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

GEOTHERMAL RESOURCES OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

by
Kenneth L. Buelow, Henry P. Heasler
and Bern S. Hinckley

Report of Investigations No. 36
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Laramie, Wyoming

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Cover photograph - Typical scene in the southern Powder River Basin, Wyoming. Shallow, wind-powered well near Pine Tree provides water for range cattle. (Photograph by Gary B. Glass.)

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Report of Investigations No. 26

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Kenneth L. Buelow, Henry P. Heasler and Bern S. Hinckley

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Contents

Illustrations

Figures

Illustrations continued

Sheets (back pocket)

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 third in a series of reports describing the geothermal resources of Wyoming basins (**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 (**Sheets 1** through **4**, back pocket): a generalized geological map (**Sheet 1**); a thermal gradient contour map (**Sheet 2**); and a structure contour map and ground-water temperature map for a key formation (**Sheets 3** and **4**). The report format and the detail of interpretation vary because the type of geothermal system, 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, with a general description of the State's thermal setting; and (3) a discussion of the methods used in assessing the geothermal resources. This introduction is followed by a description of the geothermal resources of the southern Powder River Basin of northeastern 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. The compilations of oil well bottom-hole temperatures used in this study can be examined at the Geological Survey of Wyoming office in Laramie.

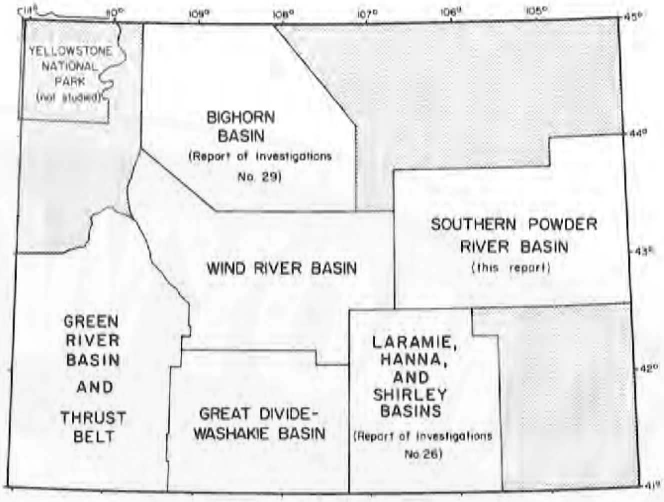


Figure 1. Study areas planned or completed in this series.

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

In this report a geothermal resource is heated water close enough to the earth's surface to be useful. Further definitions or classifications of geothermal resources are not attempted here because they are based on changing technological and economic parameters. Rather, we use geothermal data to describe the thermal regime in each basin. Thermal anomalies are identified, but no attempt is made to determine to what degree an anomaly is a resource.

Geothermal systems vary from very high-temperature, steam-dominated, naturally pressurized types to warm water, mechanically-pumped systems. The type of system depends on how the heat flowing out of the earth is modified by complex geologic and hydrologic conditions. Commonly, the earth warms 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 feet.

Heat-flow studies in Wyoming basins (Decker and others, 1980; Heasler and others, 1982) have reported heat flows of 33 to 80 milliwatts per square meter (mW/m^2) (**Figure 2**). The most notable exception is in the northwest corner of Wyoming, in Yellowstone National Park, where very high heat flows of over 105 mW/m^2 (Morgan and others, 1977) result in high-temperature water at shallow depth.

By itself, a background heat flow of 33 to 80 mW/m^2 does not suggest a significant geothermal resource. In Wyoming basins, the primary mechanism for translating moderate heat flow into above-normal temperature gradients is ground-water flow through geologic structures. **Figures** 3 and 4 illustrate systems based on two different structural regimes. Ground water flowing downward from the recharge area equilibrates with the temperature of the surrounding rock. But locally, folded permeable rocks (**Figure** 3) or faults (**Figure** 4) provide conduits for this heated water to rise rapidly toward the surface. If water proceeds through such a conduit without major heat dissipation, an elevated thermal gradient develops. 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, geothermally 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. *Forced convection* occurs where water moves in a confined aquifer from an elevated recharge area at a basin margin to a lower discharge area in the basin interior. Water is forced over folds or up faults, fractures or wells by the hydrostatic head developed within the confined aquifer. Forced convection is more important in Wyoming basins than free convection.

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 and others, 1983). Where systems like those described in **Figures** 3 and 4 create local areas of high gradient, it may be feasible to develop the shallow geothermal resource directly. Outside these scattered areas of high thermal gradients, geothermal development will probably 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, de-icing and fish farming. Through the use of ground-water heat pumps, energy can

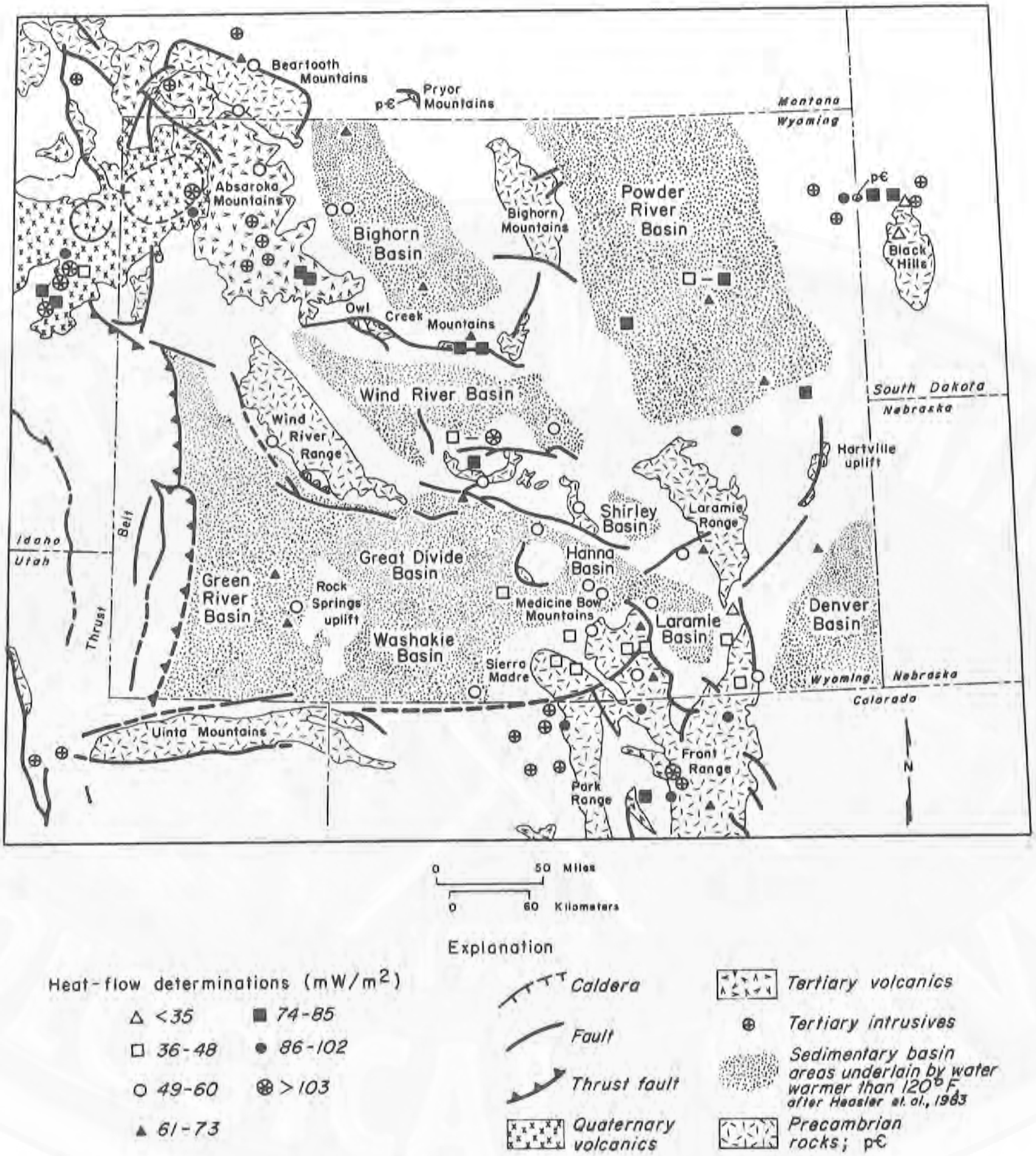


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F (after Heasler and others, 1983). Yellowstone National Park, Jackson Hole and the Idaho-Wyoming thrust belt were not investigated.

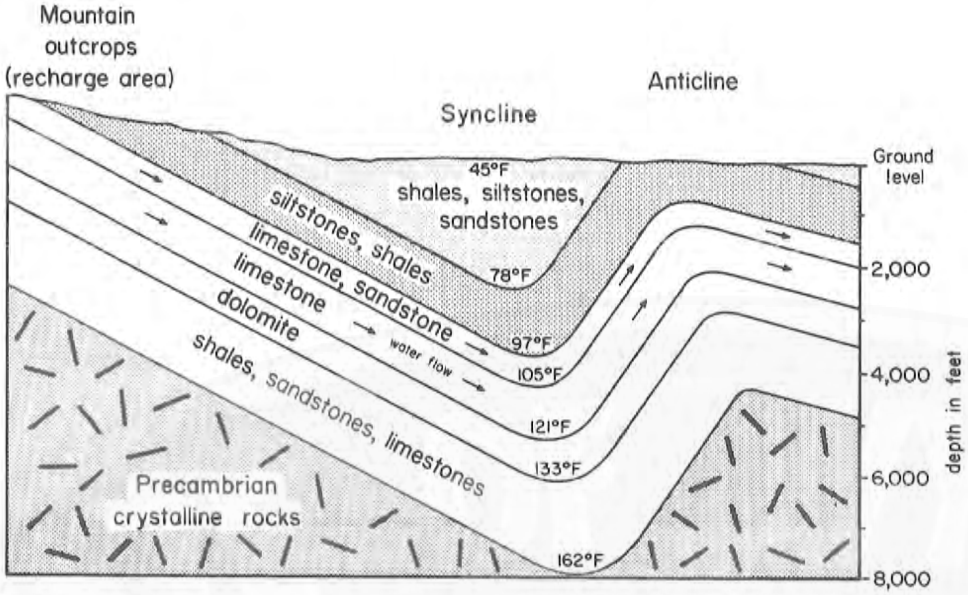


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system. Arrows indicate flow of ground water.

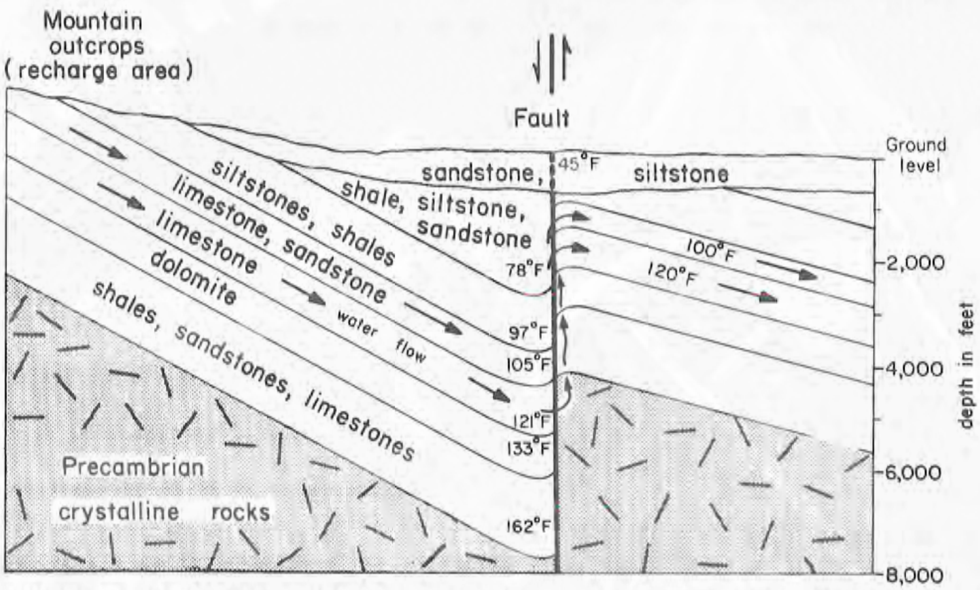


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system. Arrows indicate flow of ground water.

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 and others, 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) 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 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 moves to shallow depth. Quantification of temperatures and gradients required a variety of techniques. Sources of subsurface temperature data include: (1) thermal logs of wells; (2) oil and gas well bottom-hole temperatures; and (3) surface temperatures of springs and flowing wells.

Thermal logs of wells

Thermal logs of wells are the most reliable data on subsurface temperatures because they represent direct measurements 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 and others, 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. Decker (1973) discusses the laboratory techniques used for thermal conductivity determination. This information, coupled with the measured gradients, was used to calculate 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.

Oil and gas well bottom-hole temperatures

Oil and gas well bottom-hole temperatures (BHTs) are the most abundant subsurface temperature data. Because of their abundance, we used BHTs to assess geothermal resources in this study. Over 14,000 oil and gas well bottom-hole temperatures have been collected for the study areas (**Table 1**). Thermal gradients were calculated from BHT information using the formula:

$$\text{Gradient} = \frac{\text{BHT - Mean annual air temperature}}{\text{Depth}}$$

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. This procedure assumes that variations due to elevation and microclimatic effects are negligible compared with BHT inaccuracies. Well log data on file at 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. Problems associated with the thermal effects of drilling and with operator inattention in measuring and reporting BHTs cast doubt on the accuracy of individual temperature reports. It has been suggested, for example, that in some areas BHTs may correlate with the ambient air temperature during drilling and, specifically, that many of the thermometers used in the summer are reading their maximum temperature before they are lowered down

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 feet (°C/kilometer).	16 (29)	15 (27)	13 (24)	12-15 (22-28)	14 (25)	15 (28)
Highest recorded temperature and corresponding depth.	206°F at 23,000 ft (152°C at 2,035 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° at 16,000 ft (135°C at 4,900 m)	370°F at 21,500 ft (188°C at 6,55 m)
Basin depth in feet (kilometers).	26,000 (8.0)	26,000 (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 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 basinwide. 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 that average out over a large number of BHTs. The fact that drilling fluids are circulating, acting to homogenize temperatures within the hole, is, on the other hand, a systematic effect that 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 geothermal resources in a basin from oil and gas well bottom-hole temperatures: First, all available BHTs were compiled and gradients were 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 percentiles 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 that 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.

In these basin studies, a lower BHT cutoff 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 is of little economic value unless it occurs 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-

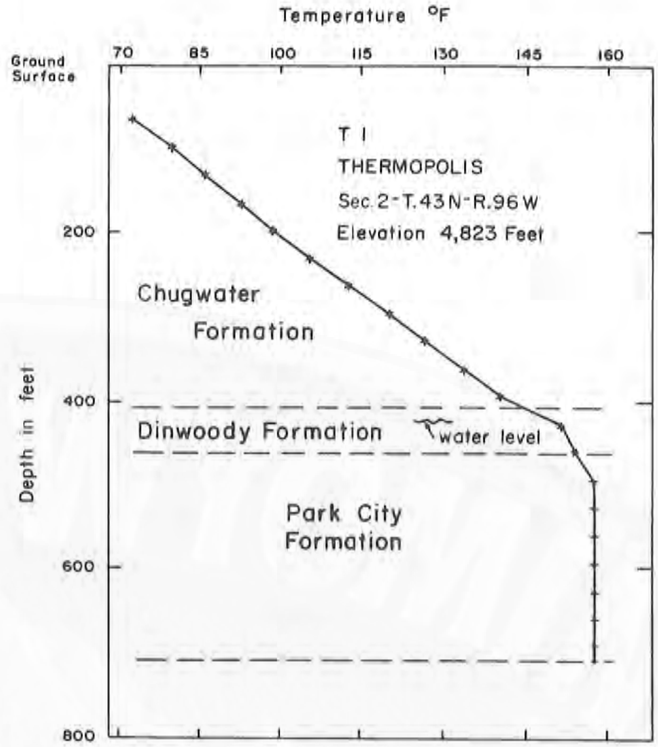


Figure 5. Temperature-depth plot showing hydrologic disturbance, based on a thermal log of a well at Thermopolis (from Hinckley and others, 1982).

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 among the Wyoming basins are all similar below levels of hydrologic disturbance.

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, basinwide aquifer that 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 BHTs of that formation are plotted and contoured, is included in each basin report. Verification is provided by the sparse thermal-logging data. No attempt was made to correct BHTs for drilling effects, so a certain degree of underestimation of temperatures may be expected in the deeper zones, as described above. The deviation of BHTs from true formation temperatures is not known; however, a drill hole in an aquifer with active circulation should equilibrate to undisturbed temperatures relatively rapidly.

Surface temperatures of springs and flowing wells

Surface temperatures of springs and flowing wells provide the third source of subsurface temperature data. The amount of cooling before the water reaches 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 rate that can be delivered to the surface. In this sense, flowing wells and springs give excellent data. Selected locations of surface discharge of thermal water (greater than 70°F) are indicated on the thermal gradient maps.

Summary

The authors investigated the geothermal resources of several Wyoming sedimentary basins. Oil-well bottom-hole temperatures, thermal logs of wells and heat flow data were 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 provided in **Table 1.**

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

(1) Large areas in Wyoming contain ground water at temperatures greater than 120°F (**Figure 2**). Although much of this water is too deep to be economically tapped solely for geothermal use, oil and gas wells may provide access to this significant geothermal resource.

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

Geothermal resources of the southern Powder River Basin, Wyoming

Geological setting

Stratigraphy

The age of geological formations within the southern Powder River Basin (**Sheet 1**, back pocket) ranges from Precambrian to Recent, with Silurian rocks completely absent. A stratigraphic column (**Figure 6**) indicates the general lithology and hydrologic properties of the rocks, along with the thickness of formations. Two major stratigraphic trends within the basin include thinning of the Paleozoic units to the south-southwest and the variation of lithologies from east to west across the basin. The maximum sedimentary thickness within the southern Powder River Basin is 18,000 feet. Most of the sediment thickness is provided by the Cretaceous and Cenozoic section (Denson and Horn, 1975).

Paleozoic formations within the basin are marine shelf deposits with an aggregate thickness ranging from 1,300 to 1,500 feet in the east and 1,100 to 2,000 feet in the west. Cambrian sediments are composed of sandstones, shales and conglomerates. In the eastern part of the basin, Cambrian Deadwood Formation is overlain by Ordovician Winnipeg Formation composed of siltstone, shale and sandstone units. A Devonian and Mississippian massive limestone/dolomite/sandy dolomite sequence overlies the above units, extending across the entire basin and pinching out in the extreme southeast. Overlying these rocks are the Tensleep Sandstone and/or Minnelusa Formation, a massive sandstone sequence interbedded with limestone, dolomite and shale in the eastern part of the basin. The upper Paleozoic consists of interbedded shale, siltstone, sandstone and claystone.

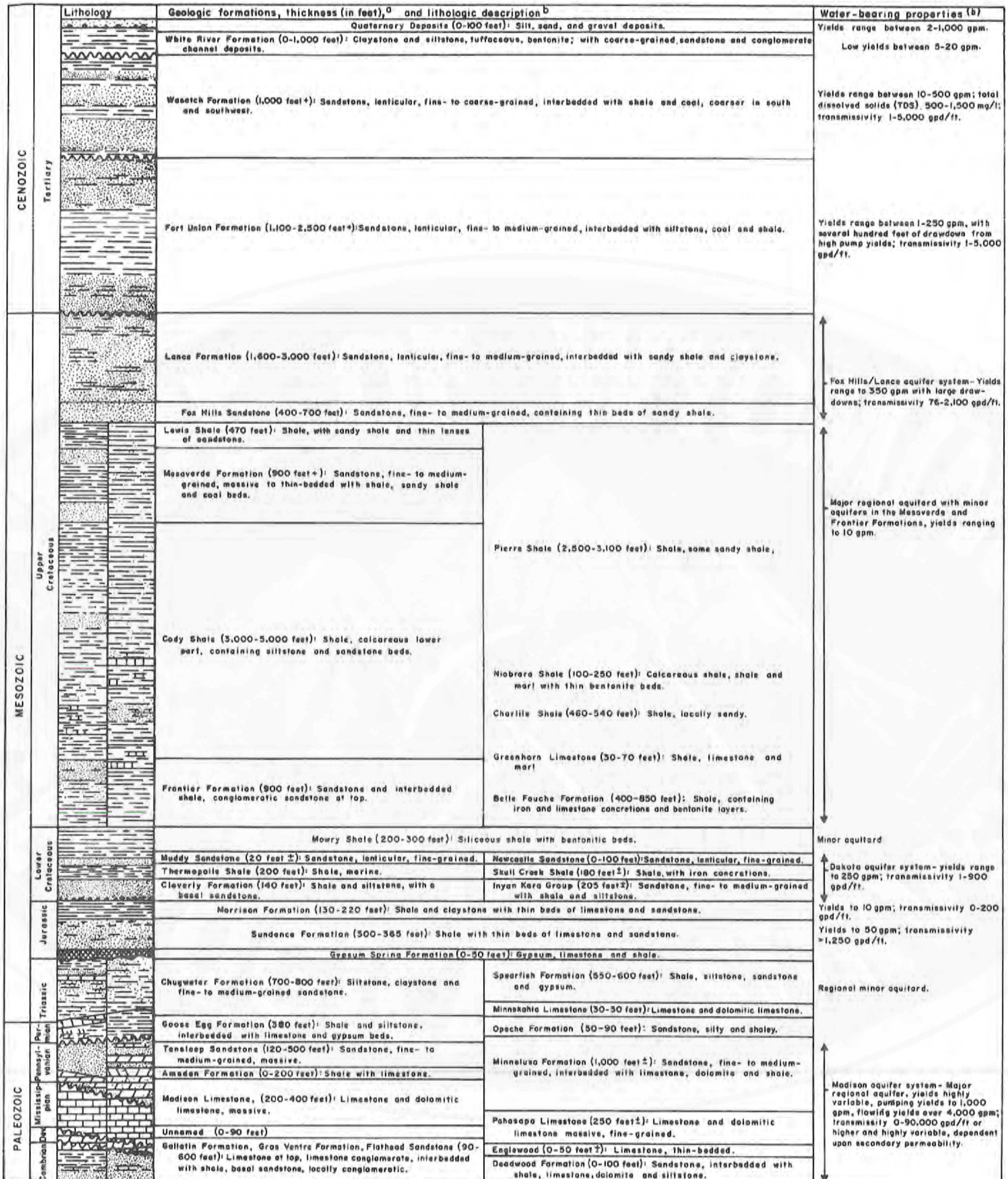
Mesozoic sediments consist of shale, siltstone, claystone and sandstone, interbedded with small amounts of limestone. The Mesozoic-Paleozoic boundary is located in the interbedded red shale-siltstone beds of the Spearfish and Goose Egg Formations in the east and west side of the basin, respectively. The Goose Egg Formation is overlain by red siltstone, claystone and fine-grained sandstone of the Chugwater Formation. Overlying this is the Gypsum Spring Formation, composed of white gypsum interbedded with shale and limestone; it is laterally continuous east to west across the basin, and absent in the southern part of the basin. The overlying Jurassic rocks are composed of shales, sandstones and claystones.

Cretaceous rocks on the western edge of the basin are primarily interbedded siltstone and limestone, and sandstones with minor shale and siltstone.

The Tertiary section is composed of sandstone, shale, siltstone, claystone and coal.

Structure

The Powder River structural basin is a broad, asymmetrical, north-south trending basin in northeastern Wyoming. The basin is bounded on the east, south and west by structural uplifts and extends northward beyond the study area into southern Montana. Over 25,000 feet of structural relief exist in the basin with a maximum sedimentary thickness of over 18,000 feet.



a Formation thicknesses from Feathers and others, 1981; Wyoming Geological Association, 1958.

b Lithologic descriptions and water-bearing properties from Feathers and others, 1981; Hodson, 1973; Wyoming Geological Association, 1958.

Figure 6. Stratigraphic column for the southern Powder River Basin, including water-bearing properties of formations. (Modified from Wyoming Geological Association, 1957, 1958, 1978.) Split columns indicate western (left) and eastern (right) facies.

The shape of the southern Powder River Basin is depicted (**Sheet 2**, back pocket) with elevation contours on top of the Muddy Sandstone and its eastern equivalent, the Newcastle Sandstone. Dips along the basin margins range from 15° to nearly vertical, with numerous high-angle faults and thrust faults creating local structural relief greater than 6,000 feet.

Major structures bordering the Powder River Basin, clockwise from the northeast margin include: the Black Hills uplift, Fanny Peak monocline, Hartville uplift, Laramie Range, Casper arch and Bighorn Mountains. These structures trend northwest to northeast. Superimposed upon the major uplifts are numerous minor structures trending in similar directions.

The basin margins represent the highest probability of geothermal potential due to increased fracture permeability; sufficient depth of burial; and potentiometric head gradient and water supply from nearby uplifts.

Hydrology

Much of the following general discussion of water-producing zones within the basin is taken from numerous sources including Feathers and others, (1981), Woodward-Clyde Consultants (1980), and Crist and Lowry (1972). Most of the data were obtained from wells located within uplifted regions. In these regions, secondary porosity and fracture permeability may be greatest. Laboratory studies (Fatt and Davis, 1952; Wyble, 1958) indicate a reduction in permeability of 20 to 60 percent with an increase in overburden pressure equivalent to 5,000 feet of overburden. Huntoon (1976) also suggested that permeabilities are lower in the central part of the basin for the Paleozoic formations. Thus, water production and transmissivity will probably be less within the central portion of the basin.

The Madison aquifer system is the most productive and most utilized aquifer in the southern Powder River Basin. The system consists of Cambrian to Pennsylvanian carbonates and sandstones (**Figure 7**). However, most of the water production is from the Madison Limestone. Permeability in the carbonate sequence is mainly secondary and is related to dolomitization and fracture control. The sandstone permeability primarily results from intergranular and secondary fracture porosity. Typical Madison aquifer transmissivities range between 1,000 to 60,000 gallons per day/foot (gpd/ft). Where secondary fractures increase permeability, transmissivities of over 300,000 gpd/ft are reported. Production rates for flowing water wells producing from the Madison Limestone aquifer range from 20 to 9,000 gallons per minute (gpm) (**Table 2**).

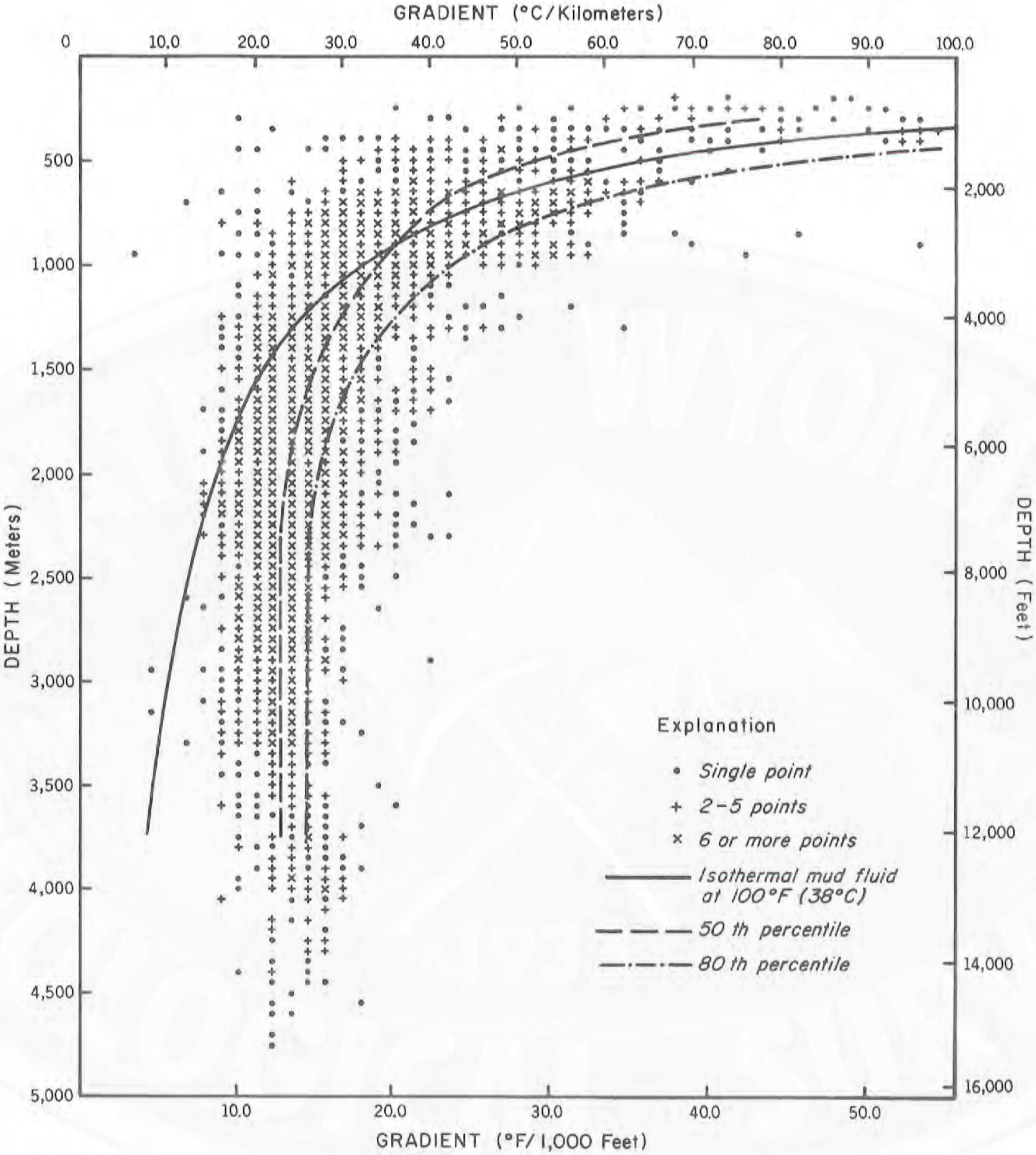


Figure 7. Gradient-depth profile for southern Powder River Basin, based on 4,652 bottom-hole temperatures.

Table 2. Water flows for selected wells in the southern Powder River Basin (gpm= gallon per minute, psi= pounds per square inch).

Map index number	Formation	Location T.	Location R.	Location Sec.	Ground elevation (feet)	Formation depth (feet)	Remarks	Reference
1	Madison	33	77	15	5,165	7,299	Original flow 65 gpm (1966).	a
2	Madison	39	78	26	5,130	6,820	Original flow 925 gpm (1965).	a
3	Madison	39	79	11	4,878	5,386	Original flow 4,700 gpm (1962).	a
4	Madison	40	79	2	4,766	7,097	Original flow 580 gpm (1954), some water from Tensleep Sandstone .	a
5	Madison	40	79	23	4,871	4,680	Original flow 1,600 gpm (1954).	a
6	Madison	40	70	25	4,808	4,388	Original flow 530 gpm (1966), some water from Tensleep Sandstone.	a
7	Madison	40	79	26	4,938	4,675	Original flow 9,000 gpm (1961), shut-in pressure 376 psi.	a
8	Madison	40	79	31	5,140	6,155	Original flow 430 gpm (1962), shut-in pressure 300 psi.	a
9	Madison	40	79	35	4,892	4,694	Original flow 7,200 gpm with 179 psi flowing pressure (1961).	a
10	Madison	40	79	35	4,946	4,655	Original flow 2,900 gp, with 28 psi flowing pressure (1959).	a
11	Madison	41	78	1	5,234	9,644	Original flow 810 gpm (1967).	a
12	Madison	41	78	11	5,357	9,710	Original flow 720 gpm (1966).	a
13	Madison	41	81	9	5,425	2,668	Original flow 900 gpm (1962), shut-in pressure 50 psi.	a
14	Madison	42	80	30	4,847	4,212	Original flow 900 gpm (1962), shut-in pressure 310 psi.	a
15	Madison	42	81	25	5,038	4,042	Original flow 1,110 gpm (1963), shut-in pressure 225 psi.	a
16	Madison	44	60	5	4,440	1,152	Flows 20 gpm (1964).	a
17	Madison	45	61	20	4,360	2,612	Flows 1,500 gpm (1974).	a
18	Madison	45	61	21	4,625	2,211	Flows 50 gpm (1974.	a
19	Madison	45	61	28	4,440	2,695	Flows 1,200 gpm (1974).	a
20	Madison	45	61	29	4,240	2,965	Flows 120 gpm (1974).	a
21	Madison	45	61	30	4,280	2,810	Flows 650 gpm (1974).	a
22	Madison	45	61	33	4,378	3,186	Flows 290 gpm (1974).	a
23	Madison	46	60	31	4,760	1,097	Flows 250 gpm (1948).	a
24	Madison	46	63	10	4,400	2,580	Original flow 800 gpm.	a
25	Madison	46	63	10		3,000	Predicted production 2,500 gpm when completed.	b
26	Madison	46	63	15	4,340	2,685	Original flow 800 gpm (1941), flows 550 gpm (1974).	a
27	Madison	46	63	15		3,200	Predicted production 2,500 gpm when completed.	b
28	Madison	46	63	17	4,172	3,181	Flow 800 gpm (1973), shut-in pressure 185 psi.	a
29	Madison	46	64	13	4,068	4,084	Flows 30 gpm (1973).	a
30	Lakota	34	80	21		3,100	Flows approx. 170 gpm (1980).	b
31	Lakota	34	80	21		2,821	Flows approximately 15 gpm (1980).	b
32	Lakota	34	80	28		2,338	Flows approximately 50 gpm (1980).	b
33	Lakota	34	80	33		2,030	Flows to 50 gpm (1980).	b

a) Hodson, W.G. (1974).

b) Feathers and others (1981).

The Mesozoic aquifer consists of sandstone units separated by thick impermeable shale units within the Sundance, Cloverly-Inyan Kara, Muddy-Newcastle, Frontier, Mesaverde and Lance-Fox Hills formations (**Figure 6**). Transmissivity values range from 1 to 1,250 gpd/ft. Production rates vary greatly within and between formations (**Table 3**).

Table 3. Water production rates of formations comprising the Mesozoic aquifer in the Powder River Basin (from Feathers and others, 1981).

Formation	Production rate
Sundance	3 to 50 gpm
Cloverly-Inyan Kara	1 to 250 gpm
Muddy-Newcastle	1 to 250 gpm
Frontier	1 to 10 gpm
Mesaverde	4 to 120 gpm
Lance-Fox Hills	0 to 350 gpm

The Tertiary aquifer is extensively used throughout the basin, with production coming from the sandstone and conglomerate units (**Figure 6**). The maximum thickness for the aquifer is 3,000 feet. Yields of 250 gpm may be obtained from the Tertiary aquifer. However, due to the shallow depth of burial, temperatures are not likely to be sufficient for geothermal use.

Potentiometric data for various aquifers indicate a regional flow pattern of water moving from the topographic highs into the central portions of the basin. Possible movement of ground water into the basin may also be from the Wind River Basin via the Casper arch. Groundwater movement out of the basin is by flow to the north and possibly the southeast (Richter, 1981). However, insufficient data exist to document conclusively the ground-water movement in the southwest and southeast corners of the basin. The volume and rate of water flow in the deeper parts of the basin are not known, but are probably minor due to low transmissivity.

Terrestrial heat flow

Terrestrial heat flow is the amount of heat that flows perpendicular to the Earth's surface at a given location. Twelve new heat-flow values were determined for the southern Powder River basin. The values are listed with previously published values in **Table 4** and shown on **Sheet 3** (back pocket). Using these values, an average heat flow for the basin and surrounding uplifts is $1.15 \pm .22 \times 10^{-6}$ calories per square centimeter per second (cal/cm^2 sec) (48.1 ± 9.2 mW/m^2). This average value does not include heat flow values calculated for the Lance Creek and Salt Creek oil fields. These areas are considered anomalous and are discussed in a later section. The range of heat flow values may be caused by variations in subcrustal heat flow, radiogenic heat production, hydrological transport of heat or igneous activity. The calculated heat flow of 1.15×10^{-6} cal/cm^2 sec ($48.1 mW/m^2$) agrees well within the limits of accuracy of the 1.25×10^{-6} cal/cm^2 sec (52.3 mW/m^2) that is required to explain the maximum recorded temperature for the basin of 275°F at a depth of 16,076 feet.

Heat flow data is used in the following sections to approximate temperature with depths at various locations in the study area. The equation used is:

Table 4. Heat flow values for the southern Powder River Basin (est. = estimated).

Hole name	West longitude	North latitude	N[a]	K (10^{-3}cal/cm sec°C)	Depth range[b](m)	Gradient (°C/km)	Heat flow ($x10^{-6}$cal/cm^2 sec)
Squaw Springs	106° 0.39'	42° 27.4'	47	5.7 ± .8	30-257	36.2	2.1
Highland Flats #0-1	105° 42.1'	43° 2.9'	15	5.4 ± .6	90-170	24.2	1.3
North Butte							
#5419	105° 59.0'	43° 48.9'	17	5.5 ± 1.1	40-110	24.9	1.4
#5059	105° 59.2'	43° 48.2'	9	5.0 ± .5	30-190	22.4	1.1
#5057	105° 59.6'	43° 48.4'	20	5.1 ± .9	100-177	21.0	1.1
#5763[3]	105° 59.7'	43° 48.8'	19	5.5 ± .9[c]	20-170	28.0	1.5
Fort Reno SE							
#5784	106° 00.0'	43° 48.2'	18	5.0 ± .9	80-152	21.7	1.1
#5786	106° 01.0'	43° 48.4'	9	4.4 ± 1.0	40-90	26.7	1.2
#5836	106° 01.8'	43° 50.1'	9	5.5 ± 1.1	50-78	23.5	1.3
#4843	106° 01.8'	43° 50.1'	8	5.1 ± .7	40-68	18.6	.9
#5358[c]	106° 02.6'	43° 48.9'	13	4.8 ± 1.2[c]	50-110	19.4	.9
#4998	106° 03.2'	43° 49.2'	17	5.1 ± .9	40-153	16.4	.8
Salt Creek[d]	106° 15'	43° 35'	est.	4.0	640 (25)	45	1.8
Lance Creek[d]	104° 38'	43° 04'	est.	4.0	964 (3)	50.5	2.0
Douglas							
LC-1[e]	105° 18.1'	42° 50.0'	15	4.8	340-500	43.8	2.1
LC-1[e]	105° 00'	43° 10.4'	15	4.8	100-540	33.8	1.6

[a] Number of conductivity samples.

[b] The depth range over which the least squares gradient was calculated.

[c] Conductivities from nearby hole penetrating similar lithology.

[d] Data from Blackwell (1969).

[e] Data from E.R. Decker (personal communication, 1982).

$$Q = K \frac{dt}{dz}$$

where

Q = heat flow

K = thermal conductivity

$\frac{dt}{dz}$ = geothermal gradient

Using average thermal conductivities for the rock units and regional heat flow values it is possible to calculate geothermal gradients and consequently the temperatures at depth. Rock thermal conductivity values were taken from Heasler (1978) and (or) approximate values for similar lithologies. The geothermal gradient in a formation is multiplied by the thickness of the formation to determine the temperature change across each formation. This calculation (conductive thermal modeling), produces an idealized temperature-depth profile.

Table 5 shows the conductive thermal model for a typical sedimentary section in the central portion of the southern Powder River Basin. The predicted formation temperatures agree with the measured bottom-hole temperatures in the

Table 5. Conductive thermal models for the southern Powder River Basin.

Formation	Thermal conductivity (10^{-3} cal/cm· sec°C)	Formation gradient in (°F/Kft)[1] for heat flows of 1.2 HFU[2]	1.6 HFU	Central Powder River Basin Thickness (feet)	Temperature (°F)	Salt Creek area Thickness (feet)	Syncline Temperature (°F) 1.2 HFU	1.6 HFU	Anticline Temperature (°F) 1.2 HFU	1.6 HFU	Fanny Peak lineament Thickness (feet)	Syncline Temperature (°F) 1.2 HFU	1.6 HFU	Anticline Temperature (°F) 1.2 HFU	1.6 HFU
Wasatch	5.5	12	16	1,000	45										
Fort Union	6.0	11	15	2,900	57										
Lance	4.5	15	20	2,800	89	1,700	45	45							
Fox Hills	4.5	15	20	600	131	200	70	79							
Lewis	4.0	16	21	380	140	500	74	83							
Mesaverde	6.0	11	15	730	147	900	82	93							
Cody (Pierre)	4.0	16	21	3,250	155	2,900	92	107	45	45	2,800	45	45		
Frontier (Colorado Group)	4.5	15	20	730	207	800	138	168	72	81	1,300	90	104	45	45
Mowry	4.0	16	21	250	218	300	150	184	84	97	220	109	130	69	71
Muddy (Newcastle)	7.0	9.4	13	40	222	30	155	190	89	103	50	113	134	73	75
Thermopolis (Skull Creek)	6.1	11	15	200	222	150	155	191	89	104	180	113	135	73	76
Cloverly (Inyan Kara)	8.7	7.6	10	170	224	130	157	193	91	106	200	115	138	75	79
Morrison	6.3	10	13	190	225	260	158	194	92	107	150	117	140	77	81
Sundance	7.4	8.9	12	330	227	230	160	198	95	111	330	118	142	78	83
Chugwater (Spearfish)	7.2	9.1	12	700	230	600	162	200	97	113	250	121	146	81	87
Goose Egg (Minnekahta)	7.0	9.4	13	250	237	300	168	207	102	120	300	124	149	84	90
Tensleep (Minnelusa)	10.4	6.3	8.4	750	239	400	171	211	105	124	1,100	127	153	87	94
Madison (Pahasapa)	9.6	6.9	9.2	300	244	400	173	215	107	128	300	134	162	94	103
Unnamed (Englewood)	9.0	7.3	9.8	30	246	30	176	218	110	131	50	136	165	96	106
Cambrian undivided	7.0	9.4	13	200	246	270	176	219	110	132	50	136	165	96	106
Precambrian					249		197	222	113	135		137	166	97	107

1 °F/Kft = degrees Fahrenheit per 1,000 feet.

2 One HFU = 10^{-6} calories/centimeter^2 second = 41.8 x 10^{-3} watts/square meter.

deeper portions of the basin. The average geothermal gradient for the conductive thermal model is 13.8°F/1,000 feet (25.2 °C/kilometer). This compares well with the average thermal gradient of 13.4°F/ 1,000 feet (24.4°C/kilometer) derived from bottom-hole temperature gradients. Thermal gradient determinations for wells in the southern Powder River Basin are listed in **Appendix A**.

The bottom-hole temperatures and predicted formation temperatures for the central-southern Powder River Basin indicate the presence of intermediate (194-302°F, 90-150°C) and low (194°F, 90°C) temperature geothermal systems. The intermediate temperature waters result from normal geothermal gradients combined with great depth of burial. Therefore, intermediate temperatures can be found throughout the basin where the sediment thickness is greater than 12,000 feet. However, the great depth of burial and probable low water quality place serious economic constraints on their use.

Low-temperature geothermal systems are also related to depth of burial, geothermal gradient and hydrologic flow. In the low-temperature systems the transfer of heat by hydrologic flow is very important. Such systems transport warm water from depth to the near surface through the limbs of anticlines, faults or drill holes. Evidence for all three types of transport systems mentioned are found in the southern Powder River Basin.

Potential geothermal areas

Definition of geothermal systems was accomplished through the use of measured thermal gradients (**Appendix A**); bottom-hole-temperature derived thermal gradients (**Table 6**); conductive thermal modeling (**Table 5**); flowing-well temperatures (**Table 2**); potentiometric surface data (**Figures 8** and **9**); and water chemistry analyses (**Appendix B**). A thermal gradient contour map (**Sheet 3**, back pocket) is based on bottom-hole temperatures and thermally logged holes. Because of the previously discussed errors in bottom-hole temperature data, a number of the anomalous gradients are not included in the contouring. Instead, these anomalous points are plotted individually. The anomalous gradient areas are also shown on **Sheets 2** and **4** (back pocket). A number of these areas are believed to be caused by movement of hydrothermal waters upward from depth. These anomalous gradient areas were determined by the process discussed earlier. **Table 7** lists the BHT temperatures used in this study. **Table 6** lists the BHT-derived gradients in 500-foot depth intervals with respect to the mean gradient and the 50th, 66th, 80th and 90th percentiles for each interval. **Figure 7** is a graphical representation of the BHT-derived gradient data.

A general structure contour map for the basin is shown on **Sheet 2**. The top of the Muddy-Newcastle Sandstone is used for contouring because it is the deepest aquifer present throughout the basin for which sufficient drill hole data exist for contouring. Chemical data for select wells are given in **Appendix B**. Most of the flowing well, potentiometric and water chemistry data are taken from Hodsen (1974), Feathers and others (1981), Woodward-Clyde Consultants (1980) and Hodsen and others (1973).

Analysis of the data determined areas of geothermal potential for the southern Powder River Basin. The areas of greatest geothermal potential are the Salt Creek-Meadow Creek area, the southeastern Powder River Basin and the Newcastle area. Each of these areas is discussed in detail in the following sections.

Salt Creek - Meadow Creek area

The Salt Creek - Meadow Creek area is situated in T.38-40N., R.78-80W., approximately four miles north of Casper. A major anticline, dipping 15° to 29° on the east flank and 5° to 10° on the west flank (Beck, 1929), dominates the area. Faulting is prevalent, with a maximum vertical displacement of 350 feet. Most of the faults trend north 60° east across the anticline. Evidence of geothermal potential includes: 1) anomalously high thermal gradients (Van Orstrand, 1940) (**Sheet 3**); 2) changes of 40°F in water temperature with drilling distances of five feet (Estabrook and Radar, 1925); and 3) water flows (4,000 gpm) from depths of 4,500 feet with surface temperatures of 183°F, implying a high temperature gradient of 30.6°F/1,000 feet (Espach and Nichols, 1941). The above information, combined with geologic evidence of numerous faults, fractures and hydrologic communication between units, implies that geothermal gradients are elevated by movement of fluids from depth. Conductive heat flow modeling and observed artesian flow confirms water circulation within the aquifers.

Table 6. Summary of gradient data and statistics, including the 50th, 66th, 80th and 90th percentiles, derived from bottom-hole temperatures from the southern Powder River Basin. A gradient under a percentile heading is the gradient below which that percent of the gradients fall. Depth intervals with few BHT measurements do not give meaningful percentile temperatures.

Depth interval (feet)	Number of measurements	Gradient (°F/1,000 ft) high	low	mean	50%	66%	80%	90%
500 - 1,000	45	77	20	43.1	41	45	50	61
1,000 - 1,500	121	138	10	38.3	34	44	53	56
1,500 - 2,000	99	40	10	25.6	25	29	31	34
2,000 - 2,500	283	36	7	24.8	25	28	30	31
2,500 - 3,000	290	53	9	21.5	20	23	26	28
3,000 - 3,500	334	42	4	20.1	19	21	23	28
3,500 - 4,000	152	31	10	17.3	17	18	19	21
4,000 - 4,500	262	34	8	16.1	16	17	18	20
4,500 - 5,000	164	22	9	14.7	14	15	17	18
5,000 - 5,500	210	23	9	15.2	14	16	17	19
5,500 - 6,000	277	22	8	13.9	13	14	16	17
6,000 - 6,500	225	21	8	13.6	13	14	15	17
6,500 - 7,000	334	24	8	13.4	13	14	14	16
7,000 - 7,500	513	22	7	13.2	13	13	14	15
7,500 - 8,000	335	23	8	13.1	12	13	14	15
8,000 - 8,500	161	20	8	13.1	12	13	14	15
8,500 - 9,000	227	19	7	12.7	12	13	13	14
9,000 - 9,500	135	17	9	13.0	13	13	14	15
9,500 - 10,000	91	22	5	12.9	13	13	14	15
10,000 - 10,500	96	16	5	12.7	13	13	14	14
10,500 - 11,000	90	17	6	13.0	13	13	14	15
11,000 - 11,500	29	19	9	13.2	13	13	14	15
11,500 - 12,000	30	19	9	13.1	13	14	14	16
12,000 - 12,500	33	18	10	14.1	14	15	15	16
12,500 - 13,000	43	18	10	14.2	14	14	16	16
13,000 - 13,500	37	17	9	14.7	14	15	16	16
13,500 - 14,000	13	16	12	14.1	14	15	15	16
14,000 - 14,500	12	16	10	14.1	15	15	15	15
14,500 - 15,000	6	17	12	14.5	14	15	15	17
15,000 - 15,500	3	13	12	13.1	13	13	13	13
15,500 - 16,000	1	12	12	12.9	12	12	12	12
16,000 - 16,500	-	-	-	-	-	-	-	-
16,500 - 17,000	2	17	12	14.7	17	17	17	17
17,000 - 17,500	-	-	-	-	-	-	-	-
17,500 - 18,000	1	11	11	11.2	11	11	11	11

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

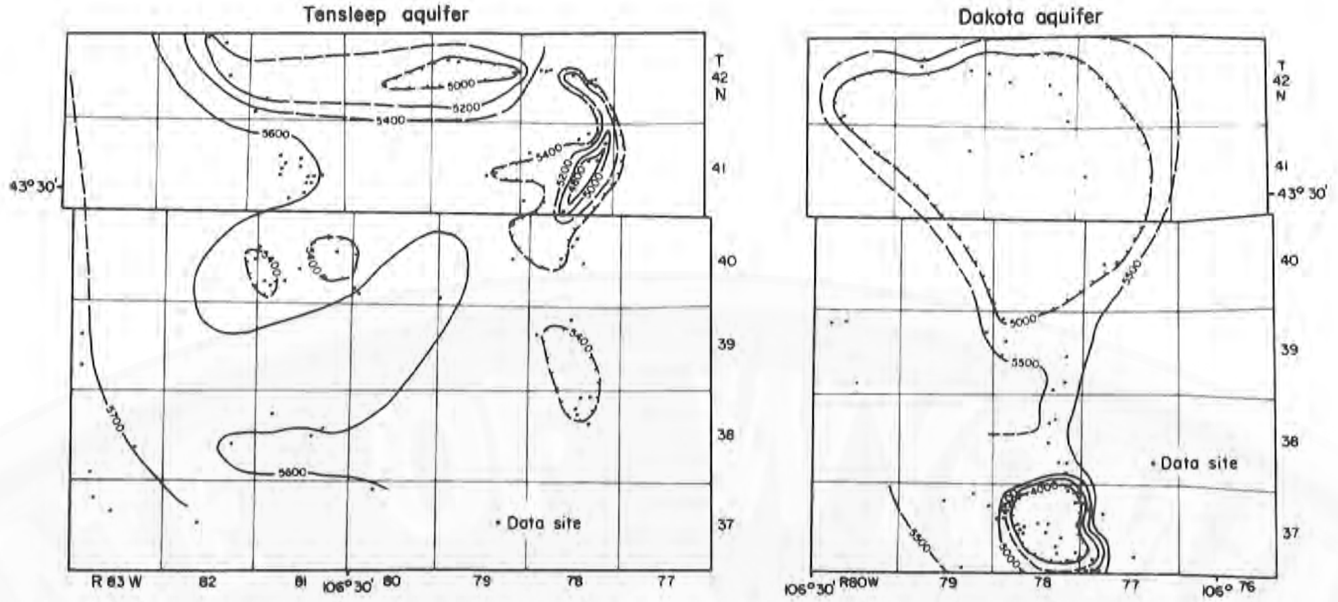


Figure 8. Potentiometric surfaces for two aquifers in the Salt Creek region. Potentiometric contours are in feet. Data were collected between 1940 and 1981.

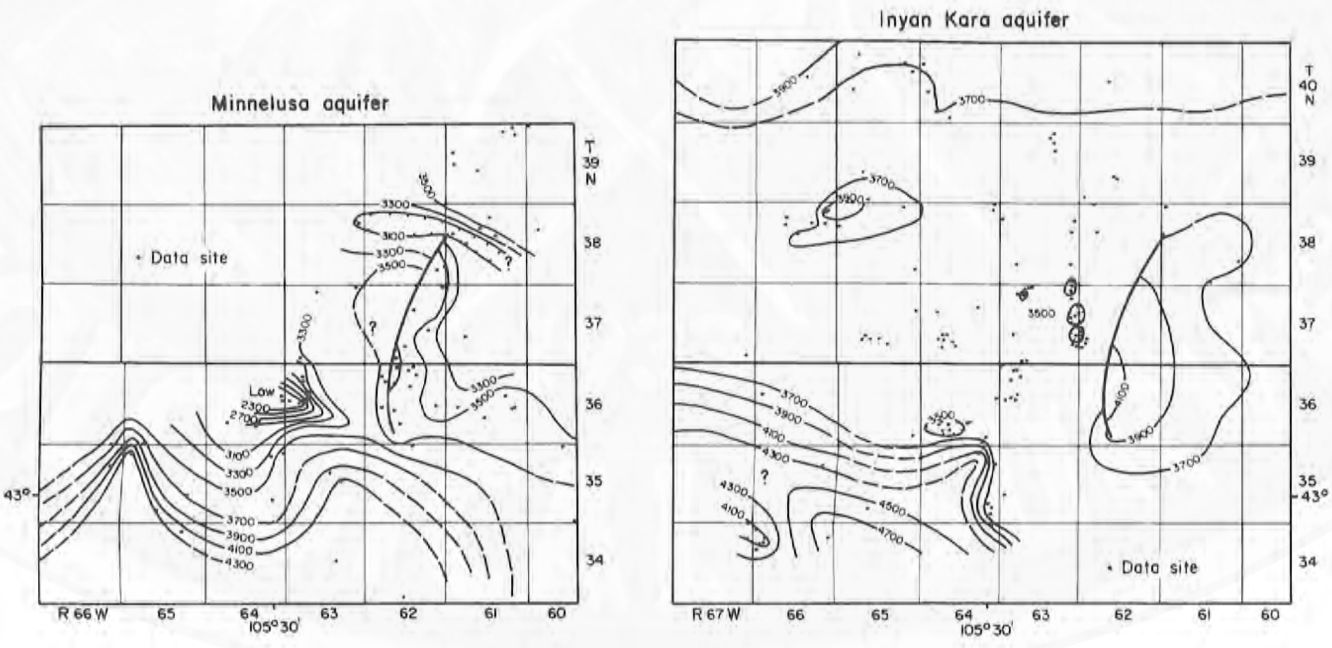


Figure 9. Potentiometric surface for two aquifers in the Fanny Peak lineament region, southeastern Powder River Basin. Potentiometric contours are in feet. Data were collected between 1940 and 1981.

Table 7. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th and 90th percentiles, from the southern Powder River Basin. A temperature under a percentile heading is the temperature below which that percent of the BHTs fall. Depth intervals with few BHT measurements do not give meaningful percentile temperatures.

Depth interval (feet)	Number of measurements	Temperature (°F)						
		high	low	mean	50%	66%	80%	90%
500 - 1,000	45	104	60	79.4	80	83	85	95
1,000 - 1,500	121	184	55	92.5	87	106	111	113
1,500 - 2,000	99	122	61	90.6	89	97	105	108
2,000 - 2,500	283	130	62	101.1	101	113	116	119
2,500 - 3,000	290	202	70	103.9	102	113	117	123
3,000 - 3,500	334	177	58	109.5	109	116	121	134
3,500 - 4,000	152	171	85	110.0	112	116	120	125
4,000 - 4,500	262	192	82	113.7	114	119	123	133
4,500 - 5,000	164	156	87	114.5	115	121	126	132
5,000 - 5,500	210	170	90	125.2	124	132	138	145
5,500 - 6,000	277	172	94	124.9	122	129	139	145
6,000 - 6,500	225	175	99	129.8	130	135	145	155
6,500 - 7,000	334	210	100	136.0	136	141	147	155
7,000 - 7,500	513	215	101	140.7	141	144	149	156
7,500 - 8,000	335	219	109	146.2	145	151	158	168
8,000 - 8,500	161	219	118	153.7	153	158	165	172
8,500 - 9,000	227	212	106	155.6	156	160	165	172
9,000 - 9,500	135	210	133	165.3	165	174	179	182
9,500 - 10,000	91	262	94	170.3	171	179	186	197
10,000 - 10,500	96	214	100	175.7	180	183	189	197
10,500 - 11,000	90	235	120	184.7	187	193	199	210
11,000 - 11,500	29	265	153	193.9	194	202	205	217
11,500 - 12,000	30	278	152	198.0	202	210	216	232
12,000 - 12,500	33	265	170	218.0	219	230	234	254
12,500 - 13,000	43	280	181	226.5	222	234	248	257
13,000 - 13,500	37	275	170	238.1	238	252	263	267
13,500 - 14,000	13	270	213	239.8	241	249	260	270
14,000 - 14,500	12	274	188	245.2	257	259	260	264
14,500 - 15,000	6	306	224	258.2	257	272	272	306
15,000 - 15,500	3	252	235	244.7	247	252	252	252
15,500 - 16,000	1	246	246	246.0	246	246	246	246
16,000 - 16,500	0	-	-	-	-	-	-	-
16,500 - 17,000	2	333	248	290.5	333	333	333	333
17,000 - 17,500	0	-	-	-	-	-	-	-
17,500 - 18,000	1	246	246	246.0	246	246	246	246

Total: 4,654 bottom-hole temperature measurements.

Conductive heat flow modeling indicates that a heat flow of 2.5×10^{-6} cal/cm^2 sec (105 mW/m^2) is needed to explain the bottom-hole temperatures and flowing water well temperatures measured in the area. This heat flow is 110 percent higher than the average basin heat flow (1.2×10^{-6} cal/cm^2 sec) (50 mW/m^2) and 40 percent higher than the maximum heat flow reported for Salt Creek of 1.8 $\times 10^{-6}$ cal/cm^2 sec (72 mW/m^2) (Blackwell, 1969). This conductive model requires the source of the water causing the high temperatures to be at a minimum depth of 10,000 feet. This is necessary for water temperatures to reach 190°F, the maximum temperature recorded for the geothermal system. A hydrologic flow system, which could add convective heat flow from the adjacent syncline, is a reasonable source of the high temperatures seen in the area.

Artesian water flow is known from Frontier, Dakota, Tensleep and Madison rocks, with the Madison aquifer being the dominate producer. Flows for the Madison aquifer are reported greater than 9,000 gpm, with reported temperatures of 184°F (**Table 2**). Potentiometric data for the Madison Limestone and Tensleep Sandstone (Swenson and others, 1976) (**Figure 8**) indicate the source for the water and artesian pressure is from the west. This includes the southern Bighorn Mountains, Casper arch region and possibly the northern Laramie Range as recharge areas (although structural data suggest possible hydrologic disconnection of aquifers along the Laramie Range). Conductive modeling of circulation depth requires that the water first enter the basin north or south of the geothermal area. Flow from the Meadow Creek-Sussex area to the north is thought to be the most probable for the following reasons:

1. The large degree of faulting in the Meadow Creek-Sussex area is similar to that of the Salt Creek field.
2. The potentiometric draw-down patterns suggest a high transmissivity zone exists to the north-northeast causing a larger flow into the field from this direction (**Figure 8**) (Swenson and others, 1976).
3. Numerous flowing Madison aquifer wells at depths of 10,000 feet are located north of the Salt Creek area (**Table 2**).
4. There are slightly lower total dissolved solids in the Madison water in the Meadow Creek-Sussex area compared to the Salt Creek area (Swenson, 1952).
5. Bottom-hole temperatures for the Tensleep Sandstone in the Meadow Creek-Sussex area range from 156° to 209°F at 9,500 feet. This implies vertical movement of water in the area.

The above data suggest a water flow pattern to the Salt Creek area beginning in the northern Bighorn Mountains. The water is then transported downward into the Meadow Creek-Sussex area of the basin where it is geothermally heated before moving to the Salt Creek region. A more detailed geothermal study should be conducted in this area because of the high temperatures (184°F) and large water flows (4,000 gpm).

Southeastern Powder River Basin

Structural and stratigraphic elements are described by Shapiro (1971), Wyoming Geological Association (1957), Anderson and Riechen (1941), Emery (1929) and Brainard and Lavington (1936). In the southeastern Powder River Basin a potential geothermal resource region is composed of the Fanny Peak lineament and numerous anticlinal systems including Lance Creek, Lightning Creek and Little Buck Creek oil fields. The Fanny Peak lineament, located in T.35 - 43N., R.61 - 62W., is interpreted as the surface expression of a series of basement faults trending north-south (Brobst and Epstein, 1963). The faults extend upward into sedimentary units, causing faulting, fracturing and folding of the rocks. The Shawnee flexure, located in

T.34 - 36N., R.65 - 66W., is the westward extension of this structural zone. Structural contours of the area indicate asymmetry to the west and north, with a major fault at depth (Denson and Horn, 1975). Well logs indicate numerous faults and fractures in the Minnelusa Formation, with increasing fault displacement at depth (Emery, 1929; Anderson and Riechen, 1941).

The region is characterized by high thermal gradients and flowing water wells. The high gradients are located along structural highs with lower gradients found in the synclinal portions of the area. The high thermal gradients are verified by flowing-well and pump-test water temperatures (Anderson and Kelly, 1976). This relationship of gradients and structure suggests vertical movement of water in areas that are structurally elevated. The relationship of water movement and geothermal gradients for the Fanny Peak lineament is observed and discussed by Kilty and Chapman (1980). They suggest high gradients are caused by water moving within the Paleozoic formations up the steep monoclinal limb. However, structural data indicate a major normal fault cores the monocline and is capable of acting as a hydrologic barrier. If the fault is a barrier, high gradients are probably caused by water moving up along fracture zones related to faulting. Evidence in the Lance Creek oil field for vertical water movement along faults includes: (1) high anomalous bottom-hole derived gradients and measured gradients (Van Orstrand, 1926); (2) bottom-hole temperatures and analyses of oil, gas and water samples that indicate vertical connection of formations along fracture zones (Anderson and Riecken, 1941); (3) an active water-drive system that maintained the well pressure at 80 percent of its original values in the Minnelusa sands from 1937 to 1952 (Churchwell, 1949, 1952); and (4) an increase in fault throw with depth that suggests a greater degree of fracturing.

The artesian flows in the region add further evidence for the existence of circulating water within aquifers. Probable sources for the water and artesian pressure are the Black Hills uplift and Hartville uplift (**Figure 9**). This speculation is based upon potentiometric and water-chemistry data.

A maximum temperature for the hydrothermal system is believed to be 170°F (77°C), based on bottom-hole temperatures in both the anticlinal and synclinal areas. Conductive modeling indicates a heat flow of 3.2×10^{-6} cal/cm^2 sec (134 mW/m^2) is needed for the temperatures recorded on the anticline. However, conductive modeling on the synclinal portion of the region results in temperatures of 137 to 166°F, using heat flows of 1.2 and 1.6×10^{-6} cal/cm^2 sec (50 - 67 mW/m^2) (**Table 5**). This drastic difference in heat flow substantiates the movement of water from the structural lows to the highs, with accompanying heat transfer.

The economic usefulness of a geothermal system depends on the temperature and amount of water available. Well field studies on the effects of a 9,000 gal/min Energy Transportation Systems, Incorporated (ETSI) well field indicate widely varying draw-down effects. Draw-down estimates for the center of the field vary from 400 feet to dewatering of the aquifer (2,000 feet) (Woodward-Clyde Consultants, 1980; Huntoon and Womack, 1975).

Newcastle Area

The Newcastle potential geothermal resource area is located on the southwestern flanks of the Black Hills uplift, in T.45-44N., R.62-65W. Structure in the area is relatively simple, with sedimentary rocks dipping 1° to 3° to the southwest. Just east of the area, the Black Hills monocline dips 55° to 75°. Descriptions of the structural and stratigraphic geology are given by Mapel and Pillmore (1963), Dobbin and others (1957) and Lisenbee (1985).

This region is characterized by high and normal thermal gradients and flowing water wells. The high gradients are found apparently randomly interspersed with the normal gradients, suggesting isolated causes for the high gradients. Because of the numerous normal gradients, it is also unlikely a high basal heat flow is causing the high gradients. Artesian flow in the region indicates the presence of circulating water within the Pahasapa and Minnelusa (Tensleep) aquifers (William, 1948; Head and Market, 1977). Potentiometric and water chemistry data indicate water circulation from the Black Hills uplift rather than out of the basin.

The cause of high gradients may be the flow of water up along breccia pipes and sinks in the Pennsylvanian to Lower Cretaceous formations. Studies by Bowles and Braddock (1963) indicate solution removal of as much as 250 feet of the upper Minnelusa Formation has occurred since early Tertiary time in the southern Black Hills. Recently, sink holes measuring 240 feet wide and 60 feet deep have formed in the Cretaceous strata (Bowles and Braddock, 1963). Thus, vertical water movement is apparent in the area.

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Appendices A and B

Appendix A. Precision thermal gradient measurements in the southern Powder River Basin.

Appendix B. Chemical data for selected wells in the southern Powder River Basin.

Appendix A. Precision thermal gradient measurements in the southern Powder River Basin. Interval refers to the depth interval over which the gradient was calculated using a statistical least squares technique. (Measured by University of Wyoming personnel following the methods of Decker, 1973.)

Hole Name	Longitude	Latitude	Depth Meters	Depth Feet	Temperature (°C)	Temperature (°F)	Gradient °C/km	Gradient °F/1,000 ft	Interval (m)
Converse County									
Coal Draw #16-1	105 34.3	43 19.6	55.0	180	13.8	56.8	27.2	14.9	0-40
Coal Draw #16-2	105 33.4	43 18.9	329.5	1,080	21.0	69.8	36.2	19.9	10-329
Coal Draw #14-1	105 35.8	43 16.5	360.0	1,181	19.8	67.6	27.0	14.8	50-140
Highland Flats #14	105 38.3	43 13.0	155.0	509	14.2	57.6	30.7	16.8	80-155
Highland Flats #1	105 41.8	43 11.9	10.0	33	11.4	52.5			
Highland Flats #349-3	105 33.5	43 5.0	162.0	531	13.3	55.9	18.3	10.0	30-160
Highland Flats #W-6	105 42.1	43 03.3	190.0	623	13.2	55.8	23.6	12.9	110-190
Highland Flats #0-1	105 42.1	43 2.9	189.0	620	13.3	55.9	24.2	13.3	90-170
Highland Flats #M-1	105 42.1	43 02.9	142.0	466	12.4	54.3			
Highland Flats #I-7	105 42.1	43 2.9	159.0	522	12.5	54.5			
Highland Flats #I-1	105 42.1	43 2.9	159.0	522	12.5	54.5	22.6	12.4	130-159
Highland Flats	105 42.1	43 2.9	153.0	502	12.4	54.3			
Highland Flats #M-8	105 42.1	43 2.9	153.0	502	12.6	54.7			
Highland Flats #I-5	105 42.1	43 2.9	156.0	512	12.5	54.5			
Highland Flats #M-3	105 42.1	43 2.9	153.0	535	12.7	54.9			
Highland Flats #I-2	105 42.0	43 2.9	149.0	489	12.5	54.5	23.7	13.0	100-149
Highland Flats #18-1	105 33.6	43 0.3	82.0	269	12.5	54.5	18.5	10.1	40-80
Natrona County									
Poison Spider #14-7	106 46.4	42 51.4	760.0	2,493	33.4	92.1	26.6	14.6	200-740
Poison Spider #13-6	106 46.4	42 51.4	380.0	1,247	24.2	75.7	33.3	18.3	20-380
Reno Hill #16	106 6.5	42 32.1	62.0	203	7.2	45.0	12.1	6.6	10-60
Reno Hill #32	106 6.4	42 32.1	86.0	282	7.1	44.8			
Reno Hill #15	106 6.4	42 32.1	62.0	203	6.8	44.2	13.7	7.5	20-62
Reno Hill #12	106 6.3	42 32.1	62.0	203	6.8	44.2	23.3	12.8	10-62
Reno Hill #13	106 6.3	42 32.1	61.0	200	6.8	44.2	12.6	6.9	20-61
Reno Hill #11	106 1.8	42 32.1	59.0	194	6.8	44.2			
Campbell County									
Fort Reno #5836	106 1.8	43 50.1	78.0	256	11.7	53.1	23.5	12.9	50-78
Fort Reno #5843	106 01.8	43 50.0	68.0	223	11.4	52.5	18.6	10.2	40-68
Fort Reno #5838	106 1.9	43 49.7	68.0	223	11.5	52.7			
Fort Reno #4998	106 3.3	43 49.2	153.0	502	13.7	56.7	16.4	9.0	40-153
Fort Reno #5254	106 03.3	43 49.0	148.0	486	13.1	55.6	11.9	6.5	50-148
Fort Reno #5320	106 2.6	43 49.0	114.0	374	12.9	55.2	18.4	10.1	60-110
Fort Reno #5322	106 2.5	43 49.0	56.0	190	11.6	52.9	14.7	8.1	30-58
Fort Reno #5362	106 2.7	43 48.9	105.0	344	12.7	54.8	16.4	9.0	50-105
Fort Reno #5348	106 2.6	43 48.9	112.0	367	13.5	56.3	6.9	3.8	20-110
Fort Reno #5344	106 2.6	43 48.9	128.0	420	14.0	57.2	14.8	8.1	90-128
Fort Reno #5358	106 2.6	43 48.9	121.0	397	13.3	55.9	19.4	10.6	50-110
Fort Reno #5340	106 2.5	43 48.9	119.0	390	13.0	55.4	15.8	8.7	60-110
North Butte #5419	106 59.0	43 48.9	160.0	525	14.4	57.9	24.9	13.7	40-110
North Butte #5051	105 59.8	43 48.8	182.0	597	15.3	59.5	19.8	10.9	70-130
North Butte #5763	105 59.7	43 48.8	170.0	558	14.5	58.1	28.0	15.4	20-170
North Butte #5095	105 59.4	43 48.8	190.0	623	15.0	54.0	23.8	13.1	30-190
North Butte #5423	105 59.0	43 48.8	189.0	620	14.7	58.5	21.7	11.9	40-189
North Butte #5025	105 59.1	43 48.7	190.0	623	15.3	59.5	18.4	10.1	30-190
North Butte #5421	105 59.1	43 48.7	190.0	623	15.1	59.2	23.6	12.9	40-190
Fort Reno #5786	106 0.1	43 48.4	90.0	295	12.5	54.5	26.7	14.6	40-90
North Butte #5057	105 59.6	43 48.4	177.0	581	15.1	59.2	21.0	11.5	100-177
North Butte #5059	105 59.6	43 48.3	190.0	623	15.2	59.4	22.4	12.3	30-190
Fort Reno #5784	106 0.0	43 48.2	152.0	499	14.0	57.2	21.7	11.9	80-152
North Butte #5794	105 59.2	43 48.2	82.0	236	12.0	53.6			
South Butte #464	105 45.0	43 44.8	146.0	479	13.7	56.7			
South Butte #465	105 45.0	43 44.8	32.0	105	11.1	52.0			
Turner Crest #4	105 38.0	43 41.2	112.0	367	12.6	54.7	23.0	12.6	60-110
Turner Crest #3	105 39.3	43 40.3	126.0	413	11.5	52.7			
Turner Crest #5A	105 36.9	43 40.0	126.0	413	12.8	55.0	38.8	21.3	80-120
Turner Crest #1	105 40.4	43 39.4	90.0	295	11.3	52.4	21.4	11.7	50-90
Turner Crest #7	105 38.0	43 39.4	104.0	341	12.4	54.3	36.1	19.8	60-100
Turner Crest #6	105 38.0	43 39.4	123.0	404	12.8	55.0	29.0	15.9	60-90
Turner Crest #14	105 36.9	43 38.6	80.0	262	11.4	52.5	19.1	10.5	30-80
Turner Crest #12	105 39.3	43 37.8	145.0	476	12.9	55.2	29.0	15.9	60-130
Turner Crest #9	105 36.9	43 37.8	90.0	294	11.5	52.7	19.5	10.7	50-190
Turner Crest #10	105 35.6	43 36.0	81.0	266	11.3	52.4			
Johnson County									
Fort Reno SE #OW-2	106 3.1	43 50.7	102.0	335	12.1	53.8	23.7	13.0	40-102
Fort Reno SE #OW-9	106 3.1	43 50.7	100.0	328	12.1	53.8	21.0	11.5	30-100
Fort Reno #OW-6	106 3.1	43 50.7	99.0	325	12.1	53.8	23.0	12.6	30-99
Fort Reno #OW-8	106 03.1	43 50.7	11.07	367	12.4	54.3	21.0	11.5	30-112
Fort Reno #OW-7	106 03.1	43 50.7	58.0	190	11.2	52.2	16.2	8.9	30-58
Fort Reno #OW-3	106 03.1	43 50.7	99.0	325	12.0	53.6	20.8	11.4	30-99

Appendix A continued.

Hole Name	Longitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/km	°F/1,000 ft	Interval (m)
Fort Reno #OW-1	106 03.1	43 50.7	98.0	322	12.2	54.0	22.4	12.3	30-98
Fort Reno #G-4	106 3.8	43 50.3	106.0	348	12.4	54.3	22.7	12.5	10-106
Fort Reno #G 4-8	106 3.7	43 50.3	87.0	285	11.8	53.2	23.6	12.9	10-87
Fort Reno #CCP-4	106 03.6	43 49.9	102.0	335	12.0	53.6	21.6	11.9	50-102
Fort Reno #5254	106 3.3	43 49.0	148.0	486	13.1	55.6	11.9	6.5	50-148
Fort Reno #CCP-2	106 3.6	43 48.9	91.0	299	11.8	53.2			
Fort Reno #CCP-3	106 3.6	43 48.9	59.0	194	10.9	51.6			
Fort Reno #CCP-1	106 3.6	43 48.9	122.0	400	12.4	54.3	21.9	12.0	60-122
Sussex #16-5	106 15.4	43 48.3	35.0	115	10.8	51.4			
Sussex #56-1	106 15.9	43 38.3	101.0	331	11.4	52.5	20.8	11.4	40-101
Sussex #34-1	106 15.8	43 38.3	52.0	171	10.9	51.6			
Sussex #44-3	106 15.3	43 37.9	40.0	131	12.0	53.6			
Sweetwater County									
Osborne Well #5	107 48.5	42 11.6	336	1,100	12.5	54.5	22.1	12.1	180-336
Hadsell Springs #3	107 38.3	42 11.2	490	1,600	14.9	58.8	11.0	6.0	220-490
Osborne Well #8	107 45.8	42 10.4	518	1,700	16.7	62.1	17.8	9.8	190-510
Superior #69-32	108 51.9	41 54.4	114	374	9.7	49.5	10.7	5.9	40-70
Boars Tusk #31-24	109 00.8	41 52.1	153	502	11.3	52.3	20.0	11.0	110-150
Boars Tusk #33-24	109 00.8	41 51.9	160	525	9.9	49.8	18.8	10.3	100-160
Superior #35-24	109 00.9	41 51.7	171	561	10.7	51.3	12.4	6.8	100-160
Superior #34-20	108 59.6	41 51.5	162	531	10.7	51.3	21.5	11.8	30-150
Superior #28-28	108 58.4	41 50.8	106	348	9.2	48.6	18.7	10.3	50-106
Superior	108 57.4	41 50.8	166	545	10.8	51.4	22.4	12.3	40-166
Superior	108 57.3	41 50.6	126	413	11.3	52.3	20.2	11.1	60-80
Superior #14-34	108 57.2	41 50.5	171	561	11.1	52.0	22.8	12.5	10-120
Superior #21-34	108 57.2	41 50.3	154	505	10.7	51.3	25.7	14.1	50-154
Superior #24-34	108 57.2	41 50.3	142	466	11.3	52.3	29.7	16.3	60-140
Superior #25-32	108 58.5	41 50.2	152	499	9.6	49.3	10.6	5.8	20-80
Superior #42-34	108 56.4	41 50.1	130	426	11.2	52.5	23.6	12.9	10-110
Superior #48-34	108 56.9	41 50.0	117	384	10.1	50.2	18.3	10.0	20-80
Superior #43-34	108 56.5	41 49.8	150	492	11.0	51.8	16.1	8.8	90-140
Superior #47-34	108 56.4	41 49.8	172	564	11.1	52.0	16.2	8.9	80-150
Superior #58-2	108 56.1	41 49.6	123	404	10.6	51.1	20.8	11.4	40-70
Superior #54-2	108 56.1	41 49.5	168	551	11.0	51.8	30.5	16.7	40-100
Superior #57-2	108 55.4	41 49.3	152	499	11.6	52.9	18.6	10.2	20-110
Red Lake #30-1	108 25.6	41 49.1	1,770	5,807	59.0	148.2	28.9	15.8	200-164
Superior #63-20	108 52.4	41 47.2	213	699	10.9	51.6	10.2	5.6	80-120
Superior #62-20	108 52.5	41 46.6	113	371	11.3	52.3	23.8	13.1	40-110
Superior #70-30	108 52.4	41 45.9	141	463	10.8	51.4	20.5	11.2	30-120
Point of Rocks	108 52.3	41 44.6	116	581	9.8	49.6			
Desert Springs	108 27.0	41 44.2	1,740	5,709	57.6	135.7	22.9	12.6	100-580
Desert Springs	108 26.4	41 42.7	950	3,117	32.9	91.2	22.6	12.4	10-950
Desert Springs	108 28.4	41 42.7	1,790	5,870	58.4	137.1	29.2	16.0	10-1,790
Desert Springs	108 25.1	41 35.9	1,800	5,900	56.9	134.4	26.5	14.5	20-1,800
Fort Lacrede	108 27.4	41 29.9	1,770	5,810	75.4	167.7	24.1	13.2	350-600

Appendix B. Chemical data for selected wells in the southern Powder River Basin. Data from: a. Woodward-Clyde (1980); b. Hodson (1974); c. Crawford (1963); d. Feathers and others (1981); e. Wells and others (1979); f. Crawford (1940).

Formation	Location T.	Location R.	Location Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	Total dissolved solids	Reference
Madison	33	73	32	156	160	32	100	590	154	1,160	a
Madison	33	75	4	1,308	500	37	500	3,229	220	5,682	b
Madison	33	75	8	527	316	60	569	1,200	93	2,712	a
Madison	33	75	8	510	334	82	557	1,370	95	2,950	a
Madison	33	75	20	112	156	30	100	512	124	1,010	a
Madison	33	76	16	572	410	64	624	1,560	112	3,350	a
Madison	33	76	33	190	69	22	18	58	129	440	a
Madison	33	77	15	496	337	55	322	1,560	124	2,920	a
Madison	34	76	7	816	460	36	1,180	1,156	159	3,726	b
Madison	36	82	22	604	150	12	82	1,365	247	2,334	b
Madison	37	63	9	2,152	342	61	2,900	1,263	465	6,947	b
Madison	38	75	26	2,553	140	34	3,140	850	708	7,067	b
Madison	39	61	2	58	91	7	67	131	185	445	b
Madison	39	78	26	789	306	40	1,052	900	133	3,240	a
Madison	39	79	11	390	263	49	474	766	104	2,260	a
Madison	40	78	10	103	287	52	454	313	230	1,322	c
Madison	40	79	23	564	614	31	770	1,149	732	3,486	b
Madison	40	79	25	602	315	67	698	1,130	125	4,280	b
Madison	40	79	26	527	326	60	649	1,074	122	2,680	a
Madison	40	79	26	513	365	28	620	1,120	112	2,770	a
Madison	40	79	31	510	300	49	621	969	122	2,570	a
Madison	40	79	35	455	327	60	641	1,060	98	2,600	a
Madison	40	80	31	467	468	99	210	2,025	230	3,382	b
Madison	41	78	1	518	288	56	977	936	110	2,640	a
Madison	41	81	9	366	227	59	443	850	134	2,040	b
Madison	42	81	25	464	282	80	584	1,079	117	2,590	a
Madison	41	81	9	270	178	60	351	593	207	1,560	a
Madison	41	81	16	354	275	72	560	800	159	2,139	b
Madison	42	80	30	475	289	72	590	1,090	115	2,600	b
Madison	43	80	34	472	329	59	647	1,109	98	2,740	a
Madison	44	60	5	45	55	13	3	27	300	300	b
Madison	44	63	26	0	182	27	95	300	131	720	b
Madison	45	61	20	4	63	28	1	38	291	292	b
Madison	45	61	21	5	76	29	1	87	276	385	b
Madison	45	61	28	5	62	29	1	37	289	290	b
Madison	45	61	29	8	76	33	3	117	257	379	b
Madison	45	61	30	7	75	33	2	108	266	372	b
Madison	45	61	33	5	76	26	1	74	276	332	b
Madison	46	60	31	4	65	24	0	12	318	276	b
Madison	46	62	18	3	62	28	1	27	296	279	b
Madison	46	62	28	42	114	31	110	122	256	744	d
Madison	46	63	10	3	74	26	1	51	295	315	b
Madison	46	63	15	3	64	27	2	24	293	279	b
Madison	46	63	17	3	61	28	1	20	299	275	b
Madison	46	64	13	3	61	26	1	29	273	268	b
Madison	46	64	19	17	75	27	11	96	268	494	b
Madison	46	64	23	5	56	28	2	33	275	279	b
Madison	46	65	20	32	101	27	2	250	119	617	b
Madison	46	65	23	3	72	32	1	125	228	460	b
Madison	46	66	25	13	175	46	4	459	177	834	b
Madison	47	60	4	2	62	23	1	5	291	249	b
Bighorn	40	80	31	584	351	75	200	1,876	270	3,219	c
Tensleep	32	73	16	210	590	210	110	2,400	150	3,610	e
Tensleep	33	76	33	544	407	36	50	2,016	220	3,161	c
Tensleep	33	81	36	156	509	120	56	2,000	-	2,930	a
Tensleep	33	83	3	356	493	103	345	1,752	145	3,120	f
Tensleep	33	83	33	445	328	92	395	1,390	135	2,716	f
Tensleep	34	65	32	46	73	50	58	259	165	567	f
Tensleep	34	82	26	471	541	116	400	2,112	105	3,692	f
Tensleep	34	82	23	397	482	100	331	1,910	25	3,232	f
Tensleep	36	81	4	280	300	56	380	960	257	2,170	e
Tensleep	36	81	4	230	450	71	450	1,100	171	2,370	e
Tensleep	36	81	7	420	-	-	24	380	595	1,090	e
Tensleep	36	82	1	330	390	79	470	1,200	150	2,520	e
Tensleep	36	82	22	660	510	56	74	2,600	158	3,970	e
Tensleep	39	83	18	16	120	24	7	310	122	570	e
Tensleep	40	70	35	680	430	84	1,100	1,200	165	3,560	e
Tensleep	40	78	15	363	293	33	168	1,191	220	2,156	c
Tensleep	40	78	31	400	290	5	190	1,200	180	2,130	e
Tensleep	40	78	31	390	280	27	320	950	279	2,110	e
Tensleep	40	78	31	370	240	8	160	790	497	1,820	e
Tensleep	40	79	25	600	320	67	700	1,100	125	2,920	e
Tensleep	40	79	25	585	314	67	699	1,130	125	2,920	a
Tensleep	40	79	25	455	327	60	640	1,060	98	2,600	a
Tensleep	40	79	26	500	310	48	630	1,000	115	2,570	e
Tensleep	40	79	31	620	440	56	740	1,400	159	3,370	e
Tensleep	40	79	35	460	380	83	600	1,200	170	2,840	e
Tensleep	40	83	19	8	62	28	2	130	182	520	e
Tensleep	41	77	18	550	200	21	160	1,200	332	2,320	e

Appendix B continued.

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	Total dissolved solids	Reference
Tensleep	41	78	31	640	440	59	700	1,4000	120	3,850	e
Tensleep	41	81	16	520	230	85	600	1,100	115	2,550	e
Tensleep	41	81	16	470	290	64	590	1,000	135	2,500	e
Tensleep	41	81	23	770	210	88	1,100	620	439	3,010	e
Tensleep	41	81	24	450	290	88	610	1,100	120	2,560	e
Tensleep	41	81	26	590	200	18	700	290	677	2,120	e
Tensleep	41	81	27	490	170	95	720	270	732	2,110	e
Tensleep	41	81	27	440	120	70	600	180	610	1,710	e
Tensleep	42	78	17	6,400	86	13	8,500	820	1,720	16,700	e
Tensleep	42	78	17	500	220	31	200	1,100	257	2,210	e
Tensleep	42	78	35	160	530	30	400	1,000	185	2,240	e
Tensleep	42	84	25	6	44	26	3	21	241	231	e
Tensleep	43	82	15	1,803	430	129	2	1,100	296	1,790	a
Tensleep	43	84	26	4	38	31	6	2	281	231	a
Tensleep	43	84	35	5	49	25	2	21	256	247	a
Minnelusa	30	82	24	175	130	21	240	380	103	1,040	a
Minnelusa	32	70	19	996	321	51	360	2,333	295	4,206	c
Minnelusa	35	63	15	250	600	240	160	2,100	709	3,710	e
Minnelusa	35	63	23	130	77	55	19	280	465	793	e
Minnelusa	35	65	4	810	310	41	440	1,800	195	3,530	e
Minnelusa	35	65	4	680	340	76	720	1,500	129	3,330	e
Minnelusa	35	65	5	670	350	38	540	1,500	223	3,300	e
Minnelusa	35	65	5	470	360	77	490	1,300	264	2,850	e
Minnelusa	35	65	5	510	380	76	540	1,400	245	2,980	e
Minnelusa	35	65	6	900	580	230	1,900	1,400	215	5,120	e
Minnelusa	35	65	7	440	330	67	540	1,000	266	2,560	e
Minnelusa	35	65	7	630	310	59	610	1,300	185	3,020	e
Minnelusa	35	65	8	730	380	58	550	1,800	190	3,600	e
Minnelusa	35	65	7	649	308	54	617	1,332	177	3,047	c
Minnelusa	35	65	35	56	130	5	49	350	34	603	e
Minnelusa	36	62	4	415	322	56	840	520	256	2,293	c
Minnelusa	36	64	26	640	270	73	160	1,600	635	2,990	e
Minnelusa	36	65	5	790	710	240	860	2,300	440	5,180	e
Minnelusa	36	65	5	470	380	85	530	1,300	245	2,930	e
Minnelusa	36	65	31	770	330	71	490	1,700	376	3,560	e
Minnelusa	36	65	32	1,300	520	60	330	3,500	394	5,910	e
Minnelusa	36	65	32	770	350	65	610	1,700	205	3,610	e
Minnelusa	36	65	33	590	320	67	500	1,400	205	3,000	e
Minnelusa	36	65	33	690	310	72	520	1,600	255	3,270	e
Minnelusa	38	61	19	9,240	750	270	13,000	4,900	305	27,800	e
Minnelusa	38	61	30	26,450	1,700	820	43,000	3,500	317	10,200	e
Minnelusa	38	61	30	1,810	500	110	800	2,900	1,900	7,040	e
Minnelusa	38	62	25	870	11	30	680	2	1,330	2,240	e
Minnelusa	38	62	25	5,700	680	160	7,600	2,600	1,530	17,600	e
Minnelusa	39	60	19	62,000	4,200	2,100	11,000	2,900	205	176,000	e
Minnelusa	39	61	2	3,134	629	283	2,700	4,816	890	12,003	c
Minnelusa	40	63	24	7,600	500	2	8,400	5,100	680	21,900	e
Minnelusa	41	60	7	16,000	460	210	10,000	1,800	3,600	47,100	e
Minnelusa	44	60	5	25	470	84	11	1,300	222	2,020	e
Minnelusa	45	61	2	40	690	37	10	1,700	141	2,530	e
Minnelusa	45	61	2	68	630	140	24	2,000	159	2,960	e
Minnelusa	46	63	10	7	78	23	5	43	307	307	e
Minnelusa	47	60	30	2	68	24	1	12	305	280	e
Minnelusa	47	61	1	98	83	12	2	13	304	351	e
Minnelusa	47	61	11	3	70	15	1	19	254	274	e
Hartville	28	66	28	9	60	26	9	18	284	312	e
Hartville	29	68	9	21	43	20	4	33	234	274	e
Hartville	29	68	9	58	42	5	9	53	214	278	e
Hartville	29	68	20	23	44	16	2	22	240	243	e
Hartville	29	68	20	18	45	13	3	3	240	222	e
Hartville	29	68	24	26	29	8	9	120	42	242	e
Hartville	29	69	33	44	23	8	7	34	183	227	e
Hartville	30	68	16	45	63	22	29	150	192	434	e
Phosphoria	45	61	33	5	64	28	1	48	288	301	c
Phosphoria	45	61	29	9	76	33	3	117	257	379	c
Phosphoria	46	60	31	42	58	10	2	16	306	292	c
Phosphoria	46	62	18	3	62	28	1	27	296	279	c
Phosphoria	46	63	15	4	64	27	2	24	293	283	c
Phosphoria	46	65	23	-	70	34	3	110	232	465	c
Phosphoria	46	66	25	-	176	39	4	310	179	824	c
Chugwater	30	83	15	24	42	13	7	31	193	242	a
Chugwater	39	83	7	109	188	67	6	788	210	1,300	a
Spearfish	36	60	30	15.7	240	73	55	650	209	1,200	a
Sundance	32	70	19	1,100	18	5	400	1,073	755	3,064	c
Sundance	33	76	9	1,492	-	-	686	1,330	1,015	4,044	f
Sundance	33	82	7	780	-	-	213	80	1,208	1,859	f
Sundance	33	82	12	873	11	-	284	135	1,435	2,135	f
Sundance	33	82	18	824	-	-	207	374	1,080	2,069	f
Sundance	33	82	2	1,096	44	Trace	775	528	1,040	2,081	f
Sundance	33	83	12	670	6	7	24	35	1,196	1,601	f
Sundance	33	83	13	700	6	14	25	99	1,454	1,519	f
Sundance	35	66	5	3,098	278	46	402	6,483	365	10,483	c
Sundance	35	66	25	418	40	52	30	224	815	1,334	c
Sundance	36	65	6	1,867	85	Trace	594	3,039	330	5,647	f
Sundance	36	65	6	2,753	265	Trace	145	5,879	395	9,236	f

Appendix B continued.

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	Total dissolved solids	Reference
Sundance	49	83	5	41	55	36	5	156	236	463	a
Sundance	40	61	35	1,411	268	101	40	3,857	98	5,725	c
Sundance	40	79	23	3,827	24	12	4,850	90	1,220	9,483	f
Sundance	40	79	24	2,988	20	10	3,550	Trace	1,930	7,517	f
Sundance	40	79	25	3,720	44	15	4,500	568	1,610	9,639	f
Sundance	40	79	35	4,511	260	16	4,125	3,905	780	13,200	f
Sundance	40	79	35	4,259	264	56	3,950	5,317	610	14,146	f
Sundance	40	79	35	4,009	334	59	4,568	2,662	710	11,916	f
Sundance	42	81	27	5,035	560	157	7,409	2,375	68	15,568	f
Sundance	43	83	31	1,144	111	18	18	2,748	8	4,080	a
Morrison	36	65	32	3,524	198	42	250	7,419	370	11,625	c
Morrison	39	84	3	168	4	205	6	878	73	11,625	a
Cloverly	33	79	24	145	1	0	7	74	278	396	a
Cloverly	37	82	36	583	10	1	18	957	351	1,780	a
Cloverly	39	60	19	304	-	-	44	233	315	795	f
Cloverly	39	61	14	338	-	-	70	63	620	813	f
Cloverly	39	61	14	336	-	-	32	298	380	890	f
Cloverly	41	60	7	372	-	-	25	544	250	1,064	f
Cloverly	41	81	25	1,226	3	3	278	341	2,449	3,110	a
Cloverly	42	82	14	599	2	2	117	565	653	1,650	a
Cloverly	44	62	22	276	77	19	13	690	162	1,190	a
Dakota	33	82	11	583	18	6	21	61	1,175	1,405	f
Dakota	33	80	21	222	-	-	54	39	325	534	f
Dakota	33	83	12	349	6	-	15	325	360	944	f
Dakota	35	77	27	4,605	38	21	2,880	4,724	1,290	13,002	c
Dakota	37	63	13	750	8	5	150	67	1,696	1,815	c
Dakota	37	78	12	5,259	42	19	7,400	40	1,390	13,445	c
Dakota	37	81	31	499	-	-	32	784	225	1,450	f
Dakota	37	82	36	607	-	-	28	981	255	1,771	f
Dakota	40	67	25	3,689	28	12	4,360	386	1,940	9,431	c
Dakota	40	79	25	3,690	30	12	5,150	82	975	9,443	f
Dakota	40	79	26	5,131	38	6	6,850	42	1,915	13,009	f
Dakota	40	79	34	5,561	56	18	7,750	137	1,500	14,399	f
Fall River	35	65	5	834	-	-	52	-	2,125	1,931	f
Fall River	35	65	4	1,295	-	-	324	-	2,880	3,035	f
Fall River	36	65	35	731	-	-	252	86	1,275	1,756	f
Fall River	37	63	25	520	15	7	350	50	795	1,343	f
Lakota	33	76	9	1,318	-	-	616	485	1,675	3,310	f
Lakota	35	77	21	2,280	67	-	2,060	1,321	995	6,237	f
Lakota	34	76	8	1,179	0	0	155	341	2,145	2,871	c
Lakota	35	65	31	347	79	27	770	0	185	1,392	c
Lakota	35	77	21	2,280	67	-	2,060	1,321	995	6,237	f
Lakota	35	79	23	1,140	8	-	107	521	1,360	2,805	f
Lakota	39	60	30	371	0	0	6	0	890	857	c
Lakota	39	79	12	1,151	Trace	-	240	-	2,640	2,689	f
Lakota	39	79	2	857	Trace	-	340	-	1,670	2,018	f
Lakota	40	79	35	1,662	-	-	1,257	-	2,125	4,024	f
Lakota	40	79	26	696	7	Trace	525	Trace	965	1,703	f
Lakota	40	79	25	2,677	Trace	-	1,600	64	3,680	6,440	f
Lakota	40	79	25	1,314	-	-	260	Trace	2,990	3,068	f
Lakota	40	79	25	1,017	6	-	139	-	2,098	2,511	f
Lakota	40	79	34	634	20	Trace	300	12	1,210	1,562	f
Lakota	40	79	15	1,507	16	-	674	58	2,327	4,639	f
Lakota	40	79	23	1,169	Trace	-	750	12	1,795	2,814	f
Lakota	40	79	23	1,187	Trace	-	850	-	1,685	2,886	f
Lakota	40	79	23	1,558	Trace	-	1,550	Trace	1,465	3,828	f
Lakota	40	79	23	1,048	12	Trace	800	Trace	1,440	2,568	f
Lakota	40	79	23	2,008	-	-	1,928	-	1,950	4,925	f
Lakota	40	79	24	1,127	25	Trace	265	-	2,610	2,691	f
Lakota	40	79	24	1,252	28	Trace	340	-	2,700	2,948	f
Lakota	40	79	27	1,035	Trace	-	650	Trace	1,625	2,484	f
Lakota	40	79	27	1,393	Trace	-	1,350	40	1,320	3,432	f
Lakota	41	77	19	7,112	167	28	10,000	687	1,445	18,706	c
Inyan Kara	37	61	19	354	200	75	9	1,400	275	2,160	a
Inyan Kara	40	61	35	335	12	2	21	560	256	1,080	a
Inyan Kara	41	61	1	322	3	3	22	454	251	956	a
Inyan Kara	41	60	7	357	21	11	13	660	200	1,190	a
Inyan Kara	41	60	17	324	22	7	10	570	183	1,050	a
Inyan Kara	42	60	7	155	234	66	18	984	153	1,570	a
Inyan Kara	43	60	30	32	78	49	12	280	171	541	a
Inyan Kara	45	61	29	71	285	118	14	1,250	24	1,760	a
Inyan Kara	46	61	10	5	42	12	2	20	167	180	a
Inyan Kara	46	62	27	185	423	248	26	2,000	276	2,840	a
Inyan Kara	46	63	5	403	-	-	26	631	255	1,240	a
Inyan Kara	46	63	31	-	-	-	29	1,159	205	1,920	a
Inyan Kara	46	64	11	667	8	-	32	1,269	183	2,100	a
Newcastle	42	65	4	5,091	36	19	7,400	200	730	13,105	c
Newcastle	45	65	27	4,766	94	33	3,700	21	5,250	12,328	c
Newcastle	46	64	15	5,227	115	0	6,719	0	2,660	13,369	c
Muddy	33	76	25	5,361	28	17	6,850	48	2,550	13,564	c
Mowry	39	83	13	192	36	10	3	424	141	765	a
Frontier	40	80	27	342	1	-	5	286	390	962	a

STATE OF WYOMING

1933

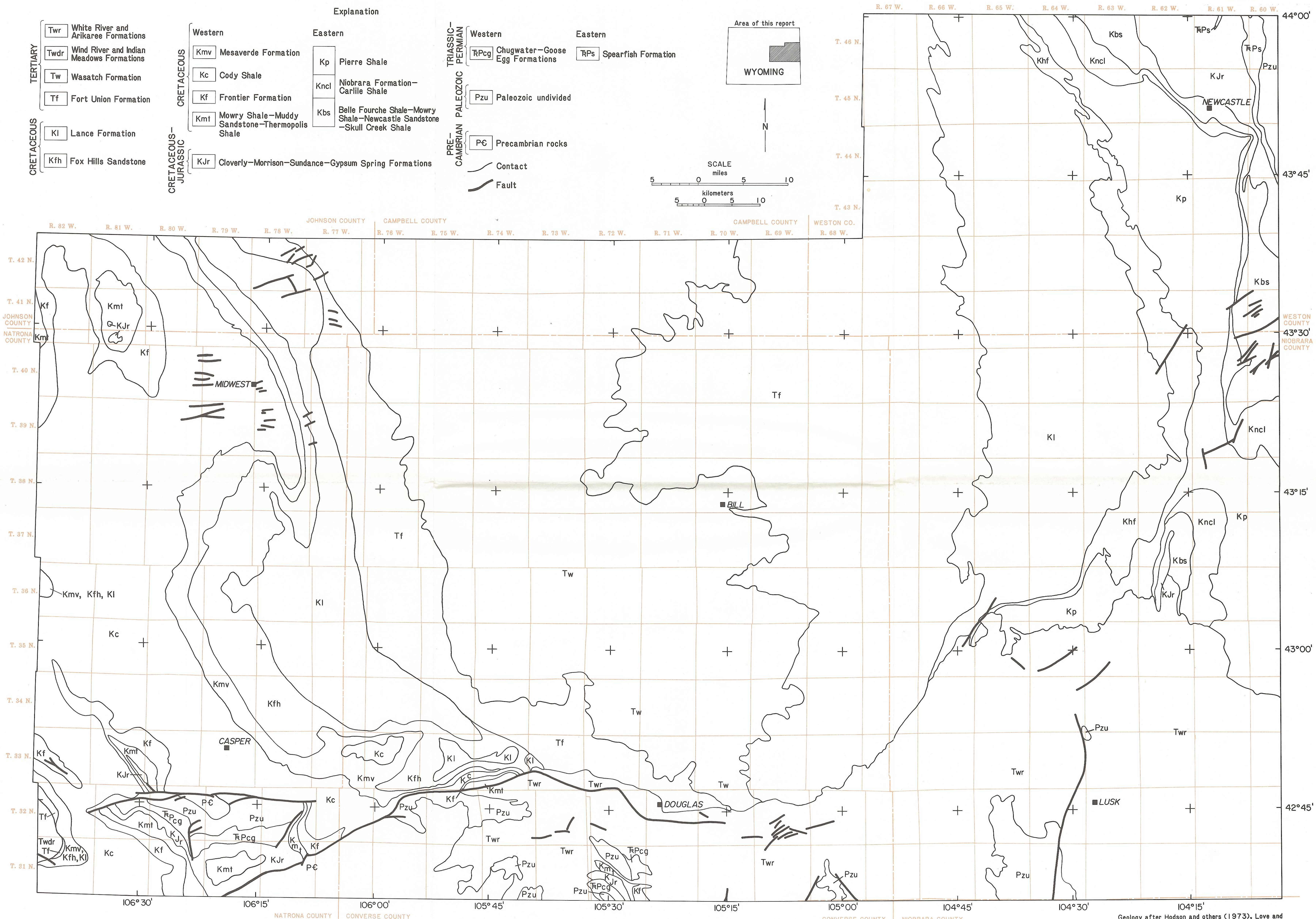
GEOLOGICAL SURVEY

STATE OF WYOMING GEOLOGICAL SURVEY 1933

Geology--Interpreting the past to provide for the future

Geothermal Resources of the Southern Powder River Basin, Wyoming

RI 36



Geology after Hodson and others (1973), Love and others (1977) and Love and Christiansen (1985).

GENERALIZED GEOLOGIC MAP OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

Compiled by
Kenneth L. Buelow

1986

RI-36

Explanation

Contour on the Newcastle/Muddy Sandstone–datum is mean sea level, contour interval 1,000 feet.

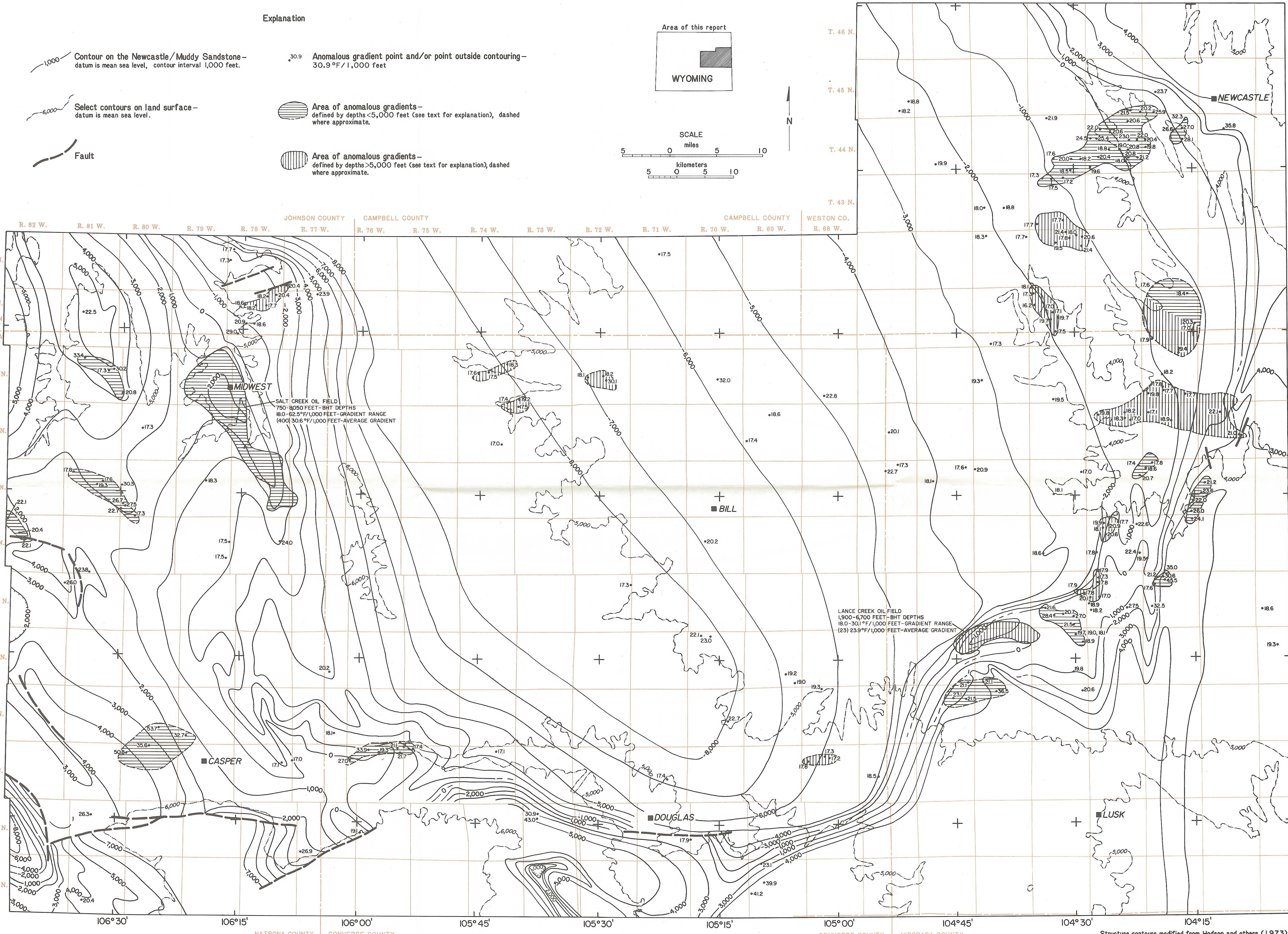
Select contours on land surface–datum is mean sea level.

Fault

30.9 Anomalous gradient point and/or point outside contouring–30.9°F/1,000 feet

Area of anomalous gradients–defined by depths <5,000 feet (see text for explanation), dashed where approximate.

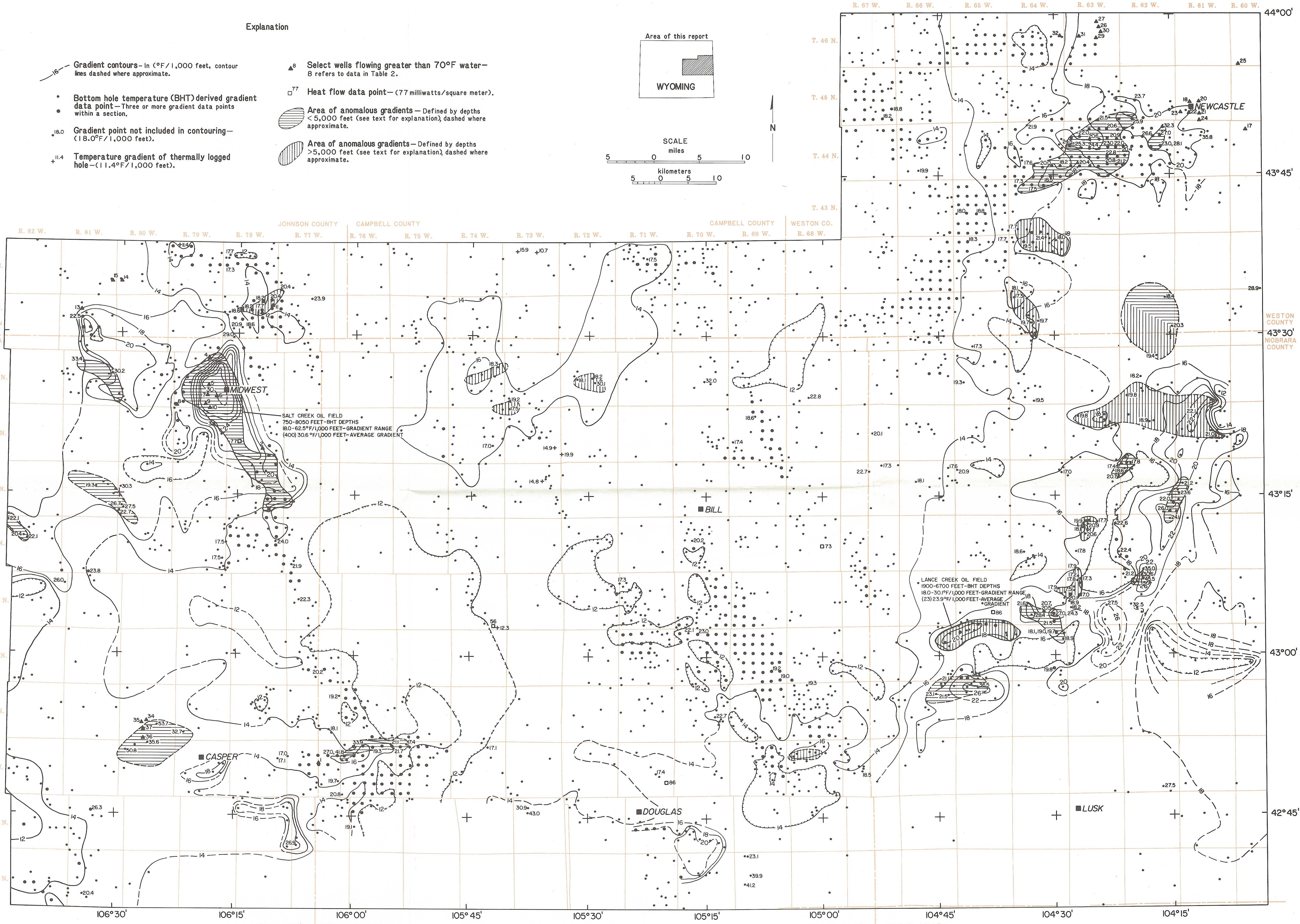
Area of anomalous gradients–defined by depths >5,000 feet (see text for explanation), dashed where approximate.



Structure contours modified from Hodson and others (1973), Head and others (1978) and Barlow and Hahn, Inc. (1978).

GENERALIZED STRUCTURE CONTOUR MAP OF THE TOP OF THE NEWCASTLE / MUDDY SANDSTONE, SOUTHERN POWDER RIVER BASIN, WYOMING

Compiled by
Kenneth L. Buelow
1986

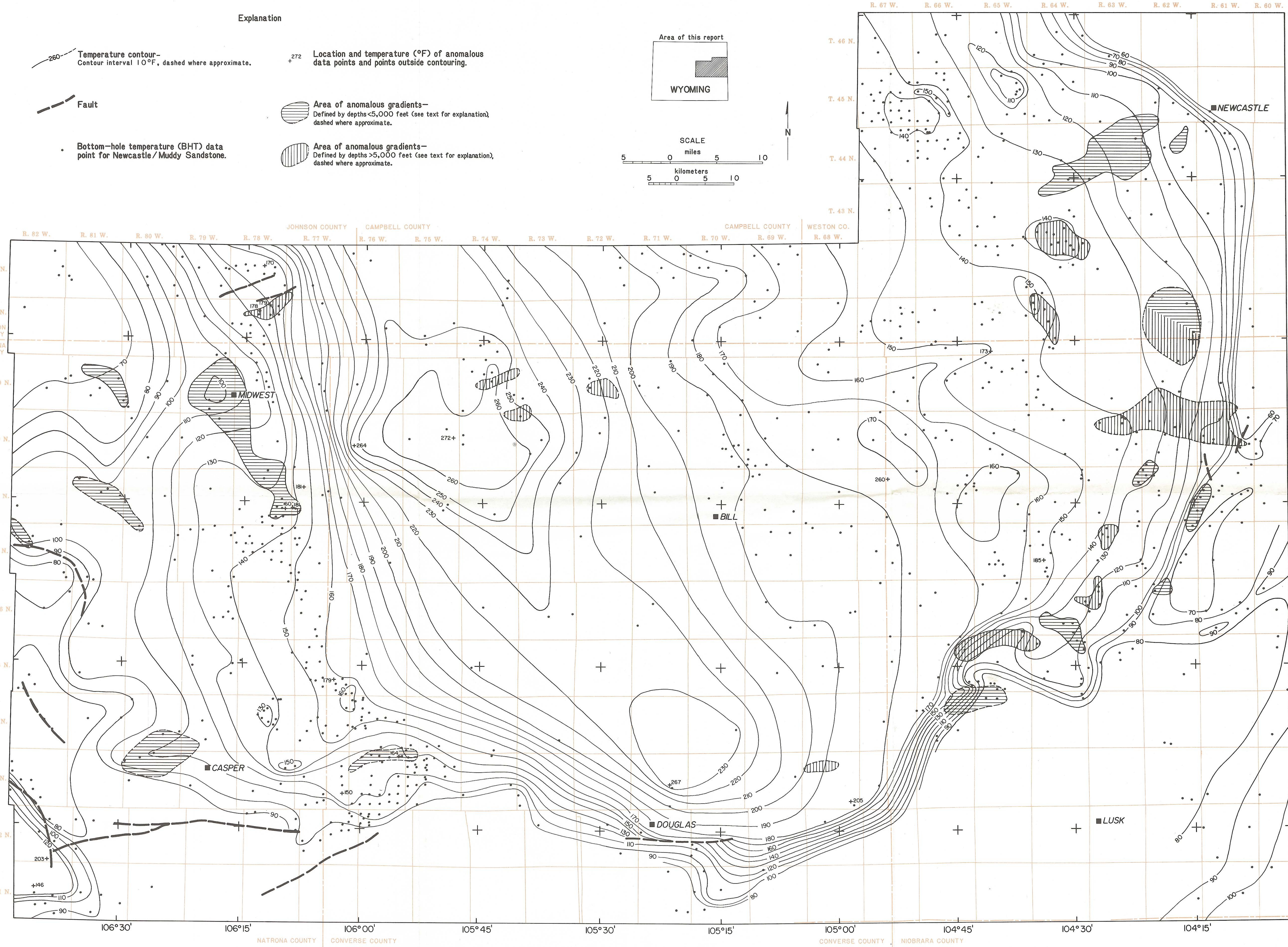


THERMAL GRADIENT CONTOUR MAP OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

Compiled by
Kenneth L. Buelow
1986

Explanation

- 260 Temperature contour– Contour interval 10°F, dashed where approximate.
- Fault
- Bottom–hole temperature (BHT) data point for Newcastle/Muddy Sandstone.
- +272 Location and temperature (°F) of anomalous data points and points outside contouring.
- Area of anomalous gradients– Defined by depths <5,000 feet (see text for explanation), dashed where approximate.
- Area of anomalous gradients– Defined by depths >5,000 feet (see text for explanation), dashed where approximate.



TEMPERATURE CONTOUR MAP OF THE NEWCASTLE / MUDDY SANDSTONE, SOUTHERN POWDER RIVER BASIN, WYOMING

Compiled by
Kenneth L. Buelow
1986