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By
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MASTER

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CONVERSION FACTORS

Length

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

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

Mass flow

1 gallon per minute = 3.785 liters per minute (lpm)

1 liter per minute = 0.2642 gallon per minute (gpm)

Pressure

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

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

Thermal gradient

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

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

Thermal conductivity

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

Heat flow

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

Temperature

1 degree Fahrenheit = 0.56 degree Celsius (°C)

1°Celsius = 1.8°Fahrenheit (°F)

°F = 1.8°C + 32 °C = (°F − 32)/1.8

INTRODUCTION

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

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

This introduction contains (1) a general discussion of how geothermal resources occur, (2) a discussion of the temperatures, distribution, and possible applications of geothermal resources in Wyoming and a general description of the State's thermal setting, and (3) a discussion of the methods we used in assessing the geothermal resources. This introduction is followed by a description of the geothermal resources of the Great Divide and Washakie Basins of southern Wyoming (Figure 1).

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

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

GEOTHERMAL SYSTEMS AND RESOURCES

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

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

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

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

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

TEMPERATURE, DISTRIBUTION, AND APPLICATION OF RESOURCES

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

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

The geothermal resources in the basins are suited to relatively small-scale, direct-use projects located close by. Energy uses include a wide range of space heating, agricultural, aquacultural, and low-temperature processing applications. (See Anderson and Lund, 1979, for a discussion of direct-use geothermal applications.) Below 100°F, uses are limited to such applications as soil and swimming pool warming, 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 trillion British thermal units (Btu's) of heat per year in cooling to ambient temperature. Like the oil springs and seeps that led developers to Wyoming's vast petroleum fields, thermal springs are simply the surface manifestation of the much larger, unseen geothermal resource. For example, Hinckley (1984) has calculated that approximately 24 trillion Btu's of heat would be released per year if all the thermal water produced as a by-product in Wyoming oil fields were cooled to ambient temperature.

METHODS OF ASSESSMENT

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

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

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

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

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

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

where MAAT is the mean annual air temperature.

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

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

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

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

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

We calculated a single *background thermal gradient* for each basin (Table

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

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

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

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

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

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

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

SUMMARY

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

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

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

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

Regional Structure

The Great Divide and Washakie Basins are geologic and physiographic basins. The general shape of the Great Divide and Washakie Basins is shown by the structure contour map (Plate III). The Washakie Basin is a roughly circular basin with dips of 8° and 15° along the eastern and western flanks, respectively. The Great Divide Basin is divided from the Washakie Basin by the Wamsutter arch, a broad structural uplift. Dips along the uplift are less than 3°, with negiligible subsidiary faulting and folding (Fisk, 1967). The Great Divide Basin is a structurally asymmetric basin whose axis trends east-west in the northwest, and north-south in the southeast. Dips along the southwest edge average 3° whereas dips along the eastern edge average greater than 30°. The northern boundary for the basin is a complicated structural zone composed of Eocene age thrusts and uplifts and more recent Pliocene and Pliestocene normal faults and graben structures (Love, 1970).

The Rock Springs uplift, Rawlins uplift, Sierra Madre uplift, and the southern tip of the Wind River Mountains constitute the major north-south trending geologic structures in the area. Major structures trending in an east-west direction include the Granite, Ferris and Seminoe Mountains, the Wamsutter arch which separates the basins, and the Cherokee Ridge arch located along the southern border of Wyoming. Structural relief of the above mentioned Laramide uplifts range from 7,000 feet (Wamsutter arch) to 33,000 feet (Sierra Madre uplift).

Numerous faults, synclines, and anticlines are evident along the major uplifted regions and to a lesser degree within the basins. The synclinal-anticlinal structures are areas of favorable geothermal potential due to the relatively high degree of fracturing in the Paleozoic aquifers, heating of water in the synclines, and artesian water pressure derived from nearby uplifts. Other structures of importance are Tertiary volcanic intrusive stocks, dikes, and flows located on the southwest flank of the Sierra Madre Mountains and on the northern end of the Rock Springs Uplift.

Stratigraphy

Geologic formations within the Great Divide-Washakie Basins range from Precambrian to Recent in age. A stratigraphic column (Figure 7) shows formation rock types and age. Maximum stratigraphic thickness is 25,000 feet for the Great Divide Basin and 28,000 feet for the Washakie Basin. Cretaceous and Cenozoic age sediments constitute the bulk of the thickness (21,000 to 24,000 feet) (Welder and McGreevy, 1966). The Washakie Basin is believed to have a greater stratigraphic thickness due to 3,000 feet of Tertiary material which apparently has been eroded from the Great Divide Basin (Fisk, 1967).

Paleozoic formations within the basins are composed of marine shelf deposits with aggregate thicknesses of 1,000 and 2,600 feet on the southwest flank of the Sierra Madre and in the central Great Divide basin, respectively. Cambrian age units in the western portion of the basins are the Flathead Sandstone, Gros Ventre Shale, and Gallatin Limestone. These formations change to undifferentiated sandstones on the eastern side of the basin with decreasing thickness in the same direction. The Cambrian units are overlain unconformably by the Madison Limestone. This early Mississippian-age unit is thickest in the northwestern region and thins to the south and east (Thomas, 1951). Pennsylvanian-age rocks are divisible into two units; the Amsden formation, composed of red shales, and the Tensleep Sandstone. These units are latterally continuous throughout the basins with the exception of the southeast corner where they are absent. The youngest Paleozoic-age unit present is the Phosphoria Formation of Permian age. In the northwest the formation consists of limestones, dolomites, bedded cherts and gray to brown shales. Eastward and southward the Phosphoria Formation equivalent consists of red shales with interbedded siltstone and sandstone (Thomas, 1951).

The Mesozoic stratigraphic section in Great Divide-Washakie Basins is composed of 3,000 feet of Triassic and Jurassic-age shelf or shelf-margin sediments and 11,000 feet of alternating and intertonguing Cretaceous sandstones and shales. The Triassic-age rocks are represented by the laterally continuous Dinwoody and Chugwater Formations. These formations consist of intertonguing siltstones and sandstones, and variable gypsiferous and calcareous red shales, siltstones, sandstones and conglomerates (Curtis, 1951). The Nugget Sandstone, Sundance Formation, and Morrison Formation of Jurassic age overlie the Chugwater Formation. The Nugget Sandstone is eolian in origin, reaches a maximum thickness in the northwestern portion of the study area, thins to the east, and is absent in the southeast (Ritzma, 1949). The Sundance Formation is divisible into a lower sandstone member and an upper shale member, laterally continuous throughout the region. A laterally continuous series of sandstones, conglomerates, claystones, and limestones comprise the Morrison Formation. The formation is 200 feet thick in the northeast corner of the study area and thickens to 600 feet toward the southwest.

The Cretaceous-age units are the Cloverly Formation, Thermopolis Shale, Muddy Sandstone, Mowry Shale, Frontier Formation, Niobrara Formation, Steele Shale, Mesaverde Formation, Lewis Shale, Fox Hills Formation and Lance Formation. A tripartite division of the Cloverly Formation is common, consisting of a lower conglomeratic sandstone unit, a middle variegated shale interval, and an upper fine- to medium-grained sandstone. The shale interval is laterally discontinuous due to facies changes. The Thermopolis Shale is a dark marine shale overlain by the Muddy Sandstone, a continuous thin sandstone. Both units are absent in the extreme southwest portion of the study area (Curtis, 1951). The Mowry Shale is a hard, siliceous shale with a maximum thickness of 450 feet in the northwestern corner, thinning to 150 feet in the southwest corner of the study area. The Frontier Formation extends throughout the Great Divide-Washakie Basins, thinning towards the southwest corner. The formation consists of several sandstones interbedded with shales. The Frontier Formation is overlain by the Niobrara Formation in the eastern portion of the basins and by the Baxter Shale in the western section. The Baxter Shale is the equivalent of the Steele Shale, Cody Shale, and Niobrara Formation in the eastern region of the basins. These units consist largely of dark shales with minor amounts of interbedded sandstone, siltstone, and limestone. The Mesaverde Formation, a thick series of sandstones and shales, lies above the Steele Shale (Baxter Shale). The sequence of sandstones and shales becomes more distinctive in the western portion of the basins and is divided into the Blair, Rock Springs, Ericson, and Almond Formations. The western Mesaverde Group contains alternating sandstones and shale members with gradational contacts. Overlying the Mesaverde section is the Lewis Shale, a marine shale similar to the Steele Shale in lithology. The Fox Hills Sandstone and Lance Formation are latest Cretaceous formations. The Fox Hills Sandstone contains massive sandstones with discontinuous irregularly bedded shales and siltstones. Above the sandstone lies 4,000 to 6,000 feet of shales and sandstones of the Lance Formation.

Tertiary-age sediments are composed of extensively intertonguing and discontinuous sandstones, siltstones, and shales. The Wasatch, Battle Springs, and Green River Formations contain claystone, sandstone, shale, and siltstone; all of which intertongue and tend to be laterally discontinuous. The Fort Union

Formation is dominated by a basal sandstone unit, with an increase in siltstone and shale upward in the formation. The Bridger and Uinta Formations consist of claystone, siltstone, sandstone, and conglomerate tuffs (Wood, 1967). The Browns Park and North Park Formations consist of a basal conglomeratic unit with an upper brown and white sandstone member.

Hydrology

The general discussion of water producing zones within the basins is taken from Collentine et al. (1981); Welder and McGreevy (1966); and Fisk (1967). The majority of the hydrologic data are from wells located within the uplifted regions where secondary fracture permeability is pervasive. Laboratory studies (Fatt and Davis, 1952; Fatt, 1953; Wyble, 1958) indicate a reduction in permeability of 20 to 60 percent with increasing overburden pressure. Thus, water production and transmissivity will likely decrease with depth in the central portions of the basins.

The Paleozoic aquifers are composed of sandstones and limestones. Sandstone permeabilities are primarily intergranular. Secondary fracture permeability increases sandstone permeabilities and is the main source of permeability in the carbonate units. Typical aquifer transmissivities are low, ranging from less than 1 to 370 gpd/ft; however, where secondary permeability is present transmissivities of 150,000 to 300,000 gpd/ft have been reported (Collentine et al., 1981). Production rates from wells and springs is the Paleozoic aquifers range from 4 to 400 gpm.

The Mesozoic aquifers consist of sandstone units within the Mesaverde, Frontier, Cloverly, Sundance, and Nugget Formations. These aquifers are separated by thick, impermeable shale units. Production varies greatly within and between formations: Ericson Formation 10 to 250 gpm; Rock Springs Formation 2 to 470 gpm, (generally 100 to 250 gpm), Blair 30 to 60 gpm, Almond (one well) 250 gpm, Frontier 1 to 106 gpm, Cloverly 25 to 120 gpm, Sundance-Nugget 27 to 200 gpm (Collentine et al., 1981). The reported yields are likely to be less in central parts of the basins due to reduced permeability. Transmissivity values reported for these formations range from 1 to 35,000 gpd/ft (Collentine et al., 1981)

Ground water chemical analyses have been compiled for the Paleozoic and Mesozoic aquifers of the Great Divide-Washakie Basins (Table 2). The Tertiary aquifer is extensively used throughout the basins, with production coming from the sandstone and conglomerate units; the maximum thickness of the aquifer is 11,000 to 12,000 feet (McDonald, 1975). Because specific capacities generally range between .1 to 4.0 gpm/ft and because of the large stratigraphic thicknesses, potential yields for the aquifer of greater than 2,000 gpm are predicted (Fisk, 1967). The central portions of the basins have the larger geothermal potential due to the greater depth of burial and greater saturated aquifer thickness. The greater depth of burial will result in higher ground water temperatures.

Potentiometric data for various aquifers indicate a regional flow pattern of water moving from the topographic highes into the central portions of the basins. Figure 8 is a generalized ground water flow map for the basins (modified from Collentine et al., 1981). The topographic highs along the eastern portion of the basins and the northern boundary of Great Divide Basin are regional ground water divides. The Rock Springs uplift and Wamsutter arch are ground water boundaries for the Tertiary aquifers. Ground water movement is over the Cherokee Ridge, the southern boundary of Washakie Basin, into the Sand Wash Basin of Colorado. The mentioned ground water divides and flow directions are conjectural due to the lack of detailed potentiometric data for pre-Tertiary aquifers.

Artesian pressure in the pre-Tertiary aquifers is developed by recharge on uplift areas. Water enters the aquifers by direct infiltration and through overlying sediments, and then migrates down dip (where the aquifers are confined) into the deeper portions of the basin. The location and flow rates for a number of warm water artesian wells from various aquifers are found in Table 3.

Heat Flow

Heat flow is defined as the amount of terrestrial heat which flows perpendicular to the surface of the earth at a given location. Heat flow is affected by numerous geologic processes including volcanic activity (increasing the heat flow), hydrologic flow (increasing or decreasing the heat flow), overthrusting (increasing or decreasing heat flow). Within the Great Divide and Washakie Basins heat flow is used to explain temperatures at depth, the effects of hydrologic flow, and effects of volcanic activity. Ten new heat flow values were determined for the Great Divide-Washakie basins. These values are listed with previously published values in Table 4 and are plotted on Plate II. Based on these values, an average heat flow for the basins and surrounding uplifts is $52 \pm 13 mW/m^2$. The heat flow values agree with the Decker et al. (1981) interpretation of the southeastern Wyoming basin areas being a zone of low to normal heat flow. 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. Papers discussing the above effects on heat flow are: Roy et al., (1968), Lachenbruch and Sass (1978), Kilty and Chapman (1980), and Kilty et al. (1979).

Heat flow data are used in the following sections to approximate subsurface temperatures at various locations in the study area. The equation used is:

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

where

Q = heat flux (flow),

K = thermal conductivity,

$\frac{dt}{dz}$ = thermal gradient.

Using approximate formation thermal conductivities (K) and regional heat flow values it is possible to obtain the temperature gradient through each formation. The formation thickness is then multiplied by the temperature gradient to determine the temperature change across the formation. An idealized temperature-depth profile is the result, with an example given in Table 5 for a typical sedimentary section in the central portion of Washakie Basin.

High Thermal Gradient Areas

The bottom-hole temperature and predicted formation temperatures for the central Washakie Basin indicate that high (>302°F), intermediate (194-302°F), and low (<194°F) temperature systems are contained within the basin. The high and intermediate temperature systems result from a normal thermal gradient and great depth of burial. High and intermediate temperatures can be found throughout both basins at depths greater than 12,000 feet. However, the depth of burial and poor water quality place a serious economic constraint on the use of these temperature waters as geothermal resources.

Low temperature systems are related to depth of burial, thermal gradient, and hydrologic flow systems. In low temperature systems it is important to consider the effects of moving water. Geothermal systems of interest are those capable of transporting warm water from depth to the near surface. This includes such natural systems as anticlines or faults which serve as natural conduits, or artificial conduits such as drill holes. Evidence for all three types of conduit systems are found in Washakie-Great Divide Basins. However, in these basins there are no natural systems known to transport warm water to the surface in the form of warm springs. Rather, the natural systems transport warm water to the near-surface, creating high gradients and allowing shallow drilling access to the geothermal waters.

Detection of geothermal systems is aided by the use of bottom-hole temperature derived thermal gradients, structure contours, flowing well data, and hydrologic data. The thermal gradient contour map (Plate II) is based on bottom-hole temperatures. Because of the discussed inherent errors of bottom-hole temperatures a number of anomalous gradient points are not included in the contouring process. These individual points are plotted with their anomalous gradient values.

Areas of anomalous gradients are shown on Plates II, III, and IV. A number of these areas are believed to be caused by movement of thermal waters close to the surface. These anomalous gradient areas were determined by the method discussed earlier applied to Table 6 and 7. These tables present BHT-derived temperature gradients in 500 feet depth intervals with mean gradient, the 50th, 66th, 80th, and 90th percentiles for each interval.

Using information of the type discussed above, areas of geothermal potential are determined for the basins. The areas of greatest potential are: Seperation Flats Region (including Lost Soldier Dome), the northern and western flanks of the Sierra Madre (including the Hatfield-Miller Hill and the Cow Creek-Cherokee Creek areas), and Baxter Basin. Each of these areas is further discussed.

Separation Flats

The Separation Flats potential area is located in T.24-27N., R.85-89W. approximately 25 miles north of Rawlins, and five miles south of Lamont. The structural geology is dominated by several anticlinal-synclinal systems trending north-south in the western part of this area, and changing to an east-west direction in the east. The structures included are the Lost Solider, Wertz, Bunker Hill, Mahoney, Ferris, G.P, Sherard, and Bull Springs domes and the O'Brian Springs anticline. To the north of these structures are the Ferris and Seminoe Mountains, and to the south is the Rawlins uplift. Complete descriptions of the structural elements are given by Krampert (1923, 1949, 1951), Fath and Moalton (1924), and McCoy (1951).

The region is characterized by high thermal gradients and near-surface water flow from depths of 1969 to 5,200 feet. The high gradients tend to be located along the structural highs, with lower, normal gradients found in the synclines. This relationship of gradients and structure again suggests the movement of water warmed at depth up along structural highs.

Artesian flows in the region add further evidence to the existence of significant water movement within various aquifers. Artesian flow is known to occur from the Mesaverde, Frontier, Dakota, Sundance, Nugget, and Tensleep Formations (Table 3). The source for the water and artesian pressure may be the Ferris and Seminoe Mountains to the north or Rawlins uplift to the south. Elevation differences between these uplifts and Seperation Flats are approximately 2,000 and 1,000 feet respectively. However, there is no direct evidence to indicate either as a water source area.

The maximum temperature for the separation flat geothermal system is believed to be 212°F. This is the bottom-hole temperature for a flowing well which produces water with a temperature of 186°F at the surface from a depth of 5,200 feet in the Tensleep Sandstone. Conductive modeling indicates a heat flow of $92mW/m^2$ is needed to produce the above temperature at 5,200 feet. This suggested heat flow is 83 percent higher than the mean heat flow, and 38 percent higher than the maximum determined heat flow. However, conductive modeling on the synclinal portion of the system indicates a Tensleep Sandstone temperature of 149-184°F using surface heat flows of $50\text{-}67mW/m^2$ (Table 5). This model further suggests water movement from the structural lows to the highs, with accompanying heat transfer.

Lost Soldier Dome is a doubly-plunging, elongated anticline trending N20°W across T.26N., R.90W. with 3,500 feet of structural closure (Kampert, 1959). Structural characteristics of the Dome are: 1) sharp, asymmetric limbs of the anticline dipping 45° to the southwest and 35° to the northeast; 2) numerous normal radial faults on the north-northeast flank, 3) major (possibly thrust) faulting in the Precambrian. (Irwin, 1929; Krampert, 1923, 1949). Evidence of geothermal potential includes: 1) abnormally high temperatures recorded at times when a drill hole penetrated a fault zone, 2) the 120°F temperature of oil produced from a fault zone which is 50°F above other bottom-hole temperatures (Krampert, 1923), 3) the anomalously high gradients obtained from oil field bottom-hole temperatures.

The above information, combined with geologic evidence of numerous faults, fractures, and hydrologic communication between units (Fath and Moalton, 1924) implies the geothermal anomalies are caused by movement of fluids from depth. Conductive heat flow modeling further indicates the movement of warm water onto the dome. The maximum temperature for the anticlinal axis of the Lost Soldier Dome ranges from 104-120°F when modeled using only conductive heat flow. This is well below the maximum recorded BHT temperature of 220°F for the axis area. The maximum range of modeled temperatures for the synclinal portion of the system however, is 160-199°F (Table 5). The similarity of modeled temperatures in the syncline and measured bottom-hole temperatures on the anticline strongly suggests the transportation of deeper, warmer waters from the synclinal areas upward onto the axis of Lost Solider Dome. Hydrologically, the force for movement of ground water may be derived from the Ferris and Seminoe Mountains to the north. Elevation difference for the Tensleep Sandstone at the Ferris Mountains and at Lost Soldier Dome is approximately 5,000 feet.

The Hatfield - Miller Hill region is located approximately 20 miles south of Rawlins in T.17-20N., R.86-89W. Structurally the region is dominated by the Miller - Lake Valley anticline with adjacent minor anticlines and synclines. These minor structures include the Upper Sage Creek, Middlewood, Pinegrove, and Espy anticlines (Del Mauro, 1953). Geological discussions and maps are provided in Del Mauro (1953), Buehner (1936), Collier and McKnight (1925), Verionda (1951), and Larson and Vieaux (1951).

Evidence for geothermal potential is found in the high gradients and flowing warm water wells, and in a ground water study by the City of Rawlins. This evidence suggests a convective system of water transport and accompanying heat transfer. Water flow direction (Del Marro, 1953) and the high thermal gradients on anticlines in this area (Plate II) indicate heat transfer from synclinal portions of the area to the anticlines. The source area for the aquifers is believed to be the northern flank of the Sierra Madre Mountains. Artesian pressure may result from 1,000 feet of structural elevation difference between the recharge areas and the Hatfield-Miller Hill area.

The average temperature gradient from 38 bottom-hole temperatures for this area is 19.6°F/1,000 ft with values ranging between 12.6-53.3°F/1,000 ft. Of importance is the location of the higher gradients along the structural highs. Predicted temperatures using the average basin heat flow for the synclinal portions of the basin agree with the observed bottom-hole temperatures for similar depths. (Table 5). However, bottom-hole gradients on structural highs indicate heat flow values 400 percent higher. Heat flow values of this magnitude are not realistic assuming conductive heat transfer. Thus, a convective heat transfer model (i.e. hydrologic flow) seems most reasonable to explain these high heat flow values.

Using conductive thermal modeling, a reasonable maximum temperature of 160°F is given for the geothermal system. This value is derived from heat flow calculated temperatures (Table 5) and agrees well with recorded bottom-hole temperatures.

High bottom-hole temperature derived gradients and flowing wells characterize the Cow Creek-Cherokee Creek area. This potential geothermal resource area is located in T.15-16N., R.91W. Few data are available on the structure of the region other than the mapping of anticlines and faults (Wyoming Geological Association, 1979).

The high gradients and flowing wells are located on the structural highs. A measured temperature-depth log in the area with a gradient of 23°F/1,000 ft, confirms the presence of high gradients. Of the numerous flowing wells, three were thermally logged and five were found to produce a water-gas mixture with surface temperatures of 60-83°F. Drill stem tests from oil and gas records of these artesian wells indicate pressure sufficient to flow water at the surface from the Tensleep, Jelm, Nugget, Frontier, Deep Creek, and Mesaverde Formations at depths of 2,652 to 10,329 feet. The source for the artesian pressure is believed to be outcrops of the formations along the Sierra Madre. However, the explanation of water being warmed in a synclinal axis and moving upward is not applicable here due to the minimal structural relief (<1,000 feet). Warm water movement up from depth along faults may provide an alternate explanation. Lack of structural and hydrologic preclude a more definitive explanation.

Baxter Basin is a topographic low located on the Rock Springs uplift (T.103-104N. R.18-19W.) Found within the basin and along the Rock Springs uplift are numerous strike slip faults trending in a northeast direction (Sears, 1926). These faults have up to 3 miles of horizontal displacement and usually less than 100 feet of vertical displacement. Detailed descriptions of the geology and geography are given by Schultz (1920) and Sears (1926).

Artesian wells within the high gradient areas on the western edge of Baxter Basin indicate geothermal potential for the area. Flowing wells produce water from the Frontier, Dakota, Nugget, and Madison Formations at depths of 2,345 to 6,527 feet (Table 3). Possible explanations for the source of artesian pressure and water supply include: 1) Water movement from locally higher topography, down the numerous fault zones. Water may then become confined beneath shale units, with artesian pressure due to elevation differences (>700 feet). 2) Regional movement of ground water through aquifers beneath the major basins and up onto the Rock Springs uplift.

The first hypothesis is more plausible in light of present hydrologic, geologic, and thermal gradient data. Available pre-Tertiary ground water potentiometric data indicates movement into the central portions of the basin, with an east-west ground water divide to the east of the Rock Springs uplift (Collentine et al., 1981). Conclusions from water chemistry data are less definitive but include the movement of water over the Rock Springs uplift and vertical movement in zones of faulting and fracturing (Collentine et al., 1981).

Conductive heat flow based temperatures calculated for the Baxter Basin are given in Table 5. These temperatures agree with the regional normal gradient (14-15°F/1,000 ft) and bottom-hole temperatures. Anomalous bottom-hole temperature gradients range up to 43°F/1,000 ft. These high gradients suggest water movement from depths of 10,000 feet up to depths of 3,000 feet based on comparison of conductive modeling to the reported bottom-hole temperatures.

Possible Volcanic Geothermal Resource Areas

Volcanic activity within the Great Divide-Washakie Basins represents a possible geothermal resource due to transport of molten rock to the near-surface. Two volcanic areas, the Elk Head and Leucite Hills regions, are located on the western flank of the Sierra Madre - Park Range and along the northern end of the Rock Springs uplift. Both have geologic evidence showing Pliestocene (1-3 million years old) volcanic activity (McDowell, 1971; Buffler, 1967). However, geologic evidence and the large distance between the two igneous areas give no suggestion of similar origin or emplacement.

The Elk Head region includes a group of volcanic peaks known as the Elk Mountains; only a small portion of the volcanic field is located within the southern boundary of Wyoming. The volcanic rocks at the surface consist of basic to intermediate composition extrusive and shallow intrusive rocks isotopically dated at 7.6-11.1 million years old (Buffler, 1967; Sergerstorm and Young; 1972; McDowell, 1971). Regional geophysical modeling of heat flow, gravity, and seismic data suggests recent (1-5 million years) intrusion of high temperature (1,500 to 1,400°F) heat sources at shallow depth (16,000 feet) in northern Colorado and extreme southern Wyoming (Buelow, 1980). The northern Elkhead volcanic field is likely the northernmost extension of this igneous activity, located on the transition zone between abnormally high heat flow to the south and low to normal heat flow to the north.

Geothermal resource potential for this region is tenuous, with the possibility of moderate to high temperature geothermal reservoirs at depth. Bottom-hole temperature gradients two miles to the northwest are anomalously high and suggest two possibilities. One is that the high gradients are caused by the flow of warm water from depth within an aquifer or between aquifers along faults and fractures. The other possibility is that the high gradients are the result of a high heat flow caused by cooling of an igneous intrusion at depth. The explanation may also be a combination of both possibilities. More accurate igneous age dates, heat flow data, and hydrologic data are required for a more specific determination of the region's geothermal potential.

The Leucite Hills are located on the northern end of the Rock Springs uplift, approximately 30 miles northeast of Rock Springs. The volcanic field consists of mafic-ultrapotassic volcanic lava flows, cones, dikes, and plugs. Petrologic studies of volcanic rock suggest the upper mantle as the source for these rocks, with little or no anatexism occurring (Ogden, 1974; Barton and Hamilton, 1978). The volcanic rocks have been isotopically dated at $11 \pm .4$ million years old (McDowell, 1971).

Preliminary modeling of a cooling igneous body (15 miles by 30 miles, 10,000 feet thick at a depth of 16,000 feet), indicates a present maximum increase in heat flow at the surface of $17 mW/m^2$. This increase in heat flow would increase the temperature gradient to 19.3°F/1,000 ft compared to the average basin value of 14.5°F/1,000 ft. Twenty-four thermally logged holes and numerous bottom-hole temperature gradients within and surrounding the volcanic field indicate a present average gradient of 11.5°F/1,000 ft with no definable variations across the volcanic area. Possible explanations for the lack of gradient anomalies are: 1) rapid cooling of the igneous bodies has occurred by convective flow of water; 2) the source for the igneous rock bodies is not large enough or near enough to the surface to cause a measurable increase in the temperature gradient; or

3) a combination of the above. In any case, the Leucite Hills volcanic area does not appear to represent a potential geothermal resource 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. Ground-water chemical analyses for the Great Divide and Washakie Basins.

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Mesaverde	12	90	11	54	97	32	26	108	371	602	c
Mesaverde	13	89	32	0	0	5	4	170	2300	2300	f
Mesaverde	13	90	22	256	2	0	4	4	640	615	f
Mesaverde	15	91	15	499	3	1	39	11	1300	1230	f
Mesaverde	16	90	2	90	190	140	13	890	385	1540	f
Mesaverde	16	90	6	90	38	35	3	99	404	477	f
Mesaverde	16	91	21	479	4	1	61	69	1100	1190	f
Mesaverde	16	91	22	469	5	1	48	66	1139	1190	f
Mesaverde	18	90	15	33	290	150	10	850	624	1650	f
Mesaverde	19	89	30	943	5	2	1247	60	670	2671	a
Mesaverde	19	103	1	-	509	690	600	4397	720	7860	f
Mesaverde	19	105	23	46	37	20	18	160	111	342	f
Mesaverde	20	95	12	5343	143	52	807	7100	1635	14250	a
Mesaverde	20	101	27	318	726	542	180	4000	449	6378	c
Almond	13	90	27	458	4	1	7	7	1190	1090	f
Almond	13	90	27	438	-	2	7	5	1149	1050	f
Almond	14	90	3	11	77	26	61	28	354	341	f
Almond	14	90	10	158	6	3	4	26	410	423	f
Almond	14	90	22	86	22	12	3	15	360	330	f
Almond	15	90	31	206	1	0	5	3	531	516	f
Almond	16	101	2	27676	1099	599	85	46000	549	75729	a
Almond	18	99	13	10300	171	66	16	13200	5441	26433	a
Almond	18	100	7	692	21	17	91	363	1580	2763	f
Almond	18	101	13	5739	519	720	8412	5097	1180	21667	f
Almond	19	98	9	6242	124	53	41	6000	6832	15825	a
Almond	19	98	30	6113	28	56	81	5624	6412	15825	a
Almond	19	105	28	40	35	22	15	150	94	329	f
Almond	20	99	33	23022	330	125	490	32800	5673	59561	a
Ericson	12	103	11	3668	126	37	3448	2920	903	10644	a
Ericson	12	105	22	385	64	17	371	98	510	1210	f
Ericson	12	105	22	87	34	16	42	69	237	382	f
Ericson	14	103	18	10	61	28	10	90	234	325	f
Ericson	19	92	20	6284	94	30	3	8500	2135	16130	a

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Ericson	19	100	33	34	180	56	8	640	103	1010	f
Ericson	21	101	4	50	73	26	122	16	302	436	a
Rock Springs	14	103	7	43	110	53	17	280	369	697	f
Rock Springs	17	102	4	41	150	150	32	630	545	1290	f
Rock Springs	18	100	8	83	210	90	38	750	204	1280	f
Rock Springs	19	105	35	1812	519	640	1302	4597	996	9430	f
Blair	16	101	2	6926	322	23	663	10300	990	18722	a
Blair	16	103	4	6	90	34	4	110	314	415	f
Blair	17	101	16	15596	54	24	700	22600	2050	40062	a
Blair	18	104	33	44	110	70	14	310	399	765	f
Baxter	16	104	27	16	83	41	7	160	310	472	f
Baxter	17	103	8	8	85	34	3	170	228	425	f
Baxter	17	104	15	21	40	20	3	35	215	248	f
Cody	14	89	1	24	91	24	7	150	283	465	f
Cody	27	89	15	1046	201	192	70	3078	568	4920	f
Frontier	13	87	15	49	126	17	10	157	293	534	c
Frontier	17	104	2	8790	-	-	-	8150	7175	21515	d
Frontier	18	88	10	291	6	2	37	7	556	720	e
Frontier	18	103	21	21889	397	238	-	33660	7585	57456	b
Frontier	18	103	18	20010	74	112	-	27900	5875	50985	d
Frontier	18	103	18	19750	78	107	-	27500	5925	50345	d
Frontier	18	103	30	12856	48	57	41	15652	7450	32318	d
Frontier	18	103	30	9508	17	46	91	11702	4900	23952	d
Frontier	19	88	34	522	-	-	Trace	49	1195	1209	b
Frontier	19	89	23	9878	390	80	5	15400	1293	26390	a
Frontier	19	104	12	10879	222	125	-	16667	1490	28626	b
Frontier	23	88	6	1101	-	-	-	503	2050	2614	d
Frontier	23	88	8	1591	-	-	-	738	2940	3775	d
Frontier	24	88	30	2002	-	-	-	1257	3150	4804	d
Frontier	25	88	31	806	-	-	309	225	1360	2009	b
Frontier	25	88	35	1326	-	-	-	587	2500	3145	d
Frontier	25	89	11	1157	-	-	-	343	2480	2720	a
Frontier	25	89	26	1064	-	-	-	140	2430	2471	d
Frontier	26	88	19	2346	-	-	-	1467	2950	5634	b

Formation	Location T.	Location R.	Location Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Frontier	26	90	3	4901	Trace	-	18	5000	4310	12038	d
Frontier	26	90	2	6098	-	-	-	6466	4757	15037	a
Frontier	26	90	11	5376	36	-	-	5100	5595	13970	b
Frontier	28	93	9	2486	12	11	249	3420	560	6550	a
Muddy	19	103	18	3729	122	Trace	-	3744	3825	9476	b
Muddy	25	88	6	1514	16	0	0	270	2500	3572	a
Muddy	26	90	3	3909	-	-	-	3200	4870	9506	b
Muddy	26	90	4	2109	53	18	497	1900	1950	5163	a
Cloverly	17	88	11	223	1.5	1.	85	3	342	557	e
Cloverly	17	88	11	179	-	-	76	3	210	468	e
Cloverly	18	88	3	302	-	-	16	7	640	738	f
Cloverly	18	88	10	78	4	1	32	2	175	223	e
Cloverly	25	89	26	1004	5	2	0	120	2200	2470	g
Cloverly	28	92	18	1919	-	-	203	2200	1050	4838	e
Dakota	16	104	21	3136	Trace	38	298	2542	3760	7866	b
Dakota	16	104	24	9787	51	7	44	8600	8223	24051	a
Dakota	17	104	2	3328	-	-	44	3202	2705	8180	d
Dakota	17	104	2	4093	56	33	-	4032	4260	10309	d
Dakota	18	103	18	6461	-	-	36	5928	6900	15818	d
Dakota	19	88	2	1943	26	3	50	2000	1745	5076	b
Dakota	19	88	2	2905	25	-	-	3510	1645	7299	d
Dakota	19	104	13	12500	232	164	-	19200	1645	32905	d
Dakota	20	88	35	4331	14	76	34	6000	1425	11215	b
Dakota	20	88	35	9000	314	95	-	14256	785	24051	d
Dakota	20	104	11	5975	110	Trace	116	8476	1460	15395	b
Dakota	21	103	32	6435	60	57	101	10000	475	16986	d
Dakota	21	103	32	6546	164	81	306	9800	1025	17401	d
Dakota	25	89	1	1271	18	5	0	900	1905	3132	a
Dakota	26	89	21	2700	Trace	Trace	125	1902	3735	6564	b
Dakota	26	90	3	1781	-	-	-	1119	2800	4277	b
Dakota	26	90	3	2580	Trace	-	93	1150	4750	6073	d
Dakota	26	90	3	2019	16	Trace	120	700	4050	4803	d
Dakota	26	90	11	2219	32	20	265	1300	3510	5436	d
Dakota	27	89	32	1211	-	-	325	358	1600	2969	b
Dakota	28	93	4	2229	18	5	51	2700	1285	5636	a
Lakota	19	88	22	417	2	1	0	44	964	975	a
Lakota	23	88	8	1591	-	-	738	-	2940	3775	b
Lakota	25	88	32	1413	-	-	-	1186	1710	3440	b

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Lakota	25	89	14	1503	0	0	0	1156	2000	3642	a
Lakota	26	89	21	1437	44	12	119	1060	2035	3673	b
Lakota	26	90	3	2580	Trace	-	93	1150	4750	6158	b
Lakota	28	93	8	2132	14	8	0	2735	1034	5398	a
Morrison	16	104	2	3266	-	-	1048	2450	2780	8299	b
Morrison	19	103	30	15479	854	243	7020	20800	202	44496	a
Morrison	26	90	11	1786	-	-	-	1051	2930	4278	b
Morrison	27	95	29	4330	22	2	30	5400	2240	10887	a
Sundance	16	104	10	3162	12	Trace	153	3250	2510	7876	d
Sundance	19	88	34	467	2	0	1	26	1120	1100	e
Sundance	19	103	18	6819	Trace	-	159	7696	4650	16960	d
Sundance	19	103	18	6082	62	31	1737	6240	3540	15893	d
Sundance	19	103	18	5288	23	Trace	151	3900	7200	12902	d
Sundance	19	103	18	5068	25	Trace	183	3744	6850	12388	d
Sundance	19	103	18	3069	82	Trace	451	2964	2720	7905	d
Sundance	19	103	18	3729	122	Trace	-	3744	3825	9476	d
Sundance	19	103	18	4006	101	52	16	4004	4280	10289	d
Sundance	19	104	2	18560	348	252	3407	26970	840	49950	d
Sundance	19	104	2	15687	122	170	2733	22450	750	41531	d
Sundance	19	104	24	6350	36	41	872	7124	3800	16292	d
Sundance	20	104	11	11361	326	121	905	17160	1070	30399	d
Sundance	20	104	11	2022	269	27	1469	1560	1770	6217	d
Sundance	23	88	6	1898	0	0	150	1140	2490	4005	a
Sundance	26	88	19	2056	-	-	76	2392	1145	5134	b
Sundance	26	88	25	2056	0	0	76	2392	1145	5136	a
Sundance	26	89	7	1657	-	-	-	1078	2395	3985	b
Sundance	26	89	16	1332	20	Trace	Trace	771	2275	3278	b
Sundance	26	90	10	1649	15	-	-	996	2710	3992	d
Sundance	26	90	10	1591	Trace	-	38	1050	2000	3841	d
Sundance	26	90	11	1546	22	Trace	32	1100	2235	3800	d
Sundance	26	90	11	1625	-	-	-	995	2600	3899	b
Nugget	18	103	18	3899	20	38	60	3267	4900	9677	b
Nugget	19	103	30	4443	69	19	21	3700	5700	11059	a
Nugget	19	104	?	2809	78	26	200	3705	580	7220	f
Nugget	19	104	10	3568	33	26	334	3213	2913	9017	e
Nugget	27	94	36	11758	374	29	2333	17000	85	31632	a
Nugget	28	93	13	1870	15	7	105	2250	940	4758	a
Nugget	28	93	16	1642	13	1	95	1922	973	4152	a

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Permian Rx	21	87	22	1091	898	351	318	3930	128	6660	e
Phosphoria	18	103	6	1555	386	71	1795	188	3050	5500	b
Phosphoria	18	103	18	5634	29	88	4395	3495	3700	15552	a
Phosphoria	28	93	4	1198	244	56	2428	480	330	4579	a
Tensleep	16	104	21	4312	-	-	1180	4263	2610	11038	b
Tensleep	18	103	6	11159	812	286	2163	16434	2500	32085	b
Tensleep	19	88	2	1440	315	53	1724	886	1333	5074	b
Tensleep	19	104	11	26637	973	370	2329	41000	2013	72300	a
Tensleep	19	104	13	15641	921	296	1977	23760	2405	43779	b
Tensleep	20	88		3123	194	44	1755	3000	1710	8958	a
Tensleep	23	88	6	1581	466	60	1675	2100	175	5968	a
Tensleep	23	88	20	29	43	35	93	20	222	339	e
Tensleep	24	88	32	1505	654	81	3217	1191	255	6773	b
Tensleep	25	86	34	863	570	157	1609	1493	201	4791	a
Tensleep	25	88	31	564	406	79	1556	612	100	3266	b
Tensleep	26	88	34	529	477	99	1820	399	355	3499	b
Tensleep	26	89	6	4790	51	137	3952	4312	2550	14956	b
Tensleep	26	89	21	572	303	56	1656	219	240	2924	b
Tensleep	26	90	11	1795	320	100	2124	1911	255	6375	b
Tensleep	26	90	12	5195	410	126	4100	4600	2147	15488	a
Tensleep	28	92	18	367	214	19	827	263	219	1798	a
Amsden	26	89	6	6895	Trace	-	5221	5746	1780	18737	b
Madison	21	87	9	82	46	18	161	50	150	514	c
Madison	21	87	16	369	144	40	663	229	246	1650	e
Madison	26	88	34	302	54	21	491	162	170	1114	b
Madison	26	89	6	3543	347	42	2828	3454	1138	10773	b
Madison	26	89	6	4884	536	126	3177	5500	1730	15075	a
Madison	26	89	24	455	262	24	1058	379	131	2242	a
Madison	26	90	11	2816	396	71	1998	3215	969	8973	b
Madison	28	94	2	204	98	11	380	20	375	899	a
Madison	29	96	20	411	289	111	32	495	1245	2142	a
Cambrian	21	87	10	399	74	35	655	86	329	1522	c
Cambrian	21	87	17	100	108	21	189	124	210	663	e
Cambrian	21	88	11	10	46	13	24	3	190	214	e
Cambrian	26	89	1	2886	430	229	2496	2391	1286	9964	a

Formation	Location T.	R.	Sec.	Na+K	Ca	Mg	SO_4	Cl	HCO_3	TDS	Reference
Cambrian	26	89	1	2886	430	229	2496	2391	1286	9964	a
Cambrian	27	97	22	248	19	-	258	98	220	731	a
Cambrian	27	97	28	338	-	-	72	230	312	841	a

(a) Berry, Delmar W., 1960, Geology and ground-water resources of the Rawlins area, Carbon County, Wyoming: U.S. Geol. Surv. Water-Wupply Paper 1458.

(b) Briggs, Paul and Espach, Ralph; 1960 Petroleum and natural gas fields in Wyoming. Bureau of Mines. Bulletin 582

(c) Collentine, Michael; Libra, Robert; Feathers, Kenneth; and Hamden, Latif; 1981, Occurrence and characteristics of Groundwater in the Great-Divide, and Washakie Basins, Wyoming: Report to U.S. Environmental Protection Agency.

(d) Crawford, Jame, G. 1940, Oil-fields waters of Wyoming and their relationto Geological Formations, American Association of Petroleum Geologists, Bulletin v. 24, #7, pp. 1214-1329.

(e) Welder, G. E., and McGreevy, L. J., 1966, Ground-water reconnaissance of the Great Divide and Washakie Basins and adjacent areas, southwestern Wyoming, U.S. Geological Survey Hydrologic Investigations Atlas HA-219.

(f) Crawford, J. G., 1963(?), Rocky Mountain Oil Field Waters: Chemical and Geological Laboratories, Casper, Wyoming.

Table 3. Flowing Thermal wells in the Great Divide-Washakie Basins, Wyoming.

Location T.	R.	Sec.	Formation	Formation depth feet	Map No.	Remarks
North Flank of the Sierra Madre						
19	87	29	Madison	5,798	3	BHT-148°F
19	87	15	Tensleep	6,068	2	Flowrate 3-5 gpm, BHT-134°F
19	88	12	Tensleep	5,416	4	BHT-135°F
20	88	35	Nugget	3,440	8	BHT-104°F
18	87	27	Dakota	2,523	1	Flowrate 145 gpm
19	88	22	Dakota	2,162	5	Flowrate 35 gpm, Surface Temp. 90°F
19.	88	34	Dakota	1,890	6	Flowrate 28 gpm, BHT-85°F
19	89	23	Frontier	5,712	7	Flowrate 7 gpm, BHT-111°F
Western Flank of the Sierra Madre						
16	92	12	Madison	12,150	19	Flow uncertain, BHT-240°F
15	91	11	Tensleep	10,093	11	Flowrate 10 gpm, BHT-188°F
16	92	12	Jelm	9,835	18	BHT-185°F
16	91	21	Nugget	9,193	15	BHT-197°F
16	91	22	Frontier	7,875	16	Flowrate 1.5 gpm, BHT-180°F
13	92	12		5,990	9	Flowrate 30 gpm, BHT-140°F
15	91	2	Deep Creek	2,680	10	Flowrate 20 gpm, Surface Temp. 70°F
15	91	15	Deep Creek	3,137	13	Flowrate 20 gpm, Surface Temp. 79°F
16	91	21	Deep Creek	2,834	14	Surface Temp. 69°F
16	91	22	Deep Creek	2,935	17	Flowrate 30 gpm, Surface Temp. 83°F
16	92	13	Deep Creek	3,932	NP*	Flowrate 5 gpm, Surface Temp. 70°F
15	91	14	Mesaverde	2,482	12	BHT-100°F
Separation Flats - Lost Soldier Region						
23	89	1	Tensleep	4,770	20	Flowrate 35 gpm, BHT-110°F
24	88	6	Tensleep	5,120	23	Surface Temp. 186°F
25	86	34	Tensleep	6,886	24	Flowrate 24 gpm, BHT-135°F
25	88	3	Tensleep	4,800	25	BHT-110°F
26	87	5	Tensleep	4,600	32	Flowrate 3 gpm, BHT-120°F
25	89	14	Jelm	3,472	29	BHT-96°F
25	88	4	Nugget	3,000	26	Flowrate 5 gpm, BHT-90°F
24	87	13	Sundance	3,300	21	BHT-95°F
24	88	5	Lakota	3,094	22	Flowrate 14 gpm, BHT-96°F
25	89	26	Dakota	2,662	31	Flowrate 58 gpm, Surface Temp 98°F
26	87	25	Dakota	2,662	33	Flowrate 1 gpm, BHT-88°F
25	88	32	Frontier	1,969	27	Flowrate 35 gpm, BHT-95°F
25	89	2	Frontier	2,097	28	BHT-80°F
25	89	24	Frontier	1,990	30	BHT-75°F
Baxter Basin						
19	104	22	Madison	6,505	40	Flowrate 145 gpm, BHT-155°F
19	103	10	Nugget	4,694	36	Strong flow??, BHT-104°F
19	103	16	Nugget	4,350	37	BHT-107°F
19	103	18	Nugget	4,120	38	Flowrate 350 gpm, BHT-104°F
19	104	11	Nugget	4,087	39	Flowrate 35 gpm, BHT-110°F
18	103	16	Dakota	2,654	34	BHT-96°F
18	103	18	Frontier	2,345	35	BHT-90°F
Isolated Locations						
22	97	28	Tensleep	2,500	41	Flowrate 225 gpm
27	193	28	Mesaverde	13,150	42	Flowrate 1.5 gpm, BHT-305°F

*Not plotted

Table 4. *Conductivity and heat flow values for the Great Divide-Washakie Basins, Wyoming.*

Hole Name	West Longitude	North Latitude	N+	Thermal conductivity 10^{-3}cal/ cm sec°C	Depth Range (feet)	Gradient °C/Km	Heat Flow 10^{-6}cal/ cm^2 sec	Reference
Baggs	107° 45.9	41° 3.8	24	6.0 ∓.9	394-705	26.9	1.6	
Sierra Madre								
#C & K	107° 14.4	41° 13.7	65	8.7 ∓.91	131-4,757	14.1	.9	
Bull Springs								
#1&3	107° 36.1	42° 5.9	15	5.0 ∓.6	66-505	18.5	.9	
#4	107° 35.9	42° 6.4	24	5.3 ∓.7	459-778	14.4	.8	
Hadsell Springs								
#5	107° 45.8	42° 10.4	54	5.8 ∓.6	623-1,673	17.8	1.0	
#3	207° 38.3	42° 10.4	54	5.8 ∓.6	722-1,608	11.0	.6	
Bringolf Ranch								
#79-8	108° 17.3	42° 50.6	27	6.0 ∓.9	131-394	18.1	1.1	
#79-4	108° 18.6	42° 51.4	14	6.0 ∓.9	164-591	19.6	1.2	
#79-5	108° 17.1	42° 51.1	11	6.0 ∓.9	131-951	17.8	1.1	
#79-3	108° 18.4	42° 52.2	20	6.0 ∓.9	66-705	19.2	1.2	
Sierra Madre								
SM-8	106° 53.8	41° 10.7	12	8.64∓.64	197-656	8.3	.8	Buelow, 1980
SM-11	107° 8.2	41° 13.3	20	6.32∓.25	210-840	15.2	1.0	Buelow, 1980
Green River	109° 25.0	41° 32.0	7	3.64∓.34	174-499	44.1	1.6	Sass et al., 1971
Rawlins	107° 27.0	41° 44.0	11	6.7 ∓.8	1,312-2,493	16.4∓.2	1.1	Decker and Bucher, 1979
Ferris	107° 8.0	42° 10.0	est	4.0	2,759*	34.5	1.4	Blackwell, 1969
Lost Soldier	107° 34.0	42° 14.0	est	4.0	2,395*	39.3-86.3		Blackwell, 1969
Pedro Mountain	106° 47.1	42° 18.2	16	9.02∓.22	1,640-2,116	14.8∓.03	1.3	Decker et al., 1980
21-12	107° 49.2	42° 22.3	16	7.01∓.22	459-1,181	21.0∓.1	1.5	Decker et al., 1980
KL7-8	107° 48.8	42° 22.4	12	6.60∓.10	984-1,509	24.6∓.4	1.6	Decker et al., 1980
SD 17-9	107° 49.5	42° 22.4	16	7.01∓.22	394-591	17.4∓.4	1.2	Decker et al., 1980
SD 3-8	107° 48.8	42° 22.6	16	7.01∓.22	558-951	25.6∓.1	1.8	Decker et al., 1980
Sheep Mountain								
KL-1	107° 48.4	42° 22.8	16	7.01∓.22	328-787	19.8∓.4	1.4	Decker et al., 1980
KL-2	107° 48.6	42° 22.8	16	7.01∓.22	689-1,083	18.0∓.2	1.3	Decker et al., 1980
PB 1-1	107° 48.9	42° 22.8	16	7.01∓.22	525-984	19.5∓.2	1.4	Decker et al., 1980
H6-2C	107° 48.9	42° 22.9	16	7.01∓.22	656-951	21.2	1.5	Decker et al., 1980
Jeffrey City								
GM-1	107° 39.4	42° 30.5	37	8.84∓.11	328-1,312	17.0∓.03	1.5	Decker et al., 1980
GM-2	107° 39.4	42° 30.5	30	8.77∓.19	459-1,542	16.4∓.04	1.4	Decker et al., 1980

*Average depth of logged hole
+Number of conductivity samples

Table 5. Conductive heat flow modeling of temperatures at select locations in the Great Divide-Washakie Basins, Wyoming.

Formation	Thermal Conductivity (10^{-3} cal/cm-sec. °C)	Temperature at Base of Formation (°F)[1]						
		Generalized Washakie Basin[2] Heat flow	Miller Hill Heat Flow		Lost Soldier and Separation Rim Heat Flow		Baxter Basin Heat Flow	
		58mW/m²	50mW/m²	67mW/m²	50mW/m²	67mW/m²	50mW/m²	67mW/m²
Lance	4.5	102						
Lewis	4.0	128						
Almond	6.0	134						
Ericson	7.0	140						
Rock Springs	5.5	158						
Blair	5.0	179						
Baxter	4.5	247	93	109	104	124	94	111
Frontier	4.4	256	103	123	115	138	99	117
Mowry	3.9	263	110	132	123	149	103	123
Thermopolis	6.1	265	111	133	126	153	105	125
Cloverly	8.7	266	111	134	127	154	106	126
Morrison	6.3	270	114	137	129	157	111	134
Sundance	7.4	273	115	139	131	160	113	137
Nugget	7.8	277	116	141	132	161	122	148
Chugwater	7.2	291	120	148	144	176	129	157
Dinwoody	2.8	295	124	150				
Phosphoria	9.6	297	125	155	146	179	131	160
Tensleep	10.4	301	127	159	149	184	134	163
Amsden	8.0	302	130	159	151	186	142	174
Madison	9.6	304	130	160	153	189	144	178
Cambrian	8.5	308	134	164	160	199	162	202

Notes: 1) The temperature increase across a formation is calculated by the expression: T = (Q/K) x C where Q = heat flow (mW/m²), K = thermal conductivity (10^{-3} cal/cm-sec-°C), x = formation thickness (ft.), and C = a conversion constant (1.31×10^{-3} m²-cal-°F/mW-cm-sec-ft-°C)

2) Average conductivity to the base of the Tertiary section is 4.6; 1,500 feet of Tertiary sediments will produce a temperature of 68° if heat flow is 58mW/m² and the surface temperature is 43°F. The table continues below this point.

Table 6. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Washakie-Great Divide 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	2	339	47	193.8	339	339	339	339
1,000 - 1,500	21	48	22	35.1	36	40	41	45
1,500 - 2,000	18	38	7	23.6	23	26	29	35
2,000 - 2,500	23	46	14	23.7	21	23	24	36
2,500 - 3,000	38	31	11	20.1	19	21	23	24
3,000 - 3,500	59	42	12	17.2	16	17	18	20
3,500 - 4,000	103	30	8	16.0	15	16	17	19
4,000 - 4,500	110	33	10	15.1	14	15	16	18
4,500 - 5,000	202	22	10	14.0	13	14	15	16
5,000 - 5,500	165	23	9	13.8	13	14	15	16
5,500 - 6,000	99	23	3	14.2	13	15	16	16
6,000 - 6,500	100	20	9	14.1	13	14	16	17
6,500 - 7,000	104	20	9	13.4	13	13	15	16
7,000 - 7,500	121	24	10	13.9	13	14	15	16
7,500 - 8,000	74	17	10	13.8	13	14	15	15
8,000 - 8,500	74	17	9	13.2	13	13	14	15
8,500 - 9,000	84	19	8	13.2	13	13	14	15
9,000 - 9,500	69	20	10	13.6	13	14	15	15
9,500 - 10,000	66	23	11	14.2	14	14	15	16
10,000 - 10,500	80	18	7	13.7	13	14	15	16
10,500 - 11,000	36	16	10	13.7	14	14	14	15
11,000 - 11,500	41	17	8	14.2	14	14	15	16
11,500 - 12,000	35	17	10	14.2	14	15	15	16
12,000 - 12,500	25	18	10	13.8	14	14	15	16
12,500 - 13,000	16	18	10	14.6	14	15	16	17
13,000 - 13,500	20	19	10	13.8	13	14	15	17
13,500 - 14,000	20	16	10	13.9	14	14	15	15
14,000 - 14,500	17	17	10	14.0	13	15	15	16
14,500 - 15,000	19	17	10	13.5	12	13	15	16
15,000 - 15,500	5	16	12	14.1	13	15	16	16
15,500 - 16,000	7	15	11	13.0	13	13	13	15
16,000 - 16,500	10	16	7	13.1	13	13	14	16
16,500 - 17,000	4	13	10	12.1	12	12	13	13
17,000 - 17,500	2	14	14	14.4	14	14	14	14
17,500 - 18,000	0	-	-	-	-	-	-	-
18,000 - 18,500	4	16	11	13.5	13	13	16	16
18,500 - 19,000	1	14	14	14.0	14	14	14	14
19,000 - 19,500	1	13	13	13.6	13	13	13	13
19,500 - 20,000	2	13	13	13.7	13	13	13	13
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	1	14	14	14.4	14	14	14	14
21,000 - 21,500	0	-	-	-	-	-	-	-
21,500 - 22,000	1	11	11	11.4	11	11	11	11

Total: 2,035 bottom-hole temperature measurements.

Table 7. Summary of gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperatures from the Washakie-Great Divide 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	2	313	88	200.5	313	313	313	313
1,000 - 1,500	21	113	68	85.9	85	88	95	95
1,500 - 2,000	18	118	54	83.4	82	87	90	108
2,000 - 2,500	23	145	79	96.0	94	95	102	122
2,500 - 3,000	38	132	72	97.3	96	102	108	112
3,000 - 3,500	59	170	82	98.0	96	99	104	110
3,500 - 4,000	103	158	75	102.2	101	105	112	118
4,000 - 4,500	110	180	85	106.1	105	109	113	119
4,500 - 5,000	202	152	92	108.8	107	112	116	121
5,000 - 5,500	165	162	92	114.1	113	116	121	128
5,500 - 6,000	99	182	64	124.0	120	129	135	145
6,000 - 6,500	100	170	102	130.0	128	135	144	151
6,500 - 7,000	104	180	107	132.6	131	137	144	153
7,000 - 7,500	121	220	118	142.5	141	149	156	159
7,500 - 8,000	74	180	123	148.3	148	53	158	162
8,000 - 8,500	74	181	124	151.0	151	156	160	164
8,500 - 9,000	84	210	118	157.7	160	165	169	179
9,000 - 9,500	69	232	135	168.0	166	176	185	186
9,500 - 10,000	66	274	151	179.7	179	184	193	200
10,000 - 10,500	80	228	123	182.1	180	186	198	208
10,500 - 11,000	36	218	158	189.2	192	197	202	209
11,000 - 11,500	41	241	140	201.6	205	210	219	225
11,500 - 12,000	35	242	160	208.5	214	220	228	231
12,000 - 12,500	25	270	168	210.5	213	219	224	239
12,500 - 13,000	16	280	176	227.4	225	243	250	262
13,000 - 13,500	20	305	183	224.1	220	232	248	280
13,500 - 14,000	20	270	193	232.7	236	244	255	256
14,000 - 14,500	17	292	190	242.6	240	261	275	280
14,500 - 15,000	19	298	203	240.6	235	241	276	279
15,000 - 15,500	5	292	230	255.6	240	282	292	292
15,500 - 16,000	7	286	228	246.4	248	250	251	286
16,000 - 16,500	10	303	156	253.1	262	263	270	303
16,500 - 17,000	4	264	222	243.0	250	250	264	264
17,000 - 17,500	2	300	285	292.5	300	300	300	300
17,500 - 18,000	-	-	-	-	-	-	-	-
18,000 - 18,500	4	334	256	288.5	296	296	334	334
18,500 - 19,000	1	302	302	302.0	302	302	302	302
19,000 - 19,500	1	305	305	305.0	305	305	305	305
19,500 - 20,000	2	318	310	314.0	318	318	318	318
20,000 - 20,500	0	-	-	-	-	-	-	-
20,500 - 21,000	0	-	-	-	-	-	-	-
21,000 - 21,500	1	350	350	350.0	350	350	350	350
21,500 - 22,000	1	289	289	289.0	289	289	289	289

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

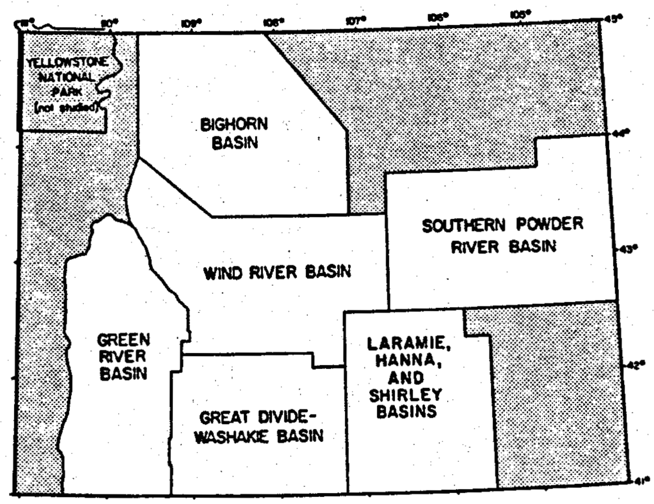


Figure 1. Study areas planned or completed in this series.

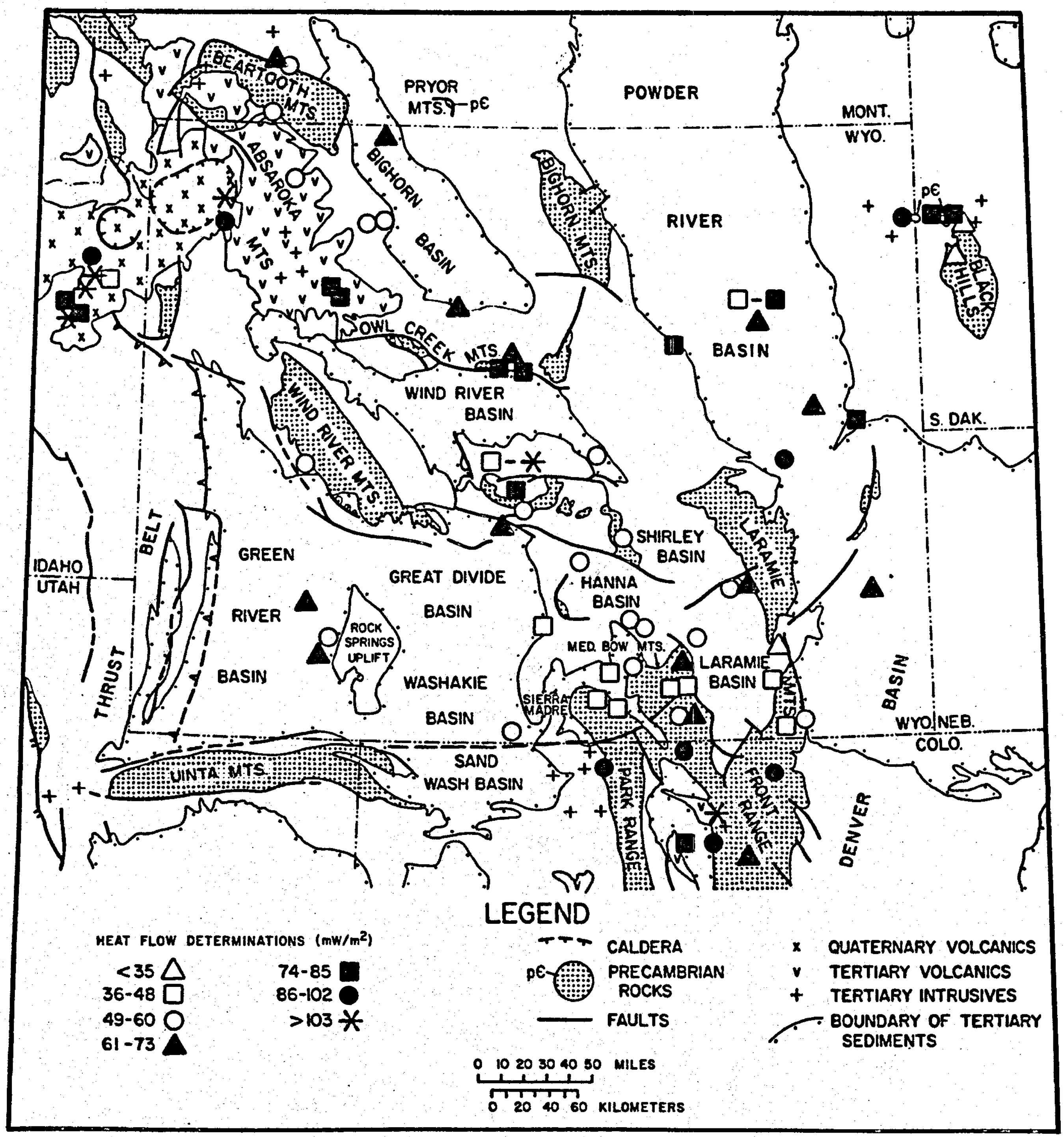


Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.

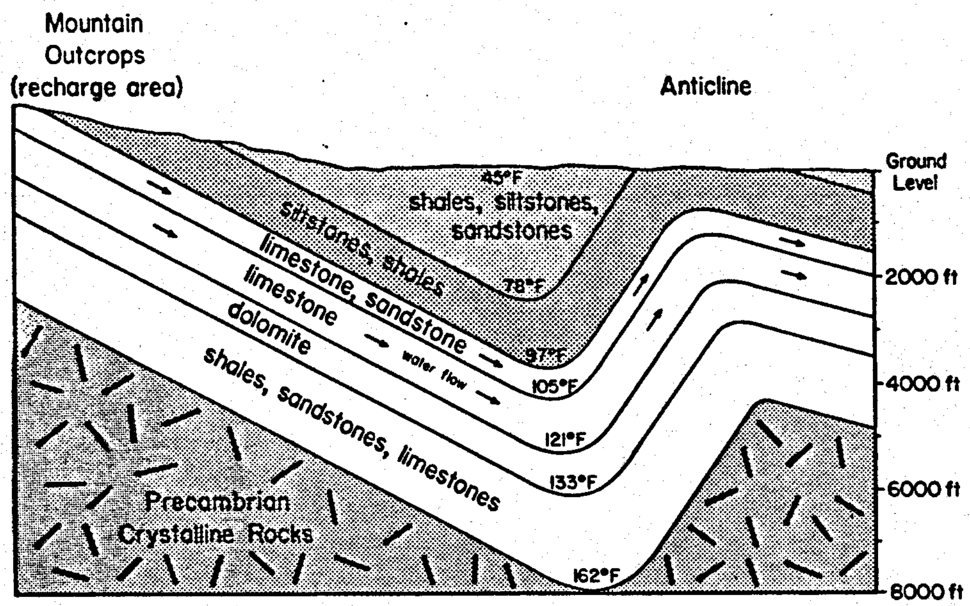


Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.

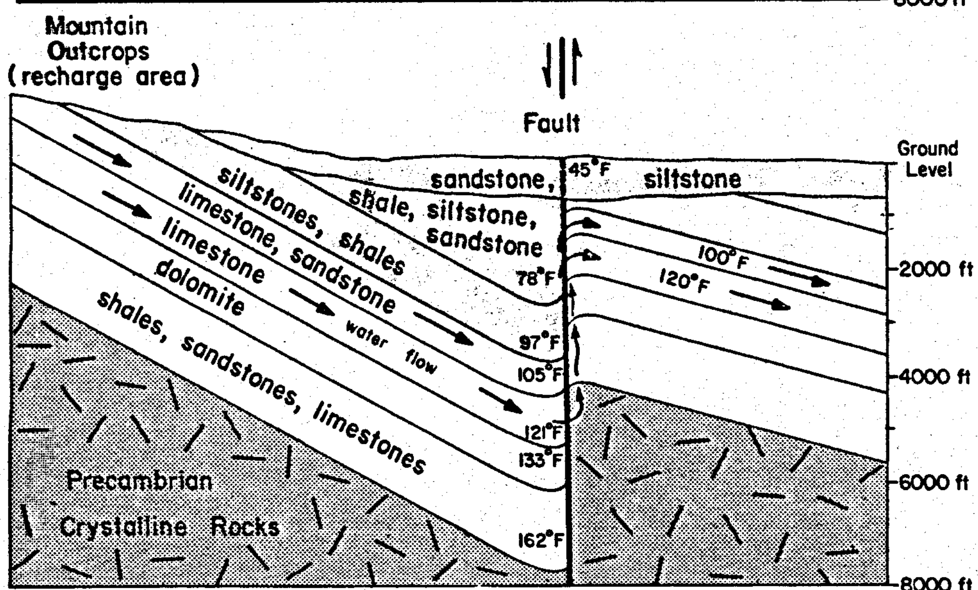


Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.

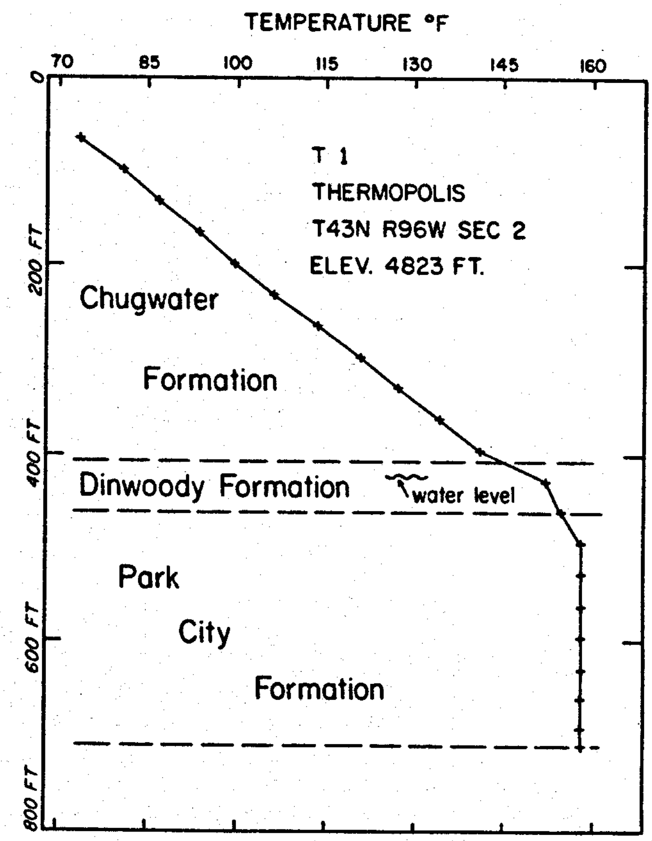


Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.

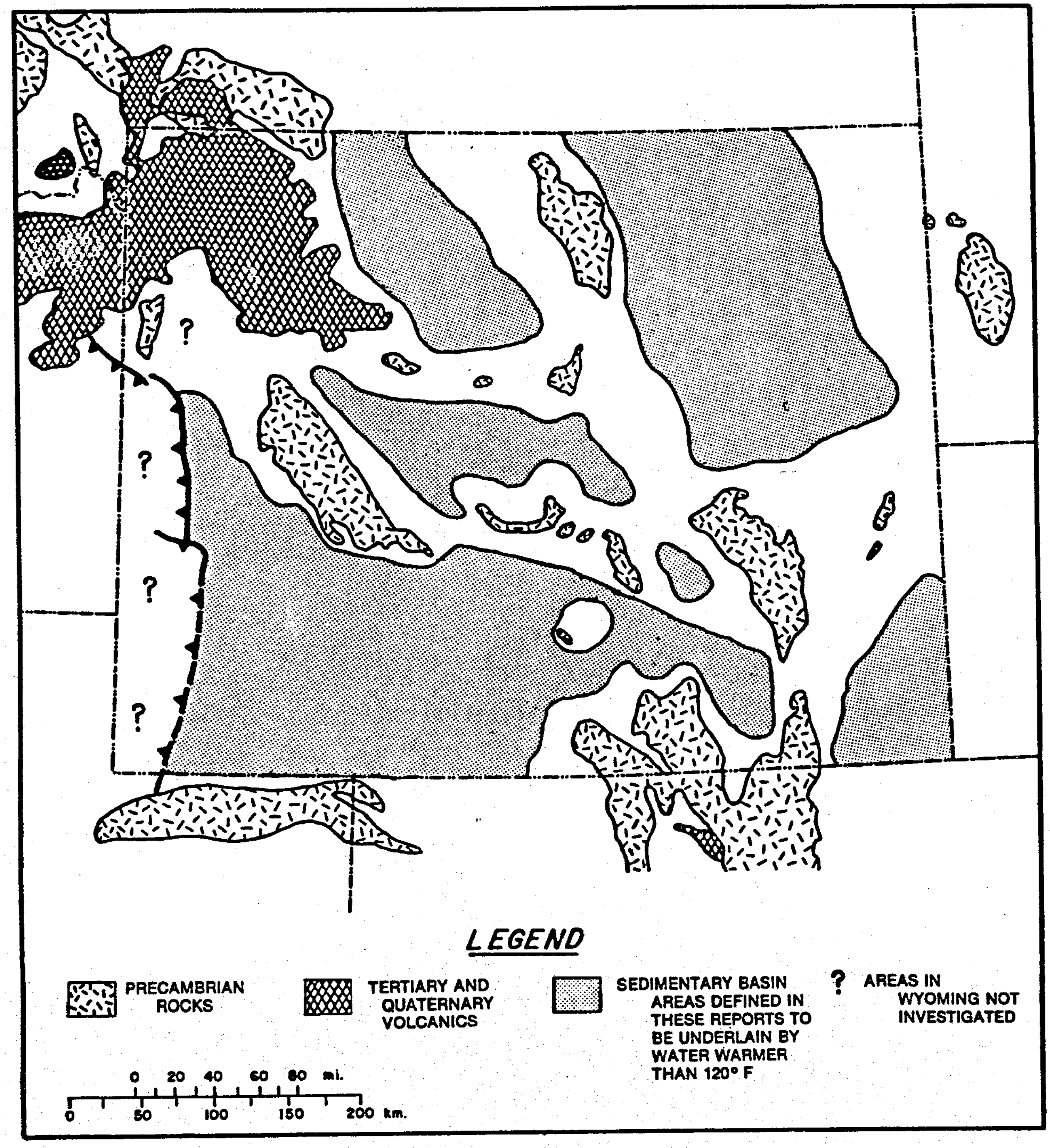
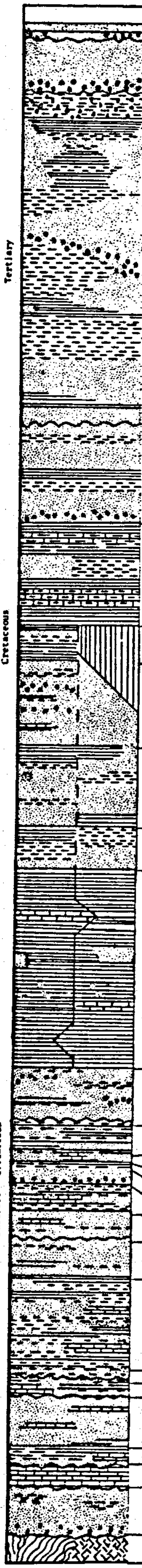


Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.



Age	Geologic Formation	Thickness (ft)[a]	Lithologic Description[b]	Water-Bearing Properties[b]
	Quaternary Deposits	0-70	Unconsolidated sands, silts, clays, and gravels	Well yields are generally less than 30gpm
	Browns Park, North Park, and South Pass Formations	0-1,200	Sandstone, fine to medium-grained, tuffs, limestone, and a basal conglomerate; South Pass Fm.- conglomerate with ashy sandstone matrix	Well yields range from 3-42 gpm; contains one spring flowing 343 gpm
	Bridger and Uinta Formations	0-3,200	Claystone, tuffaceous fine-grained sandstone with minor amounts of shale, limestone, and dolomite	Impermeable unit, low yields expected
	Green River and Wasatch Formations	0-1,500	Laney Shale Member- marlstone, shale, muddy and tuffaceous sandstone, and algal limestone Wilkins Peak Member- marlstone, claystone, oil shale, siltstone, tuff, and arkosic sandstone Cathedral Bluffs Tongue- claystone and shale, with coarse arkosic sandstone(north) and fine-grained sandstone(south)	
Cenozoic Tertiary	Wasatch Formation (West and South) Battle Spring Formation (Northeast)	0-4,000+ 0-4,700	Tipton Tongue and Tipton Shale Member- oil shale, fine-grained calcareous sandstone, clay, shale and algal limestone Wasatch Fm. (main body)- claystone, siltstone, fine-to medium-grained sandstone, oil shale, and coal Battle Springs Fm.- arkosic, fine-to coarse grained sandstone and claystone; with conglomerates and boulders present in the Green Mtn. area	Highly variable water yields due to very heterogeneous lithology; yields range between 5-250 gpm
	Fort Union Formation	0-2,700+	Sandstone, fine to coarse-grained, shale, and coal; contains siltstone and claystone in upper portion	Major aquifer; well yields range from 3 to 300 gpm; with water-bearing sandstones lenticular in shape causing discontinued isolated water-bearing zones
	Lance Formation	0-4,500+		
	Fox Hills Sandstone	0-400	Sandstone, very fine-to fine-grained lenticular, clayey, calcareous, shale, coal, and lignite	Well yields generally less than 25 gpm
	Lewis Shale	0-2,700	Shale, calcareous to noncalcareous, carbonaceous; contains beds of siltstone and very fine-grained sandstone	Major regional aquitard
Upper Cretaceous	Almond Formation — Mesaverde Formation (East)	0-5,600	Sandstone, siltstone, shale, and coal	Major aquifer, with reported yields generally less than 100 gpm; a maximum yield of 470 gpm is reported for a well producing from the Rock Springs Formation
	Ericson Formation — Mesaverde Formation (East)		Sandstone, fine-grained to conglomeratic; a middle siltstone and shale unit	
	Mesaverde Formation (East)		Sandstone, very fine to medium-grained, interbedded shale, lignite, and coal	
	Rock Springs Formation — Mesaverde Formation (East)		Sandstone, fine-to medium grained with interbedded shale and coal	
	Blair Formation — Mesaverde Formation (East)		Shale interbedded with siltstone and sandstone	
	Baxter Shale (West)	2,000-5,000	Shale with a small amount of interbedded sandstone, siltstone, and limestone	Major regional aquitard
	Cody Shale (Northeast)		Shale, contains beds of siltstone and lesser amounts of bentonite	
Mesozoic	Steele Shale and Niobrara Formation (East)		Shale, silty; with small amounts of fine-grained sandstone Shale, calcareous; contains some limestone	
	Frontier Formation	190-900+	Sandstone and shale; with beds of bentonite and lenses of chert-pebble conglomerate	Good water supply, with yields ranging from 1-100 gpm
Lower Cretaceous	Mowry Shale	150-525	Shale, siliceous; with siltstone and bentonite	Aquitard
	Muddy Sandstone	20-155	Sandstone, fine-grained; with beds of siltstone and shale	Some water produced within oil fields
	Thermopolis Shale	40-235	Shale, fissile; with beds of sandstone, siltstone, and bentonite	
	Cloverly Formation	45-240	Sandstone, shale, and conglomerate	Major aquifer, with yields of 25-120 gpm
Jurassic	Morrison Formation	170-450+	Claystone, shale, lenticular sandstone, and conglomerate	Confining unit
	Sundance Formation	130-450+	Sandstone, shale, siltstone, and limestone; upper portion is glauconitic	Artesian flows of 27-35 gpm in the Rawlins region
	Nugget Sandstone	0-650+	Sandstone, fine- to medium-grained; with minor amounts of interbedded shale and siltstone	Two wells are reported to produce from the Nugget with yields of 35 and 200 gpm
Triassic	Chugwater Formation	900-1,500+	Shale, siltstone, and interbedded sandstone, fine-grained; contains the Alcova Limestone Member	Confining unit
Perm.	Dinwoody Formation Phosphoria-Park City Formation	170-460	Shale, siltstone, and sandstone; interbedded	Unknown water-bearing characteristics
Paleozoic Penn.	Tensleep Sandstone	0-840+	Sandstone, medium-to fine-grained, locally quartzitic, with lesser amounts of thin-bedded limestone and dolomite	Major aquifer, with well yields ranging from 24-400 gpm; a Rawlins area spring flows 200 gpm
	Amsden Formation-Darwin Sandst.	0-260+	Sandstone, shale, and siltstone; contains cherty limestone	Unknown water-bearing characteristics
Miss.	Madison Limestone	5-325+	Limestone, dolomite, and thin-bedded sandstone and chert	Good secondary permeablity, yields <400 gpm
Cambrian	Flathead Sandstone and Cambrian undivided	0-800+	Sandstone, quartzitic and conglomeratic in lower portion, upper portion contains glauconitic sandstone and interbedded siltstone, shale, and limestone	Flathead Sandstone is a good aquifer, with well yields of between 4-250 gpm
P€	Precambrian		Granite, gneiss, and schist	Yields range between 10-20 gpm

(a) Formation thicknesses after Collentine et.al. 1981.

(b) Lithologic description and water-bearing properties from Berry, 1960; Collentine et.al., 1981; Welder and McGreevy, 1966.

Figure 7. Stratigraphic column for the Great Divide-Washakie Basins.

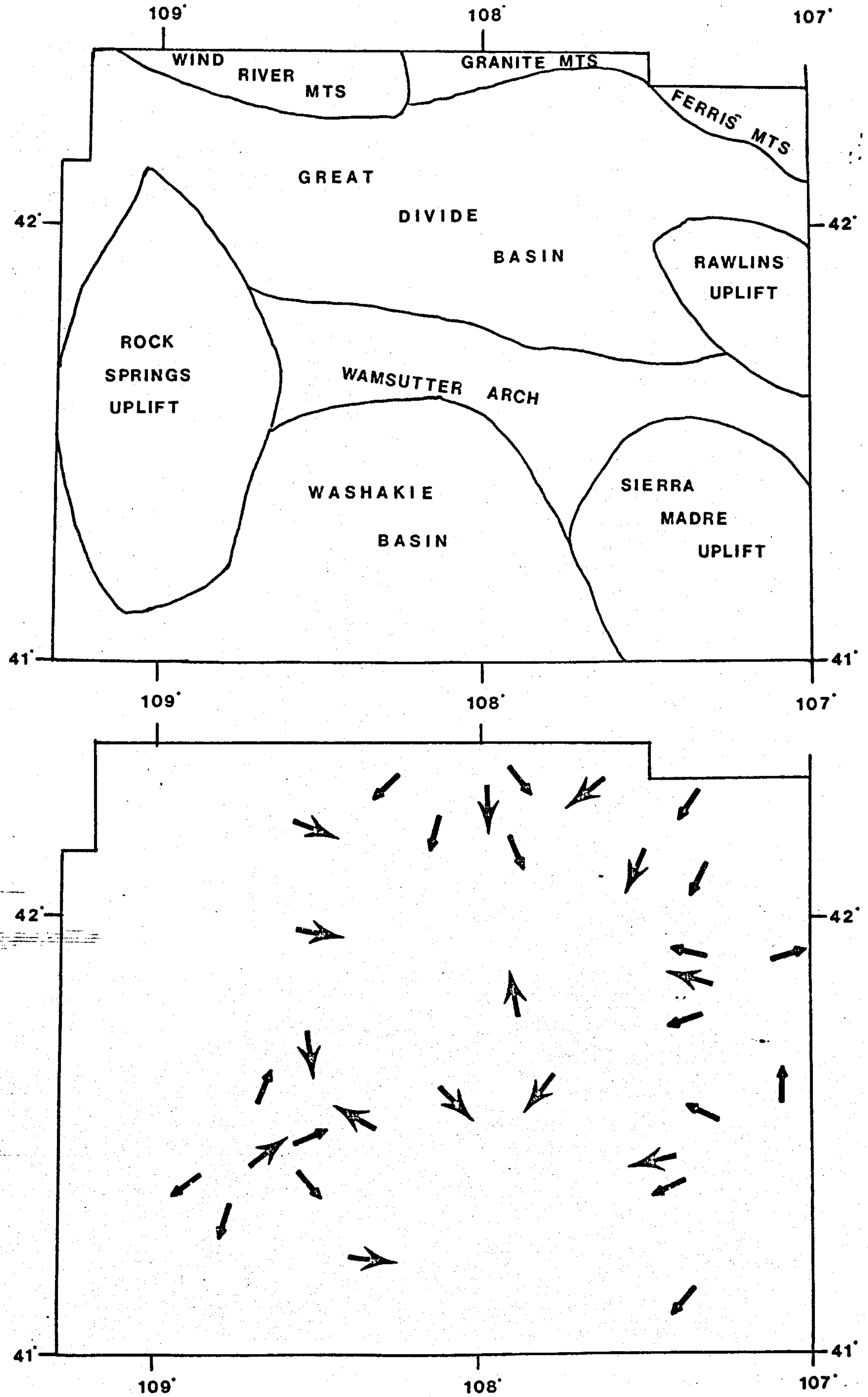


Figure 8. Major structural areas and generalized groundwater flow patterns (from Collentine et al.,1981) for the Great Divide and Washakie Basins.

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PLATE I

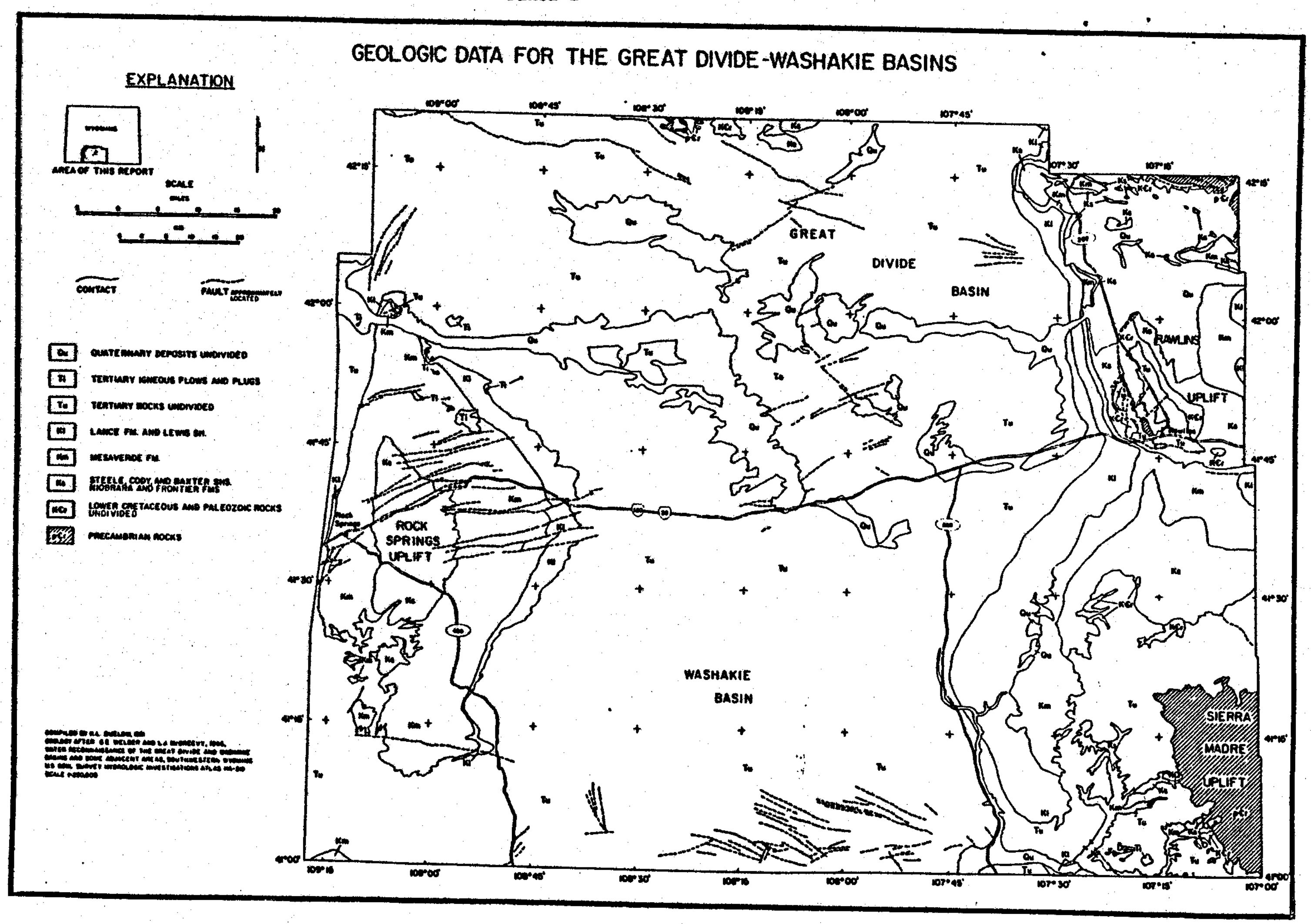

GEOLOGIC DATA FOR THE GREAT DIVIDE-WASHAKIE BASINS
EXPLANATION
AREA OF THIS REPORT
SCALE
CONTACT
FAULT
QUATERNARY DEPOSITS UNDIVIDED
TERTIARY IGNEOUS FLOWS AND PLUGS
TERTIARY ROCKS UNDIVIDED
LANCE FM. AND LEWIS SH.
MESAVERDE FM.
STEELE, CODY, AND BAXTER SHS. NIOBRARA AND FRONTIER FMS
LOWER CRETACEOUS AND PALEOZOIC ROCKS UNDIVIDED
PRECAMBRIAN ROCKS
GREAT
DIVIDE
BASIN
RAWLINS
UPLIFT
ROCK
SPRINGS
UPLIFT
WASHAKIE
BASIN
SIERRA
MADRE
UPLIFT

PLATE II

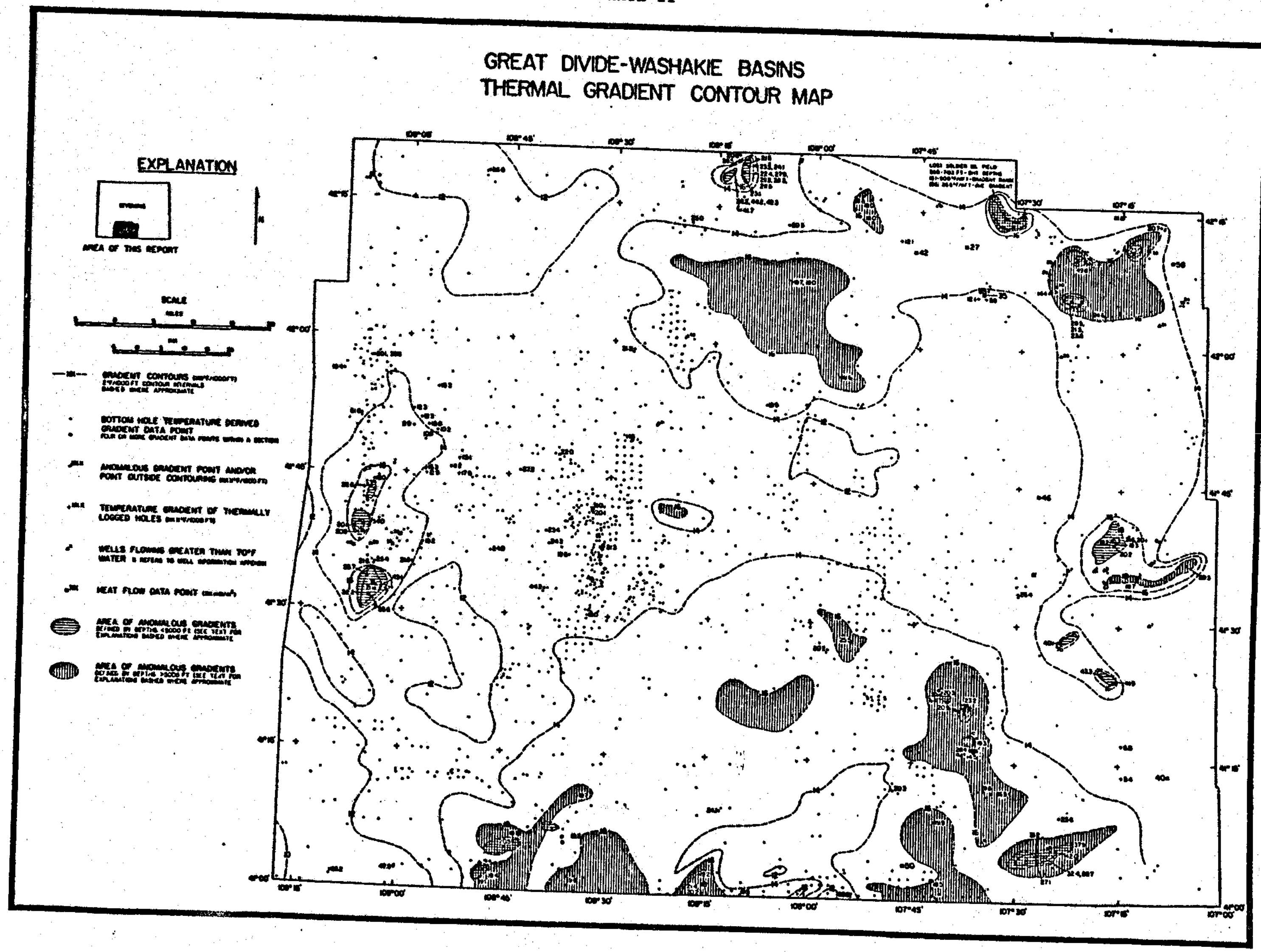

GREAT DIVIDE-WASHAKIE BASINS
THERMAL GRADIENT CONTOUR MAP
EXPLANATION
AREA OF THIS REPORT
SCALE
GRADIENT CONTOURS
BOTTOM HOLE TEMPERATURE DERIVED GRADIENT DATA POINT
ANOMALOUS GRADIENT POINT AND/OR POINT OUTSIDE CONTOURING
TEMPERATURE GRADIENT OF THERMALLY LOGGED HOLES
WELLS FLOWING GREATER THAN 70°F WATER
HEAT FLOW DATA POINT
AREA OF ANOMALOUS GRADIENTS
AREA OF ANOMALOUS GRADIENTS

PLATE III

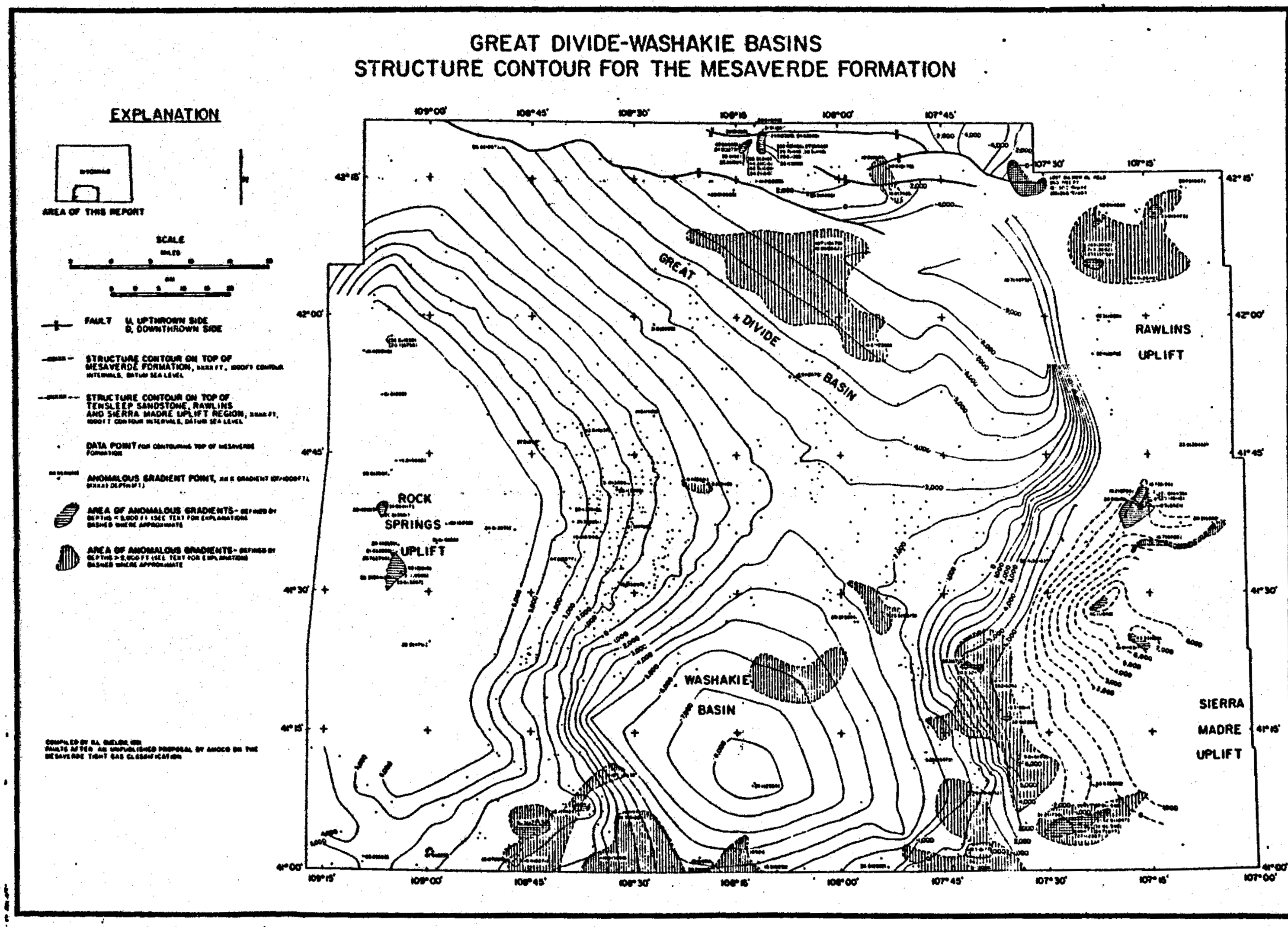
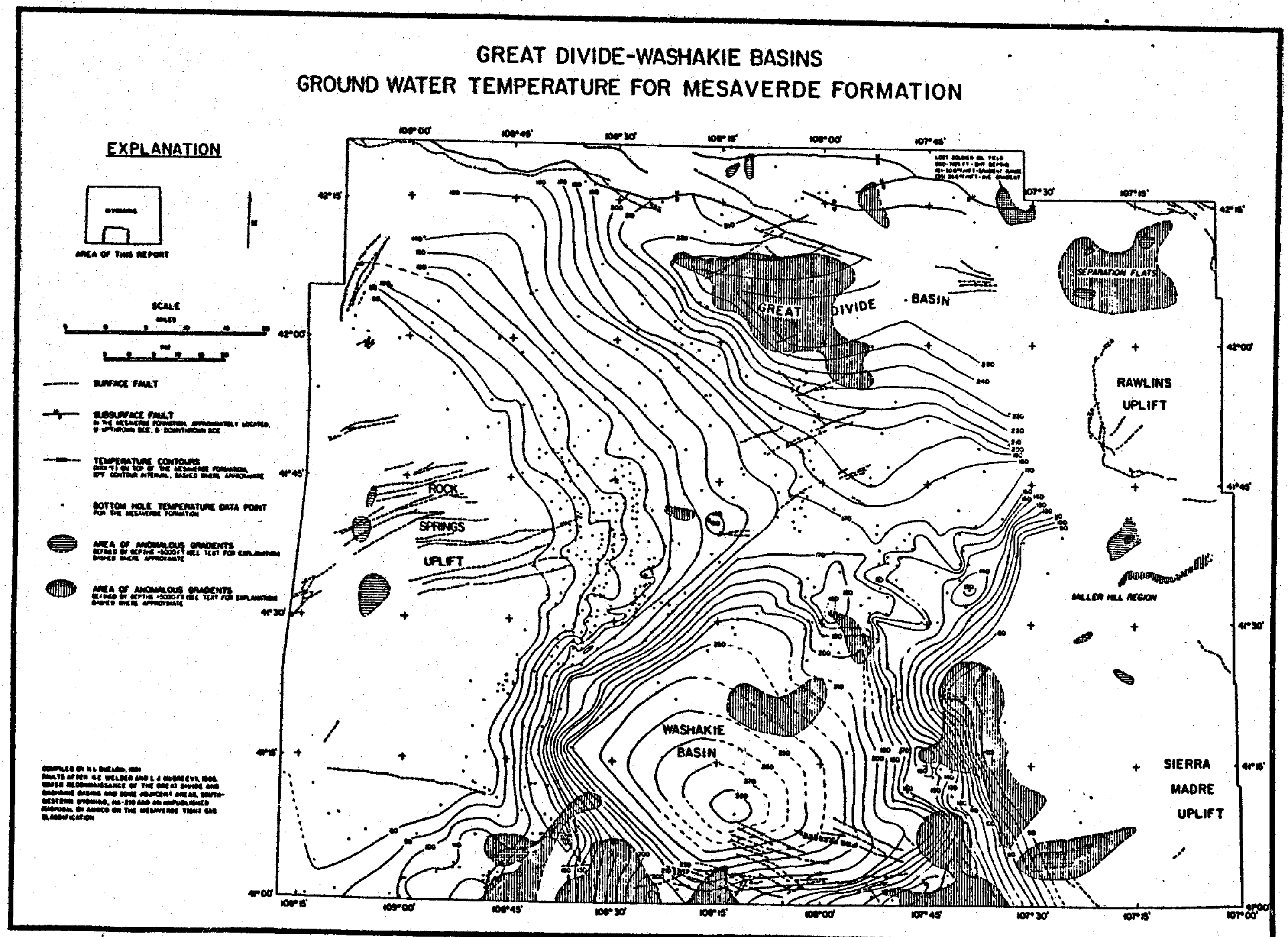

GREAT DIVIDE-WASHAKIE BASINS
STRUCTURE CONTOUR FOR THE MESAVERDE FORMATION
EXPLANATION
AREA OF THIS REPORT
SCALE
FAULT U, UPTHROWN SIDE D, DOWNTHROWN SIDE
STRUCTURE CONTOUR ON TOP OF MESAVERDE FORMATION
STRUCTURE CONTOUR ON TOP OF TENSLEEP SANDSTONE, RAWLINS AND SIERRA MADRE UPLIFT REGION
DATA POINT
ANOMALOUS GRADIENT POINT
AREA OF ANOMALOUS GRADIENTS
AREA OF ANOMALOUS GRADIENTS
GREAT DIVIDE BASIN
RAWLINS UPLIFT
ROCK SPRINGS UPLIFT
WASHAKIE BASIN
SIERRA MADRE UPLIFT
109°00'
108°45'
108°30'
108°15'
108°00'
107°45'
107°30'
107°15'
107°00'
109°15'
42°15'
42°00'
41°45'
41°30'
41°15'
41°00'

PLATE IV


GREAT DIVIDE-WASHAKIE BASINS
GROUND WATER TEMPERATURE FOR MESAVERDE FORMATION
EXPLANATION
AREA OF THIS REPORT
SCALE
SURFACE FAULT
SUBSURFACE FAULT
TEMPERATURE CONTOURS
BOTTOM HOLE TEMPERATURE DATA POINT
AREA OF ANOMALOUS GRADIENTS
AREA OF ANOMALOUS GRADIENTS
GREAT DIVIDE BASIN
SEPARATION FLATS
RAWLINS UPLIFT
ROCK SPRINGS UPLIFT
MILLER HILL REGION
WASHAKIE BASIN
SIERRA MADRE UPLIFT
109°00'
108°45'
108°30'
108°15'
108°00'
107°45'
107°30'
107°15'
107°00'
42°15'
42°00'
41°45'
41°30'
41°15'
41°00'