Energy

GEOTHERMAL

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CONVERSION FACTORS

Length   1 meter = 3.281 feet (ft)   1 foot = 0.3048 meter (m)

                 1 kilometer = 0.6214 mile (mi)   1 mile = 1.6093 kilometers (km)

Mass   1 gallon per minute = 3.785 liters per minute (lpm)
flow
                 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   1 degree Fahrenheit per thousand feet =
gradient   = 1.823 degrees Celsius per kilometer (°C/km)

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

Thermal   1 millicalorie per centimeter per second per degree Celsius
conduc-   (10^{-3} cal/cm sec°C) =
tivity   = 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   1 microcalorie per square centimeter per second ($10^{-6}cal/cm^2sec$)=
flow   = 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 fourth in a series of re-
ports describing the geothermal re-
sources of Wyoming basins (see Figure
1). Each basin report contains a dis-
cussion of hydrology as it relates to
the movement of heated water, a descrip-
tion and interpretation of the thermal
regime, and four maps: a generalized
geological map (Plate I), a structure
contour map (Plate II), and a thermal
gradient 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 sys-
tem, the quantity and reliability of
thermal data, and the amount of avail-
able geologic information vary substan-
tially 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 dis-
cussion of the methods we used in asses-
sing the geothermal resources. This
introduction is followed by a descrip-
tion of the geothermal resources of the
Southern Powder River Basin of north-
eastern Wyoming (Figure 1).

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physics, and by the Wyoming Water
Research Center. Compilations of oil-
well bottom-hole temperatures can be
examined at the office of the Geological
Survey of Wyoming in Laramie.

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

GEOTHERMAL SYSTEMS AND RESOURCES

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

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

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

In Wyoming basins, the primary mechanism for the translation of moder-

ate 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 sedi-

mentary basins of Wyoming fall mostly
into the low-temperature and interme-
diate-temperature groups.

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

The geothermal resources in the
basins are suited to relatively small-
scale, direct-use projects located close
by. Energy uses include a wide range of
space heating, agricultural, aquacul-
tural, 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 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 tril-
lion British thermal units (Btu's) of
heat per year in cooling to ambient tem-
perature. 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 pro-
duced as a by-product in Wyoming oil
fields were cooled to ambient tem-
perature.

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 $\pm 0.005°C$ (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

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

where MAAT is the mean annual air temperature.

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

The use of oil field bottom-hole temperatures in geothermal gradient studies is the subject of some controversy among geothermal researchers. There are problems associated with the thermal effects of drilling and with operator inattention in measuring and reporting BHT's which cast doubt on the accuracy of individual temperature reports. It has

been suggested, for example, that in some areas BHT's may correlate with the ambient temperature during drilling and, specifically, that many of the thermometers used in the summer are reading their maximum temperature before they are lowered down the drill hole. Similarly, drilling fluids may transfer heat to the bottom of a drill hole, warming or cooling the rock depending on the drilling fluid temperature and the depth of the hole. The magnitude of a thermal disturbance depends on the temperature difference between the drilling fluid and the rock, the time between the end of fluid circulation and temperature measurement, the type of drilling fluid used, the length of time of fluid circulation, and the degree to which drilling fluids have penetrated the strata.

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

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

As explained above, temperature gradient values may be lower in deeper

holes because of drilling effects. This
was taken into account in identifying
gradient anomalies by grouping all tem-
perature 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 tabu-
lated 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 con-
ductivities 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 anoma-
lous 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 identifica-
tion of an area of anomalous gradient is
that a group of anomalous points (deter-
mined 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 gra-
dients 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 distur-
bance*. As a general check on the down-
ward projection of thermal gradients, we
know from heat flow and rock thermal
conductivity considerations that gradi-
ents below levels of hydrologic distur-
bance 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. There-
fore, we have identified for each basin
a productive, basin-wide aquifer which
is deep enough to contain water at use-
ful 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 tem-
perature gradient maps, verification is
provided by the much sparser thermal
logging data. No attempt was made to
correct BHT's for drilling effects, so a
certain degree of underestimation of
temperatures may be expected in the
deeper zones, as described above.
Although the deviation of BHT's from
true formation temperatures is not
known, a tempering effect is that a
drill hole in an aquifer with active
circulation should equilibrate to undis-
turbed temperatures relatively quickly.

(3) The third source of subsurface
temperature data is measurements in
springs and flowing wells. The amount

that these waters cool before they reach the surface is generally unknown; therefore, they provide only a minimum temperature check on BHT data. There is also commonly some uncertainty about the depth and source of flow. One can assume that all flow is from the bottom of a flowing well to obtain a minimum gradient. The most useful subsurface temperature data from springs and wells come from those whose source aquifer can be determined.

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

SUMMARY

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

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

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

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

GEOTHERMAL RESOURCES OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

Regional 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 plains of Montana. Up to 24,000 ft of structural relief exist in the basin with a maximum sedimentary thickness of 17,500 ft. The majority of the sediment thickness is provided by the Cretaceous and Cenozoic-age sediments (14,000 ft).

A general geologic map, a structure contour map, and stratigraphic section for the southern Powder River Basin are provided as Plates I, II, and Figure 7, respectively. The shape of southern Powder River Basin is depicted on Plate II with elevation contours on top of the Muddy Sandstone and the equivalent formation to the east, the Newcastle Sandstone. Dips along the basin margins range from 15° to near vertical, with numerous high angle faults and thrust faults creating local structural relief greater than 6000 ft.

Major structures encompassing the sourthern 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 and are generally regarded to be associated with basement faults. 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.

Stratigraphy

The geologic formations within the southern Powder River Basin range from Precambrian to Recent in age, with the Silurian age rocks completely absent. The stratigraphic column shown in Figure 7 indicates the general lithology and hydrological properties, along with the thickness of various geologic formations. Two major stratigraphic trends within the basin are the thinning of the Paleozoic units to the south-southwest and the variation of lithologies east-west across the basin. The maximum sedimentary thickness within southern Powder River Basin is 16,500 ft.

Paleozoic formations within the basin are marine shelf deposits with an aggregated thickness ranging from 1,300 - 1,500 ft in the east and 1,100 - 2,000 ft in the west. Cambrian age sediments are composed of sandstones, shales, and conglomerates of the Flathead Sandstone, Galletin, Gros Ventre, and Deadwood Formations. In the eastern part of the basin the Deadwood formation is overlain by the Ordovician age Winnipeg Formation composed of siltstone, shale, and sandstone units. A Devonian and Mississippian age massive limestone, dolomite, sandy dolomite sequence overlie the above units. This sequence is composed of the Whitewood Dolomite, Englewood Limestone, and Phahasapa Limestone (Madison Limestone) and extend across the entire basin pinching out in the extreme southeast. Overlying these units 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 is represented by the Goose Egg, Opech, and Minnekahta Formations, consisting of interbedded shale, siltstone, sandstone, and claystone.

Mesozoic sediments consist of shales, siltstone, claystone, and sandstone interbedded with small amounts of limestone. The Mesozoic-Paleozoic age

boundary is located in the interbedded red shale-siltstone beds of the Spearfish and Goose Egg Formation in the east and west side of the basin, repsectively. The Goose Egg Formation is overlain by the Chugwater Formation, a red siltstone, claystone, fine-grained sandstone. Overlying this is the Gypsum Spring Formation composed of white gypsum interbedded with shale and limestone; laterally continuous east-west across the basin, and absent in the southern part of the basin. The Sundance and Morrison Formations overlie the Gypsum Spring Formation and are composed of shales, sandstones, and claystones.

The Cretaceous age units on the western edge of the basin are: Cloverly, Thermopolis, Muddy, Mowry, Frontier, Cody, Mesaverde, Lewis, Fox Hills, and Lance Formations. Formations of the same age along the eastern edge of the basin are: Inyan Kara, Skull Creek, Newcastle, Mowry, Belle Fourche, Greenhorn, Carlile, Niobrara, Pierre, Fox Hills, and Lance Formations. The Cretaceous age formations are primarily interbedded siltstone and limestone and sandstones with minor shale and siltstone.

Tertiary age sediments are composed of sandstone, shale, siltstone, claystone, and coal. The Fort Union, Wasatch, and White River Formations represent the Tertiary stratigraphy.

Hydrology

The 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). The majority of the data is obtained from wells located within uplifted regions. In these regions secondary porosity and fracture permeability may be greatest where lithostatic loading is reduced. Laboratory studies

(Fatt and Dowis, 1952, Wyle, 1958) indicate a reduction in permeability of 20-60% with an increase in overburden pressure equivalent to 5,000 ft of overburden. Huntoon (1975) has also suggested that permeabilities are lower in the central paret of the basin for the Paleozoic formations. Thus, reported water productions and transmissivity will probably be less within the central portion of the basin.

The Madison aquifer system is the most productive and utilized aquifer in southern Powder River basin. The Madison aquifer system consists of Cambrian to Pennsylvanian age carbonates and sandstones. However, the majority of the water production is obtained from the Madison Limestone aquifer. Permeability in the carbonate sequence is mainly secondary permeability related to dolomitization and fracture control. The sandstone permeability is primarily intergranular with secondary fracture porosity. Typical Madison aquifer transmissivities range between 1,000 to 60,000 gpd/ft. Where secondary fracture permeability is present 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 7,000 gpm (Table 2).

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. Transmissivity values range from 1 to 1250 gpd/ft. Production rates vary greatly within and between formations as follows: 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 (Feathers and others, 1981).

The Tertiary aquifer is extensively used throughout the basins with production coming from the sandstone and

conglomerate units. The maximum thickness for the aquifer is 3,000 ft. 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 groundwater into the basin may also be from the Wind River Basin via the Casper Arch. Ground-water 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 groundwater movement in the southwest and southeast corners of the basin. The volume and rate of water flow in the deeper parts of the basin is not known, but is probably minor due to low transmissivity.

Terrestrial Heat Flow

Terrestrial heat flow is the amount of heat which flows perpendicular to the earth's surface at a given location. Within southern Powder River basin heat flow is used to explain temperatures at depth. Twelve new heat flow values were determined for the southern Powder River basin. The values are listed with previously published values in Table 3 and shown on Plate III. Using these values, an average heat flow for the basins and surrounding uplifts is $1.15 \pm .22 \times 10^{-6}$ cal/cm^2 sec. 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 agrees well within the limits of accuracy of

the 1.25 cal/cm^2 sec that is required to explain the maximum recorded temperature for the basin of 275°F at a depth of 16,076 ft.

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:

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

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 a geothermal gradient and consequently 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 process (conductive thermal modeling), calculates an idealized temperature-depth profile.

Table 4 shows the above discussed process for a typical sedimentary section in the central portion of southern Powder River Basin. The predicted formation temperatures agree with the measured bottom-hole temperatures in the deeper portions of the basin. The average geothermal gradient for the conductive thermal model is 13.8°F/1,000 ft (25.2° C/km). This compares well with the average thermal gradient of 13.4°F/1,000 ft (24.4°C/km) from bottom-hole temperature derived gradients. Listed in Table 5 are precision thermal gra-

dient determinations for wells in the southern Powder River Basin.

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, the intermediate temperatures can be found throughout the basin where the sediment thickness is greater than 12,000 ft. However, the great depth of burial and probable low water quality place a serious economic constraint on their use.

Low-temperature geothermal systems are also related to the 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, fault conduits, or drill holes. Evidence for all three types of transport systems mentioned are found in southern Powder River Basin.

Definition of Potential Geothermal Areas

Definition of geothermal systems was accomplished through the use of measured thermal gradients (Table 5), bottom-hole temperature derived thermal gradients, conductive thermal modeling, flowing well temperatures, potentiometric surface data, and water chemistry analyses. A thermal gradient contour map based on bottom-hole temperatures and thermally logged holes is shown on Plate III. Because of the previously discussed errors in bottom-hole temperature data, a number of the anomalous gradients are not included in the contouring process. Instead, these anomalous points are plotted individually. The anomalous gradient areas are also shown on Plates

II and IV, 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 6 lists the BHT temperatures used in this study. Table 7 lists the BHT-derived gradients in 500 foot depth intervals with respect to the mean gradient and the 50, 66, 80, and 90 percentiles for each interval. Figure 8 is a graphical representation of the BHT-derived gradient data. A general structure contour map for the basin is shown on Plate II. The top of the Muddy-Newcastle Sandstone is used for contouring because it is the deepest aquifer present throughout the basin and sufficient drill hole data exist for contouring. Chemical data for select wells are given in Table 8. The majority of flowing well, potentiometric, and water chemistry data is taken from Hodsen (1974), Feathers and others (1981), Woodward-Clyde Consultants (1980), and Hodsen and others (1978).

Analysis of the data has determined areas of geothermal potential for the Southern Powder River Basin. The areas of greatest geothermal potential are the Salt Creek-Midwest region, Fanny Peak lineament area, Lance-Buck Creek region, and the southwestern flank of the Black Hills uplift. 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. The structural geology is dominated by a major anticline dipping 15° to 29° on the east flank and 5° to 10° on the west flank (Beck, 1922). Faulting is prevalent throughout the area with a maximum vertical displacement of 350 ft. The majority of the faulting trends in a north 60° east direction across the anticline feature.

Evidence of geothermal potential inclu-
des: 1) anomalously high thermal gra-
dients (Van Orstrand, 1939; Plate III);
2) changes of 40°F in water temperature
with drilling distances of five feet
(Estabrook, 1929); 3) water flows (4,000
gpm) from depths of 4,500 ft with sur-
face temperatures of 183°F, implying a
high temperature gradient of 30.6°F/
1,000 ft (Eapach and Nichols, 1941).
The above information combined with
geologic evidence of numerous faults,
fractures, and hydrological communica-
tion between units implies the geother-
mal gradients are caused by movement of
fluids from depth. Conductive heat flow
modeling and artesian flow confirms
water circulation within the various
aquifers.

Conductive heat flow modeling indica-
tes that a heat flow of 2.5 x 10^{-6}
cal/cm^2 sec (105 mW/m^2) is needed to
explain the bottom-hole temperatures and
flowing water well temperatures seen in
the area. This heat flow is 110 percent
higher than the average basin heat flow
(1.2 x 10^{-6} cal/cm^2 sec) and 40 percent
higher than the maximum heat flow re-
ported for Salt Creek of 1.8 x 10^{-6}
cal/cm^2 sec (Blackwell, 1969). Thus,
to obtain the temperatures found in the
Madison Limestone an unrealistic high
conductive heat flow is required. Be-
cause of the various data mentioned
earlier, a hydrological flow system is a
reasonable solution to the high tempera-
tures seen in the area. The conductive
model further requires the source of the
water causing the high temperatures to
be at a minimum depth of 10,000 ft.
This is necessary for water temperatures
to reach 190°F, the maximum temperature
recorded for the geothermal system.

Artesian water flow is known to occur
from Frontier, Dakota, Tensleep, and
Madison formations, with the Madison
aquifer being the predominate producer.
Flows for the Madison aquifer are
reported greater than 9,000 gpm, with
reported temperatures of 184°F (Table 2;
Espach and Nichole, 1941; Collentine and

others, 1981). Potentiometric data for
the Madison Limestone and Tensleep
Sandstone (Swenson and others, 1976;
Figure 9) indicate the source for the
water and artesian pressure is from the
west. This includes the following areas
as recharge sources: southern Bighorn
Mountains, Casper Arch region, and
possibly the northern Laramie Range,
(although structural data suggest pos-
sible hydrologic disconnection of
aquifers along the Laramie Range).
Placing the conductive modeling restric-
tion on depth of circulation requires
the water circulation flow pattern first
enter the basin to the 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 similar to
   that of the Salt Creek field.

2. The potentiometric draw-down patterns
   suggest a high transmissivity zone
   exit to the north-northeast and thus
   greater degree of flow into the field
   from this direction (Figure 9, Swen-
   son and others, 1976).

3. Numerous flowing Madison aquifer
   wells at depths of 10,000 ft extend-
   ing to the north of the Salt Creek
   area (Table 2).

4. The slightly lower total dissolved
   solid water chemistry of the Madison
   water in the Meadow Creek-Sussex area
   compared to Salt Creek area (Swenson
   and others, 1976).

5. Bottom-hole temperatures for the
   Tensleep Sandstone in the Meadow
   Creek-Sussex area ranges from 156 to
   209°F at 9,500 ft. This implies ver-
   tical movement of water in the area.

   The authors, using the above data,
speculate 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 sufficient temperatures are reached before moving to the Salt Creek region. The authors suggest a more detailed geothermal study be conducted of this area because of the high temperatures (184°F) and large water flows (4,000 gpm).

Southeastern Powder River Basin

In the southeastern Powder River Basin a potential geothermal resouce 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. The faults extend upwards into sedimentary units causing faulting, fracturing, and folding of the rock units. The Shawnee flexure located in T.34 - 36N., R.65 - 66W., is the westward extention of this structural zone and contains the above mentioned anticlinal systems. Structural contours of the area indicate asymmetry to the west and north, with a major thrust fault at depth encompassing the north and west side of the structure. Well logs indicate numerous faults and fractures in the Minnelusa formation, with increase fault displacement at depth (Emery, 1927; Anderson and Riechen, 1941). Complete descriptions of the structural and stratigraphic elements are given by Shapiro (1971), Brobso and Epsten (1963), WGA (1957), Anderson and Riechen (1941), Emery (1927).

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 the vertical movement of water in areas of structural highs. The relationship of water movement and geothermal gradients for the Fanny Peak lineament is observed and discussed by Kilty and Chapman (1980). Kilty and Chapman suggest water movement within the Paleozoic formations that move up the steep monocline limb causing high gradients. However, structure data indicate a major normal fault cores the monocline and is capable of acting as a hydrological barrier. If the fault acts as a barrier, high gradients are likely caused by water movement up along fracture zones related to faulting. Evidence in the Lance Creek oil field for vertical water movement along faults are: 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 indicate vertical connection of formations along fracture zones (Anderson and Riecken, 1941); 3) an active water drive system maintains the well pressure at 80 percent of its original values in the Minnelusa sands from 1937-1952 (Churchwell, 1952); 4) the increase in fault throw with depth suggesting a greater degree of fracturing.

The artesian flows in the region add further evidence to the existance of circulating water within various aquifers. The source for the water and artesian pressure is probably from the Black Hills uplift and Hartville uplift (Figure 10). 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 tem-
peratures of 137 to 166°F using heat
flows of 1.2 and 1.6 x 10^{-6} cal/cm^2 sec
(50 - 67 mW/m^2) (Table 4). This drastic
difference in heat flow substansiates
the movement of water from the struc-
tural lows to the highs, with accom-
panying heat transfer.

Economics for the use of this
geothermal system are dependent on the
temperature and amount of water
available. Well field studies on the
effects of 9,000 gal/min ETSI well field
indicate widely varying draw-down
effects. Draw-down for the center of
the field varies from 400 ft to dewa-
tering of the aquifer (2,000 ft) (Wood-
ward-Clyde Consultants, 1980; Huntoon
and Womack, 1975).

Newcastle Area

The Newcastle potential geothermal
resource area is located on the south-
western 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 to the
east of the area the Black Hills mono-
cline dips 55 to 75°. Complete descrip-
tions of the structural and strati-
graphic geology is given by Mapel and
Pillmore (1963) and Dobbin and others
(1957).

This region is characterized by
interspersed high and normal thermal
gradients and flowing water wells. The
high gradients are found randomly lo-
cated with the normal gradients, sug-
gesting isolated causes for the high
gradients. Because of the numerous nor-
mal gradients it is also unlikely a high
basal heat flow is causing the high gra-
dients. Artesian flow in the region
indicates the presence of circulating
water within the Phasapa and Minnelusa
(Tensleep) aquifers. Potentiometric and
water chemistry data indicate water cir-
culation from the Black Hills uplift
rather than out of the basin.

The above mentioned evidence suggests that the cause of high gradients is 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 ft of the upper Minnelusa Formation has occurred since early Tertiary time in the southern Black Hills. During recent time, sink holes measuring 240 ft in diameter and 60 ft in depth have formed in the Cretaceous strata (Bowlea and Braddock, 1963). Thus, vertical water movement is readily apparent in the area.

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

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

Table 2. *Water flows for selected wells in the southern Powder River Basin.*

FORMATION	LOCATION			Ground Elevation (feet)	Formation Depth (feet)	Remarks	Ref.
	T.	R.	Sec.				
Madison	33	77	15	5,165	7,299	Original flow 65 gpm (1966)	b
Madison	39	78	26	5,130	6,820	Original flow 925 gpm (1965)	b
Madison	39	79	11	4,878	5,386	Original flow 4,700 gpm (1962)	b
Madison	40	79	2	4,766	7,097	Original flow 580 gpm (1954), some water from Tensleep Sandstone	b
Madison	40	79	23	4,871	4,680	Original flow 1,600 gpm (1954)	b
Madison	40	70	25	4,808	4,388	Original flow 530 gpm (1966), some water from Tensleep Sandstone	b
Madison	40	79	26	4,938	4,675	Original flow 9,000 gpm (1961), shut-in pressure 376 psi	b
Madison	40	79	31	5,140	6,155	Original flow 430 gpm (1962), shut-in pressure 300 psi	b
Madison	40	79	35	4,892	4,694	Original flow 7,200 gpm with 179 psi flowing pressure (1961)	b
Madison	40	79	35	4,946	4,655	Original flow 2,900 gp, with 28 psi flowing pressure (1959)	b
Madison	41	78	1	5,234	9,644	Original flow 810 gpm (1967)	b
Madison	41	78	11	5,357	9,710	Original flow 720 gpm (1966)	b
Madison	41	81	9	5,425	2,668	Original flow 900 gpm (1962), shut-in pressure 50 psi	b
Madison	42	80	30	4,847	4,212	Original flow 900 gpm (1962), shut-in pressure 310 psi	b
Madison	42	81	25	5,038	4,042	Original flow 1,110 gpm (1963), shut-in pressure 225 psi	b
Madison	43	80	34	4,880	8,690	Original flow 525 gpm (1963), shut-in pressure 380 psi	b
Madison	44	60	5	4,440	1,152	Flows 20 gpm (1964)	b
Madison	45	61	20	4,360	2,612	Flows 1,500 gpm (1974)	b
Madison	45	61	21	4,625	2,211	Flows 50 gpm (1974)	b
Madison	45	61	28	4,440	2,695	Flows 1,200 gpm (1974)	b
Madison	45	61	29	4,240	2,965	Flows 120 gpm (1974)	b
Madison	45	61	30	4,280	2,810	Flows 650 gpm (1974)	b
Madison	45	61	20	-	3,245	Flows 640 gpm (1980)	a
Madison	45	61	33	4,378	3,186	Flows 290 gpm (1974)	b
Madison	46	60	31	4,760	1,097	Flows 250 gpm (1948	b
Madison	46	63	10	4,400	2,580	Original Flow 800 gpm	b
Madison	46	63	10		3,000	Predicted production 2,500 gpm when completed	a
Madison	46	63	10		2,300	Predicited production 2,500 gpm when completed	a
Madison	46	63	15	4,340	2,685	Original Flow 800 gpm (1941), flows 550 gpm (1974)	b
Madison	64	63	15		3,200	Predicited production 2,500 gpm when completed	a
Madison	46	63	17	4,172	3,181	Flow 800 gpm (1973), shut-in pressure 185 psi	b
Madison	46	64	13	4,068	4,084	Flows 30 gpm (1973)	b
Hartville	29	68	20		410	Flows 225 gpm (1980)	a
Lakota	34	80	21		3,100	Flows approx. 170 gpm (1980)	a
Lakota	34	80	21		2,821	Flows approx. 15 gpm (1980)	a
Lakota	34	80	28		2,338	Flows approx. 50 gpm (1980)	a
Lakota	34	80	33		2,030	Flows to 50 gpm (1980)	a

a) Feathers and others, 1981.

b) Hodson, W.G., 1974

Table 3. Heat flow values for the southern Powder River Basin.

Hole Name	West longitude	North latitude	N[1]	K (10⁻³cal/cm sec°C)	Depth Range[2] (m)	Gradient (°C/km)	Heat Flow (X10⁻⁶ca./cm² sec)
Squaw Springs	106° 0.39'	42° 27.4'	47	$5.7 \pm .8$	30–257	36.2	2.1
Highland Flats							
#0-1	105° 42.1'	43° 2.9'	15	$5.4 \pm .6$	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	$5.0 \pm .5$	30–190	22.4	1.1
#5057	105° 59.6'	43° 48.4'	20	$5.1 \pm .9$	100–177	21.0	1.1
#5763[3]	105° 59.7'	43° 48.8'	19	$5.5 \pm .9$[3]	20–170	28.0	1.5
Fort Reno SE							
#5784	106° 00.0'	43° 48.2'	18	$5.0 \pm .9$	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	$5.1 \pm .7$	40–68	18.6	.9
#5358[3]	106° 02.6'	43° 48.9'	13	4.8 ± 1.2[3]	50–110	19.4	.9
#4998	106° 03.2'	43° 49.2'	17	$5.1 \pm .9$	40–153	16.4	.8
Salt Creek[4]	106° 15'	43° 35'	est.	4.0	640 (25)	45	1.8
Lance Creek[4]	104° 38'	43° 04'	est.	4.0	964 (3)	50.5	2.0
Douglas							
LC-1[5]	105° 18.1'	42° 50.0'	15	4.8	340–500	43.8	2.1
LC-1[5]	105° 00'	43° 10.4'	15	4.8	100–540	33.8	1.6

[1] Number of conductivity samples.

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

[3] Conductivitites from nearby hole penetrating similar lithology.

[4] Data from Blackwell, 1969.

[5] Data from Decker, E.R. (personnel communication, 1982).

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 Elevation (feet)	Thickness (feet)	Temperature (°F)	Salt Creek Area Elevation (feet)	Thickness (feet)	Temperature (°F)[3] 1.2 HFU	1.6 HFU	Temperature (°F)[4] 1.2 HFU	1.6 HFU	Fanny Peak Lineament Elevation (feet)	Thickness (feet)	Temperature (°F)[3] 1.2 HFU	1.6 HFU	Temperature (°F)[4] 1.2 HFU	1.6 HFU
Wasatch	5.5	12	16	5,000	1,000	45												
Fort Union	6.0	11	15	4,000	2,900	57												
Lance	4.5	15	20	1,100	2,800	89	5,000	1,700	45	45								
Fox Hills	4.5	15	20	-1,700	600	131	3,300	200	70	79								
Lewis	4.0	16	21	-2,300	380	140	3,100	500	74	83								
Mesaverde	6.0	11	15	-2,680	730	147	2,600	900	82	93								
Cody (Pierre)	4.0	16	21	-3,410	3,250	155	1,700	2,900	92	107	45	45	4,000	2,800	45	45		
Frontier (Colorado Group)	4.5	15	20	-6,660	730	207	-1,200	800	138	168	72	81	1,200	1,300	90	104	45	45
Mowry	4.0	16	21	-7,390	250	218	-2,000	300	150	184	84	97	100	220	109	130	69	71
Muddy (Newcastle)	7.0	9.4	13	-7,640	40	222	-2,300	30	155	190	89	103	-120	50	113	134	73	75
Thermopolis (Skull Creek)	6.1	11	15	-7,680	200	222	-2,330	150	155	191	89	104	-170	180	113	135	73	76
Cloverly (Inyan Kara)	8.7	7.6	10	-7,880	170	224	-2,480	130	157	193	91	106	-350	200	115	138	75	79
Morrison	6.3	10	13	-8,050	190	225	-2,610	260	158	194	92	107	-550	150	117	140	77	81
Sundance	7.4	8.9	12	-8,240	330	227	-2,870	230	160	198	95	111	-700	330	118	142	78	83
Chugwater (Spearfish)	7.2	9.1	12	-8,570	700	230	-3,100	600	162	200	97	113	-1,030	250	121	146	81	87
Goose Egg (Minnekahta)	7.0	9.4	13	-9,270	250	237	-3,700	300	168	207	102	120	-1,280	300	124	149	84	90
Tensleep (Minnelusa)	10.4	6.3	8.4	-9,520	750	239	-4,000	400	171	211	105	124	-1,580	1,100	127	153	87	94
Madison (Pahasapa)	9.6	6.9	9.2	-10,270	300	244	-4,400	400	173	215	107	128	-2,680	300	134	162	94	103
Unnamed (Englewood)	9.0	7.3	9.8	-10,570	30	246	-4,800	30	176	218	110	131	-2,980	50	136	165	96	106
Cambrian und.	7.0	9.4	13	-10,600	200	246	-4,830	270	176	219	110	132	-3,130	50	136	165	96	106
Precambrian				-10,800		249	-5,100		197	222	113	135	-3,180		137	166	97	107

[1] °F/Kft equals degrees Fahrenheit per 1,000 feet

[2] One HFU equals 10^{-6} cal/cm^2 sec equals 41.8×10^{-3} Watts/square meter

[3] In syncline for heat flows

[4] In anticline for heat flows

Table 5. Precision thermal gradient measurements in the Southern Powder River Basin[1].

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (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			
CAMPELL 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

Table 5 continued

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (m)
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

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (m)
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

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (m)
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
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

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (m)
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

Hole Name	Logitude	Latitude	Depth Meters	Feet	Temperature (°C)	(°F)	Gradient °C/KM	°F.1,000	Interval[2] (m)
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

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

[2] This refers to the depth interval over which the gradient was calculated using a statistical least squares technique.

Table 6. *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 is the temperature below which that percent of the BHT's fall. For a depth interval for which very few BHT's have been measured, the percentile temperatures have little meaning.*

Depth interval (feet)	Number	Temperature (°F)						
		high	low	mean	50%	66%	80%	90%
500 – 1,000	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 tempreature measurements.

Table 7. *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 is the gradient below which that percent of the gradients fall. For a depth interval for which very few BHT's have been measured, the percentile gradients have little meaning.*

Depth interval (feet)	Number	Gradient (°F/1,000ft)						
		high	low	mean	50%	66%	80%	90%
500 - 1,000	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

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

Table 8. Chemical data for selected wells in the southern Powder River Basin.

FORMATION	Location			Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
	T.	R.	Sec.								
Madison	33	73	32	156	160	32	100	590	154	1,160	e
Madison	33	75	4	1,308	500	37	500	3,229	220	5,682	c
Madison	33	75	8	527	316	60	569	1,200	93	2,712	e
Madison	33	75	8	510	334	82	557	1,370	95	2,950	e
Madison	33	75	20	112	156	30	100	512	124	1,010	e
Madison	33	76	16	572	410	64	624	1,560	112	3,350	e
Madison	33	76	33	190	69	22	18	58	129	440	e
Madison	33	77	15	496	337	55	322	1,560	124	2,920	e
Madison	34	76	7	816	460	36	1,180	1,156	159	3,726	c
Madison	36	82	22	604	150	12	82	1,365	247	2,334	c
Madison	37	63	9	2,152	342	61	2,900	1,263	465	6,947	c
Madison	38	75	26	2,553	140	34	3,140	850	708	7,067	c
Madison	39	61	2	58	91	7	67	131	185	445	c
Madison	39	78	26	789	306	40	1,052	900	133	3,240	e
Madison	39	79	11	390	263	49	474	766	104	2,260	e
Madison	40	78	10	103	287	52	454	313	230	1,322	b
Madison	40	79	23	564	614	31	770	1,149	732	3,486	c
Madison	40	79	25	602	315	67	698	1,130	125	4,280	c
Madison	40	79	26	527	326	60	649	1,074	122	2,680	e
Madison	40	79	26	513	365	28	620	1,120	112	2,770	e
Madison	40	79	31	510	300	49	621	969	122	2,570	e
Madison	40	79	35	455	327	60	641	1,060	98	2,600	e
Madison	40	80	31	467	468	99	210	2,025	230	3,382	c
Madison	41	78	1	518	288	56	977	936	110	2,640	e
Madison	41	81	9	366	227	59	443	850	134	2,040	c
Madison	42	81	25	464	282	80	584	1,079	117	2,590	e
Madison	41	81	9	270	178	60	351	593	207	1,560	e
Madison	41	81	16	354	275	72	560	800	159	2,139	c
Madison	42	80	30	475	289	72	590	1,090	115	2,600	c
Madison	43	80	34	472	329	59	647	1,109	98	2,740	e
Madison	44	60	5	45	55	13	3	27	300	300	c
Madison	44	63	26	0	182	27	95	300	131	720	c
Madison	45	61	20	4	63	28	1	38	291	292	c
Madison	45	61	21	5	76	29	1	87	276	385	c
Madison	45	61	28	5	62	29	1	37	289	290	c
Madison	45	61	29	8	76	33	3	117	257	379	c
Madison	45	61	30	7	75	33	2	108	266	372	c
Madison	45	61	33	5	76	26	1	74	276	332	c
Madison	46	60	31	4	65	24	0	12	318	276	c
Madison	46	62	18	3	62	28	1	27	296	279	c
Madison	46	62	28	42	114	31	110	122	256	744	f
Madison	46	63	10	3	74	26	1	51	295	315	c
Madison	46	63	15	3	64	27	2	24	293	279	c
Madison	46	63	17	3	61	28	1	20	299	275	c
Madison	46	64	13	3	61	26	1	29	273	268	c
Madison	46	64	19	17	75	27	11	96	268	494	c
Madison	46	64	23	5	56	28	2	33	275	279	c
Madison	46	65	20	32	101	27	2	250	119	617	c
Madison	46	65	23	3	72	32	1	125	228	460	c
Madison	46	66	25	13	175	46	4	459	177	834	c

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Table 8 continued.

FORMATION	Location T.	R.	Sec.	Na+K	Ca	Mg	SO₄	Cl	HCO₃	TDS	Reference
Minnelusa	35	65	5	670	350	38	540	1,500	223	3,300	d
Minnelusa	35	65	5	470	360	77	490	1,300	264	2,850	d
Minnelusa	35	65	5	510	380	76	540	1,400	245	2,980	d
Minnelusa	35	65	6	900	580	230	1,900	1,400	215	5,120	d
Minnelusa	35	65	7	440	330	67	540	1,000	266	2,560	d
Minnelusa	35	65	7	630	310	59	610	1,300	185	3,020	d
Minnelusa	35	65	8	730	380	58	550	1,800	190	3,600	d
Minnelusa	35	65	7	649	308	54	617	1,332	177	3,047	b
Minnelusa	35	65	35	56	130	5	49	350	34	603	d
Minnelusa	36	62	4	415	322	56	840	520	256	2,293	b
Minnelusa	36	64	26	640	270	73	160	1,600	635	2,990	d
Minnelusa	36	65	5	790	710	240	860	2,300	440	5,180	d
Minnelusa	36	65	5	470	380	85	530	1,300	245	2,930	d
Minnelusa	36	65	31	770	330	71	490	1,700	376	3,560	d
Minnelusa	36	65	32	1,300	520	60	330	3,500	394	5,910	d
Minnelusa	36	65	32	770	350	65	610	1,700	205	3,610	d
Minnelusa	36	65	33	590	320	67	500	1,400	205	3,000	d
Minnelusa	36	65	33	690	310	72	520	1,600	255	3,270	d
Minnelusa	38	61	19	9,240	750	270	13,000	4,900	305	27,800	d
Minnelusa	38	61	30	26,450	1,700	820	43,000	3,500	317	10,200	d
Minnelusa	38	61	30	1,810	500	110	800	2,900	1,900	7,040	d
Minnelusa	38	62	25	870	11	30	680	2	1,330	2,240	d
Minnelusa	38	62	25	5,700	680	160	7,600	2,600	1,530	17,600	d
Minnelusa	39	60	19	62,000	4,200	2,100	11,000	2,900	205	176,000	d
Minnelusa	39	61	2	3,134	629	283	2,700	4,816	890	12,003	b
Minnelusa	40	63	24	7,600	500	2	8,400	5,100	680	21,900	d
Minnelusa	41	60	7	16,000	460	210	10,000	1,800	3,600	47,100	d
Minnelusa	44	60	5	25	470	84	11	1,300	222	2,020	d
Minnelusa	45	61	2	40	690	37	10	1,700	141	2,530	d
Minnelusa	45	61	2	68	630	140	24	2,000	159	2,960	d
Minnelusa	46	63	10	7	78	23	5	43	307	307	d
Minnelusa	47	60	30	2	68	24	1	12	305	280	d
Minnelusa	47	61	1	98	83	12	2	13	304	351	d
Minnelusa	47	61	11	3	70	15	1	19	254	274	d
Hartville	28	66	28	9	60	26	9	18	284	312	d
Hartville	29	68	9	21	43	20	4	33	234	274	d
Hartville	29	68	9	58	42	5	9	53	214	278	d
Hartville	29	68	20	23	44	16	2	22	240	243	d
Hartville	29	68	20	18	45	13	3	3	240	222	d
Hartville	29	68	24	26	29	8	9	120	42	242	d
Hartville	29	69	33	44	23	8	7	34	183	227	d
Hartville	30	68	16	45	63	22	29	150	192	434	d
Phosphoria	45	61	33	5	64	28	1	48	288	301	b
Phosphoria	45	61	29	9	76	33	3	117	257	379	b
Phosphoria	46	60	31	42	58	10	2	16	306	292	b
Phosphoria	46	62	18	3	62	28	1	27	296	279	b
Phosphoria	46	63	15	4	64	27	2	24	293	283	b
Phosphoria	46	65	23	-	70	34	3	110	232	465	b
Phosphoria	46	66	25	-	176	39	4	310	179	824	b
Chugwater	30	83	15	24	42	13	7	31	193	242	e

Table 8 continued.

FORMATION	T.	R.	Sec.	Na+K	Ca	Mg	SO4	Cl	HCO3	TDS	Reference
Chugwater	39	83	7	109	188	67	6	788	210	1,300	e
Spearfish	36	60	30	15.7	240	73	55	650	209	1,200	e
Sundance	32	70	19	1,100	18	5	400	1,073	755	3,064	b
Sundance	33	76	9	1,492	–	–	686	1,330	1,015	4,044	a
Sundance	33	82	7	780	–	–	213	80	1,208	1,859	a
Sundance	33	82	12	873	11	–	284	135	1,435	2,135	a
Sundance	33	82	18	824	–	–	207	374	1,080	2,069	a
Sundance	33	82	2	1,096	44	Trace	775	528	1,040	2,081	a
Sundance	33	83	12	670	6	7	24	35	1,196	1,601	a
Sundance	33	83	13	700	6	14	25	99	1,454	1,519	a
Sundance	35	66	5	3,098	278	46	402	6,483	365	10,483	b
Sundance	35	66	25	418	40	52	30	224	815	1,334	b
Sundance	36	65	6	1,867	85	Trace	594	3,039	330	5,647	a
Sundance	36	65	6	2,753	265	Trace	145	5,879	395	9,236	a
Sundance	49	83	5	41	55	36	5	156	236	463	e
Sundance	40	61	35	1,411	268	101	40	3,857	98	5,725	b
Sundance	40	79	23	3,827	24	12	4,850	90	1,220	9,483	a
Sundance	40	79	24	2,988	20	10	3,550	Trace	1,930	7,517	a
Sundance	40	79	25	3,720	44	15	4,500	568	1,610	9,639	a
Sundance	40	79	35	4,511	260	16	4,125	3,905	780	13,200	a
Sundance	40	79	35	4,259	264	56	3,950	5,317	610	14,146	a
Sundance	40	79	35	4,009	334	59	4,568	2,662	710	11,916	a
Sundance	42	81	27	5,035	560	157	7,409	2,375	68	15,568	a
Sundance	43	83	31	1,144	111	18	18	2,748	8	4,080	e
Morrison	36	65	32	3,524	198	42	250	7,419	370	11,625	b
Morrison	39	84	3	168	4	205	6	878	73	11,625	e
Cloverly	33	79	24	145	1	0	7	74	278	396	e
Cloverly	37	82	36	583	10	1	18	957	351	1,780	e
Cloverly	39	60	19	304	–	–	44	233	315	795	a
Cloverly	39	61	14	338	–	–	70	63	620	813	a
Cloverly	39	61	14	336	–	–	32	298	380	890	a
Cloverly	41	60	7	372	–	–	25	544	250	1,064	a
Cloverly	41	81	25	1,226	3	3	278	341	2,449	3,110	e
Cloverly	42	82	14	599	2	2	117	565	653	1,650	e
Cloverly	44	62	22	276	77	19	13	690	162	1,190	e
Dakota	33	82	11	583	18	6	21	61	1,175	1,405	a
Dakota	33	80	21	222	–	–	54	39	325	534	a
Dakota	33	83	12	349	6	–	15	325	360	944	a
Dakota	35	77	27	4,605	38	21	2,880	4,724	1,290	13,002	b
Dakota	37	63	13	750	8	5	150	67	1,696	1,815	b
Dakota	37	78	12	5,259	42	19	7,400	40	1,390	13,445	b
Dakota	37	81	31	499	–	–	32	784	225	1,450	a
Dakota	37	82	36	607	–	–	28	981	255	1,771	a
Dakota	40	67	25	3,689	28	12	4,360	386	1,940	9,431	b
Dakota	40	79	25	3,690	30	12	5,150	82	975	9,443	a
Dakota	40	79	26	5,131	38	6	6,850	42	1,915	13,009	a
Dakota	40	79	34	5,561	56	18	7,750	137	1,500	14,399	a
Fall River	35	65	5	834	–	–	52	–	2,125	1,931	a
Fall River	35	65	4	1,295	–	–	324	–	2,880	3,035	a
Fall River	36	65	35	731	–	–	252	86	1,275	1,756	a

Table 8 continued.

FORMATION	Location T.	R.	Sec.	Na+K	Ca	Mg	SO4	Cl	HCO3	TDS	Reference
Fall River	37	63	25	520	15	7	350	50	795	1,343	a
Lakota	33	76	9	1,318	-	-	616	485	1,675	3,310	a
Lakota	35	77	21	2,280	67	-	2,060	1,321	995	6,237	a
Lakota	34	76	8	1,179	0	0	155	341	2,145	2,871	b
Lakota	35	65	31	347	79	27	770	0	185	1,392	b
Lakota	35	77	21	2,280	67	-	2,060	1,321	995	6,237	a
Lakota	35	79	23	1,140	8	-	107	521	1,360	2,805	a
Lakota	39	60	30	371	0	0	6	0	890	857	b
Lakota	39	79	12	1,151	Trace	-	240	-	2,640	2,689	a
Lakota	39	79	2	857	Trace	-	340	-	1,670	2,018	a
Lakota	40	79	35	1,662	-	-	1,257	-	2,125	4,024	a
Lakota	40	79	26	696	7	Trace	525	Trace	965	1,703	a
Lakota	40	79	25	2,677	Trace	-	1,600	64	3,680	6,440	a
Lakota	40	79	25	1,314	-	-	260	Trace	2,990	3,068	a
Lakota	40	79	25	1,017	6	-	139	-	2,098	2,511	a
Lakota	40	79	34	634	20	Trace	300	12	1,210	1,562	a
Lakota	40	79	15	1,507	16	-	674	58	2,327	4,639	a
Lakota	40	79	23	1,169	Trace	-	750	12	1,795	2,814	a
Lakota	40	79	23	1,187	Trace	-	850	-	1,685	2,886	a
Lakota	40	79	23	1,558	Trace	-	1,550	Trace	1,465	3,828	a
Lakota	40	79	23	1,048	12	Trace	800	Trace	1,440	2,568	a
Lakota	40	79	23	2,008	-	-	1,928	-	1,950	4,925	a
Lakota	40	79	24	1,127	25	Trace	265	-	2,610	2,691	a
Lakota	40	79	24	1,252	28	Trace	340	-	2,700	2,948	a
Lakota	40	79	27	1,035	Trace	-	650	Trace	1,625	2,484	a
Lakota	40	79	27	1,393	Trace	-	1,350	40	1,320	3,432	a
Lakota	41	77	19	7,112	167	28	10,000	687	1,445	18,706	b
Inyan Kara	37	61	19	354	200	75	9	1,400	275	2,160	e
Inyan Kara	40	61	35	335	12	2	21	560	256	1,080	e
Inyan Kara	41	61	1	322	3	3	22	454	251	956	e
Inyan Kara	41	60	7	357	21	11	13	660	200	1,190	e
Inyan Kara	41	60	17	324	22	7	10	570	183	1,050	e
Inyan Kara	42	60	7	155	234	66	18	984	153	1,570	e
Inyan Kara	43	60	30	32	78	49	12	280	171	541	e
Inyan Kara	45	61	29	71	285	118	14	1,250	24	1,760	e
Inyan Kara	46	61	10	5	42	12	2	20	167	180	e
Inyan Kara	46	62	27	185	423	248	26	2,000	276	2,840	e
Inyan Kara	46	63	5	403	-	-	26	631	255	1,240	e
Inyan Kara	46	63	31	-	-	-	29	1,159	205	1,920	e
Inyan Kara	46	64	11	667	8	-	32	1,269	183	2,100	e
Newcastle	42	65	4	5,091	36	19	7,400	200	730	13,105	b
Newcastle	45	65	27	4,766	94	33	3,700	21	5,250	12,328	b
Newcastle	46	64	15	5,227	115	0	6,719	0	2,660	13,369	b
Muddy	33	76	25	5,361	28	17	6,850	48	2,550	13,564	b
Mowry	39	83	13	192	36	10	3	424	141	765	e
Frontier	40	80	27	342	1	-	5	286	390	962	e

Data from: a. Crawford, 1940; b. Crawford, 1963; c. Hodson, 1974; d. Well and others, 1979; e. Woodward-Clyde, 1980; and f. Feathers and others, 1981.

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

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

Mountain
Outcrops
(recharge area)

Anticline

shales, siltstones,
sandstones

siltstones, shales

limestone, sandstone

limestone

dolomite

shales, sandstones, limestones

Precambrian
Crystalline Rocks

water flow

45°F

78°F

97°F

105°F

121°F

133°F

162°F

Ground
Level

2000 ft

4000 ft

6000 ft

8000 ft

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

Mountain
Outcrops
(recharge area)

Fault

sandstone,
shale, siltstone,
sandstone

siltstone

siltstones, shales

limestone, sandstone

limestone

dolomite

shales, sandstones, limestones

Precambrian
Crystalline Rocks

water flow

45°F

78°F

97°F

105°F

121°F

133°F

162°F

100°F

120°F

Ground
Level

2000 ft

4000 ft

6000 ft

8000 ft

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

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

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

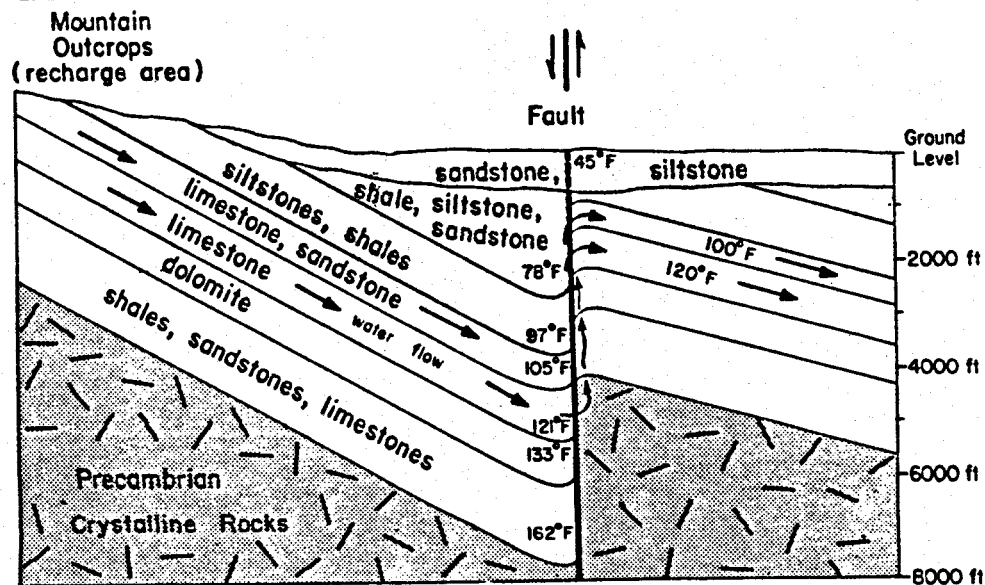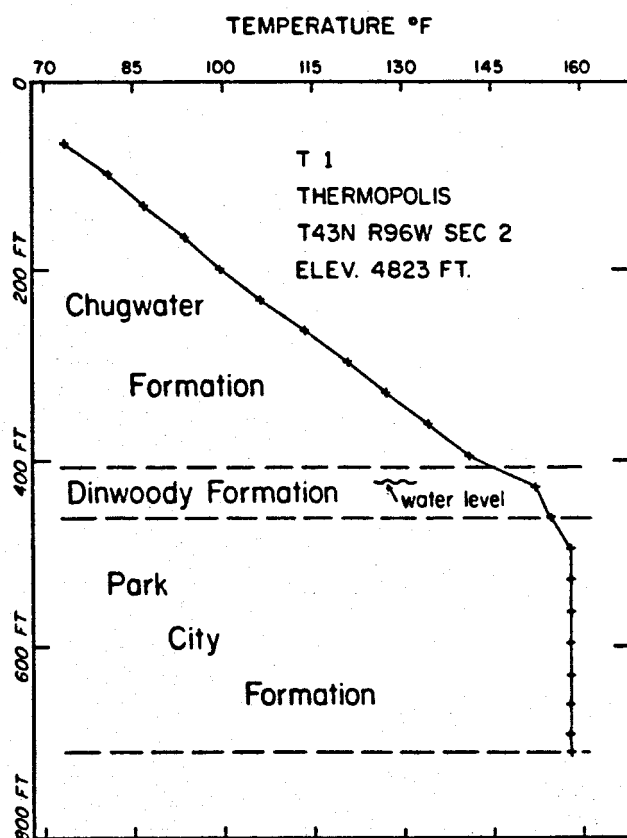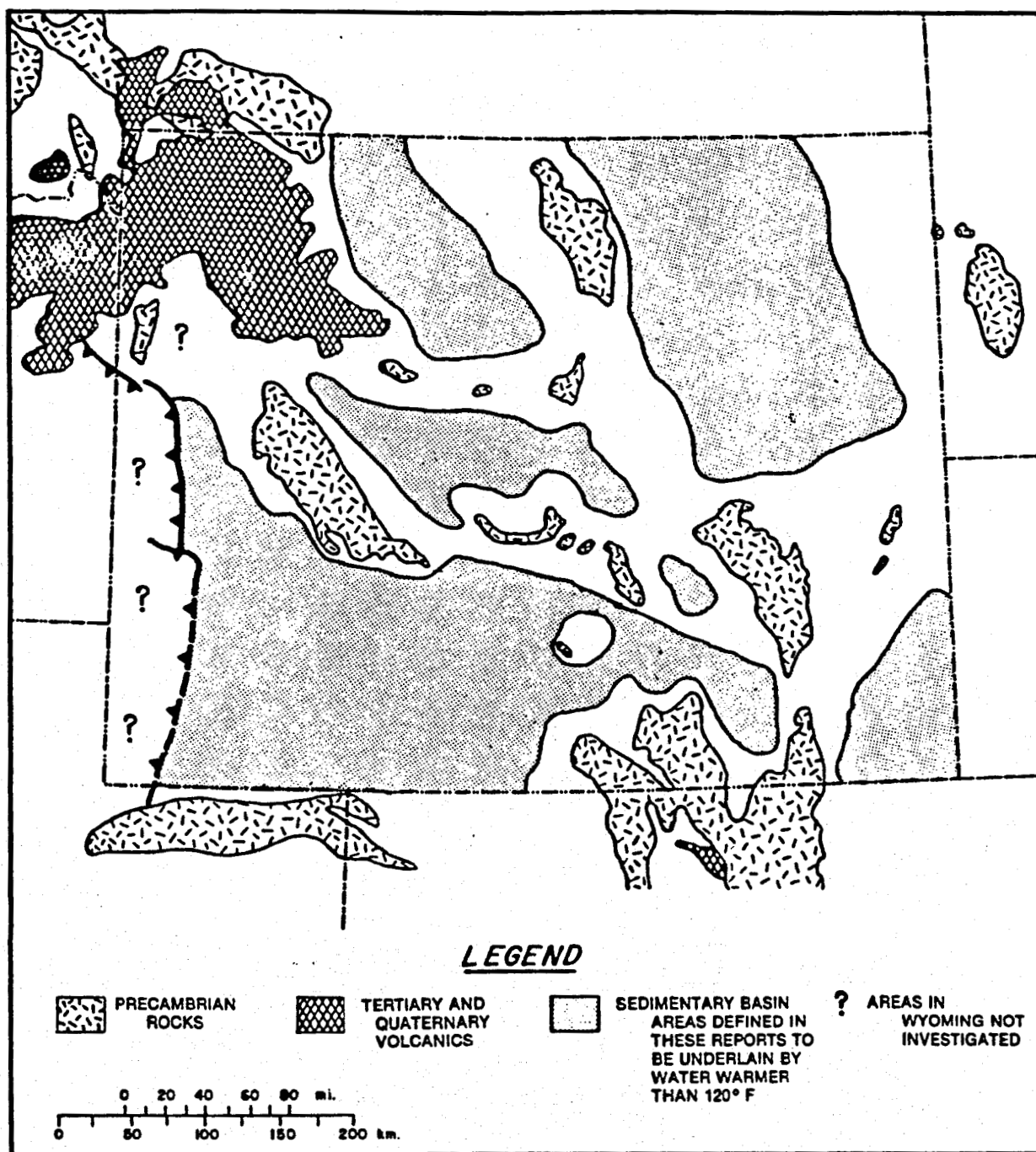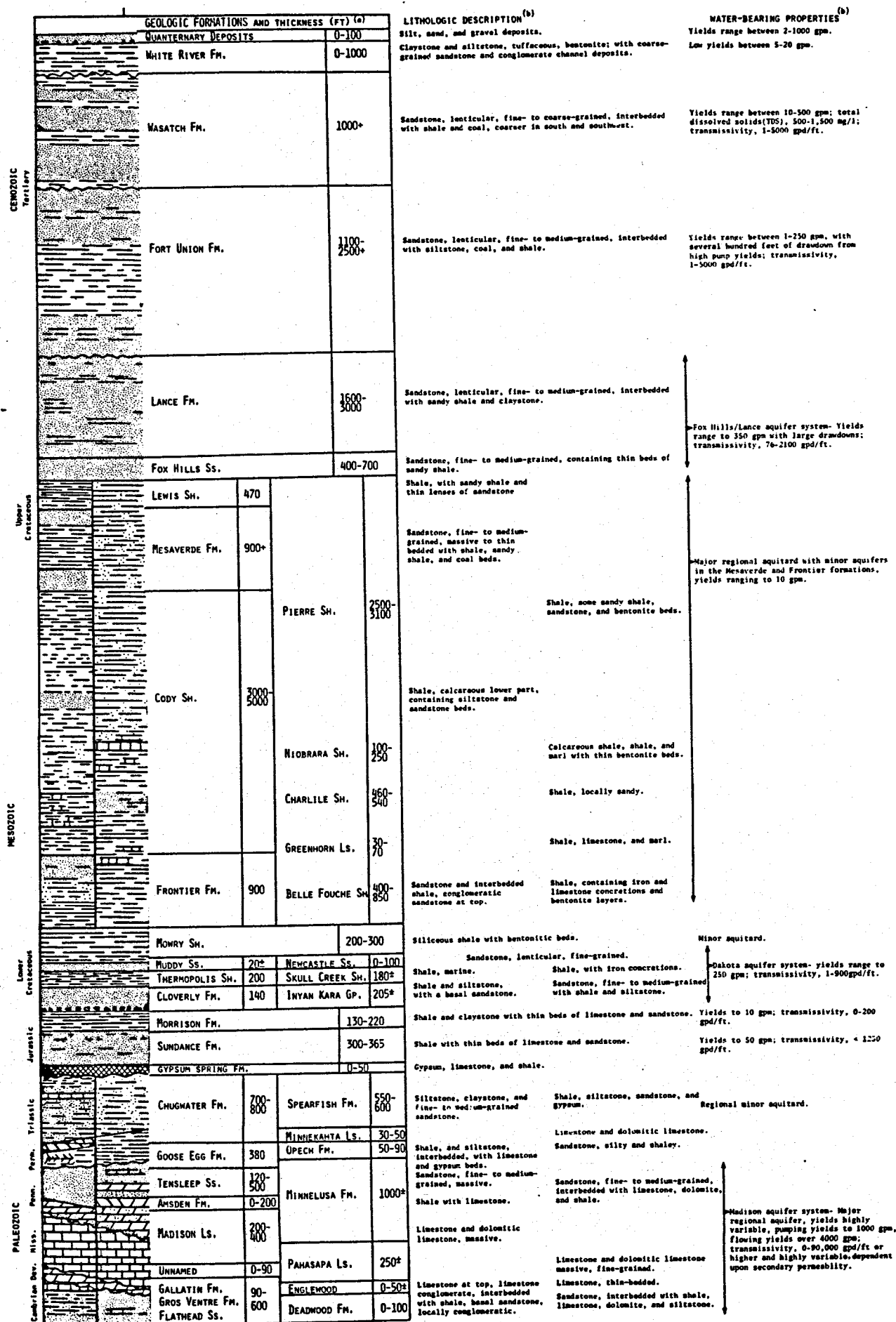| GEOLOGIC FORMATIONS AND THICKNESS (FT) (a)			LITHOLOGIC DESCRIPTION (b)	WATER-BEARING PROPERTIES (b)
Quanternary Deposits	0-100		Silt, sand, and gravel deposits.	Yields range between 2-1000 gpm.
White River Fm.	0-1000		Claystone and siltstone, tuffaceous, bentonite; with coarse-grained sandstone and conglomerate channel deposits.	Low yields between 5-20 gpm.
Wasatch Fm.	1000+		Sandstone, lenticular, fine- to coarse-grained, interbedded with shale and coal, coarser in south and southwest.	Yields range between 10-500 gpm; total dissolved solids(TDS), 500-1,500 mg/l; transmissivity, 1-5000 gpd/ft.
Fort Union Fm.	1100-2500+		Sandstone, lenticular, fine- to medium-grained, interbedded with siltstone, coal, and shale.	Yields range between 1-250 gpm, with several hundred feet of drawdown from high pump yields; transmissivity, 1-5000 gpd/ft.
Lance Fm.	1600-3000		Sandstone, lenticular, fine- to medium-grained, interbedded with sandy shale and claystone.	Fox Hills/Lance aquifer system- Yields range to 350 gpm with large drawdowns; transmissivity, 76-2100 gpd/ft.
Fox Hills Ss.	400-700		Sandstone, fine- to medium-grained, containing thin beds of sandy shale.	
Lewis Sh.	470		Shale, with sandy shale and thin lenses of sandstone	
Mesaverde Fm.	900+		Sandstone, fine- to medium-grained, massive to thin bedded with shale, sandy shale, and coal beds.	Major regional aquitard with minor aquifers in the Mesaverde and Frontier formations, yields ranging to 10 gpm.
		Pierre Sh. 2500-3100	Shale, some sandy shale, sandstone, and bentonite beds.	
Cody Sh.	3000-5000		Shale, calcareous lower part, containing siltstone and sandstone beds.	
		Niobrara Sh. 100-250	Calcareous shale, shale, and marl with thin bentonite beds.	
		Charlile Sh. 460-540	Shale, locally sandy.	
		Greenhorn Ls. 30-70	Shale, limestone, and marl.	
Frontier Fm. 900		Belle Fouche Sh. 400-850	Sandstone and interbedded shale, conglomeratic sandstone at top.	Shale, containing iron and limestone concretions and bentonite layers.
Mowry Sh.		200-300	Siliceous shale with bentonitic beds.	Minor aquitard.
Muddy Ss. 20±	Newcastle Ss.	0-100	Sandstone, lenticular, fine-grained.	
Thermopolis Sh. 200	Skull Creek Sh.	180±	Shale, marine. / Shale, with iron concretions.	Dakota aquifer system- yields range to 250 gpm; transmissivity, 1-900gpd/ft.
Cloverly Fm. 140	Inyan Kara Gp.	205±	Shale and siltstone, with a basal sandstone. / Sandstone, fine- to medium-grained with shale and siltstone.	
Morrison Fm.		130-220	Shale and claystone with thin beds of limestone and sandstone.	Yields to 10 gpm; transmissivity, 0-200 gpd/ft.
Sundance Fm.		300-365	Shale with thin beds of limestone and sandstone.	Yields to 50 gpm; transmissivity, < 1250 gpd/ft.
Gypsum Spring Fm.		0-50	Gypsum, limestone, and shale.	
Chugwater Fm. 700-800	Spearfish Fm.	550-600	Siltstone, claystone, and fine- to medium-grained sandstone. / Shale, siltstone, sandstone, and gypsum.	Regional minor aquitard.
	Minnekahta Ls.	30-50	Limestone and dolomitic limestone.	
Goose Egg Fm. 380	Opech Fm.	50-90	Shale, and siltstone, interbedded, with limestone and gypsum beds. / Sandstone, silty and shaley.	
Tensleep Ss. 120-500			Sandstone, fine- to medium-grained, massive. / Sandstone, fine- to medium-grained, interbedded with limestone, dolomite, and shale.	
Amsden Fm. 0-200	Minnelusa Fm.	1000±	Shale with limestone.	
Madison Ls. 200-400			Limestone and dolomitic limestone, massive.	Madison aquifer system- Major regional aquifer, yields highly variable, pumping yields to 1000 gpm, flowing yields over 4000 gpm; transmissivity, 0-90,000 gpd/ft or higher and highly variable,dependent upon secondary permeablity.
Unnamed 0-90	Pahasapa Ls.	250±		Limestone and dolomitic limestone massive, fine-grained.
Gallatin Fm. 90-600	Englewood	0-50±	Limestone at top, limestone conglomerate, interbedded with shale, basal sandstone, locally conglomeratic.	Limestone, thin-bedded.
Gros Ventre Fm.	Deadwood Fm.	0-100		Sandstone, interbedded with shale, limestone, dolomite, and siltstone.
Flathead Ss.				

(a) Formation thicknesses from Feathers et.al., 1981; Wyoming Geological Association, 1958.

(b) Lithologic description and water-bearing properties from Feathers et.al., 1981; Madsen et.al., 1973; Wyoming Geological Association, 1958, 1978.

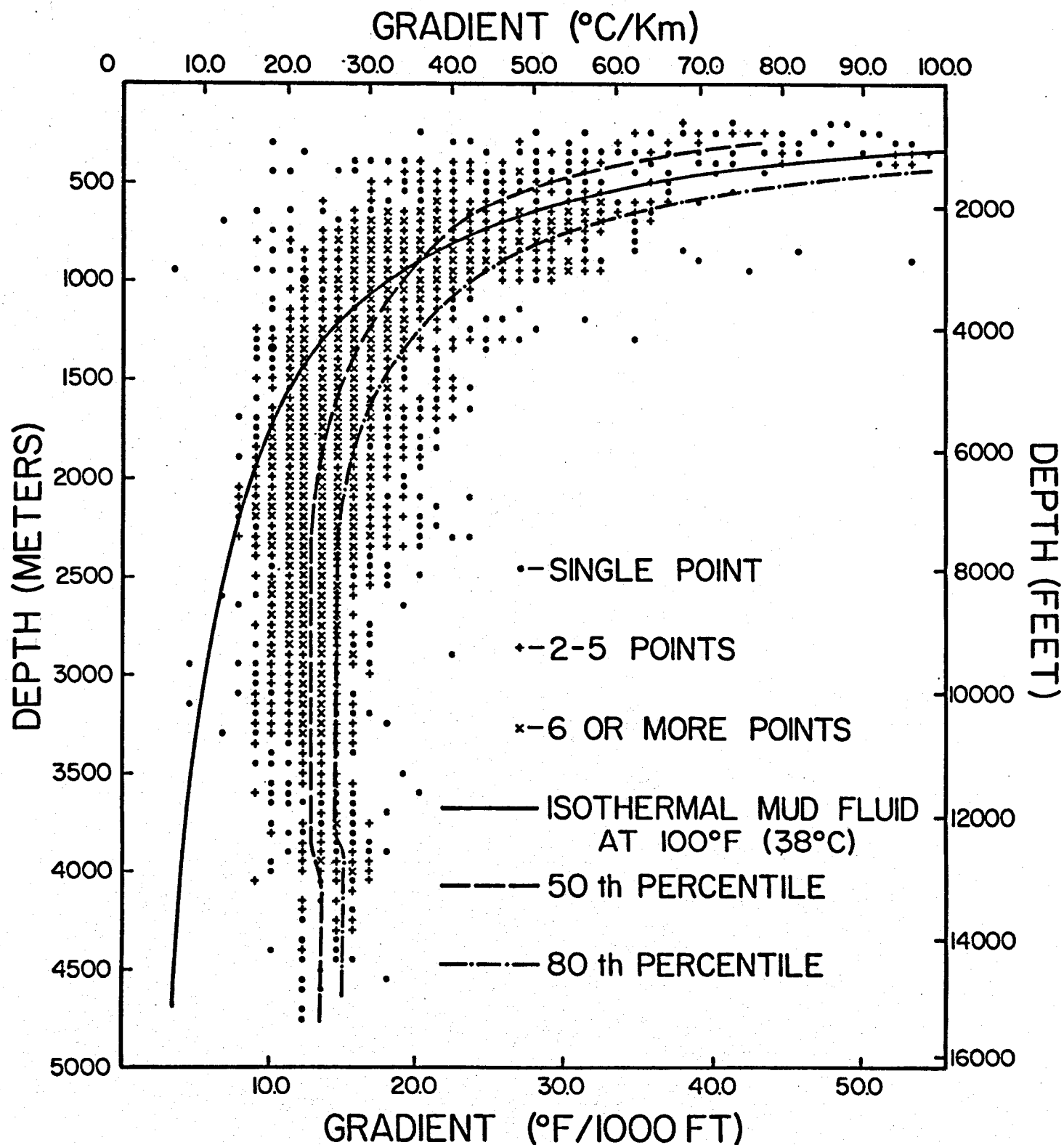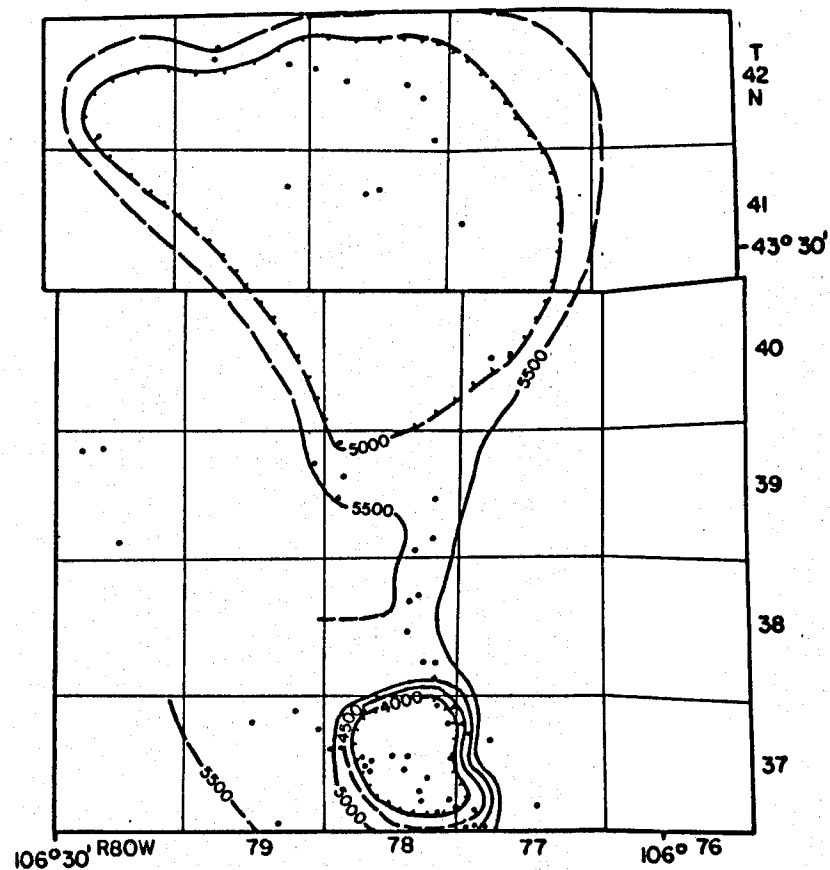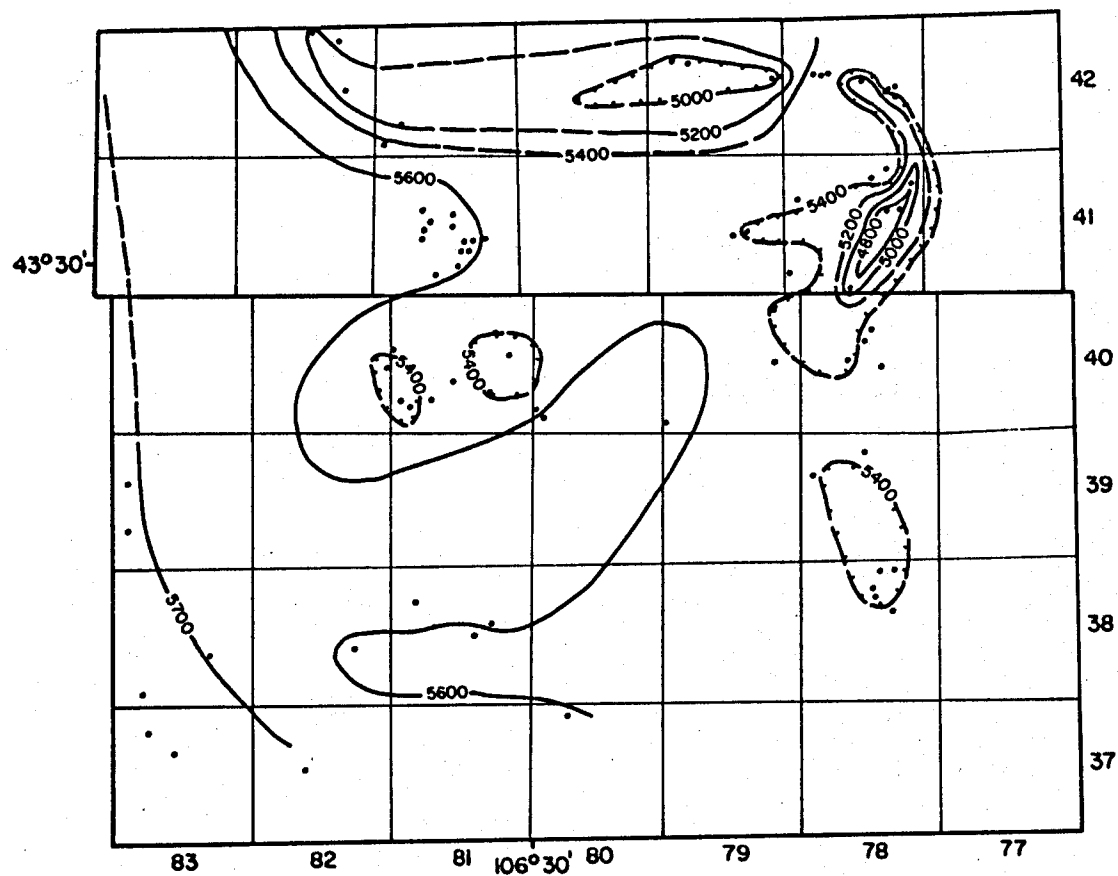Figure 7. Stratigraphic column for the southern Powder River Basin.

Figure 8.

GRADIENT-DEPTH PROFILE FOR SOUTHERN POWDER RIVER BASIN, BASED ON 4652 BOTTOM-HOLE TEMPERATURES.
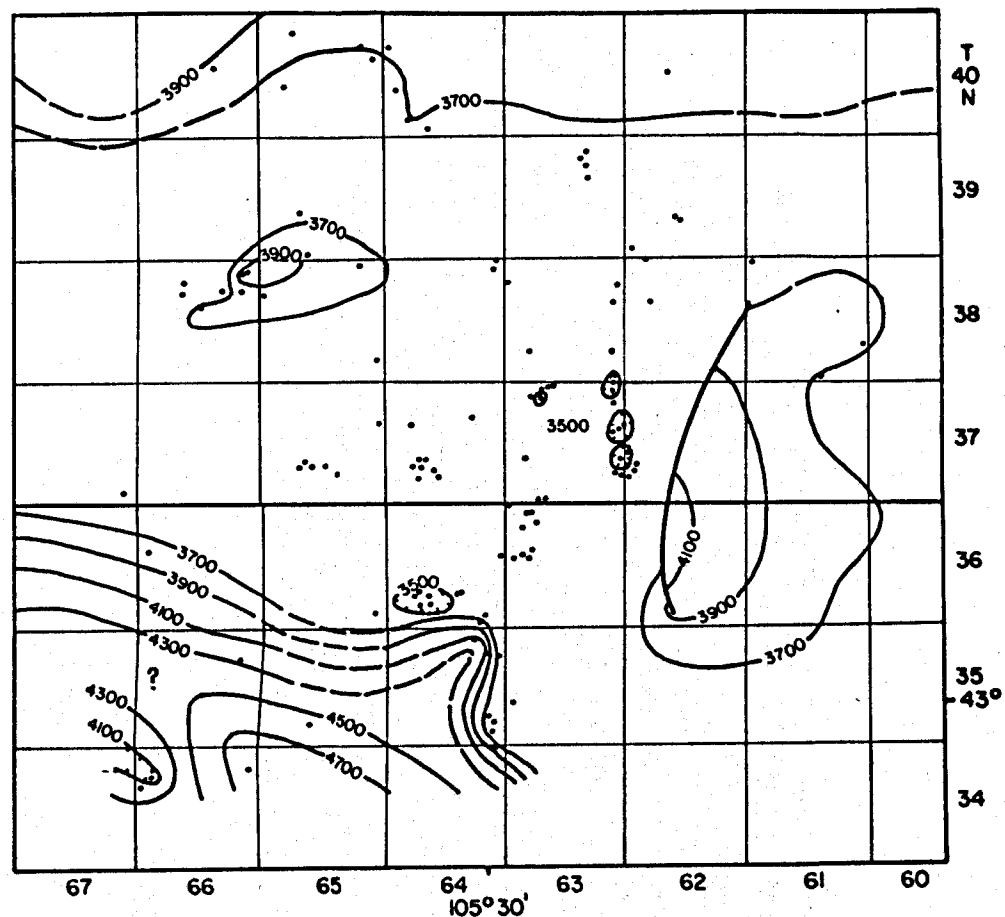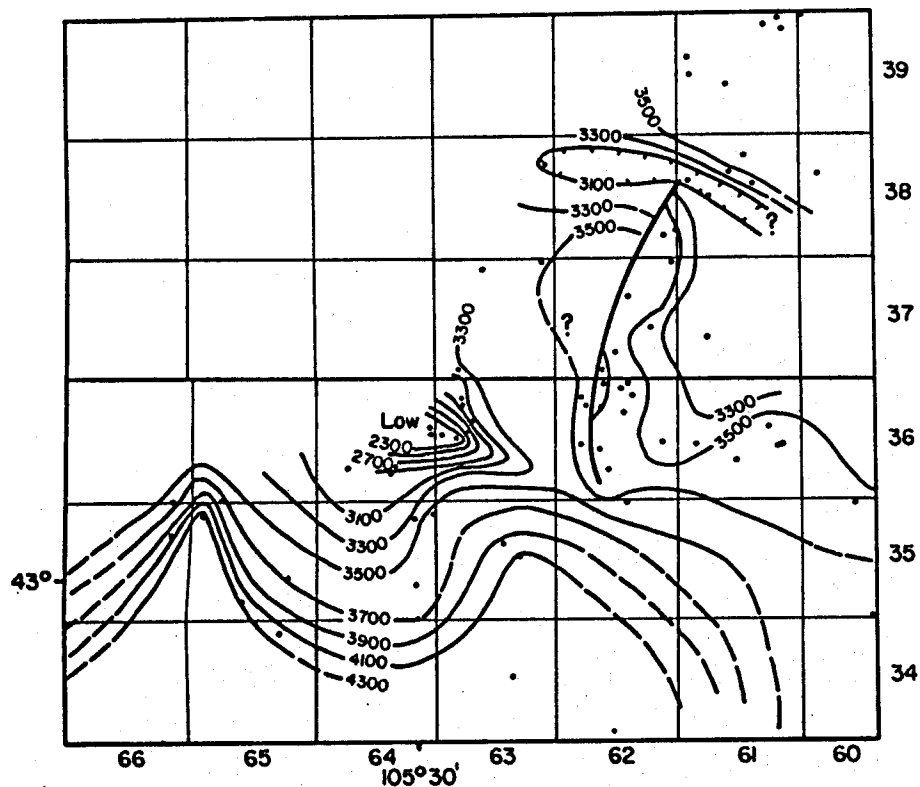
Explanation: Potentiometric contours in feet.   • Data Site

Figure 9.   Potentiometric surface for the Tensleep aquifer (left) and the Dakota aquifer (right)
            for the Salt Creek region. Data range in age from 1940 to 1981.
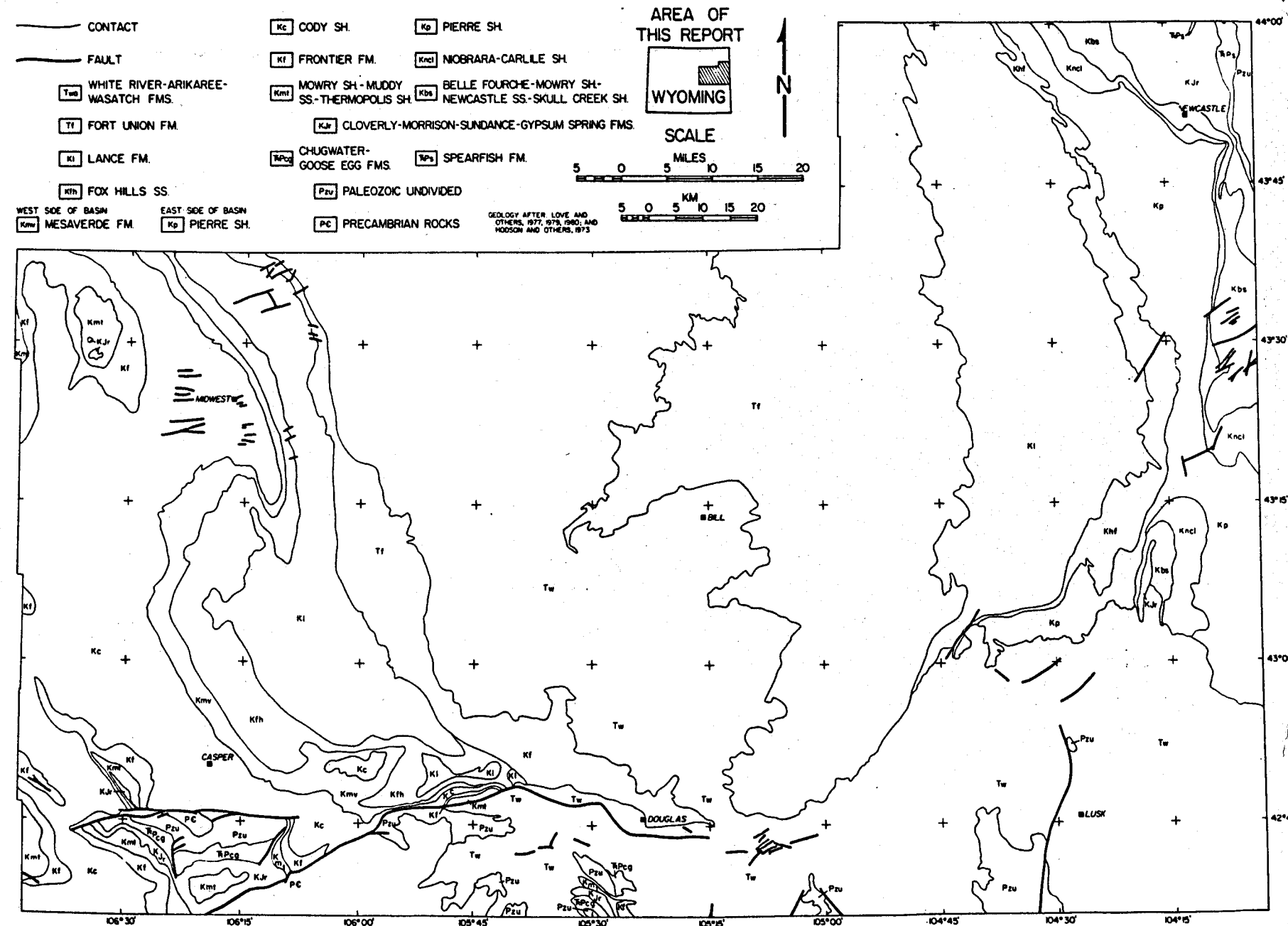
Explanation: Potentiometric contours in feet.   • Data Site

Figure 10. Potentiometric surface for the Minnelusa aquifer (left) and the Inyan Kara auifer (right) for the Fanny Peak lineament region. Data range in age from 1940 to 1980.

PLATE I

GENERAL GEOLOGY OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

CONTACT

FAULT

Twa WHITE RIVER-ARIKAREE-WASATCH FMS.

Tf FORT UNION FM.

Kl LANCE FM.

Kfh FOX HILLS SS.

WEST SIDE OF BASIN
Kmv MESAVERDE FM.

EAST SIDE OF BASIN
Kp PIERRE SH.

Kc CODY SH.

Kf FRONTIER FM.

Kmt MOWRY SH.-MUDDY SS.-THERMOPOLIS SH.

Kjr CLOVERLY-MORRISON-SUNDANCE-GYPSUM SPRING FMS.

TRPcg CHUGWATER-GOOSE EGG FMS.

Pzu PALEOZOIC UNDIVIDED

PC PRECAMBRIAN ROCKS

Kp PIERRE SH.

Kncl NIOBRARA-CARLILE SH.

Kbs BELLE FOURCHE-MOWRY SH.-NEWCASTLE SS.-SKULL CREEK SH.

TRPs SPEARFISH FM.

GEOLOGY AFTER LOVE AND OTHERS, 1977, 1979, 1980; AND HODSON AND OTHERS, 1973

AREA OF THIS REPORT

WYOMING

N

SCALE

MILES
5 0 5 10 15 20

KM
5 0 5 10 15 20

PLATE II

GENERAL STRUCTURE CONTOUR MAP OF THE NEWCASTLE AND MUDDY SANDSTONE, SOUTHERN POWDER RIVER BASIN, WYOMING

—— CONTOUR ON THE NEWCASTLE
AND MUDDY SANDSTONE
DATUM IS MEAN SEA LEVEL
CONTOUR INTERVAL 1000 FT

-·-—·-· SELECT CONTOURS ON LAND
SURFACE - DATUM IS MEAN SEA LEVEL

——— FAULT

·•· ANOMALOUS GRADIENT POINT
AND/OR POINT OUTSIDE
CONTOURING - (XX X°F/1000 FT)

AREA OF ANOMALOUS
GRADIENTS - DEFINED BY DEPTHS
<5000 FT (SEE TEXT FOR EXPLANATION)
DASHED WHERE APPROXIMATE

AREA OF ANOMALOUS
GRADIENTS - DEFINED BY DEPTHS
>5000 FT (SEE TEXT FOR EXPLANATION)
DASHED WHERE APPROXIMATE

STRUCTURE CONTOURS GENERALIZED FROM HODSON
AND OTHERS, 1973 WATER RESOURCES OF THE
POWDER RIVER BASIN AND ADJACENT AREAS,
NORTHEASTERN WYOMING. U.S. GEOLOGICAL
HYDROLOGICAL ATLAS HA-465 ADDITIONAL
CONTOURING ADDED WHERE NECESSARY BASED ON:
BARLOW & HAHN, INC., 1978 WYOMING STRUCTURE
CONTOUR MAP POMCO CASPER, WYOMING.

AREA OF
THIS REPORT

WYOMING

N

SCALE

MILES
5 0 5 10 15 20
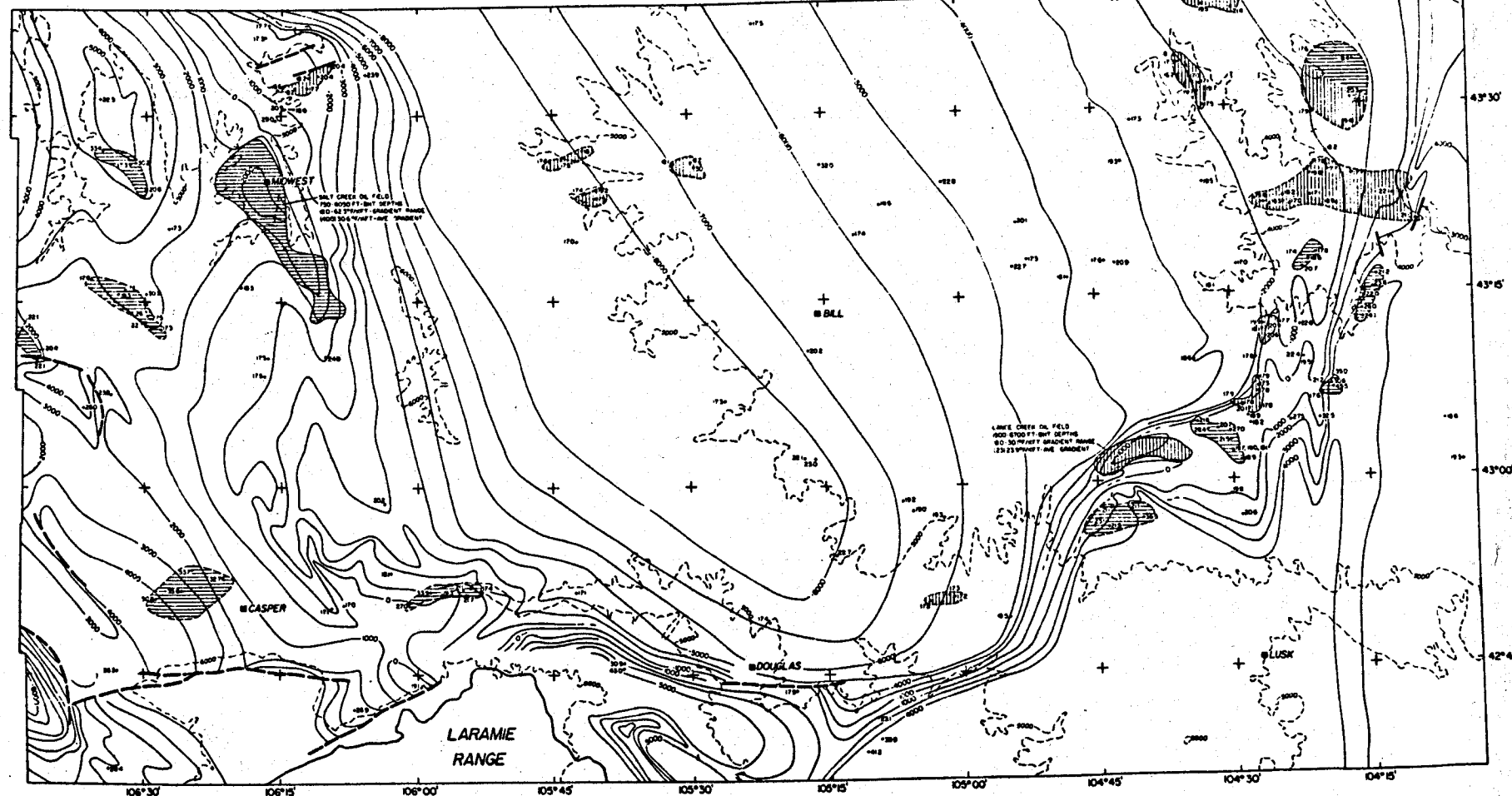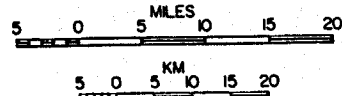
KM
5 0 5 10 15 20

LARAMIE
RANGE

PLATE III

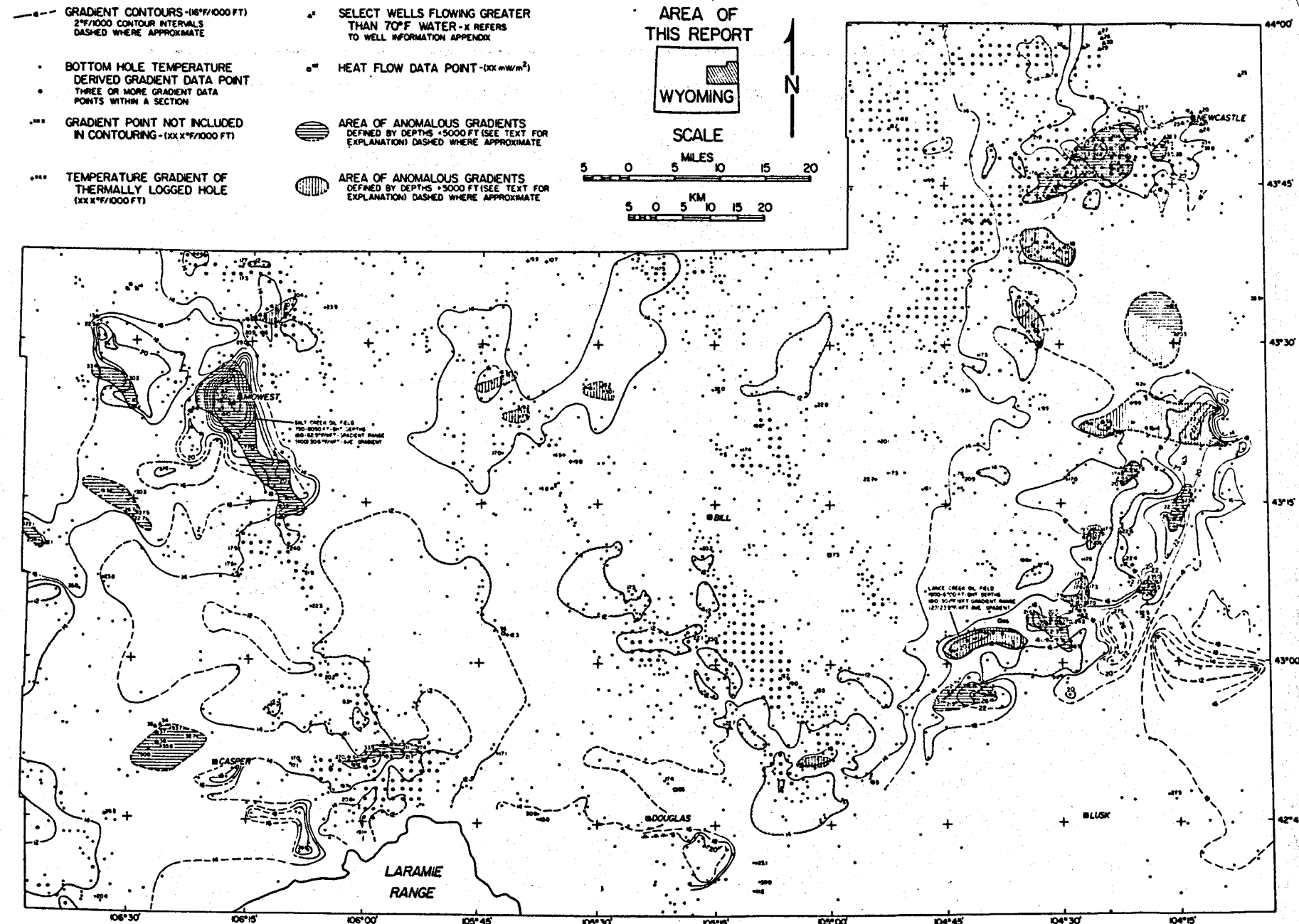# THERMAL GRADIENT CONTOUR MAP OF THE SOUTHERN POWDER RIVER BASIN, WYOMING

PLATE IV

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

TEMPERATURE CONTOUR
CONTOUR INTERVAL 10°F
DASHED WHERE APPROXIMATE

FAULT

BOTTOM-HOLE TEMPERATURE
DATA POINT FOR NEWCASTLE
OR MUDDY SANDSTONE

LOCATION AND TEMPERATURE
(°F) OF ANOMALOUS DATA POINTS
AND POINTS OUTSIDE CONTOURING

AREA OF ANOMALOUS
GRADIENTS - DEFINED BY DEPTHS
<5000 FT (SEE TEXT FOR EXPLANATION)
DASHED WHERE APPROXIMATE

AREA OF ANOMALOUS
GRADIENTS - DEFINED BY DEPTHS
>5000 FT (SEE TEXT FOR EXPLANATION)
DASHED WHERE APPROXIMATE

AREA OF
THIS REPORT

WYOMING

N

SCALE

MILES
5 0 5 10 15 20

KM
5 0 5 10 15 20

NEWCASTLE

MIDWEST

BILL

CASPER

DOUGLAS

LUSK

LARAMIE
RANGE

44°00'
43°45'
43°30'
43°15'
43°00'
42°45'

106°30' 106°15' 106°00' 105°45' 105°30' 105°15' 105°00' 104°45' 104°30' 104°15'