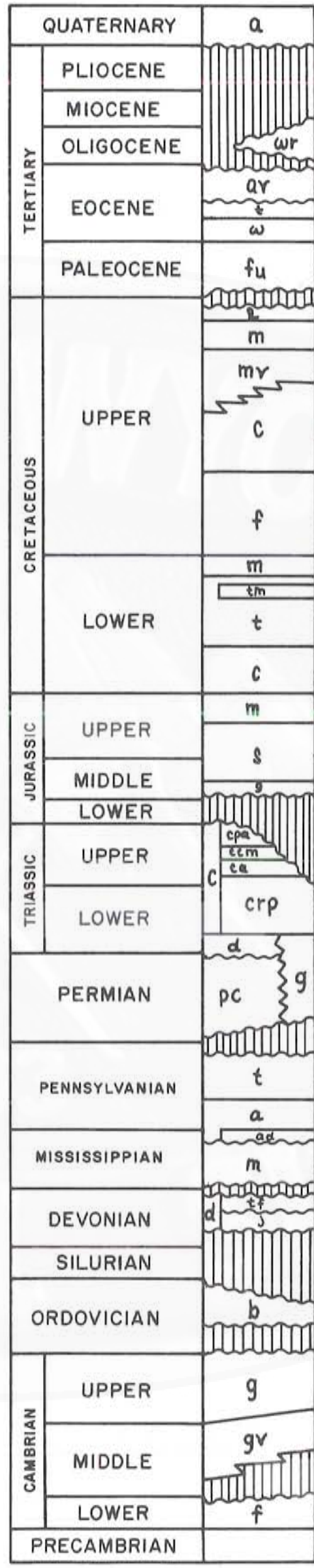
STRATIGRAPHY AND HYDROLOGY

This section contains discussions of those strata which accomodate significant water movement (see Figure 7 and Plate I). Chemical characteristics are described in terms of total dissolved solids (TDS). Much of the hydrologic data is drawn from a report by the Wyoming Water Resources Research Institute (Libra et al., 1981).

The youngest deposits in the basin are Quaternary alluvial materials. Located along the courses of present and past streams, these deposits rarely exceed 100 feet in thickness, yet yield the largest quantity of ground water of any aquifer in the basin (Libra et al., 1981). Ground water at temperatures of 48 to 54°F (9 to 12°C) in the alluvium can be exploited for such geothermal uses as heat pumps and deicing operations (National Water Well Association Map, no date). TDS values for the alluvial deposits vary both in space and time, ranging from 77 to 6,080 mg/l (milligrams per liter, approximately equal to parts per million) for the Bighorn Basin (Libra et al., 1981).

The Tertiary Absaroka volcanics are zero to 6,500 feet thick (Lowry et al., 1976) and occur along the mountainous western border of the basin. Lowry et al. assume these rocks to be highly variable in water yield due to a very heterogeneous lithology. Libra et al. (1981) present only two analyses of water from these volcanic rocks, both less than 200 mg/l TDS. The shallow depth of burial and location near recharge areas suggest a geothermal potential similar to that of the Quaternary alluvium, discussed above.

The next six formations below the Quarternary alluvium and the Tertiary volcanics are the Tatman, Willwood, Fort Union, Lance, Meeteetse, and Mesaverde Formations (Figure 7). The Tatman Formation is a generally thin, localized unit. The Willwood through the Mesaverde Formations are grouped by Libra et al. (1981) into an aquifer system "characterized by large variation in both the quantity and quality of water produced due to sporadically changing lithologies." Water yields are primarily a function of sandstone distribution (Lowry et al., 1976). Thus, site-specific studies would be required to accurately determine local water-bearing properties. Measured well yields are as high as 100 gpm, but most are around 20 gpm. TDS values generally fall in the 1,000 to 3,000 mg/l range. Impermeable shale beds allow artesian pressure to develop locally.



UNIT	THICKNESS (FEET)
QUARTERNARY ALLUVIUM	0 TO OVER 100
WHITE RIVER FM. EROSIONAL REMNANTS IN BIGHORN MOUNTAINS	
ABSAROKA VOLCANIC SGP	UP TO 6,500
TATMAN FM	UP TO 870 IN SW BASIN
WILLWOOD FM	2,500 IN CENTER OF BASIN
FORT UNION FM	5,000 ALONG BASIN AXIS
LANCE FM	UP TO 1,800
MEETEETSE FM	UP TO 1,200
MESAVERDE FM	UP TO 1,800
CODY SH	2,100 (NW) TO 3,000 (SE)
FRONTIER FM	500 (E-C, S-C) TO 700 (NE, SE)
MOWRY SH	300 TO 400
THERMOPOLIS SH	400 TO 600
CLOVERLY FM	200 TO 400
MORRISON FM	200 TO 300
SUNDANCE FM	200 TO 300
GYPSUM SPRING FM	100 TO 300
CHUGWATER FM	450 (NE) TO 1,000 (S)
DINWOODY FM	0 (E AND NE) TO 100 (SW)
GOOSE EGG FM	100 (N) TO 300 (SE)
PARK CITY (PHOSPHORIA) FM	
TENSLEEP SS	100 (N) TO 400 (S)
AMSDEN FM	200 TO 300
MADISON LS	800 (NW) TO 300 (SE)
THREE FORKS FM	0 TO 56 (ONLY IN W)
JEFFERSON FM	0 (SE) TO 286 (NW)
BIGHORN DOLOMITE	0 (SE) TO 400 (NW)
GALLATIN FM	450
GROS VENTRE FM	470 (S) TO 740 (NW)
FLATHEAD SS	100 TO 200
[PRECAMBRIAN]	

Figure 7. Stratigraphic chart for the Bighorn Basin. Stratigraphic units chosen following Wyoming Geological Association, 1969. Thicknesses, lithologic descriptions, and water-bearing properties generally from Lowry et al., 1976. Chemical quality from Libra et al., 1981.

CGL = Conglomerate
E-C = east-central
FM = Formation
GP = Group
GPM = gallons per minute of water flow
LS = Limestone
MBR = Member
mg/l = milligrams of solids per liter of water
N-S = north-south
S-C = south-central
SGP = Supergroup
SH = Shale
SS = Sandstone
STS = Siltstone

The Thermopolis Shale contains the Muddy Sandstone Member, a minor aquifer. The Chugwater Formation includes the Popo Agie Member; the Crow Mountain Sandstone Member, an important minor aquifer; the Alcova Limestone Member; and the Red Peak Member. The Amsden Formation contains the Darwin Sandstone Member, a minor aquifer.

LITHOLOGIC DESCRIPTION	WATER-BEARING PROPERTIES	CHEMICAL QUALITY
FLOODPLAIN ALLUVIUM AND TERRACE GRAVEL DEPOSITS. SILT, SAND, GRAVEL, AND BOULDERS.	MAJOR AQUIFER. YIELDS GENERALLY <50 GPM, AS HIGH AS 200 GPM.	TDS RANGE 77 TO 6,080 mg/l.
SAND, VOLCANIC ASH, GRAVEL, AND BOULDERS.	(NO DATA)	(NO DATA)
PREDOMINATELY VOLCANIC SEDIMENTS IN SOUTHERN ABSAROKA MTS, PREDOMINATELY VOLCANIC AGGLOMERATE, TUFF, AND EXTRUSIVE ROCKS IN NORTHERN ABSAROKAS.	WATER-BEARING PROPERTIES VARY GREATLY BECAUSE OF DIVERSE LITHOLOGY.	TWO SAMPLES GIVE TDS <200 mg/l.
INTERBEDDED CLAYSTONE, SH, MUDSTONE, MARL, AND MINOR COAL.	(NO DATA)	(NO DATA)
VARICOLORED INTERBEDDED CLAYSTONE AND CHANNEL SS. SS LOCALLY CONGLOMERATIC.	AQUIFER. YIELDS 5 TO 20 GPM.	TDS RANGE 621 TO 4,910 mg/l.
CLAYSTONE, STS, AND SS WITH SOME CARBONACEOUS MATERIAL. CROSSBEDDING AND CHANNEL SS COMMON.	AQUIFER. YIELDS GENERALLY <10 GPM.	
CONCRETIONARY SS INTERBEDDED WITH CLAYSTONE, SH, AND CARBONACEOUS SH.	AQUIFER. NOT EXTENSIVELY DEVELOPED.	
STS, CLAYSTONE, SH, INDURATED SS, AND MINOR COAL BEDS.	AQUIFER. YIELDS <15 GPM.	
MASSIVE SS, THIN-BEDDED SS, SH, CARBONACEOUS SH, AND COAL.	AQUIFER. YIELDS GENERALLY <20 GPM.	
BLACK SH, SHALEY SS (IN UPPER PART), CALCAREOUS SH, AND THIN BENTONITE BEDS.	REGIONAL AQUITARD. LOCAL, CONFINED SS MAY YIELD UP TO 20 GPM.	(NO DATA)
FINE- TO MEDIUM-GRAINED SS, CONGLOMERATIC SS, SH, AND SOME BENTONITIC AND CARBONACEOUS SH.	MINOR AQUIFER. SS PRODUCES WATER UNDER ARTESIAN CONDITIONS.	TDS RANGE 4 TO 10,300 mg/l.
THIN-BEDDED, SILICEOUS SH INTERBEDDED WITH THIN SS AND BENTONITE BEDS.	AQUITARD. YIELDS WATER LOCALLY IN FRACTURE ZONES.	(NO DATA)
SOFT, BLACK SH WITH MUDDY SANDSTONE MBR ABOUT 200 FEET ABOVE BASE.	AQUITARD. MUDDY SANDSTONE YIELDS MINOR AMOUNTS OF WATER.	(NO DATA)
VARIEGATED BENTONITIC MUDSTONE WITH CHANNEL SS IN UPPER PART AND LENTICULAR CGL IN LOWER PART.	MINOR AQUIFER. YIELDS 2 GPM.	TDS RANGE 254 TO 14,825 mg/l.
CALCAREOUS SS AND SANDY MUDSTONE WITH LENTICULAR FRESH-WATER LS.	MINOR AQUIFER. SS BEDS LOCALLY PRODUCE SMALL YIELDS.	HIGHLY VARIABLE
GREENISH-GRAY SS, LS, STS, AND SH.	MINOR AQUIFER. SS LAYERS PRODUCE SMALL YIELDS.	
REDDISH-BROWN CLAYSTONE AND STS WITH THIN LS AND MASSIVE GYPSUM BEDS.	MINOR AQUIFER. SOLUTION ZONES IN GYPSUM LOCALLY YIELD SMALL AMOUNTS OF WATER.	
VERY-FINE-GRAINED RED SS, STS, AND SH, AND ONE THIN LS (ALCOVA MBR) IN SOUTHERN PART OF BASIN.	MINOR AQUIFER. SS UNITS PRODUCE SMALL AMOUNTS OF WATER LOCALLY.	
YELLOWISH STS INTERBEDDED WITH GYPSUM AND SH.	AQUITARD.	(NO DATA)
RED SH, STS, GYPSUM, AND THIN LS BEDS. RECOGNIZED EAST OF A N-S LINE THROUGH WORLAND. ROUGHLY EQUIVALENT TO PARK CITY FM.	AQUITARD. LEAKY CONFINING BED. SOME FACIES PRODUCE WATER UNDER ARTESIAN CONDITIONS.	TDS RANGE 254 TO 9,072 mg/l.
TAN TO GRAY, CHERTY DOLOMITE AND SANDY LS. RECOGNIZED WEST OF A N-S LINE THROUGH WORLAND. ROUGHLY EQUIVALENT TO GOOSE EGG FM.	MINOR AQUIFER. LOCALLY PRODUCES WATER UNDER ARTESIAN CONDITIONS.	
TAN TO WHITE, MASSIVE SS WITH SOME INTERBEDDED LS IN LOWER PART.	MAJOR AQUIFER. ARTESIAN WELLS OFTEN FLOW AT SURFACE AT 50 TO 200 GPM.	TDS <500 mg/l NEAR OUTCROPS, >3,000 mg/l IN BASIN INTERIOR.
RED SH WITH SOME LS AND DOLOMITE IN THE LOWER PART. DARWIN SANDSTONE MBR PRESENT LOCALLY AT BASE.	MINOR AQUIFER. DARWIN SS MBR YIELDS WATER.	(NO DATA)
BLUE-GRAY MASSIVE LS, DOLOMITIC IN PART.	MAJOR AQUIFER. ARTESIAN FLOW UP TO 3,000 GPM.	TDS <500 mg/l NEAR OUTCROPS, >3,000 mg/l IN BASIN INTERIOR.
YELLOW TO DARK-GRAY, DOLOMITIC SS, BLACK FISSILE SH, AND SILTY DOLOMITE. DARBY FM EQUIVALENT IN E BASIN.	AQUITARD.	(NO DATA)
BROWN DOLOMITE, GRAY TO TAN LS, AND YELLOWISH-GRAY STS. DARBY FM EQUIVALENT IN E BASIN.	AQUITARD.	(NO DATA)
GRAY, MASSIVE DOLOMITE AND DOLOMITIC LS.	AQUIFER. PRODUCES ARTESIAN WATER IN AREAS OF FRACTURING AND SOLUTION.	TDS <500 mg/l NEAR OUTCROPS, >3,000 mg/l IN BASIN INTERIOR.
GRAYISH-GREEN, CALCAREOUS SH AND FLAT-PEBBLE CGL. BASAL MASSIVE LS (PILGRIM LS) IN NW AND S. PILGRIM LS AND SNOWY RANGE FM MAKE UP GALLATIN GR IN W BASIN.	AQUITARD. DISPERSED SANDY INTERBEDS AND BASAL LS MAY YIELD SOME WATER.	(NO DATA)
GREENISH-GRAY, THIN-BEDDED LS AND LIMESTONE-PEBBLE CGL.	AQUITARD. MAY YIELD SMALL AMOUNTS OF WATER.	(NO DATA)
RED, ARKOSIC AND QUARTZITIC SS WITH INTERBEDDED SH IN UPPER PART.	AQUIFER. SOME YIELDS OF >2,000 GPM UNDER HIGH ARTESIAN PRESSURE.	TWO SAMPLES GIVE 136 AND 400 mg/l TDS.
GRANITIC AND METASEDIMENTARY ROCKS.	LOCALLY YIELD SMALL AMOUNTS OF WATER TO WELLS.	(NO DATA)

The outcrop patterns on the geologic map (Plate I) reflect the general structure of the basin. The Tertiary sediments (Tatman, Willwood, and Fort Union Formations) are generally flat lying to gently dipping, occupying broad areas in the central basin. Within the 8,000-foot aggregate thickness of these three formations (Lowry et al., 1976), temperatures up to 160°F (70°C) could be developed at normal thermal gradients. As there are neither syncline-anticline couples nor major faults in these formations, access of such waters to near-surface areas is restricted to wells.

Mesozoic and Paleozoic formations, in contrast, are folded up along the margins of the basin, creating the complicated outcrop patterns seen on Plate I and the types of flow system diagrammed in Figures 3 and 4. Recharge of these formations occurs when surface water enters at outcrop areas. Discharge is through springs, seeps, and wells, or into adjacent units by migration. The Lance, Meeteese, and Mesaverde Formations, as discussed above, are of low to moderate water-bearing potential and of generally poor water quality. The Cody Shale is virtually barren of ground water over the entire basin. It forms a relatively impermeable cap which allows significant artesian pressure to develop in underlying units. The continuous sandstone beds of the Frontier Formation and Cloverly (also known as the Dakota) Formation yield small quantities of marginal to poor quality water. However, wells into the Frontier and Cloverly Formations near the basin margin may produce 10 to 100 gpm (Libra et al., 1981). In the Mesozoic formations below the Frontier and Cloverly, minor water yields are reported for the discontinuous, sandstone-rich zones. Libra et al. note great variation in the chemical quality of ground water from this sequence -- 75 percent of their reported values are greater than 1,000 mg/l.

The only major aquifers in the Bighorn Basin, excluding the surface alluvial deposits, are found in the Paleozoic section. The Park City Formation (also called Phosphoria or Embar) is only a minor aquifer, but may generate significant water production due to communication with underlying units (Hinckley et al., 1982). The Tensleep Sandstone, Madison Limestone, Bighorn Dolomite, and Flathead Sandstone are highly productive aquifers which yield up to several thousand gallons per minute under artesian flow to wells in the easternmost Bighorn Basin (Cooley, 1981). The Amsden Formation is a minor aquifer. The Gallatin and Gros Ventre Formations are regional aquitards (Libra et al., 1981). Transmissivity determinations from oil-field data for the Tensleep Sandstone range from 2 gpd/ft (gallons per day per foot) to 3,000 gpd/ft (Libra et al.). Data are sparse for older formations, but Libra et al. report that the Madison has a generally "higher, more uniform transmissivity than even the Tensleep."

Paleozoic outcrop areas on the flanks of the mountains surrounding the basin and the much less permeable nature of overlying strata create extensive artesian conditions. Wellhead pressures as high as 150 pounds per square inch (psi) from the Tensleep Sandstone, 250 psi from the Madison Limestone, and 400 psi from the Flathead Sandstone are reported by Cooley (1981) from the central east edge of the basin.

As the Paleozoic rocks dip beneath overlying strata, their temperature increases. In the west central basin, a temperature of over 300°F (150°C) was measured in the Tensleep Sandstone at a depth of 23,000 feet (see Table 1). Where Paleozoic strata underlie the Mesozoic section and then return to the surface along basin-flanking folds, as at Thermopolis, Cody, southeast of Lovell, and north of Greybull (see Plate I), thermal springs occur, with temperatures from 70 to 133°F (21 to 56°C) and flow up to 3,000 gpm (Breckenridge and Hinckley, 1978). More commonly, folds bring water-bearing strata near, but not to, the surface. These folds do not produce thermal springs, but do produce locally elevated temperature gradients.

The geologic map (Plate I) can be used in conjunction with the thicknesses from the geologic column (Figure 7) to obtain a rough idea of the depth to any given stratum. If, for example, one decides that the Tensleep Sandstone would provide an economically viable geothermal resource if it were no deeper than 3,000 feet, he can see from the column that only those areas with Lower Cretaceous (Kcf) or older strata exposed at the surface meet this criterion. The map would direct him to a belt along the margin of the Bighorn Basin. The width of the belt would depend upon the chosen economic depth. Since the population centers of the basin are similarly distributed around the basin margin, geothermal resources and energy use areas will coincide.

In general, the Paleozoic rocks, particularly the Madison Limestone and Tensleep Sandstone, are well suited for development of geothermal resources due to their favorable hydrologic characteristics, their depth of burial, and their accessibility to population center.

STRUCTURE

The generalized structure contour map of the Bighorn Basin (Plate III) shows the elevation of the top of the Tensleep Sandstone. Most of the folding and faulting of this surface occurred in latest Mesozoic and early Cenozoic time. Thus, all Paleozoic and Mesozoic units have similar structure and geometry to that shown in Plate III, although they have different elevations.

The Tensleep Sandstone was chosen for the structure map because it is a major aquifer and because there is an abundance of data on it from oil and gas wells. Plate III is generalized from Zapp (1956) and Barlow and Haun (1978). Many of the deep basin contours are highly conjectural. The two types of points plotted on Plate III represent the locations of drill holes for which bottom-hole temperatures were available, and are representative in their distributions of the density of the data from which the map was compiled. Thus, the accuracy of this map should be greatest where the point density is greatest and considerably less where points are scarce.

Bredehoeft and Bennett (1972) have developed a potentiometric surface map for the Tensleep Sandstone in the Bighorn Basin (Figure 8). Though their data are sparse, their map shows a general flow of water from mountain outcrops (recharge areas) to the lowest, central portions of the basin. As water descends within a given aquifer it warms as a function of its depth below the surface. Selected surface contours have been included on the Tensleep Sandstone structure map so that the depth of burial can be estimated at any point. Returning to Plate III, we can see that where water-bearing strata rise upward from deeper areas in a down-flow direction, a geothermal anomaly may be formed. The greater the water flow, the less the temperature will fall as the water moves up to a shallower zone. Thus, the most extreme geothermal anamolies should develop where folds or faults (like those in Figures 3 and 4) have the greatest elevation difference from bottom to top, occur along the flow path from mountain to basin, and are associated with a productive aquifer.

For example, one can locate areas on the structure map (Plate III) where the Tensleep Sandstone will bear 100°F water within 500 feet of the surface. The background gradient of 15 to 16°F/1,000 ft (discussed below) requires a depth of burial of approximately 3,600 feet for water to reach 100°F (55 degrees above a 45°F mean annual surface temperature). For an anomaly to be produced, not only must the aquifer rise to within 500 feet of the surface, but water must move through the aquifer from the syncline and up the anticline or fault (see Figures 3 and 4).

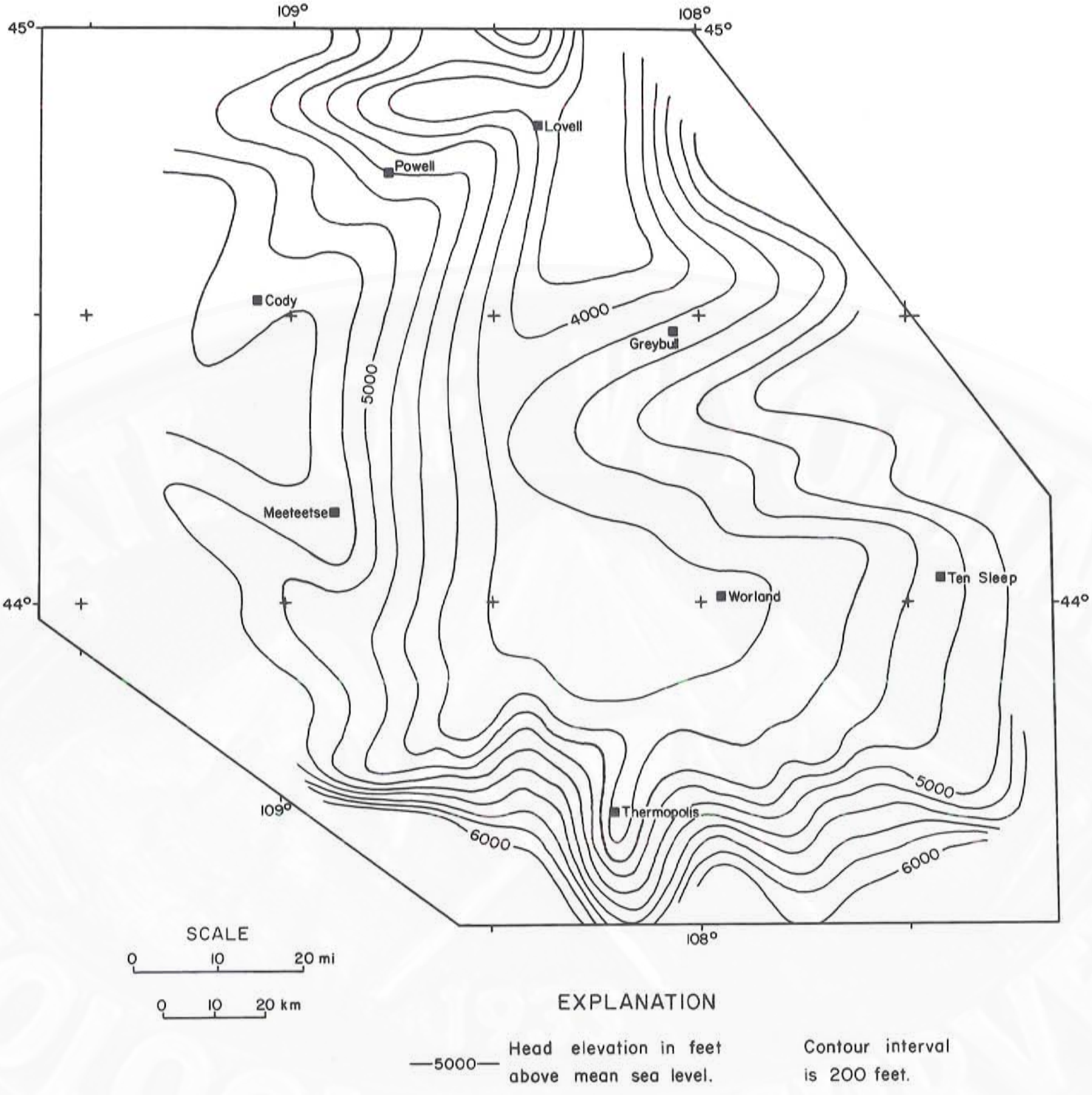


Figure 8. Potentiomentric surface map of the Tensleep Sandstone in the Bighorn Basin. After Bredehoeft and Bennet, 1972.

Thermally Anomalous Areas

SOUTHEAST OF LOVELL. In the northeast portion of the basin, water flow in the Tensleep Sandstone should be generally east to west. In an area centered 10 miles east-southeast of Lovell, the Tensleep Sandstone forms a syncline at an elevation of 1,000 feet. Since surface elevation above the syncline is around 4,000 feet, the temperature of the Tensleep Sandstone may reach 90°F in the syncline. Basinward of this syncline is a sharp anticline that brings the Tensleep Sandstone to the land surface, creating the potential for 90°F water at the surface. [The anticline does not appear as an anomaly on Plates II-IV because no BHT or logged well data are available for the area.]

NORTHWEST OF GREYBULL. There is an area of similar geometry 12 miles north and northwest of Greybull. As near Lovell, water in the Tensleep Sandstone moves downdip to a depth of over 3,000 feet, then to near the surface on its way from the Bighorn Mountains (recharge area) to the central basin.

NORTHWEST OF THERMOPOLIS. A third anomalous area resulting from a syncline, anticline couple is northwest of Thermopolis along the Thermopolis antilcine (Hinckley et al., 1982). Depending on the precise flow pattern, Tensleep Sandstone waters could be moving eastward from depths greater than 7,000 feet to depths less than 1,000 feet.

SOUTHWEST OF CODY. The west side of the basin has several structures which could produce elevated gradients. The only place where the Tensleep Sandstone is known to be folded to near the surface, however, is south of Cody (Heasler, 1982). As at the sites discussed above, this area is preceded (in terms of Bredehoeft and Bennett's (1972) and Heasler's (1982) flow direction) by an area of deep burial, centered about 16 miles south-southwest of Cody, as much as 8,000 feet below the surface.

Thus, by considering general structure and hydrologic conditions, we have identified four areas likely to have abnormally high geothermal gradients. With the additional observation that these areas are topographically lower than the corresponding mountain-flank recharge area, we have an explanation of the four thermal spring localities in the Bighorn Basin.

Geothermal Systems

The key element in the type of geothermal system seen in the Bighorn Basin is rapid circulation of ground water from deep to shallow zones. Fault and fracture systems may take the place of upwarped folds in transferring deep-heated water upward. The force moving the water in this case may be the type of confined artesian flow presented in Figure 4 or free convection as a result of thermally-induced density differences within a highly permeable fracture zone.

The hydrologic implications of faulting vary with the type of fault and the nature of the faulted strata. By juxtaposing permeable and impermeable units, compressional faulting may block water flow entirely. However, a highly fractured, tensional fault zone may create substantial permeability even in otherwise highly unproductive strata. A fault of the latter variety extending from the surface to a productive aquifer at depth would be an excellent target for geothermal exploration.

Prediction of fault-controlled geothermal systems in the Bighorn Basin is difficult. As late as 1976 (Lowry et al.), workers were suggesting that many shallow faults do not extend to depth, a conclusion based in part on Zapp's structural mapping (1956). More recent studies interpret many previously unrecognized faults at the Tensleep Sandstone level (Barlow and Haun, 1978) and perhaps much deeper (Stearns, 1975). For example, Barlow and Haun propose a fault in the Tensleep Sandstone with 4,000 feet of vertical displacement in an area southeast of Meeteetse. Oil well logs report temperatures of over 300°F (150°C) for Tensleep Sandstone fluids in that area. As in the rest of the basin, it is not known if fluids are or are not rising along this fault. Bredehoeft and Bennett's (1976) potentiometric surface map (Figure 8) indicates hydraulic head sufficient to lift Tensleep waters to near the surface. The major questions are the permeability of the fault zones and their vertical extent.

Several of the anticlines discussed above have associated faults. At both Cody and Thermopolis, faults are be-

Table 2. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Bighorn 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	13	145	55	91.8	88	106	116	126
500 - 1,000	13	161	49	84.4	80	85	116	116
1,000 - 1,500	53	130	68	85.2	83	88	92	100
1,500 - 2,000	37	150	68	88.7	85	95	96	110
2,000 - 2,500	50	140	70	90.4	90	95	102	112
2,500 - 3,000	84	143	73	99.5	100	108	115	124
3,000 - 3,500	197	148	67	105.9	104	115	123	132
3,500 - 4,000	254	162	76	103.9	103	108	113	121
4,000 - 4,500	232	188	73	106.6	106	111	116	121
4,500 - 5,000	194	197	66	110.4	111	115	120	126
5,000 - 5,500	163	152	76	115.0	115	120	129	134
5,500 - 6,000	90	162	77	112.2	115	119	123	131
6,000 - 6,500	97	200	83	118.2	118	124	130	140
6,500 - 7,000	79	155	87	121.1	124	127	131	141
7,000 - 7,500	53	160	95	122.7	124	130	134	142
7,500 - 8,000	45	171	86	121.7	123	130	142	151
8,000 - 8,500	33	145	82	120.2	122	132	138	142
8,500 - 9,000	44	168	88	123.4	121	135	147	156
9,000 - 9,500	48	182	90	127.2	120	135	154	165
9,500 - 10,000	45	210	93	133.7	120	155	166	171
10,000 - 10,500	46	196	98	139.2	136	148	165	178
10,500 - 11,000	95	202	108	136.6	134	140	148	162
11,000 - 11,500	37	220	110	140.8	134	144	155	169
11,500 - 12,000	10	214	140	171.3	174	182	200	214
12,000 - 12,500	4	268	159	197.5	194	194	268	268
12,500 - 13,000	1	208	208	208.0	208	208	208	208
13,000 - 13,500	7	212	171	188.1	188	195	200	212
13,500 - 14,000	1	196	196	196.0	196	196	196	196
14,000 - 14,500	3	215	195	195.0	193	215	215	215
14,500 - 15,000	1	265	265	265.0	265	265	265	265
15,000 - 15,500	1	251	251	251.0	251	251	251	251
15,500 - 16,000	1	234	234	234.0	234	234	234	234
16,000 - 16,500	1	210	210	210.0	210	210	210	210
16,500 - 17,000	0	-	-	-	-	-	-	-
17,000 - 17,500	1	252	252	252.0	252	252	252	252
17,500 - 18,000	0	-	-	-	-	-	-	-
18,000 - 18,500	1	228	228	228.0	228	228	228	228
18,500 - 19,000	0	-	-	-	-	-	-	-
19,000 - 19,500	0	-	-	-	-	-	-	-
19,500 - 20,000	0	-	-	-	-	-	-	-
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	0	-	-	-	-	-	-	-
21,000 - 21,500	0	-	-	-	-	-	-	-
21,500 - 22,000	0	-	-	-	-	-	-	-
22,000 - 22,500	0	-	-	-	-	-	-	-
22,500 - 23,000	0	-	-	-	-	-	-	-
23,000 - 23,500	1	306	306	306.0	306	306	306	306

Total: 2,035 bottom-hole temperature measurements.

Table 3. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Bighorn 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	13	305.0	25.6	156.2	109.4	239.2	265.6	265.6
500 - 1,000	13	160.4	4.6	58.4	57.1	60.7	79.7	114.0
1,000 - 1,500	53	60.3	17.3	31.2	28.7	32.0	37.0	46.6
1,500 - 2,000	37	58.4	11.5	24.9	22.9	25.6	30.0	38.5
2,000 - 2,500	50	41.7	11.4	20.4	19.2	22.1	24.7	30.6
2,500 - 3,000	84	35.2	9.7	19.9	18.8	22.8	25.3	27.5
3,000 - 3,500	197	31.5	6.3	18.5	17.2	21.3	23.3	25.9
3,500 - 4,000	254	32.1	8.6	15.6	15.1	16.3	17.9	20.5
4,000 - 4,500	232	32.5	6.4	14.5	14.4	15.1	16.6	17.6
4,500 - 5,000	194	32.4	4.3	13.9	13.8	14.5	15.9	16.9
5,000 - 5,500	163	20.4	5.7	13.4	13.1	14.0	15.9	16.6
5,500 - 6,000	90	20.8	5.4	11.7	12.0	12.7	13.6	14.6
6,000 - 6,500	97	24.0	6.1	11.8	11.4	12.4	13.6	15.1
6,500 - 7,000	79	16.8	6.3	11.3	11.6	12.1	12.8	14.4
7,000 - 7,500	53	16.0	6.8	10.7	10.9	11.8	12.5	13.1
7,500 - 8,000	45	16.7	5.4	9.9	10.0	10.9	12.3	13.7
8,000 - 8,500	33	12.2	4.5	9.1	9.5	10.4	11.1	11.7
8,500 - 9,000	44	14.4	4.8	9.0	8.9	10.3	11.8	12.4
9,000 - 9,500	48	14.9	4.8	8.9	8.0	9.7	11.6	13.0
9,500 - 10,000	45	16.8	5.0	9.1	7.8	11.1	12.4	13.0
10,000 - 10,500	46	14.9	5.1	9.2	8.8	10.3	11.6	13.2
10,500 - 11,000	95	14.6	5.9	8.5	8.2	8.8	9.5	10.8
11,000 - 11,500	37	15.3	5.9	8.6	8.0	8.9	9.9	11.2
11,500 - 12,000	10	14.2	8.2	10.8	10.9	11.2	13.2	14.2
12,000 - 12,500	4	18.0	9.5	12.5	12.3	12.3	18.0	18.0
12,500 - 13,000	1	12.6	12.6	12.6	12.6	12.6	12.6	12.6
13,000 - 13,500	7	12.7	9.6	10.8	10.7	11.3	11.7	12.7
13,500 - 14,000	1	11.2	11.2	11.2	11.2	11.2	11.2	11.2
14,000 - 14,500	3	12.0	9.2	10.6	10.5	12.0	12.0	12.0
14,500 - 15,000	1	15.0	15.0	15.0	15.0	15.0	15.0	15.0
15,000 - 15,500	1	13.5	13.5	13.5	13.5	13.5	13.5	13.5
15,500 - 16,000	1	11.9	11.9	11.9	11.9	11.9	11.9	11.9
16,000 - 16,500	1	10.0	10.0	10.0	10.0	10.0	10.0	10.0
16,500 - 17,000	0	-	-	-	-	-	-	-
17,000 - 17,500	1	12.0	12.0	12.0	12.0	12.0	12.0	12.0
17,500 - 18,000	0	-	-	-	-	-	-	-
18,000 - 18,500	1	10.0	10.0	10.0	10.0	10.0	10.0	10.0
18,500 - 19,000	0	-	-	-	-	-	-	-
19,000 - 19,500	0	-	-	-	-	-	-	-
19,500 - 20,000	0	-	-	-	-	-	-	-
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	0	-	-	-	-	-	-	-
21,000 - 21,500	0	-	-	-	-	-	-	-
21,500 - 22,000	0	-	-	-	-	-	-	-
22,000 - 22,500	0	-	-	-	-	-	-	-
22,500 - 23,000	0	-	-	-	-	-	-	-
23,000 - 23,500	1	11.3	11.3	11.3	11.3	11.3	11.3	11.3

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

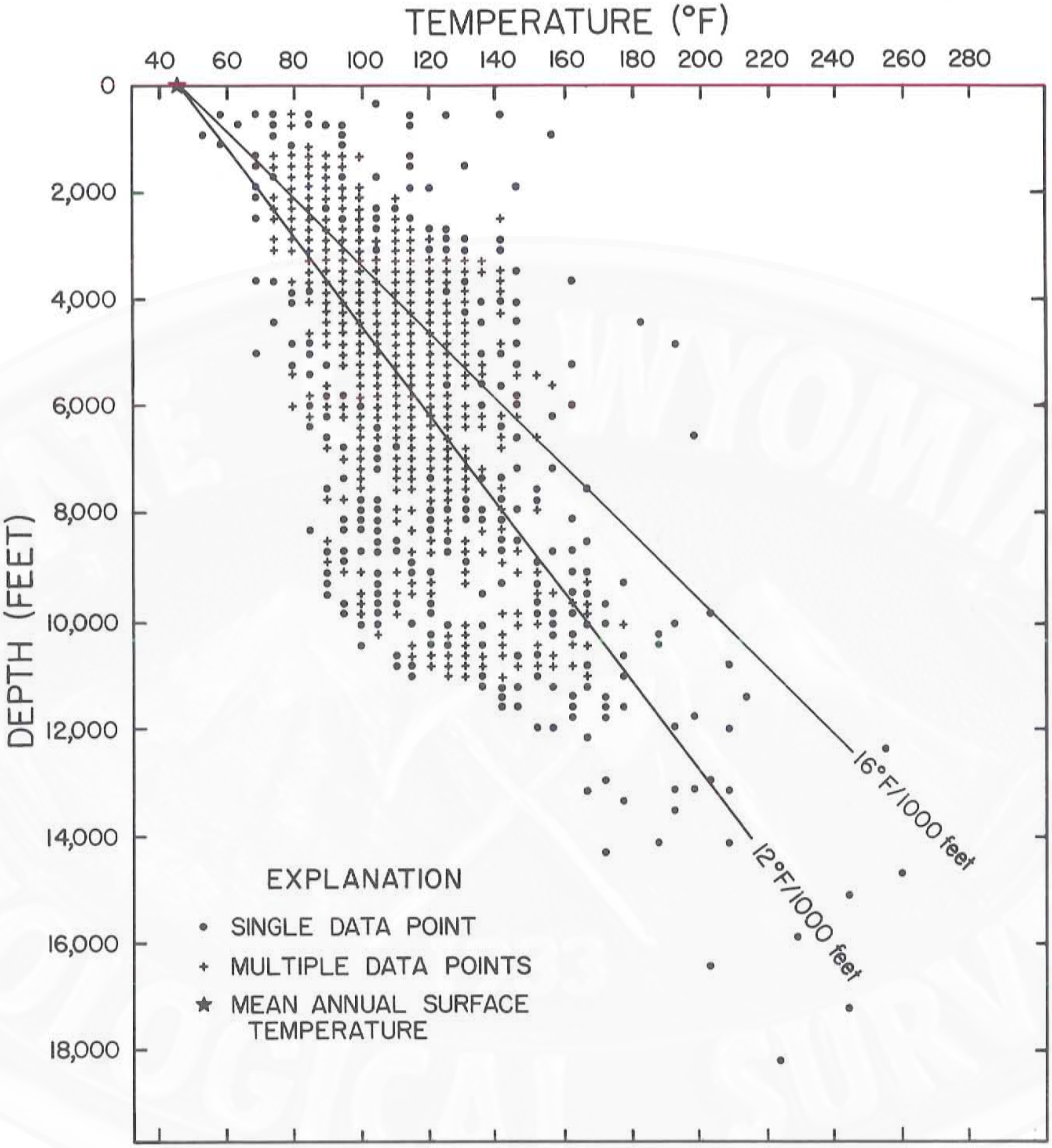


Figure 9. Temperature-depth plot of bottom-hole temperatures in the Bighorn Basin.

lieved to aid the flow of geothermal waters through predominantly fold-controlled systems (see studies by Heasler, 1982 and Hinckley et al., 1982). Beyond this general discussion of fault extent, stress conditions, and stratigraphy, delineation of fault-controlled systems must await additional detailed studies.

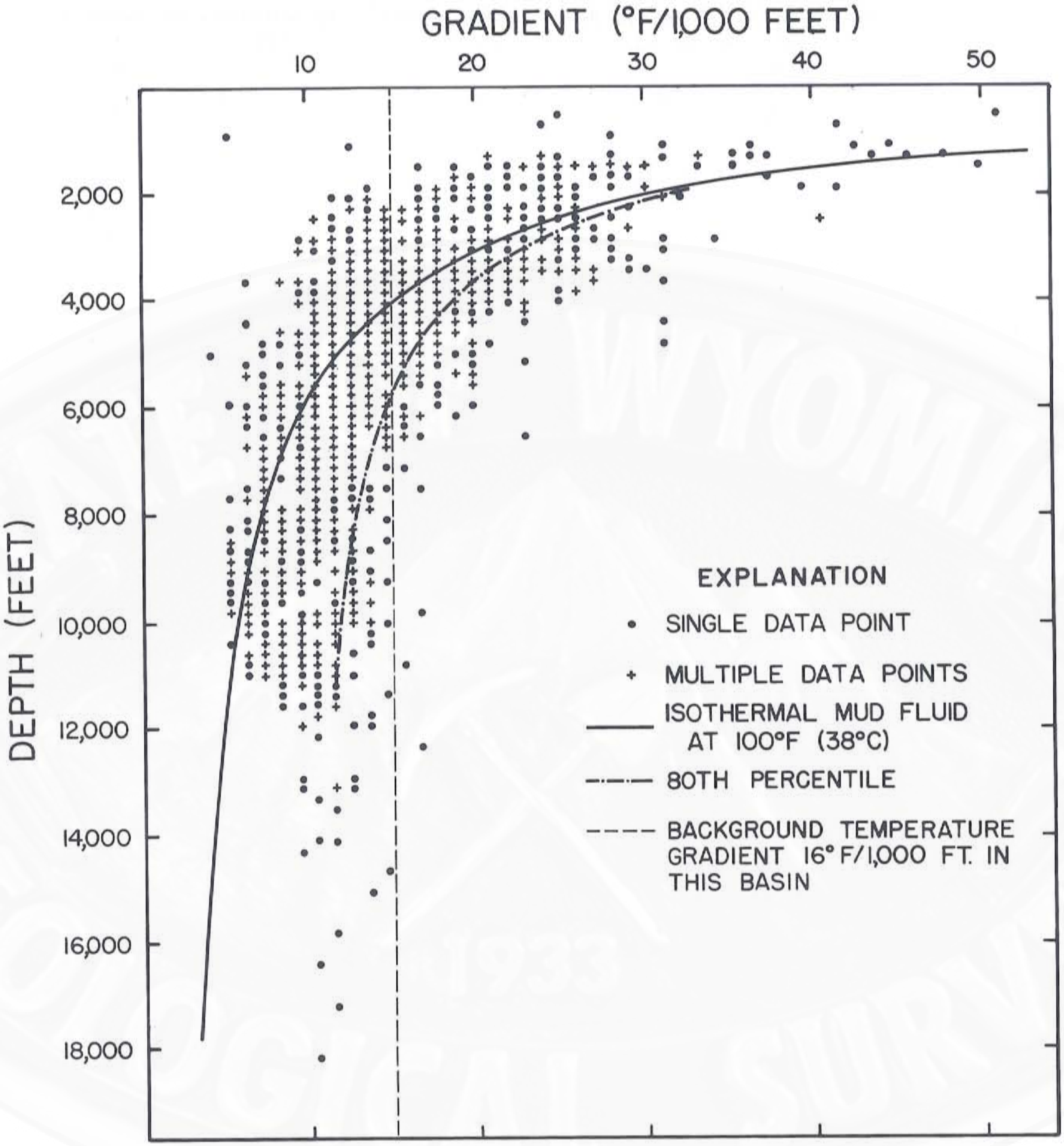


Figure 10. Gradient-depth plot, based on bottom-hole temperatures, for the Bighorn Basin.

A third way to tap deep-heated waters is drill holes. Deep water encountered in petroleum production or exploration, while not anomalous in gradient or temperature, may provide valuable geothermal resources. A rough prediction of a formation's temperature can be made on the basis of its depth.

The locations of drill holes to deep water have been determined by oil company strategies. A preliminary inventory of oil-field geothermal waters in Wyoming has been completed by Hinckley (1984). An example from that inventory is the Hamilton Dome oil field, which discharges 3,400 gpm of 143°F water to the surface.

THERMAL GRADIENTS

As explained in the Introduction, the main source of thermal gradient data is oil and gas well bottom-hole temperatures (BHT's). Approximately 2,035 BHT's have been collected from the Bighorn Basin -- these are tabulated in Table 2 and presented graphically in Figure 9. Thermal gradients were computed using values for the mean annual air temperature of 41 to 45°F (Lowers, 1960), depending on the nearest reporting station -- these are tabulated in Table 3 and presented graphically in Figure 10. The overall average of the 2,035 gradients is 15.5°F/1,000 ft. As explained in the Introduction, gradients derived from shallow BHT's tend to be higher than average, and gradients derived from deep BHT's lower, because of drilling effects. The "crossover" occurs at a depth between 4,000 and 4,500 feet in the Bighorn Basin.

The estimation of a purely conductive gradient ($G = \Delta T/\Delta X$, where G = gradient, T = temperature, and X = depth) can be made using heat flow (H) and thermal conductivity (C). These quantities are related by the expression:

$$G = \frac{H}{C}$$

(see footnote, page 2). Heat flow values for the Bighorn Basin have been reported by Blackwell (1969), Heasler (1978, 1982), Decker et al. (1980), and Buelow (1980). These values are listed in Table 4 and are plotted on Plate II. Using an average heat flow of 73 mW/m^2 and conductivity information compiled by Hinckley et al. (1982), an average gradient of 16°F/1,000 ft for the Precambrian to Cody Shale section has been calculated. Conductivity determinations are rare for younger strata, so calculations like those just described have not been made for post-Cody strata. The lithology of the post-Cody strata, however, is such that its conductivity may be roughly comparable, in aggregate, to the overall conductivity of the Precambrian-Cody setion, and so long-interval conductive gradients in these strata may not differ substantially from 15 to 16°F/1,000 ft. Thus, the gradient value derived from conductivity and heat flow determinations agrees with the average BHT gradient.

A particularly interesting aspect of formation-by-formation gradient calculations is the great variability encountered. In the rock section at Thermopolis considered by Hinckley et al. (1982) and thermally measured at Elk Basin by Heasler (1978), gradients vary from 9.2 to 24°F/1,000 ft as a result of rock conductivity changes. The possibility of such variation decreases as the temperature gradient is calculated over larger depth intervals. Thus, gradients over small intervals -- shallow holes, for example -- may be deceptive.

The case-by-case analysis required for the precise evaluation of this effect is beyond the scope of this report, but a few generalizations may be made. In general, sandstone and limestone tend to have lower thermal gradients than siltstone and shale. The geologic column (Figure 7) shows a gross lithologic difference between the Paleozoic and Mesozoic-Cenozoic sections, and Paleozoic gradients are somewhat lower. Thus, as a general rule, a high gradient determined from Paleozoic rocks (or limestone elsewhere in the section) is indicative of greater heat transfer than the same gradient in a general Mesozoic or Cenozoic section is. (Compare geologic outcrop and gradient contour maps, Plates I and II.)

Table 4. Heat flow values from the Bighorn Basin.

Location (township-range-section)	Heat flow (mW/m^2)	Thermal conductivity (W/m°K)	Age and lithology	Reference
58-99-30	75	2.84	Lower Cretaceous-Mississippian sediments	Decker and others, 1980
58-99-30	63	2.94	Lower Cretaceous-Mississippian sediments	Decker and others, 1980
51-100-20	54	1.68^e	Cretaceous shale	Blackwell, 1969
46-104-25	74	2.65	Precambrian diorite	Buelow, 1980
45-104-24	75	2.91	Tertiary volcanics	Blackwell, 1969
44-96-2	54	1.68^e	Cretaceous shale	Blackwell, 1969
44-95-22	67	1.68^e	Cretaceous shale	Blackwell, 1969

e=estimated

Another check on BHT-derived gradients is provided by actual thermal logs of drill holes. Those points marked "+" on the gradient map denote holes in which the temperature was measured at intervals of 32 feet or less. BHT data provide only single, average, top-to-bottom gradients, whereas thermal logging measures small gradient changes (see discussion, pages 5-8 of the Introduction).

In areas with deep BHT's, thermal logging is in general agreement with BHT-derived gradients. As noted above, discrepancies may arise in shallow wells. In the Spence Dome area, midway between Greybull and Lovell, for example, BHT's at 500 feet indicate gradients in excess of 65°F/1,000 ft. These values are surprising because the structure and hydrology suggest that waters moving into the Spence Dome area have not circulated deep. Thermal logging of six holes in the Spence area gives gradients consistently around 8.2 to 11.8°F/1,000 ft. Since the conductivity of the rocks in these holes is (a relatively high) 3.40 to 4.4 W/m°C (Heasler, 1978), the assumed background heat flow of 73 mW/m^2 (see Table 2) should produce gradients of 9.0 to 11.6 °F/1,000 ft (16.6 to 21.5 x 10^{-3} °C/m). Apparently, this area is subject to primarily conductive gradients, and water movement is insufficient either to raise or lower these gradients significantly. As discussed in the Introduction, we believe that the high oil-well BHT gradients defined for shallow depth result from drilling disturbances.

The Greybull area presents a situation similar to that at Spence Dome.

Here again, oil production, and consequently most BHT's, are from shallow zones. While a legitimate temperature of 95°F at 500 feet would represent an extreme geothermal anomaly (gradient = 100°F/1,000 ft), such a temperature may be the result only of drilling conditions. If the same gradient were established by a BHT of 245°F at 2,000 feet, we could be more confident of its accuracy. The apparent anomaly at Greybull was also investigated by thermal logging, which measured gradients of 16 to 20 °F/1,000 ft in two drill holes.

All available data have been incorporated into the thermal gradient map (Plate II). Gradients established by thermal logging have been directly measured, generally well after drilling disturbances have dissipated. BHT data is less reliable than thermal logging data, but is generally supported both by thermal logging and by heat flow and thermal conductivity calculations. The most consistent discrepancies between thermal gradient calculation based on thermal logging data and those based on BHT data have appeared in either shallow areas (as explained above) or in high-gradient areas (greater than 25°F/1,000 ft) where gradient values tend to vary widely in response to local hydrologic conditions. Contouring is generalized; i.e., one odd value in an area of many consistent values has not been independently contoured.

The data points on the thermal gradient map are the control points for contouring. Where these are sparse, the contouring is generalized and local areas of higher or lower gradients may have been overlooked. Where geothermal systems are controlled by the general patterns of folding, they will probably appear on this map. They will be known because the resultant anomalies will be fairly large and the known anticlinal portions of the systems will likely have been drilled during oil exploration. The areas of shallow, high gradients predicted on the basis of structures and water movement in the previous section are indicated by the gradient contours.

On the other hand, an area of high gradient due to water movement along a fault not associated with a major fold may create a fairly local anomaly in an area with sparse well data (without obvious oil production potential). We have identified no systems of this type within the Bighorn Basin, although a number of large faults are indicated on the structure contour map.

Hot water may rise in a deep drill hole because of hydrostatic pressure. Although this may place hot water near the surface, it would not indicate a high gradient and would not be shown by gradient contours.

The exact delineation of geothermal anomalies depends on both the quality and the quantity of available data. Most of the interior Bighorn Basin is mapped as having a geothermal gradient of less than 15°F/1,000 ft, much of it less than 10°F/1,000 ft. Data is sparse over a great deal of this area, and the structure is poorly known. Thus, the lack of interruption in the 15°F/1,000 ft contour may be due simply to insufficient data. Furthermore, because most BHT's from this area tend to be quite deep, they are subject to underestimation due to drilling effects.

The geothermal potential of the deep basin may be partially evaluated from its structure. The fold system at Thermopolis rises approximately 7,000 feet from synclinal trough to anticlinal crest, and is one of the largest folds in the Bighorn Basin. If such a fold were present in the interior of the basin, rising, for example, from 25,000 to 18,000 feet deep, the thermal gradient would only be raised at most from 15°F/1,000 ft to 20°F/1,000 ft. To produce thermal gradients in excess of 30°F/1,000 ft, even an ideal fold system of this large amplitude could have its crest no deeper than 7,000 feet. For the Tensleep Sandstone, depths of 7,000 feet or less are equivalent to elevations higher than -2,000 feet (see Plate III). Consequently, the Tensleep Sandstone is unlikely to possess attractive geothermal resources in the deep, interior basin even if large unrecognized folds exist. Given the great thickness of Upper Cretaceous and Cenozoic strata in the central basin, and the inferred lack of significant structure in underlying units, the basin margins are believed to have the highest geothermal potential.

As noted above, BHT-derived gradients shift from above average to below average at about 4,500 feet. This is also approximately the point where BHT gradients change from being greater than the background thermal gradient (see page 7) to being less than the background thermal gradient. Consequently, 4,500 feet is used to separate areas of anomalous gradient into two sets. In areas with a horizontal-line pattern on Plates II, III, and IV, anomalous gradients were determined from BHT's taken above 4,500 feet deep. Anomalous gradients in areas with a vertical-line pattern on Plates II, III, and IV were determined from BHT's taken deeper than 4,500 feet. Anomalies have been defined through comparison of BHT's in the same depth range (see Table 2), as explained in the Introduction.

TEMPERATURES

The temperature contour map (Plate IV) was compiled from oil-field bottom-hole temperatures (BHT's) and thermal logging data for the Tensleep Sandstone and the Park City Formation. The Tensleep - Park City section is an important regional aquifer, and ample temperature data has been collected from it. No extrapolation of gradients based on deeper or shallower formations was used; data points represent temperature values measured in those two formations. In the deep interior basin, where insufficient data are available for contouring, individual temperature values are listed.

Given the structural similarities of the Mesozoic and Paleozoic sections in the Bighorn Basin, the Tensleep - Park City temperature contour map roughly brackets the geothermal resource throughout the basin. Approximately 2,500 feet of sedimentary rock lie below the Tensleep Sandstone - Park City Formation. At a background gradient of 15 to 16°F/1,000 ft, the highest temperatures likely to be produced from any sedimentary strata are around 40°F higher than those mapped. In none of the areas of anomalous gradient are significant quantities of water in excess of 200°F likely to be found at any depth. (Rock temperature continues to rise with depth, but the absence of water-bearing strata precludes the existence of a resource.)

Besides a general view of temperatures basinwide, the water temperature contour map (Plate IV) shows absolute temperatures for the identified geothermal anomalies. (Temperatures will be somewhat higher in the deeper Madison, Bighorn, and Flathead aquifers). None of these areas, though anomalous, can produce water warmer than 180°F from the Park City - Tensleep aquifer. If water in excess of 200°F is required, deep areas of normal gradient must be examined. Such areas will likely produce thermal water economically only in conjunction with more valuable oil and gas resources.

SUMMARY AND CONCLUSIONS

The geothermal resources in the Bighorn Basin are created by heat flow, geologic structures, and hydrology. Water is heated under normal temperature gradients and may reach temperatures in excess of 400°F in the deepest part of the basin. Deep-heated waters are brought nearer to the surface along basin-flanking anticlines, creating anomalously high gradient areas and, in some cases, thermal springs. Near the margin of the basin, temperatures within anomalous gradient areas are unlikely to exceed 200°F.

The distribution of BHT data has focused attention on fold-controlled geothermal systems. Deep faults may produce local geothermal anomalies which have not been seen in the present study. An additional mode of access to deep-heated water, including that in areas of normal gradient, is oil and gas wells. The geothermal potential of a well at any location can be roughly assessed from the structure contour and thermal gradient maps (Plates II and III) and the geologic column (Figure 7).

Since the Bighorn Basin geothermal resource is hydrothermal, resource potential is largely confined to productive aquifers. Major aquifers deep enough to develop significant temperatures are the Tensleep - Park City, Madison, Bighorn, and Flathead aquifers, all of Paleozoic age. Less productive aquifers in the Mesozoic section (the Frontier and Cloverly Formations) may be locally important.

In the identified thermally anomalous areas, total dissolved solids from Paleozoic aquifers are generally below 2,500 mg/l (thermal spring values range from 270 to 2,300 mg/l). Deeper, basin-interior water from the same strata is believed to be of much higher salinity (Libra et al., 1981).

Applications of the Bighorn Basin geothermal resource are primarily direct heat processes. Commercial geothermal greenhouses as well as geothermally heated private homes currently exist in Thermopolis. Extensive recreational and therapeutic facilities utilize hot spring waters at Thermopolis and Cody. A feasibility study has been completed for a geothermal district space-heating project for Thermopolis; a ground-water heat pump system has been installed at Northwest Community College in Powell; and a commercial greenhouse south of Powell, to be heated by oil-field thermal waters, is being studied. While this is merely a sample of possible applications, it does represent the range of applications under consideration at this time.

As with any energy resource, the potential of geothermal energy is ultimately a market decision. Geothermal energy is unlikely to form a major industrial base in the Bighorn Basin, but its value as a local, locally controlled, renewable, relatively nonpolluting energy source can only increase as fossil fuel costs rise.

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THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

EXPLANATION

—— CONTACT

—— FAULT

Qal — QUATERNARY ALLUVIAL DEPOSITS

Tv — TERTIARY VOLCANICS

Ts — TERTIARY SEDIMENTS

Klmv — UPPER CRETACEOUS LANCE, MEETEETSE AND MESA VERDE FORMATIONS

Kcf — UPPER CRETACEOUS CODY AND FRONTIER FORMATIONS

KTRu — LOWER CRETACEOUS MOWRY, THERMOPOLIS AND CLOVERLY FORMATIONS AND JURASSIC AND TRIASSIC ROCKS UNDIVIDED

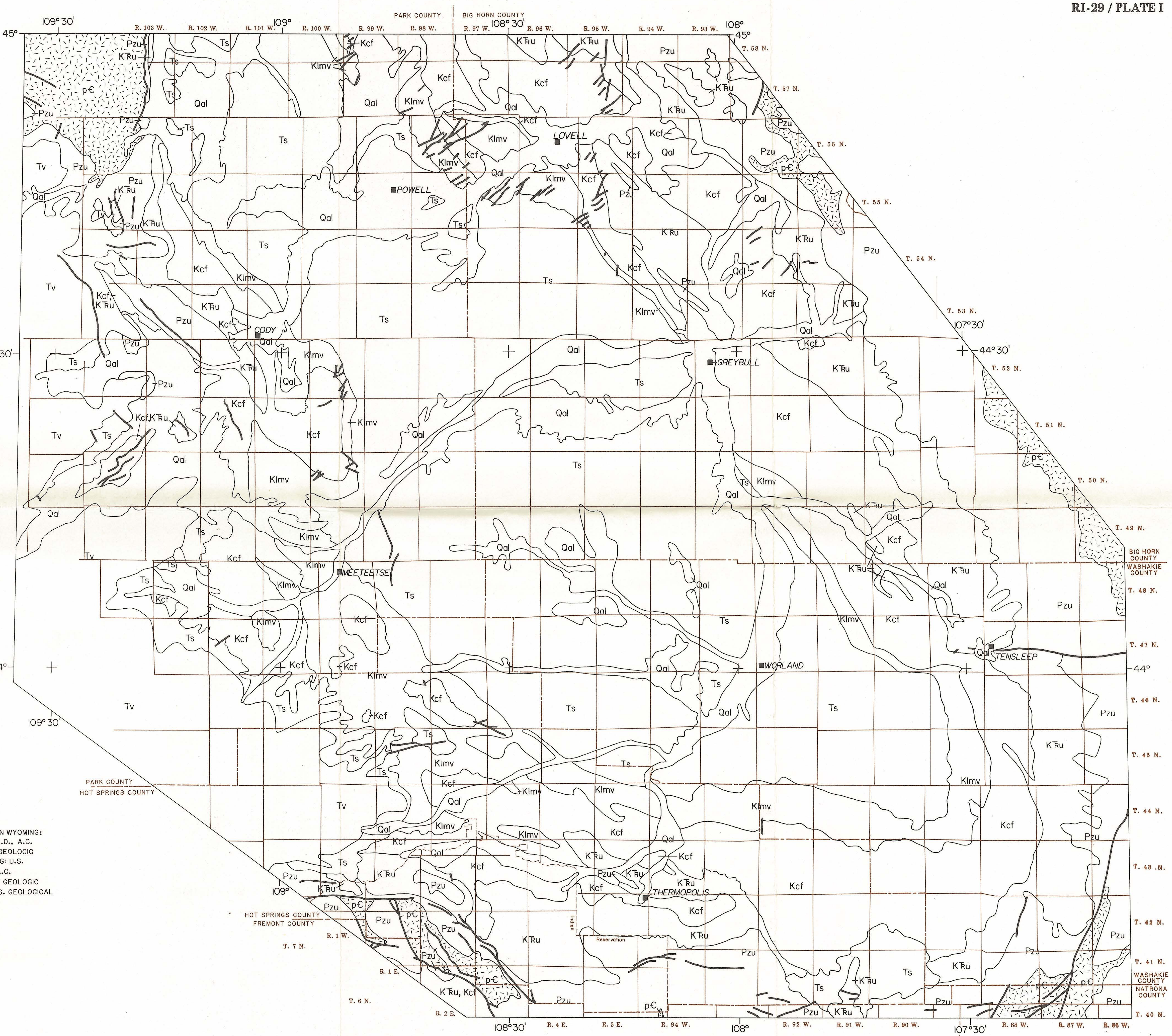
Pzu — PALEOZOIC ROCKS UNDIVIDED (INCLUDING THE TENSLEEP SANDSTONE AND PARK CITY FORMATION)

p€ — PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS

SCALE

MILES: 5 0 5 10 15 20

KILOMETERS: 5 0 5 10 15 20



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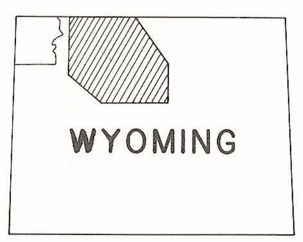

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COMPILED BY B.S. HINCKLEY AND H.P. HEASLER

GENERALIZED GEOLOGIC MAP OF THE BIGHORN BASIN, WYOMING

THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

EXPLANATION

GRADIENT CONTOUR
IN °F/1000 FT. CONTOUR LINE IS DASHED WHERE APPROXIMATE

DATA POINT DERIVED FROM BOTTOM HOLE TEMPERATURE GRADIENT

THREE OR MORE GRADIENT DATA POINTS WITHIN A SECTION

GRADIENT POINT NOT INCLUDED IN CONTOURING- ANNOTATED WITH GRADIENT IN °F/1,000 FT.

TEMPERATURE GRADIENT OF THERMALLY LOGGED HOLE- ANNOTATED WITH GRADIENT IN °F/1,000 FT. (FOR MAXIMUM DEPTH IN FEET)

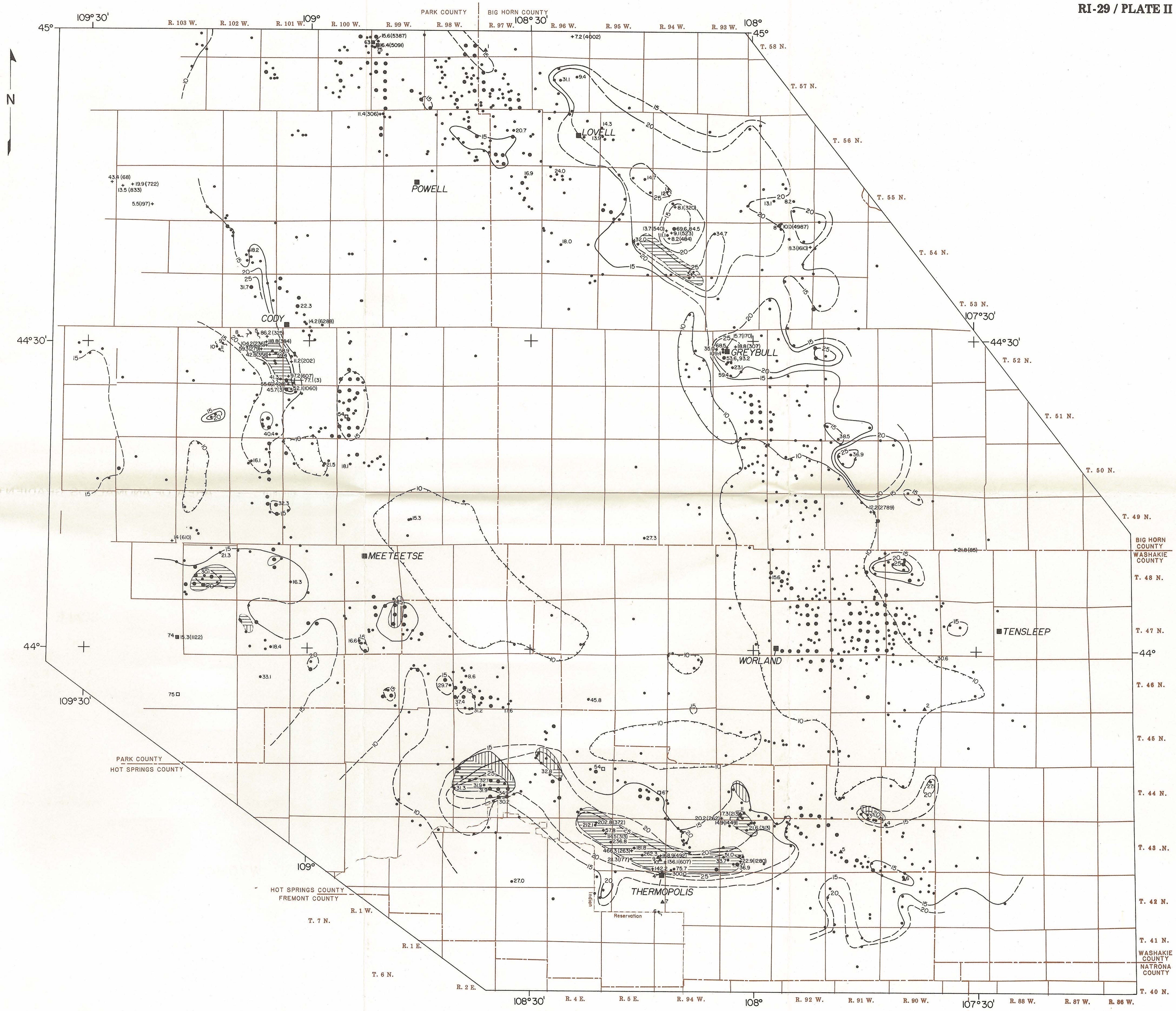
SELECT WELL FLOWING GREATER THAN 70°F WATER
ANNOTATED WITH TEMPERATURE IN °F

SPRING FLOWING GREATER THAN 70°F WATER
ANNOTATED WITH TEMPERATURE IN °F

HEAT FLOW DATA POINT
(IN mW/m^2)

AREA OF ANOMALOUS GRADIENTS- DEFINED BY DEPTHS <4,500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE

AREA OF ANOMALOUS GRADIENTS- DEFINED BY DEPTHS >4,500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE



SCALE

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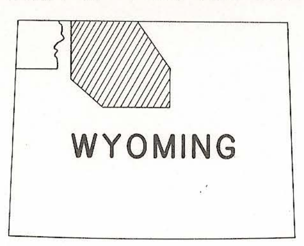
KILOMETERS
5 0 5 10 15 20

AREA OF THIS REPORT



COMPILED BY B.S. HINCKLEY AND H.P. HEASLER

GENERALIZED THERMAL GRADIENT CONTOUR MAP OF THE BIGHORN BASIN WYOMING

THE GEOLOGICAL SURVEY OF WYOMING
Gary B. Glass, State Geologist

EXPLANATION

3000 — CONTOUR ON TENSLEEP SANDSTONE
DATUM IS MEAN SEA LEVEL, CONTOUR INTERVAL 1000 FT. (QUALITY OF CONTROL VARIES)

5000 - - - SELECT CONTOUR ON LAND SURFACE
DATUM IS MEAN SEA LEVEL

— FAULT

—+— SYNCLINE AXIS

· LOCATION OF REPORTED BOTTOM-HOLE TEMPERATURE

• SECTION WITH 3 OR MORE REPORTED BOTTOM-HOLE TEMPERATURES

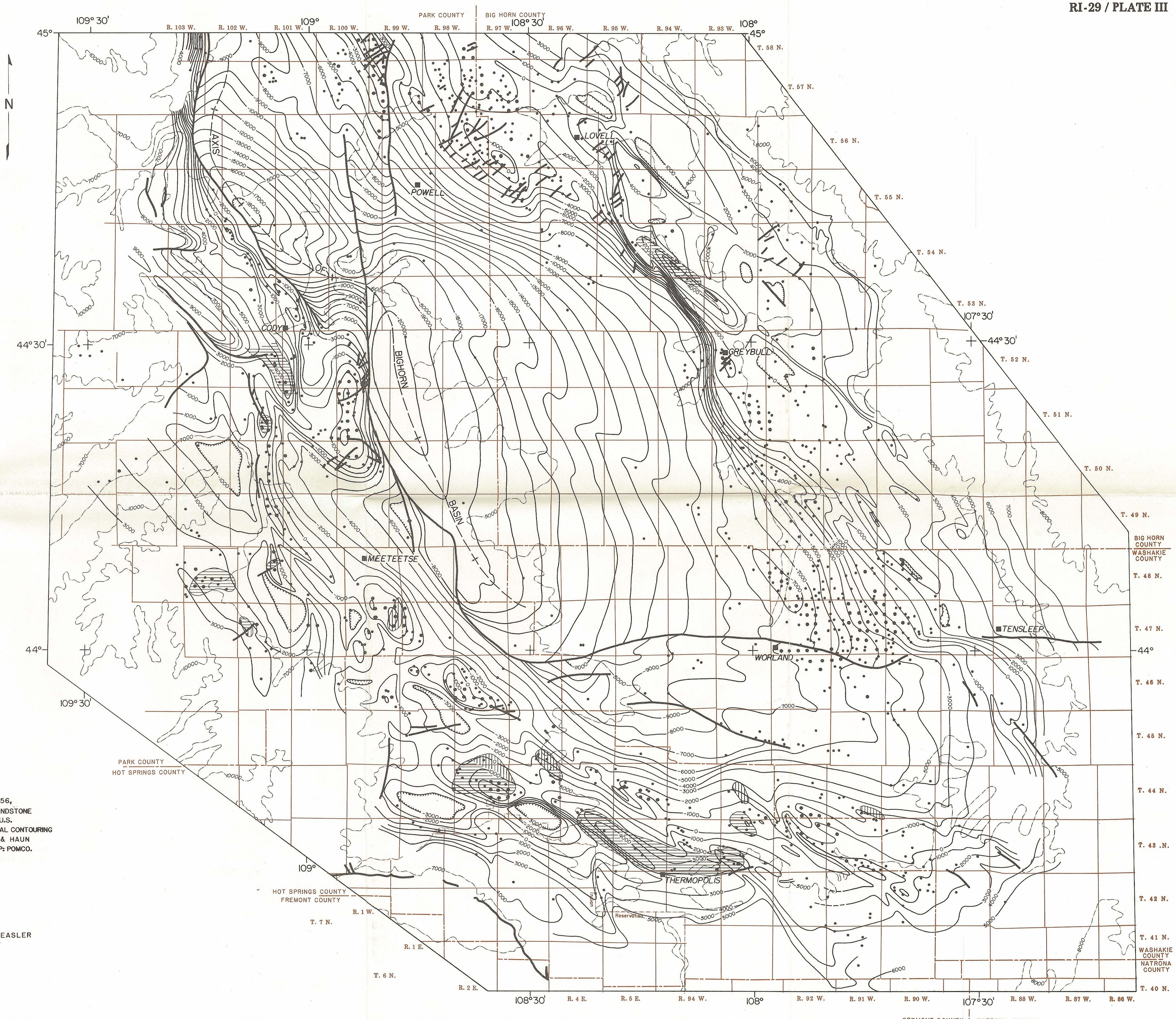
AREA OF ANOMALOUS GRADIENTS- DEFINED BY DEPTHS <4,500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE

AREA OF ANOMALOUS GRADIENTS- DEFINED BY DEPTHS >4,500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE

SCALE

MILES
5 0 5 10 15 20

KILOMETERS
5 0 5 10 15 20



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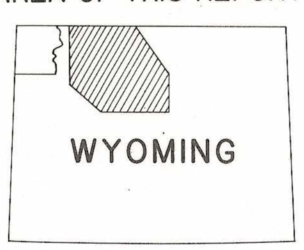

GENERALIZED FROM

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COMPILED BY B.S. HINCKLEY AND H. P. HEASLER

GENERALIZED STRUCTURE CONTOUR MAP OF THE TENSLEEP SANDSTONE, BIGHORN BASIN, WYOMING

EXPLANATION

—160°— — — TEMPERATURE CONTOUR (°F)
CONTOUR INTERVAL 10°F
DASHED WHERE APPROXIMATE

APPROXIMATE OUTCROP OF THE TENSLEEP SANDSTONE–PARK CITY FORMATION CONTACT
(AFTER ZAPP, 1956)

BOTTOM-HOLE TEMPERATURE DATA POINT FOR TENSLEEP OR PARK CITY FORMATION

SECTION WITH 3 OR MORE BOTTOM-HOLE TEMPERATURE DATA POINTS

•94° LOCATION AND TEMPERATURE (°F) OF DATA POINT NOT INCLUDED IN CONTOURING

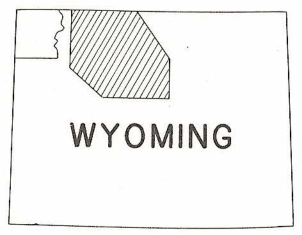
+94° DATA POINT ESTABLISHED BY THERMAL LOGGING (°F)

AREA OF ANOMALOUS GRADIENTS - DEFINED BY DEPTHS <4500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE

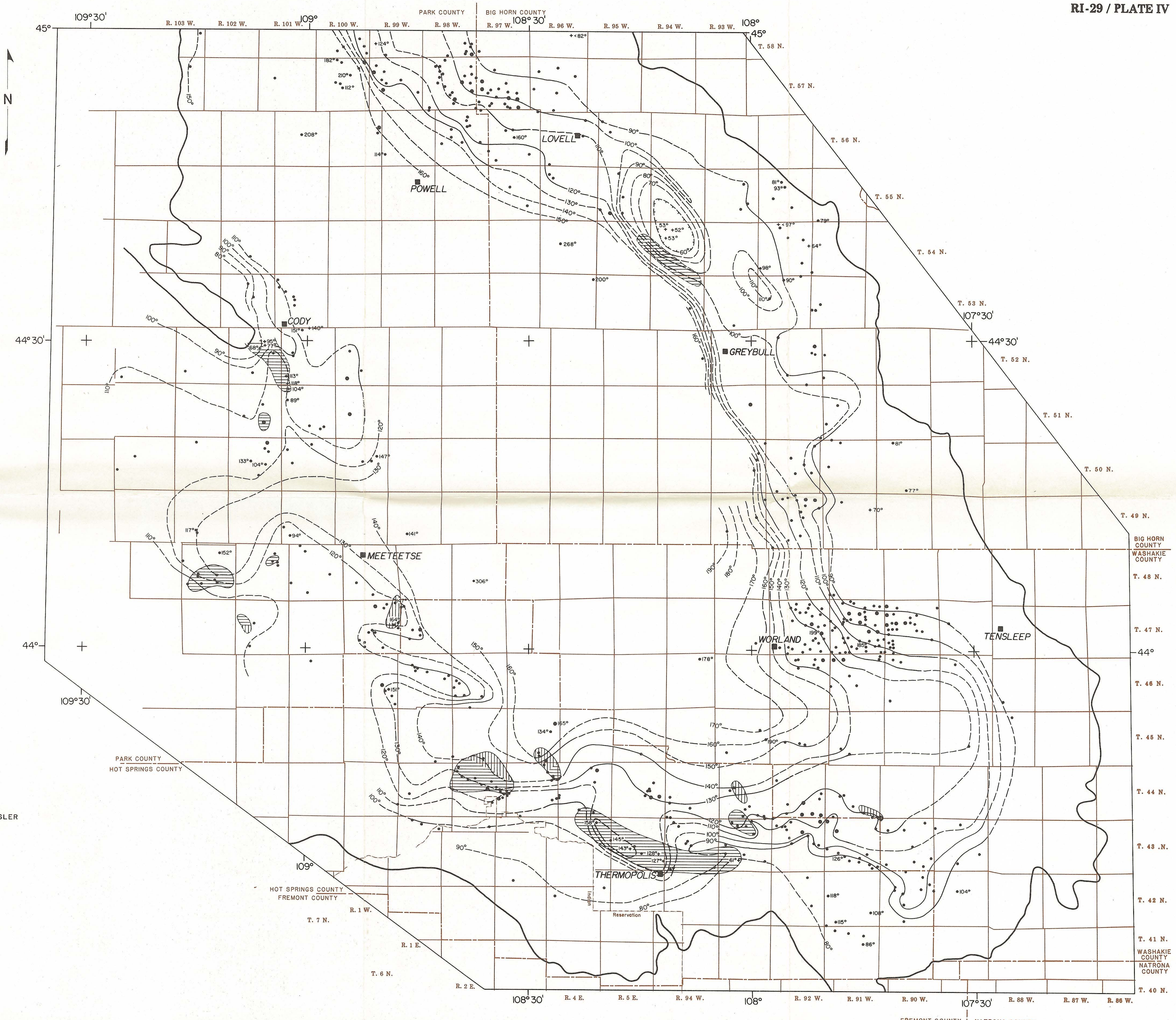
AREA OF ANOMALOUS GRADIENTS - DEFINED BY DEPTHS >4500 FT. (SEE TEXT PAGE 25 FOR EXPLANATION)
AREA BOUNDARY DASHED WHERE APPROXIMATE

SCALE
MILES
5 0 5 10 15 20
KILOMETERS
5 0 5 10 15 20

AREA OF THIS REPORT



COMPILED BY B.S. HINCKLEY AND H.P. HEASLER



GROUND-WATER TEMPERATURE CONTOUR MAP OF THE TENSLEEP SANDSTONE AND PARK CITY FORMATION, BIGHORN BASIN, WYOMING