THE GEOLOGICAL SURVEY OF WOMING

Gary B. Glass, State Geologist

REPORT OF INVESTIGATIONS NO. 26

# GEOTHERMAL RESOURCES OF THE LARAMIE, HANNA, AND SHIRLEY BASINS, WYOMING

by Bern S. Hinckley and Henry P. Heasler

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Laramie, Wyoming 82071

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## CONVERSION FACTORS

| | |
|---|---|
| Length | 1 meter = 3.281 feet (ft)  1 foot = 0.3048 meters (m)<br>1 kilometer = 0.6214 miles (mi)  1 mile = 1.6093 kilometers (km) |
| Mass flow | 1 gallon per minute = 3.785 liters per minute (lpm)<br>1 liter per minute = 0.2642 gallon per minute (gpm) |
| Pressure | 1 pound per square inch = 0.07031 kilograms per square centimeter ($kg/cm^2$)<br>= 0.06805 atmospheres (atm.)<br>1 kilogram per square centimeter = 14.22 pounds per square inch (psi)<br>= 0.9678 atm. |
| Thermal gradient | 1 degree Fahrenheit per thousand feet =<br>= 1.823 degrees Celsius per kilometer (°C/km)<br>1 degree Celcius 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) =<br>= 241.8 British thermal units per foot per hour per degree Fahrenheit (Btu/ft hr°F)<br>= 0.418 watts per meter per degree Kelvin (W/m°K) |
| Heat flow | 1 microcalorie per square centimeter per second ($10^{-6} cal/cm^2 sec$)=<br>= 1 heat flow unit (HFU)<br>= 0.013228 British thermal units per square foot per hour ($Btu/ft^2 hr$)<br>= 0.418 milliwatts per square meter ($10^{-3} W/m^2$ or $mW/m^2$) |
| Temperature | 1 degree Fahrenheit = 0.56 degrees Celsius (°C)<br>1°Celcius = 1.8°Fahrenheit (°F)<br>°F = 1.8°C + 32  °C = (°F - 32)/1.8 |

# INTRODUCTION

This is the first in a series of reports describing the geothermal resources of Wyoming basins (see Figure 1). Each basin report will contain a generalized geological map, a thermal gradient contour map, a structure contour map and ground-water temperature map for a key formation, a discussion of hydrology as it relates to the movement of heated water, and a description and interpretation of the thermal regime.

The format of the reports will vary, as will 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 Laramie, Hanna, and Shirley Basins of southeastern 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. Compilations of oil well bottom-hole temperatures for each basin can be examined at the office of the Geological Survey of Wyoming in Laramie.

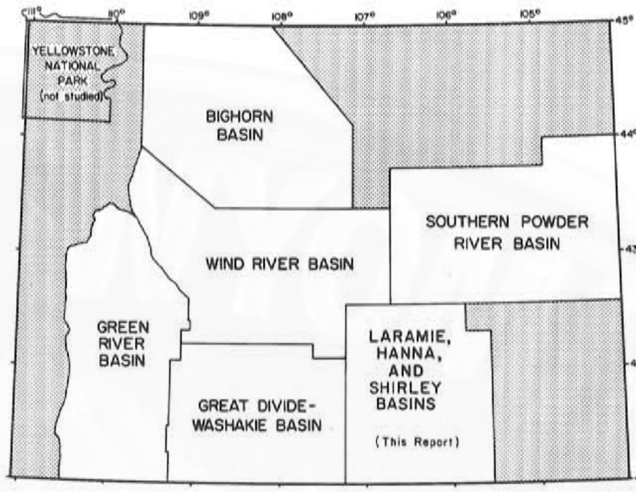


*Figure 1. Study areas planned or completed in this series.*

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

## GEOTHERMAL SYSTEMS AND RESOURCES

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

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

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

$$G=H/C$$

or,

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

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 in the basin interior. 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 gradients, it is likely that geothermal development will depend

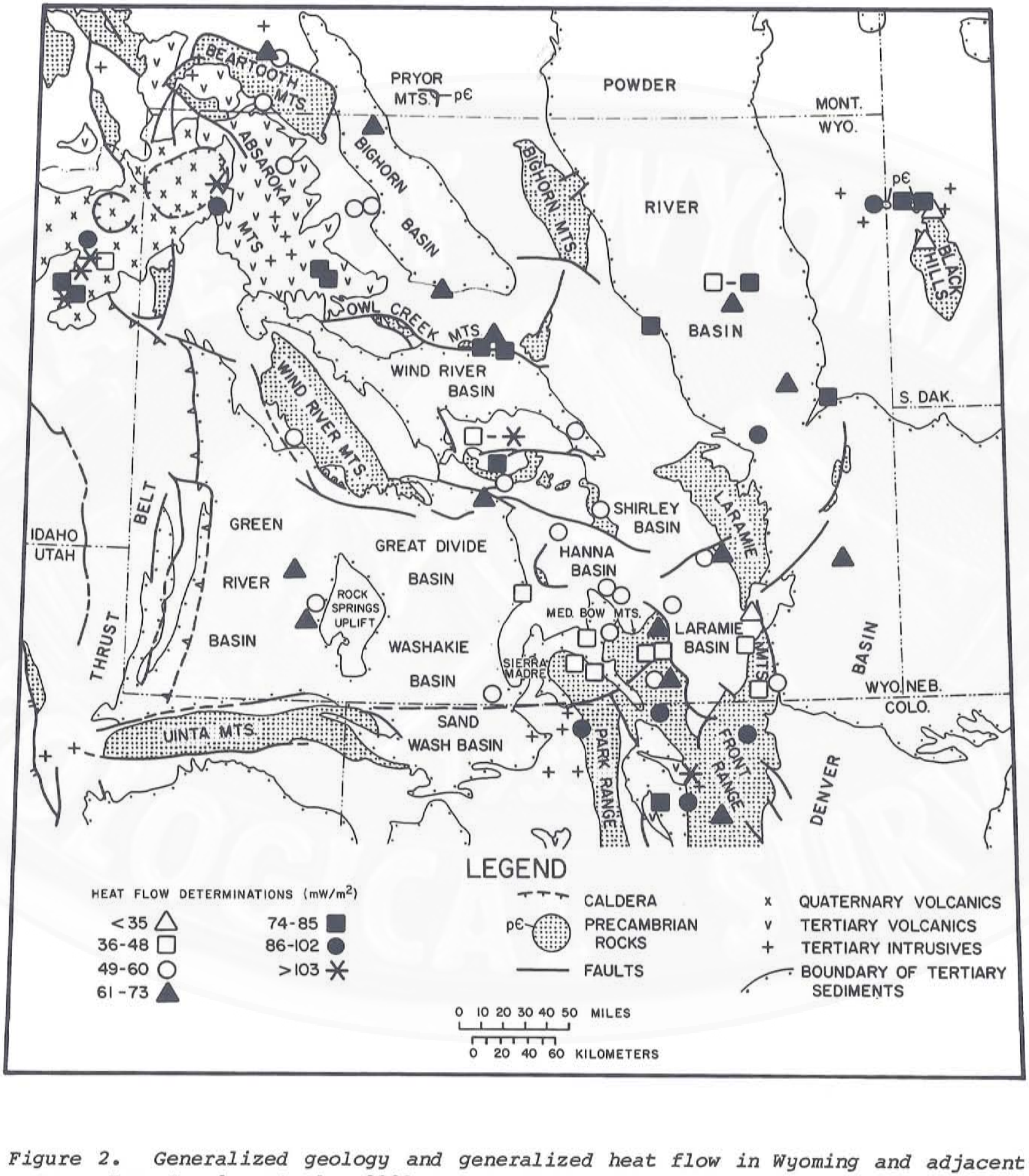


*Figure 2. Generalized geology and generalized heat flow in Wyoming and adjacent areas. From Heasler et al., 1982.*

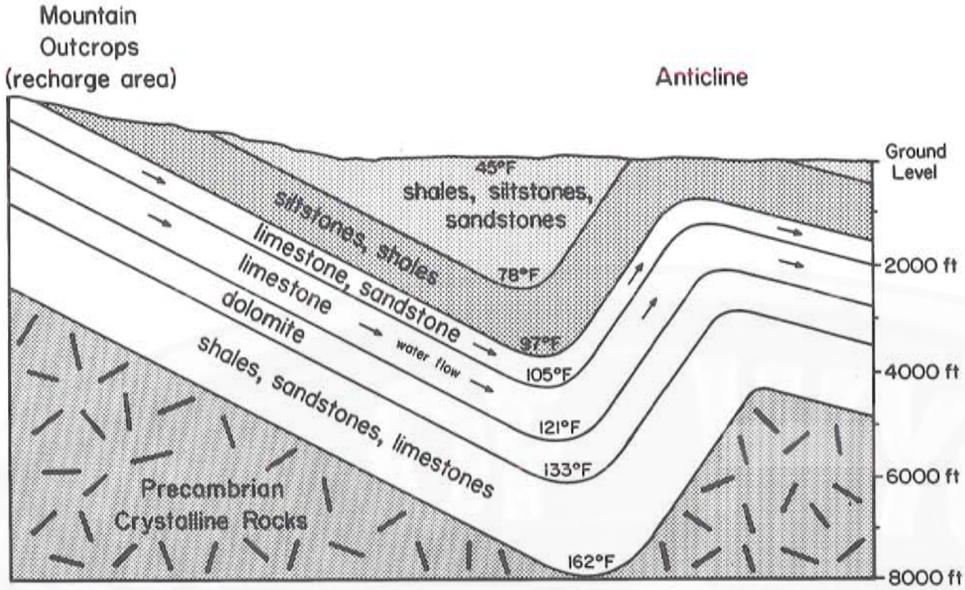


*Figure 3. Simplified cross section of a typical Wyoming fold-controlled geothermal system.*

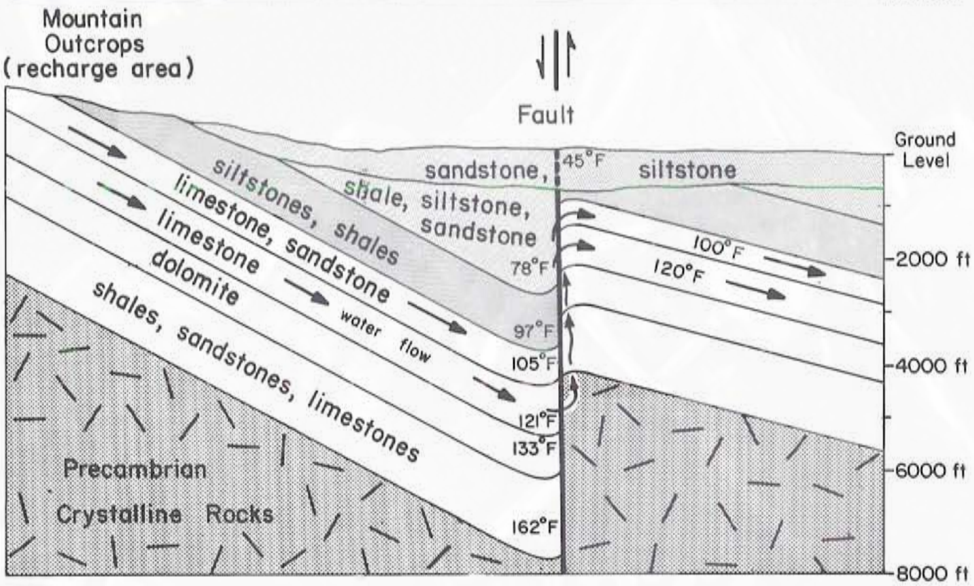


*Figure 4. Simplified cross section of a typical Wyoming fault-controlled geothermal system.*

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 (1983) 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 Resourçe 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 have been 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

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

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

| Basin: | Bighorn | Great Divide and Washakie | Green River | Laramie, Hanna, and Shirley | Southern Powder River | Wind River |
|---|---|---|---|---|---|---|
| Number of bottom-hole temperatures analyzed | 2,035 | 1,880 | 1,530 | 445 | 6,100 | 1,740 |
| Number of wells thermally logged | 70 | 68 | 47 | 57 | 60 | 67 |
| Background thermal gradient in °F/1,000 ft (°C/km) | 16 (29) | 15 (27) | 13 (24) | 12-15 (22-28) | 14 (25) | 15 (28) |
| Highest recorded temperature and corresponding depth | 306°F at 23,000 ft (152°C at 7,035 m) | 376°F at 24,000 ft (191°C at 7,300 m) | 306°F at 21,200 ft (152°C at 6.453 m) | 223°F at 12,000 ft (106°C at 3,600 m) | 275°F at 16,000 ft (135°C at 4,900 m) | 370°F at 21,500 ft (188°C at 6,555 m) |
| Basin depth in feet (km) | 26,000 (8.0) | 28,000 (8.5) | 30,200 (9.2) | 12,000; 39,000; 8,200 (3.7; 12.0; 2.5) | 16,400 (5.0) | 25,800 (7.6) |

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, whether 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. The fact that drilling fluids are circulating, acting to homogenize temperatures within the hole, is, on the other hand, 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 geothermal resources in 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 among the Wyoming basins are similar below levels of hydrologic disturbance 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 tem-

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

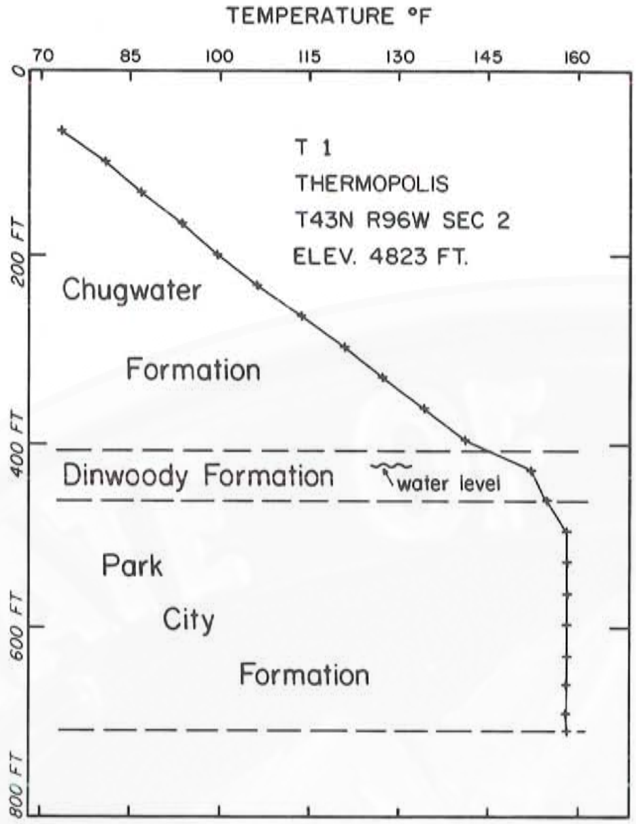


*Figure 5. Temperature-depth plot, based on a thermal log of a well at Thermopolis, showing hydrologic disturbance. From Hinckley et al., 1982.*

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 undisturbed temperatures relatively quickly.

(3) The third source of subsurface temperature data is measurements in springs and flowing wells. Since the amount of cooling which waters have undergone between an aquifer and its surface discharge is generally unknown, these sources provide only minimum temperature checks 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 of surface discharge of thermal water (greater than 70°F) are indicated on the thermal gradient maps.

## SUMMARY

Since 1979, the Wyoming Geothermal Resource Assessment Group has been investigating the geothermal resources of several Wyoming sedimentary basins. The Group has used oil well bottom-hole temperatures, thermal logs of wells, and heat flow data, all within a framework of geologic and hydrologic constraints, to reach their conclusions. These conclusions and data are being published as a series of reports on the various basins. A summary of the bottom-hole temperature data and thermal log data for each basin, along with background thermal gradients, is given 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). Much of this water is too deep to be economically tapped solely for geothermal uses (see Table 1 for the highest recorded temperatures and corresponding depths for each basin). However, both unsuccessful and producing oil and gas wells presently provide access to this significant geothermal resource.

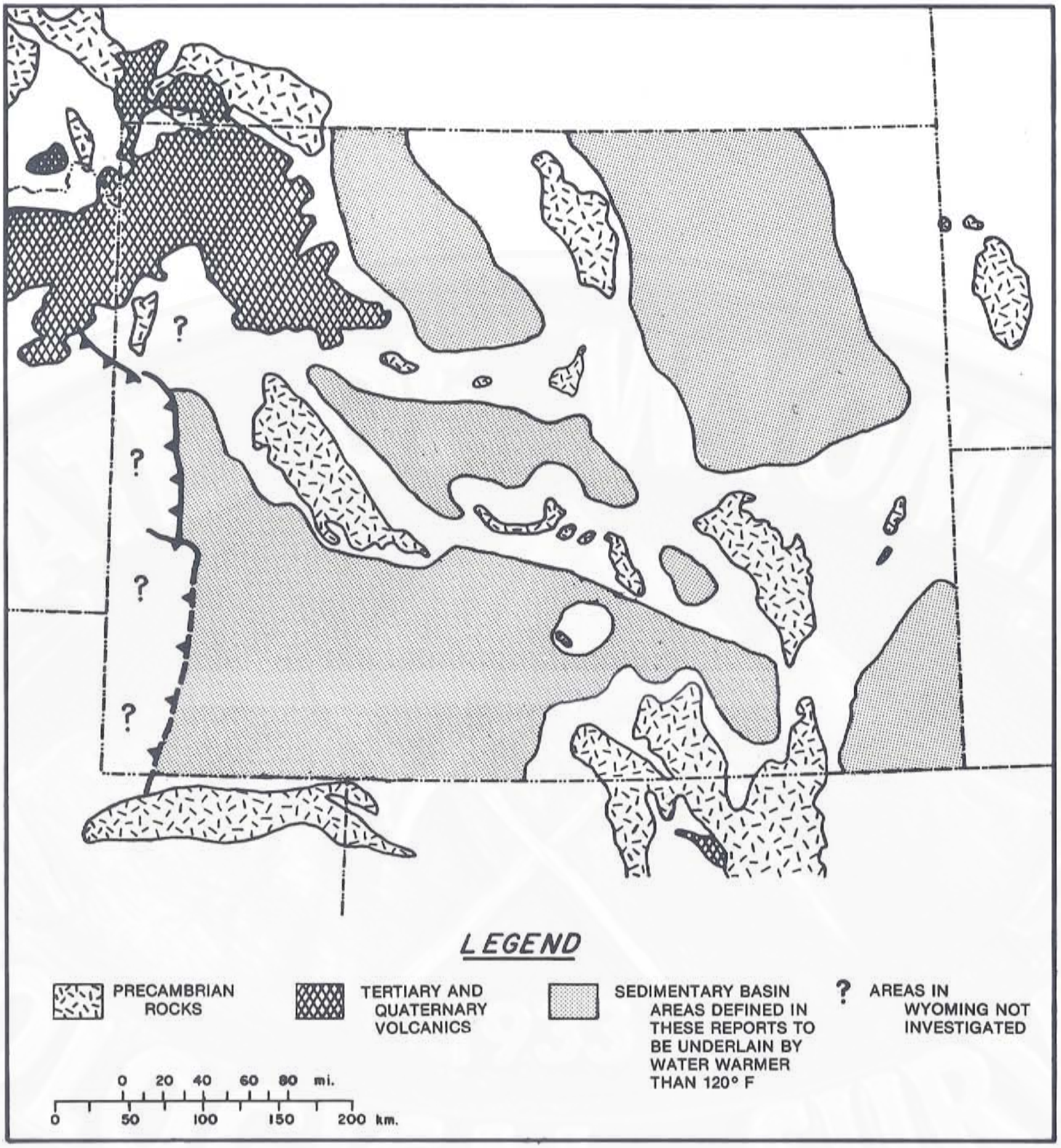


*Figure 6. Simplified geologic map of Wyoming, showing sedimentary basin areas defined in this series of reports to be underlain by water warmer than 120°F. After Heasler et al., 1983.*

(2) Isolated areas of high temperature gradients exist within each basin that was studied. These areas represent geothermal systems which might be developed economically. It will take additional work in these areas to define their extent and magnitude.

# GEOTHERMAL RESOURCES OF THE LARAMIE, HANNA, AND SHIRLEY BASINS

## STUDY AREA

The study area of this report occupies approximately 10,000 square miles in south-central Wyoming (Figure 1), including Albany County and parts of Carbon and Natrona Counties. The area is bounded on the east and north by the Laramie Range, a major uplift which exposes Precambrian rocks. The west and south boundaries are arbitrary -- the west edge roughly parallels the North Platte River, and the south boundary is the Wyoming-Colorado state line. The basins within the area are defined by major uplifts including the Sierra Madre, the Medicine Bow, Seminoe, and Shirley Mountains, and the Laramie Range.

The discussion of geothermal resources of the area includes sections on heat flow and conductive gradients, stratigraphy and hydrology, structure and water movement, measured temperatures and gradients, areas of anomalous gradient (including discussion of the warm spring systems at Alcova and Saratoga), temperatures of the Cloverly Formation, and summary and conclusions.

## HEAT FLOW AND CONDUCTIVE GRADIENTS

Heat flow has been calculated for 18 locations in the Laramie, Hanna, and Shirley Basins study area (see Table 2 and the thermal gradient map, Plate II). All heat flow values are considered moderate to low and preclude the existence of intermediate- or high-temperature geothermal systems at shallow depth. Heat flow for a hole is calculated from the measured thermal conductivity of the rocks in the hole and the thermal gradient over the depth of the hole. Since it is assumed that the heat flow is purely conductive, i.e. that there are no water movement effects (as discussed in the Introduction), the most reliable heat flow values are those from Precambrian basement rocks in which there is little water movement. In addition, the Precambrian rock conductivities are more accurately measurable than the conductivities of most available sediment samples.

The Precambrian rock heat flows - 33 to 50 $mW/m^2$ - represent the heat input to the bottom of the sedimentary section. Although such values have been determined only for the basin margins, the Cenozoic geology of the area (Blackstone, 1975) is such that the heat flow is probably similar across the basins.

Immediately south of the study area, in northern Colorado, a region of high heat flow has been identified (Buelow, 1980). The zone of transition to low heat flow in Wyoming is probably quite narrow (Buelow, 1980; Decker et al., 1980). A zone of moderate to high heat flow has been tentatively identified to the north of the study area: on the north side of the Laramie Range in the southern Powder River Basin, and in the northeastern Wind River Basin (Muffler, 1979; Decker et al., 1980). The moderate heat flows, 50-65 $mW/m^2$, calculated for the northern part of the study area may represent a broad transition zone to higher heat flows to the north.

Basement heat flow and estimates of the thermal conductivity of overlying sediments are used to calculate a thermal gradient, the gradient one would see in the absence of any water movement.

*Table 2. Heat flow values from the Laramie, Hanna, and Shirley Basins.*

| Location | Heat flow ($mW/m^2$) | Thermal conductivity (W/m°K) | Lithology | Reference |
|---|---|---|---|---|
| T.27N.,R.83W. sec. 17 | 54 | 3.77 | Precambrian granite | 2 |
| T.25N.,R.76W. sec. 4 | 70 | 2.72 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 4 | 57 | 2.42 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 4 | 53 | 2.38 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 12 | 39 | 2.80 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 12 | 56 | 2.42 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 12 | 51 | 2.42 | Tertiary sediments | 1 |
| T.25N.,R.76W. sec. 14 | 71 | 2.38 | Tertiary sediments | 1 |
| T.24N.,R.77W. sec. 27 | 69 | 2.38 | Tertiary sediments | 1 |
| T.20N.,R.78W. sec. 35 | 50 | 1.67 | Cretaceous shale | 3 |
| T.17N.,R.85W. sec. 24 | 50 | 2.51 | Tertiary sediments | 1 |
| T.17N.,R.82W. sec. 7 | 86 | 2.47 | Tertiary sediments | 1 |
| T.17N.,R.80W. sec. 11 | 41 | 5.67 | Precambrian quartzite | 4 |
| T.17N.,R.79W. sec. 2 | 45 | 5.54 | Precambrian quartzite | 4 |
| T.17N.,R.79W. sec. 27 | 50 | 2.63 | Precambrian quartz diorite | 2 |
| T.16N.,R.72W. sec. 1 | 33 | 2.09 | Precambrian anorthosite, granite | 2 |
| T.14N.,R.85W. sec. 13 | 33 | 3.61 | Precambrian quartzite, diabase | 4 |
| T.14N.,R.78W. sec. 8 | 68 | ? | Precambrian granite | 5 |

References: (1) Heasler et al., 1982; (2) Decker et al., 1980; (3) Blackwell, 1969; (4) Buelow, 1980; (5) Decker and Bucher, 1979.

Table 2 shows a representative range of thermal conductivities, expressed in watts per meter per degree Kelvin: 1.67 W/m°K for shale units, around 2.45 W/m°K for typical Tertiary sections (mixed sandstone, shale, siltstone and conglomerate), and from 3.5 to 5.5 W/m°K for various Precambrian rock types. (See Figure 7 for rock descriptions of the study area.) Decker et al. (1980) show that conductivity values for a typical Wyoming Paleozoic to middle Mesozoic section (mixed carbonate, sandstone, and shale) average 2.66 W/m°K.

In all three basins there is a general decrease in thermal conductivity upward in the sedimentary section, resulting from lithologic changes. While individual units, particularly shales, may have much higher gradients than adjacent units, a reasonable conductivity range for the thick, multi-unit sedimentary sections in the study area is 2.4-2.7 W/m°K. Thus, conductive gradients over large intervals will likely be less than approximately 12°F/1,000 ft.

A thermal gradient of 12°F/1,000 ft is not generally considered sufficient to represent a useful geothermal resource. Therefore, useful geothermal resources may exist in the Laramie, Hanna, and Shirley Basins area only where hydrologic systems significantly increase temperature gradients.

## STRATIGRAPHY AND HYDROLOGY

There are two major constraints on geothermal resources in the study area. First, thermal gradients are insufficient to provide high rock temperatures at shallow depth. This precludes development of "hot dry rock" geothermal systems in which outside water is pumped through hot rocks to produce steam. Second, high thermal gradients are created only where waters that have been equilibrated to deep rock temperatures are brought much closer to the surface. This requires the type of confined "plumbing" discussed in the Introduction and shown in Figures 3 and 4, and directs our attention to confined (artesian) aquifers. The following discussion centers on the stratigraphic column, Figure 7, and the geologic map of the Laramie, Hanna, and Shirley Basins and adjacent areas, Plate I.

There are important water-bearing strata at various depths throughout the study area. However, many of those strata which are important as water supplies (e.g. Quaternary alluvial deposits) are unconfined and do not have the deep circulation necessary to create high gradients. The Cenozoic section is reasonably permeable when considered basin-wide. Richter (1981) describes the units below the Cenozoic as "semi-confined"; artesian conditions are created locally where laterally continuous shale beds confine water-bearing sandstones.

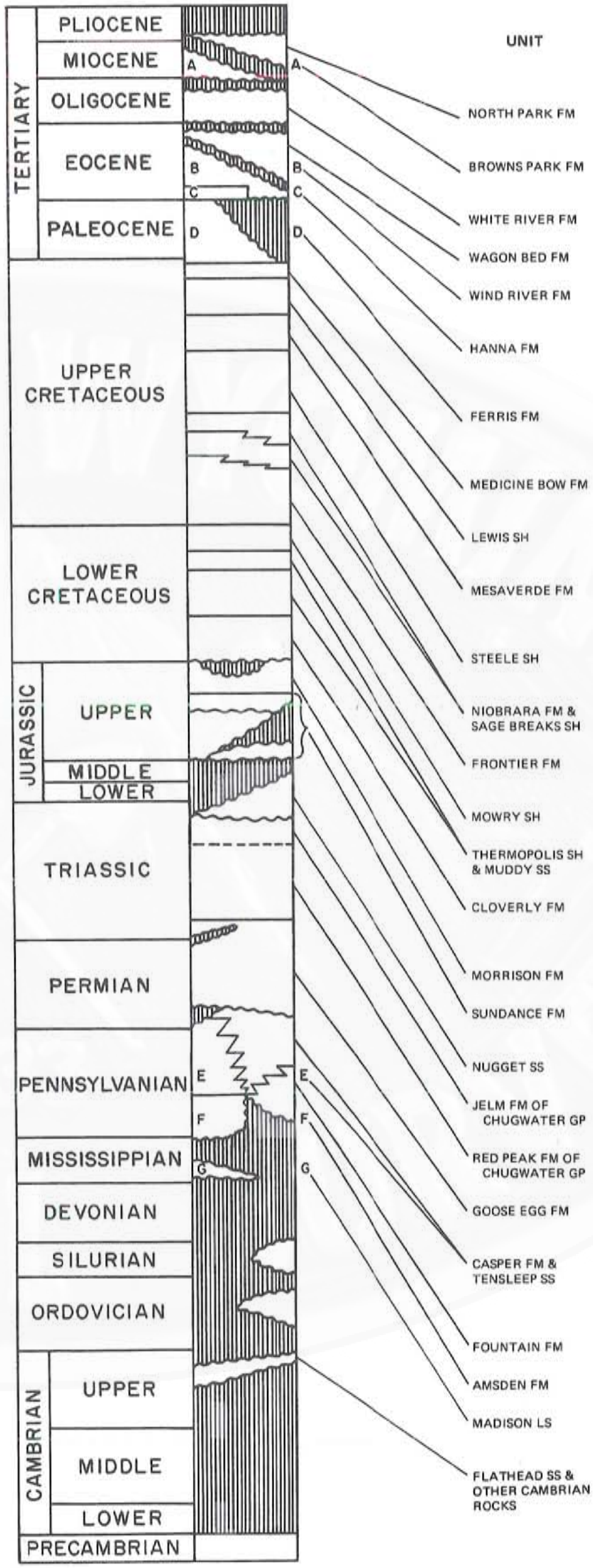


*Figure 7. Stratigraphic chart for the Laramie, Hanna, and Shirley Basins. Stratigraphic column modified from Wyoming Geological Association, 1969. Formation names from Wyoming Geological Association, 1969. Formation thicknesses from Lowry et al., 1973. Descriptions of lithology, water-bearing properties, and chemical quality from Richter, 1981. CGL=conglomerate; FM=Formation; GP=Group; GPM=gallons per minute of water flow; LS=limestone; mg/l=milligrams of solids per liter of water, SH=shale; SS=sandstone; STS=siltstone.*

*[1] According to Gary Glass (1984, personal communication); Lowry et. al., 1973 give 13,000 feet. [2] From Richter, 1981. [3] From Lowry et al., 1973.*

| THICKNESS (FEET) | LITHOLOGIC DESCRIPTION | WATER-BEARING PROPERTIES | CHEMICAL QUALITY |
|---|---|---|---|
| 0-1500 IN SARATOGA VALLEY | MEDIUM-COARSE SS WITH INTERBEDDED STS, CLAYSTONE, AND LS[3] | IMPORTANT AQUIFER; WELLS PRODUCE 1-300 GPM, SPRING FLOW UP TO 1300 GPM; TRANSMISSIVITY ESTIMATED AT 30,000 GPD/FT | GENERALLY <500 mg/1 |
| 0-1400 IN SARATOGA VALLEY; TO 180 IN SHIRLEY BASIN | FINE SS, CALCAREOUS, POORLY LITHIFIED | SHALLOW WELLS YIELD 1-100 GPM | GENERALLY <500 mg/1 |
| TO 750 IN SHIRLEY BASIN | INTERBEDDED TUFF, SS, CGL, STS, CLAYSTONE | HIGH PRIMARY PERMEABILITY; SHALLOW WELLS YIELD 1-10 GPM | GENERALLY <500 mg/1 |
| TO 150 IN SHIRLEY BASIN | CLAY-RICH SS, CLAYSTONE, TUFFACEOUS SS | LOCALLY YIELDS WATER TO SPRINGS AND SHALLOW WELLS | [NO DATA] |
| TO 300 IN LARAMIE BASIN; TO 500 IN SHIRLEY BASIN | ALTERNATING BEDS OF SS, CGL, CLAYSTONE, AND SH; GENERALLY POORLY CONSOLIDATED | IMPORTANT AQUIFER IN SHIRLEY BASIN, WATER YIELDS LOCALLY VARIABLE | GOOD WATER QUALITY; GENERALLY <500 mg/1 |
| TO 8000 IN HANNA BASIN[1] | ALTERNATING BEDS OF SS, SH, CGL, AND COAL | HIGHLY VARIABLE WATER-BEARING PROPERTIES DUE TO LOCALLY CONFINING SH, DISCONTINUOUS SS, VARIABLE LITHOLOGIES THROUGHOUT; ARTESIAN CONDITIONS EXIST LOCALLY | VARIABLE QUALITY; 550-4000 mg/1 |
| TO 6500 IN HANNA BASIN | MASSIVE CONGLOMERATIC SS WITH INTERBEDDED SH AND COAL; SS MORE LENTICULAR AND SHALEY TOWARDS TOP | HIGHLY VARIABLE WATER-BEARING PROPERTIES DUE TO LOCALLY CONFINING SH, CHANNEL SS, DISCONTINUOUS LITHOLOGIES THROUGHOUT; WELLS YIELD 1-100 GPM | GENERALLY 1000-2000 mg/1; RANGE 600-6900 mg/1 |
| 400 IN NORTH LARAMIE BASIN TO 6200 IN HANNA BASIN | MEDIUM-FINE SS WITH INTERBEDDED SH AND COAL; INCREASINGLY SHALEY TOWARDS TOP[3] | LOCALLY YIELDS WATER TO SPRINGS AND SHALLOW WELLS | [NO DATA] |
| 2500-3900 | SH AND STS WITH INTERBEDDED SILTY SS; SS PROPORTION HIGHEST IN LOWER BEDS | GENERALLY A CONFINING LAYER; LOCAL DISCONTINUOUS SS LENSES MAY YIELD SMALL AMOUNTS OF WATER | GENERALLY POOR QUALITY; >2500 mg/1 |
| 2000-4000 | INTERBEDDED SS, SH, AND STS; BEDS THIN-BEDDED TO MASSIVE, LATERALLY PERSISTENT TO LENTICULAR; COAL BEDS | AQUIFER THROUGHOUT AREA; HIGH PRIMARY PERMEABILITY; SHALLOW WELLS COMMONLY YEILD 1-33 GPM; FRACTURE-ENHANCED PERMEABILITY MAY INCREASE LOCAL FLOW | GENERALLY GOOD QUALITY; <1000 mg/1 |
| 2500-3000 | SH; INTERBEDDED SS INCREASING TOWARDS TOP; SHANNON SS MEMBER AT TOP | REGIONAL CONFINING UNIT; MINOR WATER YIELDS (1-25 GPM) FROM UPPER SS MEMBER | AROUND 1000 mg/1 IN UPPER SS MEMBER |
| 800-1100 | CALCAREOUS SH, THIN LS LAYERS INTERBEDDED, LOCAL SS LENSES | GENERALLY A CONFINING LAYER; MINOR LOCAL WATER YIELDS FROM SS BEDS | VERY POOR QUALITY; 55,000 mg/1 |
| 550-950 | SH WITH MANY DISCONTINUOUS INTERBEDDED SS BEDS | MINOR YIELDS (<10 GPM) FROM SS BEDS | [NO DATA] |
| 100-200 | SILICEOUS SH AND CLAYSTONE | REGIONAL CONFINING UNIT | [NO DATA] |
| 100-250 | SH; SILTY SS MEMBER AT TOP | REGIONAL CONFINING UNIT; SS MEMBER UNDER ARTESIAN CONDITIONS FLOWS UP TO 20 GPM | GENERALLY POOR QUALITY; 4000-10,000 mg/1 |
| 100 | FINE-MEDIUM SS, BASAL CGL, SH MEMBER NEAR MIDDLE | MAJOR AQUIFER; GOOD PRIMARY PERMEABILITY, ARTESIAN CONDITIONS COMMON; PERMEABILITY ENHANCED IN DEFORMED AREAS; PRODUCES WELLS FLOWING UP TO 150 GPM | HIGHLY VARIABLE QUALITY; RANGE 188-24,000 mg/1 |
| 200-300 | SH AND CLAYSTONE; SOME LS AND SS | GENERALLY A CONFINING LAYER; MINOR (<5 GPM) YIELDS | >5000 mg/1 |
| 54-230 | SS AND SH WITH SOME LS; BASAL SS POORLY CEMENTED | GENERALLY A CONFINING LAYER; BASAL UNITS YIELD 1-50 GPM FLOWING WELLS | 500-3000 mg/1 |
| 0-50 | LIMEY SS WITH SOME STS AND SH | HIGH PRIMARY PERMEABILITY; 50-100 GPM FLOWING WELLS | 1000-3000 mg/1 |
| 25-360 | SH, SS, AND STS; MASSIVE, CROSSBEDDED SS AT TOP | ARTESIAN CONDITIONS WITH FLOWS OF UP TO 10-25 GPM | [NO DATA] |
| 600-700 | STS, SH, FINE SS; ALCOVA LS ON TOP | REGIONAL CONFINING UNIT; MINOR YIELDS (<10 GPM) FROM BASAL SS | 1000-2500 mg/1 |
| 250-380 | SH AND STS, INTERBEDDED LS AND GYPSUM; SOME SS | REGIONAL CONFINING UNIT; MINOR YIELDS (1-15 GPM) FROM FRACTURED LS | [NO DATA] |
| 500-800 | MEDIUM-FINE SS COMMONLY CROSSBEDDED; INTERBEDDED VARY-FINE-GRAINED LS BEDS | MAJOR AQUIFER; PERMEABILITY HIGHLY DEPENDENT ON FRACTURING; POOR PRIMARY PERMEABILITY; EXCELLENT PRODUCTION (UP TO 8000 GPM) FROM ZONES OF FOLDING, FRACTURING, AND FAULTING; YIELDS 50-100 GPM BASIN-WIDE | <500 mg/1 NEAR OUTCROP AREAS; >3000 mg/1 IN BASIN INTERIORS |
| 0-575[2] | SS, STS, AND CGL | HIGHLY PERMEABLE WHERE FRACTURED | 500->2000 mg/1 |
| 0-240 | SH, SANDY SH; SS AT BASE | NO SIGNIFICANT WATER YIELD | [NO DATA] |
| 0-500 | LS AND CHERTY LS; SS AT BASE | SMALL YIELDS LOCALLY; PERMEABILITY HIGHLY DEPENDENT ON FRACTURING AND SOLUTION | [NO DATA] |
| 0-100 | QUARTZITIC SS, CONGLOMERATIC IN LOWER PART[3] | [NO DATA] | [NO DATA] |
| | GRANITIC AND METASEDIMENTARY ROCKS | YIELDS SMALL AMOUNTS IN OUTCROP AREAS (1-25 GPM) | <300 mg/1 |

In the Hanna Basin there are up to 20,000 feet of unconfined to "semi-confined" uppermost Cretaceous and Cenozoic sediments (down to the top of the Lewis Shale). Based on normal conductive gradients (see previous sections), temperatures up to 280°F can reasonably be expected at the base of this section. Some of these hot waters may move to shallower depths up folds, faults, or drill holes.

The shallowest basin-wide confining layer in the study area is the Cretaceous Lewis Shale. This formation is absent over most of the Laramie and Shirley Basin, but may confine waters in the Mesaverde aquifer in the Hanna Basin. In the central portion of the Hanna Basin, the Mesaverde Formation is likely too deep for economic geothermal development. Structures like those diagramed in Figures 3 and 4 may exist around the basin margins. The generally good primary permeability of the Mesaverde Formation is increased by fractures in areas of folding and faulting and water quality is generally good. Given favorable structures (see next section), the formation could provide locally useful geothermal resources.

Over most of the study area, the Steele Shale effectively confines all underlying units. Conductive gradients through this thick (about 3,000 feet) shale sequence are likely in the 14-17°F /1,000 ft range. (The shale conductivity of 1.67 W/m°K listed in Table 2 is an estimate for the Steele Shale, confirmed by a 1.68 W/m°K value determined by University of Wyoming laboratory tests [unpublished results, Heat Flow Laboratory, Geology Department, University of Wyoming].) Beneath the Steele Shale are the predominantly shaley Niobrara and Frontier Formations, the latter a very minor aquifer. Below these are two more regionally confining shale units, the Mowry and Thermopolis Shales. Thus, there are about 5,000 feet (up to 6,800 feet) of generally very low permeability and low thermal conductivity sediments above the first major aquifer of these basins, the Cloverly Formation.

The Cloverly Formation has good primary permeability, which is significantly enhanced by fracturing in areas of deformation. Water quality is variable, but total dissolved solids are commonly less than 500 mg/l (milligrams per liter). Artesian conditions are virtually ubiquitous: Cloverly wells flow up to 150 gpm (gallons per minute) at the surface. These characteristics, its thermally and hydrologically highly favorable stratigraphic position, and its region-wide occurrence make the Cloverly Formation an attractive geothermal target.

Beneath the Cloverly Formation is another sequence of confining layers including the Morrison and Sundance Formations and the Chugwater Group. The Nugget Sandstone is present in the middle of this sequence in the easternmost Hanna Basin and may be of local geothermal importance. Below the Goose Egg Formation is the second major aquifer of the basins, the combined Tensleep Sandstone - Casper Formation and Fountain Formation. Where present, the underlying Amsden Formation and Madison Limestone may also contribute to this aquifer. Generally termed the Casper aquifer, this sequence of rocks does not have large primary permeability, but has secondary permeability resulting from intense fracturing in areas of deformation. This fracture-induced permeability is reflected by extremely variable water yield, from 50 gpm over most areas up to 8,000 gpm from highly fractured zones. Although it is generally about 2,000 feet deeper than the Cloverly Formation, the Casper aquifer's water-bearing properties and stratigraphic postion make it a second favorable geothermal prospect.

## STRUCTURE AND WATER MOVEMENT

Given favorable water-bearing characteristics and stratigraphic confinement, an aquifer must also have the proper structure and water flow direction to be geothermally useful. The structure con-

*Table 3. Thermal springs in the Laramie, Hanna, and Shirley Basins. After Breckenridge and Hinckley, 1978. gpm=gallons per minute of water flow; ppm=parts per million of dissolved solids; TDS=total dissolved solids.*

| Location | | Temperature | Flow | Source | TDS |
|---|---|---|---|---|---|
| T.30N.,R.83W. | $SW\frac{1}{4}SE\frac{1}{4}SE\frac{1}{4}$ sec. 24 | 104°F | 400 gpm | Amsden Formation | average 1,320 ppm |
| *Alcova Hot Springs* | $NE\frac{1}{4}NW\frac{1}{4}NE\frac{1}{4}$ sec. 25 | 124°F | 40 gpm | | |
| | $SW\frac{1}{4}NW\frac{1}{4}NE\frac{1}{4}$ sec. 25 | 129°F | 5 gpm | | |
| | $SE\frac{1}{4}NW\frac{1}{4}NE\frac{1}{4}$ sec. 25 | 129°F | 5 gpm | | |
| T.17N.,R.84W. | $SW\frac{1}{4}NW\frac{1}{4}NW\frac{1}{4}$ sec. 13 | 118°F | 120 gpm | below the North Park Formation | 1,850 ppm |
| *Saratoga Hot Springs* | $SW\frac{1}{4}NW\frac{1}{4}NW\frac{1}{4}$ sec. 13 | 118°F | 3-5 gpm | | |
| | $SE\frac{1}{4}SW\frac{1}{4}SW\frac{1}{4}$ sec. 12 | 109°F | <1 gpm | | |
| | $NE\frac{1}{4}NW\frac{1}{4}NW\frac{1}{4}$ sec. 13 | 118°F | ? | | |
| | $NE\frac{1}{4}NW\frac{1}{4}NW\frac{1}{4}$ sec. 13 | 129°F | ? | | |
| | $SE\frac{1}{4}NW\frac{1}{4}NW\frac{1}{4}$ sec. 13 | 86°F | none | | |

tour map (Plate III) shows the topography of the top of the Cloverly Formation. The depth to the Cloverly Formation at any point in the study area is roughly determined by subtracting the structure contour elevation from the nearest surface contour. Plate III also shows the water flow directions proposed by Richter (1981) in the Cloverly Formation.

The Laramie and Shirley Basins are fairly shallow relative to other Rocky Mountain basins. There are about 12,000 feet of sediments over the Cloverly Formation in the Laramie Basin and about 8,000 feet in the Shirley Basin. In both basins this overburden is primarily shale (Thermopolis, Mowry, and Steele Shales), along with mixed rock types in the Frontier, Niobrara, Mesaverde, Hanna (in the Laramie Basin), and Wind River Formations. Using the general conductivities of these units and the area heat flow values discussed above, the maximum temperature in the Cloverly aquifer should not exceed 162°F in the Shirley Basin and 197°F in the Laramie Basin.

Although the Paleozoic section in the Laramie and Shirley Basins is of variable thickness (Figure 7), approximately 2,500 feet is a fair estimate of the total sub-Thermopolis Shale sedimentary section and is not likely to be greatly exceeded. Thus, the base of the Paleozoic aquifer system, given the relatively high thermal conductivities within and beneath the Cloverly Formation (average 2.7 W/m°K), will only be about 26°F warmer than the Cloverly Formation. Hydrologic enhancement of gradient is not an issue here because the base of the Paleozoic aquifer system is the maximum depth to which water can circulate to acquire the heat necessary to create gradient anomalies. The general flow patterns plotted on Plate III indicate that water is not flowing up out of these deep zones and that the available resource will be of somewhat lower temperatures than these maximum ones.

In the Hanna Basin, the geothermal system is different. At a depth of 36,000 feet in the deepest part of the basin, the Cloverly should have a temperature of nearly 500°F. Addition of the 3,600 feet of sub-Cloverly sediments should give a temperature of around 540°F at the base of the Paleozoic aquifers. Such extreme depths are well beyond the range of current drilling technologies, and it is unlikely that water flow will bring water heated to these temperatures up out of the basin

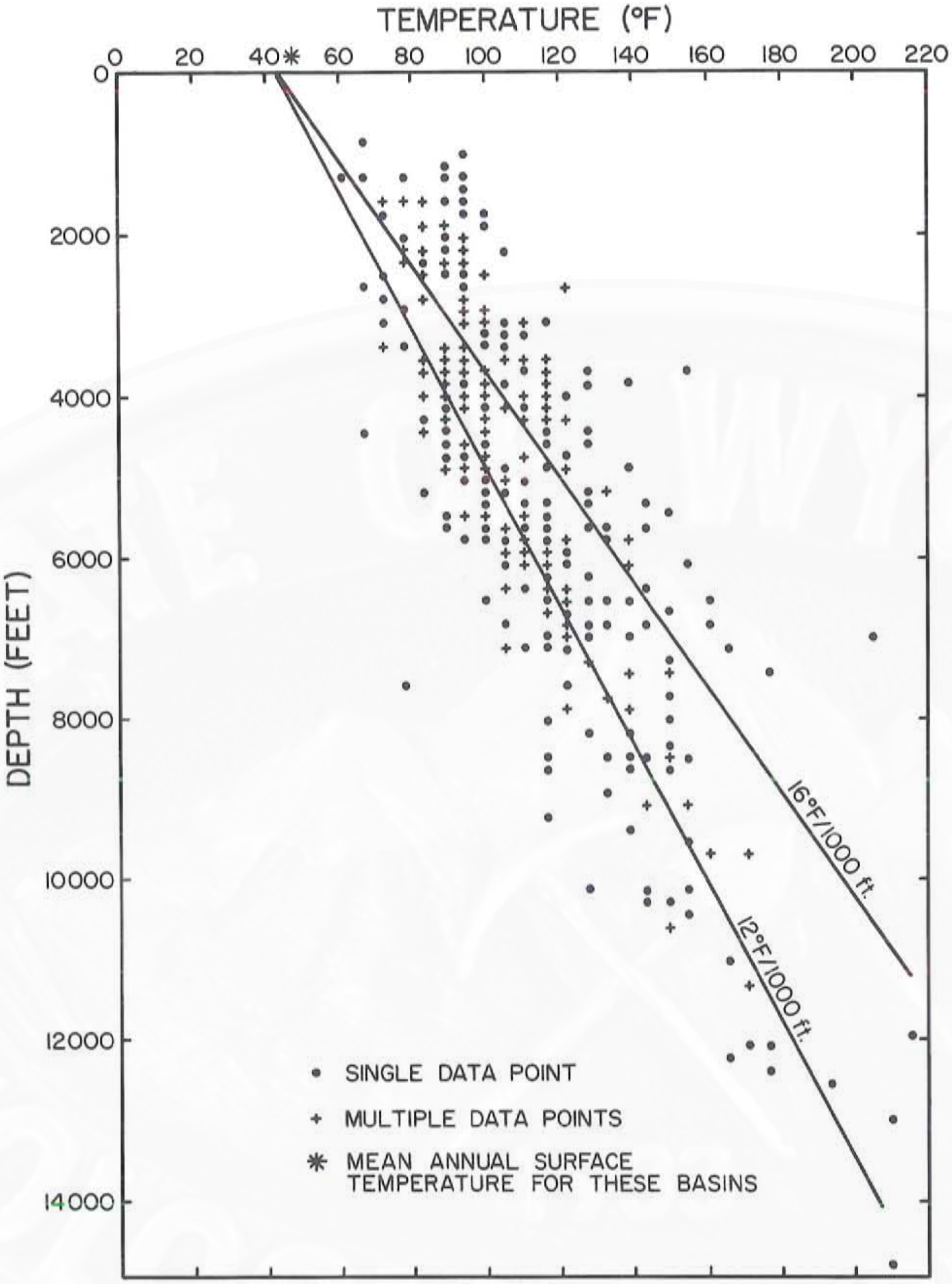


*Figure 8. Temperature-depth plot of bottom-hole temperatures in the Laramie, Hanna, and Shirley Basins.*

interior. Nonetheless, the Cloverly and Paleozoic aquifers attain sufficient depths even around the basin margin to develop significant temperatures. These are the areas where small folds are common as well, so they have potential for creating the types of systems diagramed in Figures 3 and 4.

The Saratoga Valley does not constitute a well-defined basin. At its northern end it has sedimentary thicknesses, and therefore temperatures, comparable to those of the Laramie Basin. Folding is relatively minor, but several large faults near the town of Saratoga may provide near-surface access to deep, warm water.

The structural and hydrologic details of individual areas of identified high gradients are discussed following the section on measured gradients.

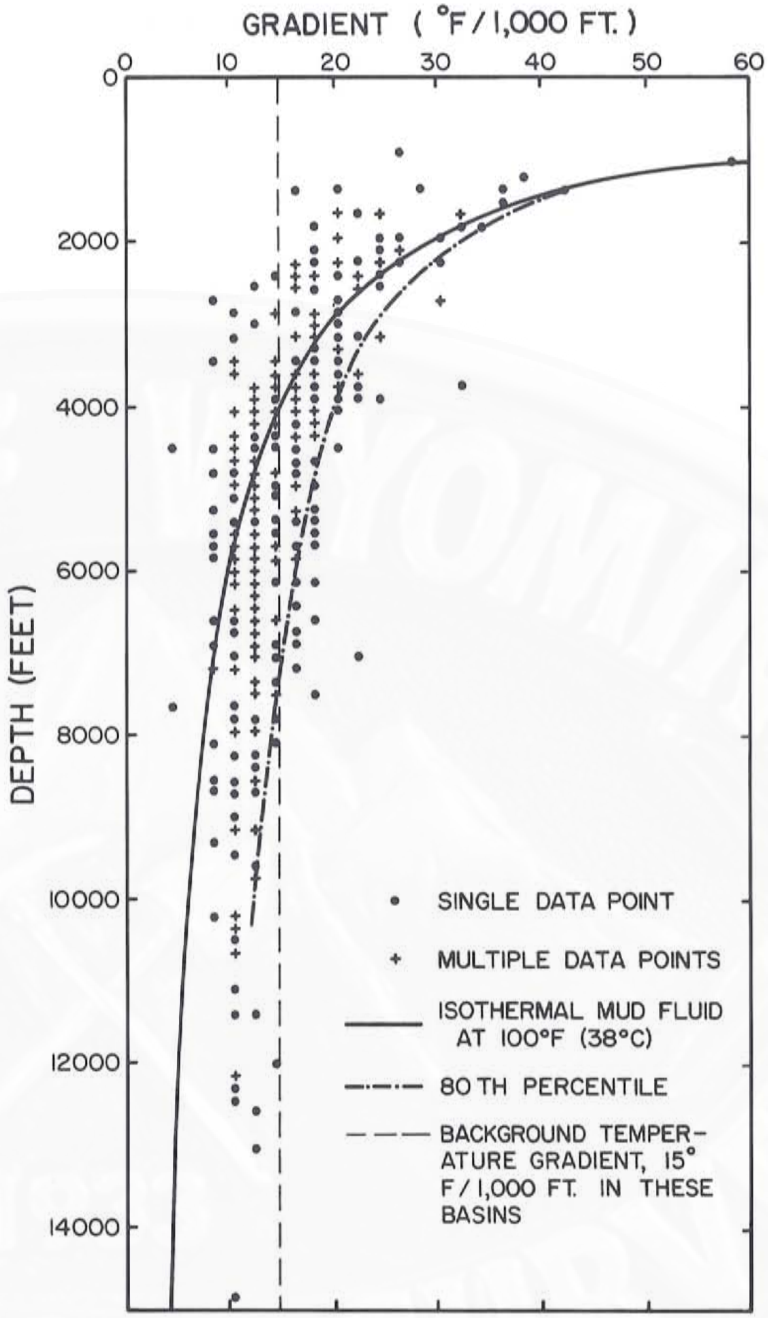


*Figure 9. Gradient-depth plot, based on bottom-hole temperatures, for the Laramie, Hanna, and Shirley Basins.*

MEASURED TEMPERATURES AND GRADIENTS

The thermal gradient contour map (Plate II) of this report is based on all available oil and gas well log and University of Wyoming thermal log data. These two data sources are in general agreement for the study area and reflect the generally low to moderate gradients predicted in the Heat Flow and Conductive Gradient section, page 10. Data from the third source - thermal springs - are listed in Table 3.

Figure 8 displays all available oil and gas well BHT data plotted against depth. As discussed above, a conductive gradient through the full sedimentary section should be around 12°F/1,000 ft. Many of the BHT data fall above this gradient, for three reasons. First, nearly 50 percent of the reported BHT values are for the Sundance, Morrison, and Cloverly Formations, which, at depths to 6,000 feet, are overlain almost exclusively by low-thermal-conductivity shales. Gradients of around

*Table 4. Summary of bottom-hole temperature data and statistics, including the 50th, 66th, 80th, and 90th percentiles, from the Laramie, Hanna, and Shirley Basins.*

| Depth interval (feet) | Number | Temperature (°F) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | high | low | mean | 50% | 66% | 80% | 90% |
| 500 - 1,000 | 2 | 100 | 68 | 84.0 | 100 | 100 | 100 | 100 |
| 1,000 - 1,500 | 12 | 98 | 64 | 84.7 | 88 | 92 | 93 | 96 |
| 1,500 - 2,000 | 20 | 105 | 75 | 87.5 | 85 | 95 | 96 | 104 |
| 2,000 - 2,500 | 38 | 112 | 74 | 91.3 | 91 | 98 | 99 | 101 |
| 2,500 - 3,000 | 25 | 125 | 68 | 96.6 | 97 | 102 | 119 | 119 |
| 3,000 - 3,500 | 33 | 122 | 73 | 100.1 | 102 | 105 | 112 | 117 |
| 3,500 - 4,000 | 63 | 162 | 85 | 106.1 | 103 | 113 | 122 | 125 |
| 4,000 - 4,500 | 40 | 138 | 85 | 108.2 | 107 | 115 | 121 | 132 |
| 4,500 - 5,000 | 34 | 140 | 68 | 104.8 | 103 | 106 | 120 | 125 |
| 5,000 - 5,500 | 26 | 146 | 88 | 113.5 | 110 | 115 | 130 | 136 |
| 5,500 - 6,000 | 40 | 152 | 73 | 116.7 | 116 | 120 | 135 | 145 |
| 6,000 - 6,500 | 22 | 160 | 109 | 124.4 | 124 | 126 | 129 | 142 |
| 6,500 - 7,000 | 21 | 165 | 110 | 132.6 | 130 | 135 | 140 | 152 |
| 7,000 - 7,500 | 15 | 212 | 111 | 136.7 | 131 | 143 | 154 | 170 |
| 7,500 - 8,000 | 12 | 182 | 124 | 141.3 | 141 | 142 | 152 | 182 |
| 8,000 - 8,500 | 5 | 156 | 122 | 141.4 | 144 | 153 | 156 | 156 |
| 8,500 - 9,000 | 10 | 160 | 123 | 144.0 | 147 | 153 | 156 | 160 |
| 9,000 - 9,500 | 6 | 158 | 122 | 143.8 | 150 | 151 | 151 | 158 |
| 9,500-10,000 | 4 | 176 | 161 | 169.3 | 175 | 175 | 176 | 176 |
| 10,000-10,500 | 5 | 158 | 130 | 147.0 | 148 | 152 | 158 | 158 |
| 10,500-11,000 | 2 | 157 | 154 | 155.5 | 157 | 157 | 157 | 157 |
| 11,000-11,500 | 3 | 179 | 172 | 175.0 | 174 | 179 | 179 | 179 |
| 11,500-12,000 | 0 | - | - | - | - | - | - | - |
| 12,000-12,500 | 5 | 222 | 173 | 187.4 | 180 | 184 | 222 | 222 |
| 12,500-13,000 | 2 | 218 | 200 | 209.0 | 218 | 218 | 218 | 218 |
| 13,000-13,500 | 0 | - | - | - | - | - | - | - |
| 13,500-14,000 | 0 | - | - | - | - | - | - | - |
| 14,000-14,500 | 0 | - | - | - | - | - | - | - |
| 14,500-15,000 | 1 | 217 | 217 | 217.0 | 217 | 217 | 217 | 217 |

Total: 446 bottom-hole temperature measurements.

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.

16°F/1,000 ft are probable in the Sundance, Morrison, and Cloverly, but are unlikely to persist in the less shaley formations below them.

Second, as shown in Figure 9, the BHT-derived gradients decrease significantly with depth. This is in part due to deeper holes penetrating rocks of lower thermal conductivity. In the shallower holes (to 4,000 feet deep), however, the effect is primarily due to inaccurate BHT measurement. Included in Figure 9 is a curve, labeled "ISOTHERMAL MUD FLUID AT 100°F," which marks the gradient which would be calculated at each depth if the BHT were 100°F. As BHT's fall below 100°F, they become increasingly subject to error (see discussion, page 7). Therefore, gradient data points to the left of the 100°F line are considered less reliable than those to the right.

*Table 5. Summary of the gradient data and statistics, including the 50th, 66th, 80th, and 90th percentiles, derived from bottom-hole temperature data from the Laramie, Hanna, and Shirley Basins.*

| Depth interval (feet) | Number | Gradient (°F/1,000ft) high | low | mean | 50% | 66% | 80% | 90% |
|---|---|---|---|---|---|---|---|---|
| 500 - 1,000 | 2 | 58.1 | 27.4 | 42.7 | 58.1 | 58.1 | 58.1 | 58.1 |
| 1,000 - 1,500 | 12 | 42.8 | 16.5 | 33.0 | 36.8 | 38.2 | 39.8 | 40.3 |
| 1,500 - 2,000 | 20 | 35.3 | 19.0 | 26.1 | 25.4 | 27.1 | 32.2 | 33.8 |
| 2,000 - 2,500 | 38 | 30.3 | 12.9 | 21.9 | 21.7 | 24.3 | 25.9 | 27.2 |
| 2,500 - 3,000 | 25 | 31.2 | 9.5 | 19.8 | 19.5 | 20.8 | 23.0 | 27.5 |
| 3,000 - 3,500 | 33 | 25.9 | 9.9 | 17.9 | 18.2 | 19.7 | 21.3 | 23.3 |
| 3,500 - 4,000 | 63 | 32.6 | 11.5 | 17.1 | 16.2 | 19.4 | 20.7 | 22.3 |
| 4,000 - 4,500 | 40 | 22.7 | 9.7 | 15.6 | 15.6 | 16.8 | 18.5 | 20.3 |
| 4,500 - 5,000 | 34 | 19.9 | 5.7 | 13.1 | 12.4 | 13.0 | 16.5 | 17.1 |
| 5,000 - 5,500 | 26 | 19.3 | 8.8 | 13.6 | 13.0 | 14.0 | 16.4 | 18.0 |
| 5,500 - 6,000 | 40 | 19.7 | 5.4 | 13.0 | 12.4 | 13.4 | 15.9 | 17.7 |
| 6,000 - 6,500 | 22 | 19.2 | 10.5 | 13.2 | 12.6 | 13.3 | 13.9 | 16.4 |
| 6,500 - 7,000 | 21 | 18.5 | 9.9 | 13.4 | 12.6 | 13.4 | 14.9 | 16.4 |
| 7,000 - 7,500 | 15 | 23.9 | 915 | 13.2 | 12.0 | 14.4 | 15.2 | 17.7 |
| 7,500 - 8,000 | 12 | 18.5 | 10.4 | 12.8 | 12.7 | 13.1 | 14.0 | 14.6 |
| 8,000 - 8,500 | 5 | 14.1 | 9.9 | 12.1 | 12.4 | 13.2 | 14.1 | 14.1 |
| 8,500 - 9,000 | 10 | 13.7 | 9.3 | 11.9 | 12.3 | 12.9 | 13.2 | 13.7 |
| 9,000 - 9,500 | 6 | 12.6 | 8.6 | 11.1 | 11.9 | 11.9 | 11.9 | 12.6 |
| 9,500-10,000 | 4 | 13.7 | 12.4 | 13.1 | 13.7 | 13.7 | 13.7 | 13.7 |
| 10,000-10,500 | 5 | 11.3 | 8.7 | 10.2 | 10.3 | 10.6 | 11.3 | 11.3 |
| 10,500-11,000 | 2 | 11.0 | 10.5 | 10.7 | 11.0 | 11.0 | 11.0 | 11.0 |
| 11,000-11,500 | 3 | 12.0 | 11.5 | 11.7 | 11.6 | 12.0 | 12.0 | 12.0 |
| 11,500-12,000 | 0 | - | - | - | - | - | - | - |
| 12,000-12,500 | 5 | 15.0 | 10.7 | 11.9 | 11.3 | 11.6 | 15.0 | 15.0 |
| 12,500-13,000 | 2 | 13.6 | 12.5 | 13.0 | 13.6 | 13.6 | 13.6 | 13.6 |
| 13,000-13,500 | 0 | - | - | - | - | - | - | - |
| 13,500-14,000 | 0 | - | - | - | - | - | - | - |
| 14,000-14,500 | 0 | - | - | - | - | - | - | - |
| 14,500-15,000 | 1 | 11.8 | 11.8 | 11.8 | 11.8 | 11.8 | 11.8 | 11.8 |

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

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.

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Tables 4 and 5 present a brief statistical analysis of the data plotted in Figures 8 and 9. Only at depths greater than 4,000 feet are BHT's consistently over 100°F. This is approximately the point at which the 100°F line on the gradient plot (Figure 9) crosses the background thermal gradient -- 12°F/1,000 ft in the study area (see page 7 of the Introduction for explanation). Also, the mean gradients below 4,000 feet are in general agreement with modeled gradients; that agreement suggests that in general, the study area is subject to low to moderate heat flow and that gradients are not systematically higher or lower than equilibrium conductive gradients. Unfortunately, a lack of deep thermal logs in the study area prevents the testing of that hypothesis.

Third, gradients may be higher than the conductive gradient because of hydrologic modification. These are the gradients of most interest, for they may go well beyond the small increase in gradient seen through low thermal conductivity shales and result in useable geothermal resources. Gradients which are apparently anomalously high (to the right of the 80 percent line on Figure 9) relative to other gradients at the same depth are considered possible indicators of areas of elevated gradient. Where a number of such points occur in the same area (and where they are also greater than the background thermal gradient), an "area of anomalous gradient" is mapped on the thermal gradient contour map, Plate II.

## AREAS OF ANOMALOUS GRADIENT

Eleven areas of high gradient, including thermal spring areas of Alcova and Saratoga, have been numbered for reference on the thermal gradient contour map, the structure contour map, and the ground-water temperature contour map (Plates II, III, and IV). We discuss these numbered areas, and we begin with one established by abundant data, Area 3. Gradients at Area 3 vary from 19.6 to 26.2°F/1,000 ft, based on BHT's as high as 130°F from depths of 2,000 to 4,000 feet, in the Morrison and Casper Formations. Rocks on the surface are the upper Steele Shale. A heat flow of 45 $mW/m^2$ and an average conductivity for the Casper-to-Steele section of 2.1 W/m°K give a conductive gradient of 12°F/1,000 ft. Thus, a minimum water circulation depth of 7,300 feet is necessary to produce the observed temperatures in the Casper Formation. Since the Casper Formation attains a total depth of around 8,500 feet, a Casper Formation temperature of 140°F is a reasonable estimate. If waters are moving northwest from the Medicine Bow Mountains recharge areas as proposed by Richter (1981) (see Plate III), they will move through the area of deep burial enroute to Area 3 and should arrive at the observed 120-130°F temperature -- this allows for some reduction in gradient due to the cooling effect of descending waters and some dissipation of heat as waters rise. Thus, the apparent gradient anomaly seen in BHT's can be explained by hydrologic, structural, and heat flow - conductivity evidence. An additional feature at Area 3 is tight folding and faulting. Particularly in the Casper Formation, this type of deformation is critical to the development of high permeability.

The discussion of Area 3 demonstrates how such areas are evaluated. The remaining areas are discussed in a more general manner, but their evaluation has drawn on the same techniques.

Area 1 is defined on the basis of two Casper Formation wells 3,000 feet deep with BHT's of 103 and 122°F. If water flows from the east and southeast, depth of flow is sufficient to bring 100°F waters to Area 1 in the Casper Formation. Further evaluation of Area 1 should focus on verification of the higher reported temperature.

Area 2 is quite similar to Area 3. Defined by both Cloverly and Casper Formation wells with BHT's as high as 125°F at 2,700 feet, the anomaly is presumably the result of eastward-flowing waters. As in Area 3, sharp folding and a major fault likely increase permeability significantly in Area 2.

The high gradient in Area 4 is based primarily on Casper Formation wells 5,000 to 6,000 feet deep with BHT's of 128°F to 152°F. The calculated gradients are not extremely high, 16-20°F/1,000 ft in this case, but are based on sufficient deep measurements to be considered reliable. Since the Lewis Shale and Hanna Formation are at the top of the sedimentary section west of Area 4, gradients to the Casper Formation should be dominated by shale. Synclinal areas southwest of Area 4 (up flow direction) reach depths of 13,000 feet in the

Casper Formation, enough to produce 200°F temperatures at conductive equilibrium. Faulting in Area 4 may allow Casper Formation waters to rise into the Cloverly Formation, increasing gradients further. The problem with Area 4 is that even the shallowest aquifer containing geothermal water, the Cloverly Formation, is 4,000 feet deep. Overlying shales likely prevent any vertical migration of water above the Cloverly.

Between Areas 4 and 6 is a long, north-northwest-trending anticline, at the crest of which are located, from south to north, the Cooper Cove, Dutton Creek, and Rock River oil fields. The water flow directions plotted on Plate III indicate that water in the Cloverly Formation should move up the west flank of the anticline from a depth of around 13,000 feet. Conductive gradients would produce water temperatures in excess of 220°F in such a system, yet the numerous Cloverly Formation BHT's along the anticline are generally from 100°F to 115°F. Although there are several high gradient points in the area, the great majority of the data from a variety of formations and depths indicate that there is no significant hydrologic disruption of conductive gradients, which are 12 to 14°F/1,000 ft.

One reason for the absence of a geothermal anomaly along this anticline is that along most of the adjacent mountain front the Cloverly and Casper aquifers do not crop out but are overthrust by Precambrian rocks. Consequently, recharge to these rocks is minimal. In addition, oil entrapped along the crest of such a tight anticline may inhibit water movement.

Area 6 is a high-gradient anomaly identified by two 7,000-foot-deep Casper(?) Formation BHT's of 148 and 165°F. South-southwest of Area 6, up the direction of water flow, the Cloverly Formation is overlain by 8,000 feet of sediments with Lewis Shale at the surface. Well logs in Area 6 demonstrate a slight thickening of the sub-Cloverly section relative to the previously discussed areas, placing the Casper Formation at a depth of approximately 10,000 feet in the syncline to the south-southwest. A heat flow of 50 $mW/m^2$ and an average Casper-to-Lewis thermal conductivity of 2.14 W/m°K would produce a conductive gradient of 13°/1,000 ft and a 168°F temperature at the top of the Casper Formation.

An important feature of Area 6 is the fault on which the area is centered. The thickness of the Paleozoic section generally increases from 200 feet to 1,000 feet from southeast to northwest across the entire study area. The importance of faulting in increasing permeability within an aquifer has already been emphasized. The importance of faults between aquifers is that they allow vertical mixing of waters of different temperatures.

Area 7 is an established anomaly based on BHT's in the range 120-160°F from 3,600 to 9,000 feet in a variety of formations. A BHT of 212°F (23.9°F/1,000 ft gradient) is reported from one 7,100-foot Casper(?) Formation hole, but is inconsistent with numerous surrounding BHT's and with reasonable flow models. Richter (1981) proposes two flow directions into Area 7. Flow from the north would supply waters from shallower, cooler areas, whereas flow from the southwest would bring up waters from depths sufficient to produce 170°F in the Casper Formation. Therefore, flow from the southwest is indicated.

Why high gradients are localized in Area 7 is not clear. Well control is insufficient to precisely delimit the area, and there is no obvious fold or fault control on water movement. Considering that there is no obvious source for fracture enhancement of permeability and that the Cloverly Formation is from 6,000 to 8,000 feet deep, Area 7 is not particularly attractive, even in the face of the elevated gradients.

Area 8 is based on BHT's of 81-122°F from a variety of formations. Gradients based on BHT's greater than 100°F are around 22°F/1,000 ft. The synclinal depth of the Cloverly Formation just to the east is approximately 5,500 feet, enough to produce 110°F in the Cloverly Formation and 130°F in the Casper Formation. Thus, the elevated gradients of Area 8 are consistent with flow into the area from the east. Faulting in the area may further increase Cloverly Formation temperatures by allowing vertical migration of Casper Formation waters.

North of Areas 6, 7, and 8 is a complex series of anticlines and faults running northwest across the entire study area. Flow directions are complicated, and there is potential for local hydrologic modification of conductive temperature gradients. The youngest (highest) stratum at the surface in this area is the Steele Shale; the Cloverly Formation is as deep as 5,000 feet, and so may develop temperatures up to 100°F (125°F in the Casper Formation).

In areas of local uplift like that just north of the town of Medicine Bow (Plate I), water-bearing strata may be brought close enough to the surface to create a useful geothermal resource. There is one reported Tensleep BHT of 132°F in this area (see Plate II). This temperature has not been confirmed by thermal logging. The existence of a geothermal anomaly here is contingent on waters moving updip into the area from the west and north, possibly aided by fault zones on the northwest flank of the structure.

For the most part, the Shirley Basin is both too shallow and insufficiently deformed to create significant geothermal systems. Possibilities increase in the structurally more complex areas to the west. High-gradient Area 9 is based on two points: 125°F and 138°F at 3,600 and 4,200 feet, respectively. Groundwater flow in the Cloverly and Casper aquifers is northward from mountain-flank recharge areas. Water enroute to Area 9 descends to approximately 3,000 feet deep in the Cloverly Formation and 4,000 feet deep in the Casper Formation. With the somewhat higher heat flows in the north part of the study area (54 $mW/m^2$) and an average thermal conductivity from the Casper Formation to the lower Steel Shale of 2.1 W/m°K, the conductive gradient is 14°F/1,000 ft. Thus, a reasonable temperature for the Casper Formation is 112°F. In Area 9 there is a significant sub-Casper Formation section, and temperatures in the lowest sedimentary units may be as high as 130°F.

Area 10 is also based on fairly low temperatures (119°F maximum). The area occupies the crest of a small anticline which exposes a small section of the Mowry Shale (Plate I). The anticline is faulted to the west. The fault achieves a displacement of 1,500 feet at Alcova, and gives rise to perhaps four 129°F hot springs (Table 3). These springs are presently submerged beneath the Alcova Reservoir, but were reported in 1935 as flowing around 100 gallons per minute from a very porous section of the Amsden Formation (Breckenridge and Hinckley, 1978).

Drilling logs in Area 10 report over 3,000 feet of sedimentary rock below the top of the Cloverly Formation. The Cloverly Formation reaches a depth of 2,500 feet in the syncline south of Area 10 and Alcova, placing the deepest sedimentary rocks at around 5,500 feet. Decker et al. (1980) describe a section of rocks very similar to these, with an overall average conductivity of 2.66 W/m°K. Using the nearest reported heat flow of 54 $mW/m^2$ (Plate II), a gradient of 11°F/1,000 ft and a temperature of only 103°F for the bottom of the syncline are indicated. Given the obviously permeable nature of the Amsden Formation in Area 10 and the presence of a major fault, it is reasonable to expect the entire Paleozoic aquifer system to be hydraulically integrated, with fracture-induced permeability perhaps even allowing deeper waters to rise into the Cloverly Formation.

Even so, the heat source for the high

gradients of Area 10 and the hot springs at Alcova is unclear. Breckenridge and Hinckley (1978) suggest that waters may be circulating deep into fractured Precambrian rocks at Alcova, picking up additional heat at normal gradients. Since this area is in the zone of transition to a higher heat flow province to the north, heat flows used above to calculate gradients may be too low. If the heat flow were 79 $mW/m^2$, for example, as was measured for the Owl Creek Mountains 70 miles northwest, the conductive gradient would be 16°F/1,000 ft and a temperature of 130°F would be possible.

The spring waters at Alcova may still flow beneath the reservoir. Considerably easier exit points for these thermal waters are springs and seeps into the drainage gallery of the power plant below the dam and a flowing well drilled just below the dam. The well flows approximately 400 gallons per minute of 105°F water. According to data collected by David Welde of the U.S. Bureau of Reclamation, there is a strong correlation between the reservoir level and the flow of this well. This suggests reservoir input into recharge areas, which may explain both the lower temperature and greater discharge of the system following dam construction. This well presently discharges directly into the North Platte River.

In the southeast corner of the town of Saratoga are at least six warm springs flowing a total of about 130 gallons per minute at 110-130°F (Table 3). The springs surface in the North Park Formation but are interpreted as coming up along faults from the Tensleep (Casper) Sandstone and Madison Limestone (Breckenridge and Hinckley, 1978). Heat flow data for the area are inconsistent (Plate II). Both of the mapped values, 50 and 86 $mW/m^2$, are from Tertiary sediments and are therefore subject to hydrologic disturbance in lower strata. Since, in the larger area, heat flows in basement rocks are 33, 41, 45, and 54 $mW/m^2$, it is believed that the 86 $mW/m^2$ value is in error and that the true basement heat flow is around 50 $mW/m^2$. Through a section of 2.5 W/m°K average conductivity, this heat flow would produce a gradient of 11°F/1,000 ft.

Well logs in the Saratoga area show Precambrian basement rocks at a depth of approximately 3,000 feet. The Cloverly Formation structural contours of Barlow and Haun (1978) indicate Precambrian rock depths of 4,000 to 5,000 feet. In either case, the sedimentary section at Saratoga is insufficient to produce the observed water temperatures without extensive circulation deep into basement rocks. Since water-bearing strata are even shallower south, east, and west of Saratoga, the only sedimentary circulation system which could deliver the observed temperatures would involve flow southward, up from the rapidly thickening section north of Saratoga. Within five miles north of Saratoga, waters in the Tensleep Sandstone (Casper Formation) are sufficiently deep to be 130°F as a result of conductive gradient. Flow directions are considered predominantly northward in this end of the Saratoga Valley (see, e.g., mapped flow directions of Richter, 1981, on Plate III). Since hydraulic head increases with depth in this area, fault-induced, high-permeability zones may allow water of the Tensleep Sandstone (Casper Formation) and Madison Limestone to locally migrate upward and southward to discharge at the Saratoga springs.

## TEMPERATURES OF THE CLOVERLY FORMATION

The two key elements in low-temperature geothermal resources are temperature and flow. Analysis of gradients is useful in predicting temperatures at depth and in identifying areas where those temperatures are likely to be anomalously high. A viable geothermal resource will exist only where high temperatures occur in a productive aquifer. Temperatures contoured for the Cloverly and Morrison Formations (Plate IV) demonstrate a basinward increase of temperature. While the Morrison Formation is not a significant aquifer itself, temperatures in the

Morrison Formation are apparently very similar to those in the Cloverly.

## SUMMARY AND CONCLUSIONS

Heat flows and thermal conductivities in the study area are insufficient to produce high conductive gradients. Only where hydrologic systems transport heat through mass movement of water do high temperatures occur at shallow depth. The major confined aquifers in the study area are the Lower Cretaceous Cloverly Formation and the Paleozoic aquifer system, called the Casper aquifer, which includes the Tensleep Sandstone, Casper Formation, Fountain Formation, and Madison Limestone. The deformation and faulting of these aquifers along the basin margins form the "plumbing" necessary to create areas of high geothermal gradient.

The geologic complexity of the study area precludes detailed site-by-site analysis. We believe it unlikely that waters in excess of 130-140°F are producable at shallow depth (less than 2,000 feet) in the area. Temperatures as high as 170°F have been identified in high-gradient areas, but depth to productive aquifers generally exceeds 5,000 feet in these cases.

The most attractive geothermal prospects are the areas of existing thermal springs at Alcova and Saratoga. Water temperatures as high as 130°F may be developed from a fault and anticline system extending eastward from the Alcova Dam. The Saratoga system is apparently immediately beneath the springs.

Geothermal resources elsewhere in the study area are probably best pursued in conjunction with oil and gas or water resources. Where oil and gas production pays drilling and pumping expenses, considerable quantities of thermal water may be available as a production by-product. Since the Cloverly and Casper Formations are important sources of both petroleum and thermal water in the study area, coincident production of the two resources is likely (see Hinckley,1983).

Both the Cloverly and Casper Formations are under artesian pressure beneath most of the study area, and flowing wells from these formations are common. Near the basin margins, the chemical quality of these aquifers is generally good -- less than 1,000 ppm TDS (total dissolved solids) -- and therefore sufficient for a wide variety of municipal, industrial, and agricultural water supply applications. In areas of elevated geothermal gradient, deep water wells may provide valuable geothermal resources as well.

At the low-temperature end of the spectrum of geothermal applications are ground-water heat pumps and systems for cycling shallow-earth heat to road and bridge surfaces. These uses follow local energy demands and the availability of alternative energy supplies and are not generally constrained by geothermal conditions.

## ACKNOWLEDGMENTS

As explained in the Introduction, this report is one chapter in a statewide study of geothermal resources. Most of the methods and the scope of analyses of the study were developed in concert by the four investigators on the "basin reports": myself, Ken Buelow, Henry Heasler, and Sue Spencer. From this cooperative pool we have partitioned responsibility for working through the specifics of individual basins. Thus my analysis of the Laramie, Hanna, and Shirley Basins has been aided considerably by the thinking of the group, by the assistance of Mr. Heasler in my work on the Bighorn Basin, and by Mr. Buelow's much earlier efforts in the adjacent Washakie-Great Divide Basins. Of particular value to the entire study has been the capable administration of Mr. Heasler, who, in his careful attention to the tiresome details, has greatly relieved the scientific cogitations of us all.

# REFERENCES


Anderson, D.N., and Lund, J.W., editors, 1979, Direct utilization of geothermal energy -- a technical handbook: Geothermal Resources Council Special Report 7, 234 p.

Barlow and Haun, Inc., 1978, Wyoming structure contour map: Pomco, Casper, Wyoming, scale 1:500,000.

Blackstone, D.L., Jr., 1975, Late Cretaceous and Cenozoic history of the Laramie Basin region, southeast Wyoming: Geological Society of America Memoir 13, p. 249-279.

Blackwell, D.D., 1969, Heat-flow determinations in the northwestern United States: Journal of Geophysical Research, v. 74, p. 992-1007.

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

Buelow, K.L., 1980, Geothermal studies in Wyoming and northern Colorado, with a geophysical model of the southern Rocky Mountains near the Colorado-Wyoming border: MS thesis, University of Wyoming, 150 p.

Chapman, D.S., and Pollack, H.N., 1975, Global heat flow -- a new look: Earth and Planetary Science Letters, v. 27, p. 23-32.

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

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

Decker, E.R., and Bucher, G.J., 1979, Thermal gradients and heat flow data in Colorado and Wyoming: a preliminary report: Los Alamos Scientific Laboratories Informal Report LA7493-M5, 9 p.

Gass, T.E., and Lehr, H.H., 1977, Groundwater energy and groundwater heat pumps: Water Well Journal, April 1977, p. 10-15.

Heasler, H.P., 1978, Heat flow in the Elk Basin oil field, northwestern Wyoming: MS thesis, University of Wyoming, 168 p.

Heasler, H.P., Decker, E.R., and Buelow, K.L., 1982, Heat flow studies in Wyoming, 1979 to 1981, *in* C.A. Ruscetta, editor, Geothermal Direct Heat Program Roundup Technical Conference Proceedings, v. I, State Coupled Resource Assessment Program: Earth Science Laboratory, University of Utah, Research Institute, p. 292-312.

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

Hinckley, B.S., 1983, Oil field geothermal waters of Wyoming: report submitted to the U.S. Department of Energy in fulfillment of Contract No. DE-F107-79ID12026, 11 p.

Hinckley, B.S., Heasler, H.P., and King, J.K., 1982, The Thermopolis hydrothermal system, with an analysis of

Hot Springs State Park: Geological Survey of Wyoming Preliminary Report 20, 42 p.

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

Lowry, E., Rucker, J., IV, and Wahl, K. L., 1973, Water resources of the Laramie, Shirley, Hanna Basins and adjacent areas, southeastern Wyoming: U.S. Gelogical Survey Hydrologic Investigations Atlas HA-471, 4 sheets.

Morgan, P., Blackwell, D.D., Spafford, R.E., and Smith, R.B., 1977, Heat flow measurements in Yellowstone Lake and the thermal structure of the Yellowstone Caldera: Journal of Geophysical Research, v.82, p. 3719-3832.

Muffler, L.J.P., editor, 1979, Geothermal energy in the western United States, *Map 1 in* Assessment of geothermal resources of the United States - 1978: U.S. Geological Survey Circular 790.

Richter, H.R., Jr., 1981, Occurrence and characteristics of ground water in the Laramie, Shirley, and Hanna Basins, Wyoming: University of Wyoming Water Resources Research Institute, Volume III-A, 116 p.

White, D.F., and Williams, D.L., editors, 1975, Assessment of geothermal resources of the United States -- 1975: U.S. Geological Survey Circular 726, 155 p.

Wyoming Geological Association, Stratigraphic Nomenclature Committee, 1969, Wyoming stratigraphic nomenclature chart: Wyoming Geological Association, 21st Annual Field Conference Guidebook, p. 7.

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



## EXPLANATION

CONTACT

FAULT, (DASHED WHERE INFERRED)

Qu QUATERNARY SEDIMENTS UNDIVIDED

Tu TERTIARY SEDIMENTS UNDIVIDED

Kmb UPPER CRETACEOUS MEDICINE BOW FORMATION

Klmv UPPER CRETACEOUS LEWIS SHALE AND MESAVERDE FORMATION

Ks UPPER CRETACEOUS STEELE SHALE

Knf UPPER CRETACEOUS NIOBRARA AND FRONTIER FORMATIONS

KJu LOWER CRETACEOUS AND JURASSIC ROCKS UNDIVIDED (INCLUDING CLOVERLY AND MORRISON FORMATIONS)

TRu TRIASSIC ROCKS UNDIVIDED

Pzu PALEOZOIC ROCKS UNDIVIDED

p€ PRECAMBRIAN IGNEOUS AND METAMORPHIC ROCKS

SCALE

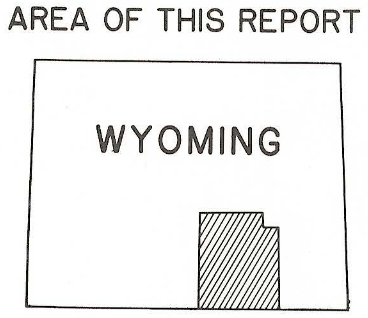
MILES

5 0 5 10 15 20

KILOMETERS

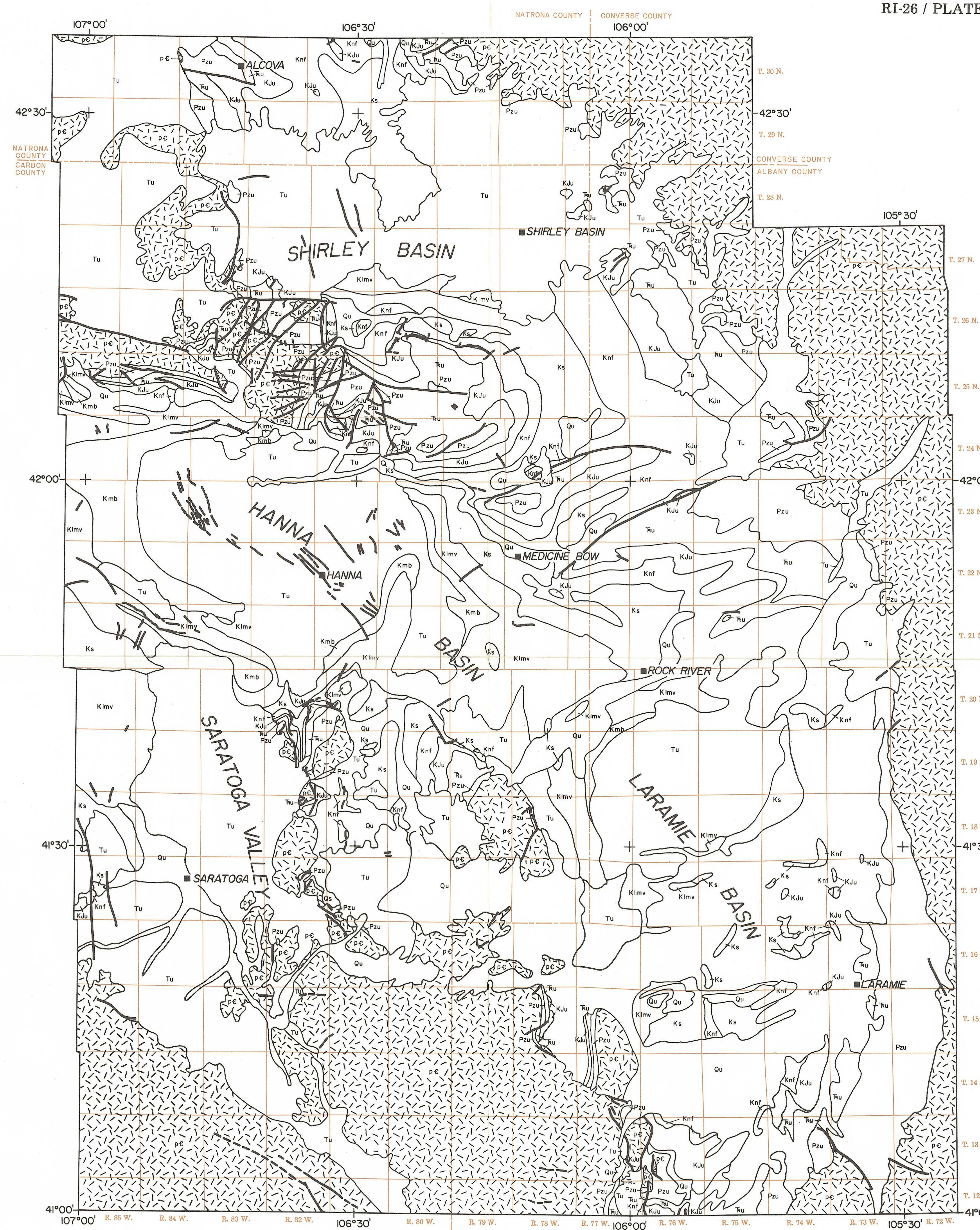
5 0 5 10 15 20

AREA OF THIS REPORT




GEOLOGY GENERALIZED FROM: LOWRY, MARLIN E., SAMUEL J. RUCKER IV, AND KENNETH L. WAHL, 1973, WATER RESOURCES OF THE LARAMIE, SHIRLEY, HANNA BASINS AND ADJACENT AREAS, SOUTHEASTERN WYOMING, U.S. GEOLOGICAL SURVEY HYDROLOGIC INVESTIGATIONS ATLAS HA-471. LOVE, J.D., J.L. WEITZ, AND R.K. HOSE, 1955, GEOLOGIC MAP OF WYOMING, U.S. GEOLOGICAL SURVEY.

COMPILED BY B.S. HINCKLEY




# GENERALIZED GEOLOGIC MAP OF THE LARAMIE, HANNA, AND SHIRLEY BASINS, WYOMING

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



## EXPLANATION

THERMAL GRADIENT CONTOUR
IN °F / 1,000 FT., DASHED WHERE APPROXIMATE
CONTOUR INTERVAL IS 5°F / 1,000 FT.

DATA POINT DERIVED FROM BOTTOM-HOLE TEMPERATURE GRADIENT

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

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

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

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

HEAT FLOW DATA POINT
IN mW/m²

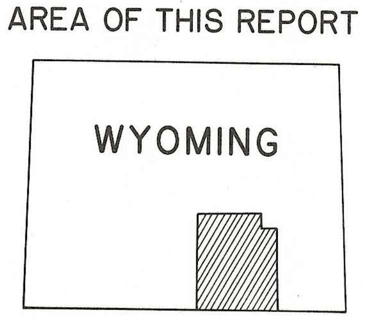
AREA OF ANOMALOUS GRADIENTS
NUMBER REFERS TO DISCUSSION IN TEXT (PAGES 20 TO 23).

## SCALE

MILES
5 0 5 10 15 20

KILOMETERS
5 0 5 10 15 20

AREA OF THIS REPORT

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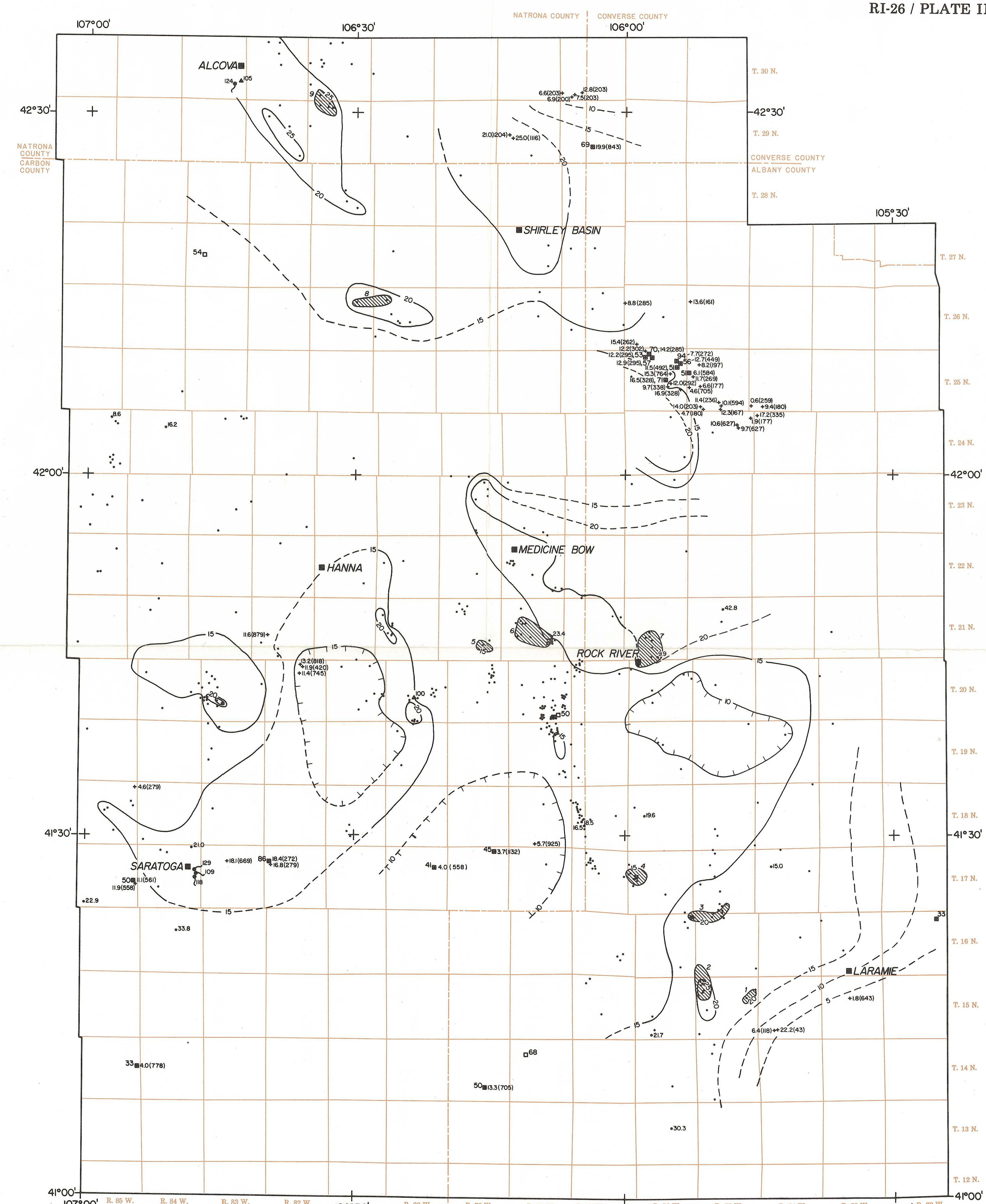



# GENERALIZED THERMAL GRADIENT CONTOUR MAP OF THE LARAMIE, HANNA, AND SHIRLEY BASINS, WYOMING

## EXPLANATION

CONTOUR ON THE CLOVERLY FORMATION
DATUM IS MEAN SEA LEVEL; CONTOUR INTERVAL IS 2,000 FT.

SELECT CONTOUR ON LAND SURFACE
DATUM IS MEAN SEA LEVEL

FAULT

ANTICLINE AXIS
ARROW SHOWS DIRECTION OF PLUNGE

SYNCLINE AXIS
ARROW SHOWS DIRECTION OF PLUNGE

AREA OF PRECAMBRIAN ROCK OUTCROP

AREA OF ANOMALOUS GRADIENTS
NUMBER REFERS TO DISCUSSION IN TEXT (PAGES 20 TO 23).

DIRECTION OF WATER MOVEMENT IN THE CLOVERLY FORMATION
AFTER RICHTER, 1981

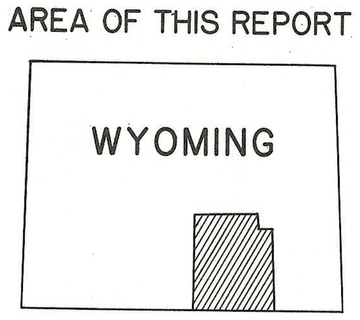
N

SCALE

MILES
5 0 5 10 15 20

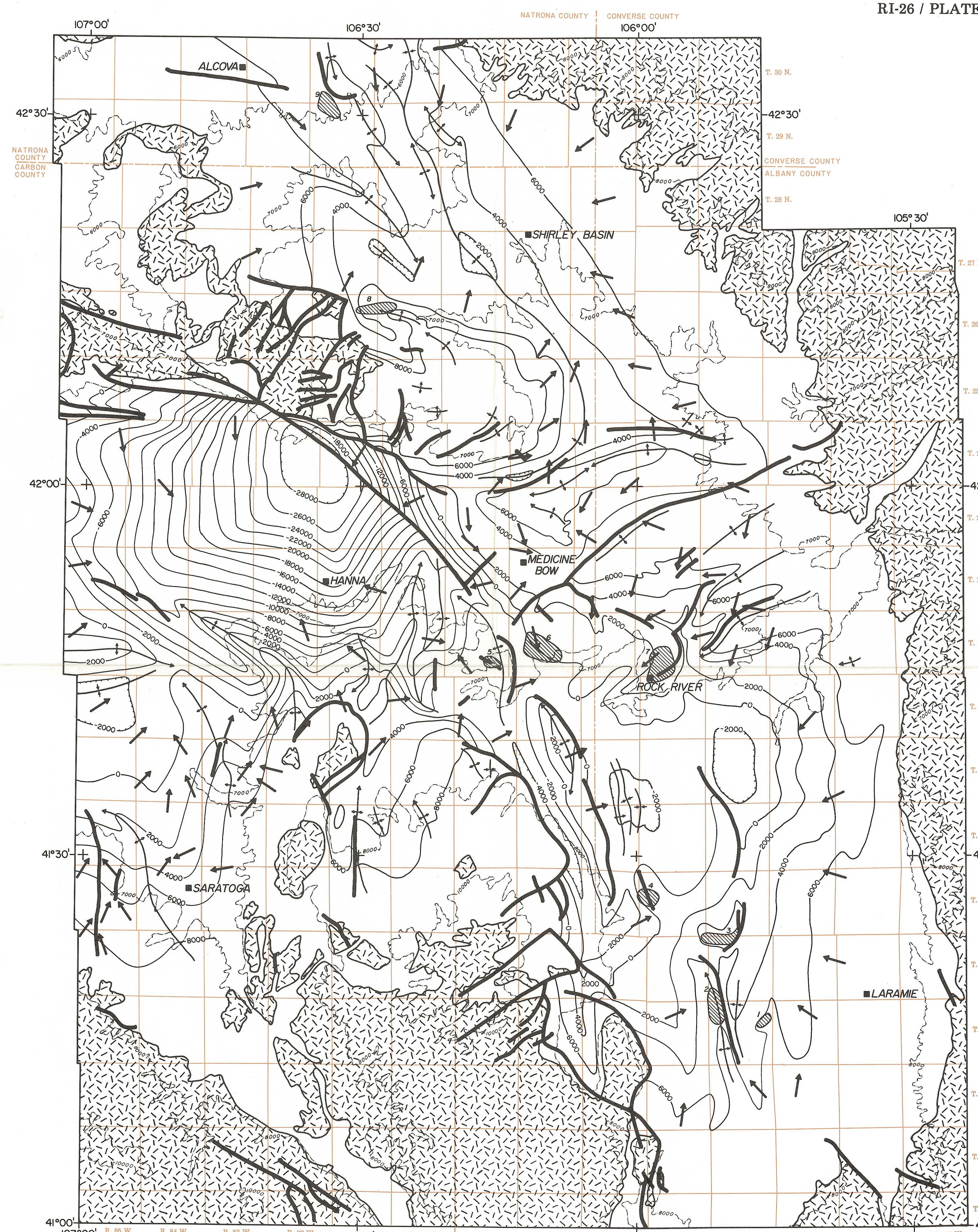
KILOMETERS
5 0 5 10 15 20

AREA OF THIS REPORT




STRUCTURE CONTOURS GENERALIZED FROM: RICHTER, H.R., JR., 1981, OCCURRENCE AND CHARACTERISTICS OF GROUND WATER IN THE LARAMIE, SHIRLEY, AND HANNA BASINS, WYOMING, UNIVERSITY OF WYOMING WATER RESOURCES RESEARCH INSTITUTE, PLATE B-1. ADDITIONAL CONTOURING WHERE NECESSARY FROM: BARLOW & HAUN, INC., 1978, WYOMING STRUCTURE CONTOUR MAP, POMCO, CASPER, WYOMING. PRECAMBRIAN ROCK OUTCROP FROM: LOWRY, M.E., ET AL., 1973, WATER RESOURCES OF THE LARAMIE, SHIRLEY, HANNA BASINS AND ADJACENT AREAS, SOUTHEASTERN WYOMING: U.S. GEOLOGICAL SURVEY HYDROLOGIC INVESTIGATION ATLAS HA-471.

COMPILED BY B.S. HINCKLEY




# GENERALIZED STRUCTURE CONTOUR MAP OF THE CLOVERLY FORMATION IN THE LARAMIE, HANNA, AND SHIRLEY BASINS, WYOMING

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



## EXPLANATION

—150— — — — TEMPERATURE CONTOUR
IN °F, DASHED WHERE APPROXIMATE; CONTOUR INTERVAL IS 10°F

———— APPROXIMATE OUTCROP OR FAULT TERMINATION OF THE CLOVERLY FM.-MORRISON FM. CONTACT

· BOTTOM-HOLE TEMPERATURE DATA POINT FOR THE CLOVERLY FM. OR MORRISON FM.

1 AREA OF ANOMALOUS GRADIENTS
NUMBER REFERS TO DISCUSSION IN TEXT (PAGES 20 TO 23).

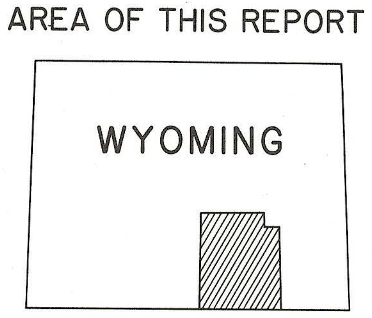
## SCALE

MILES
5 0 5 10 15 20

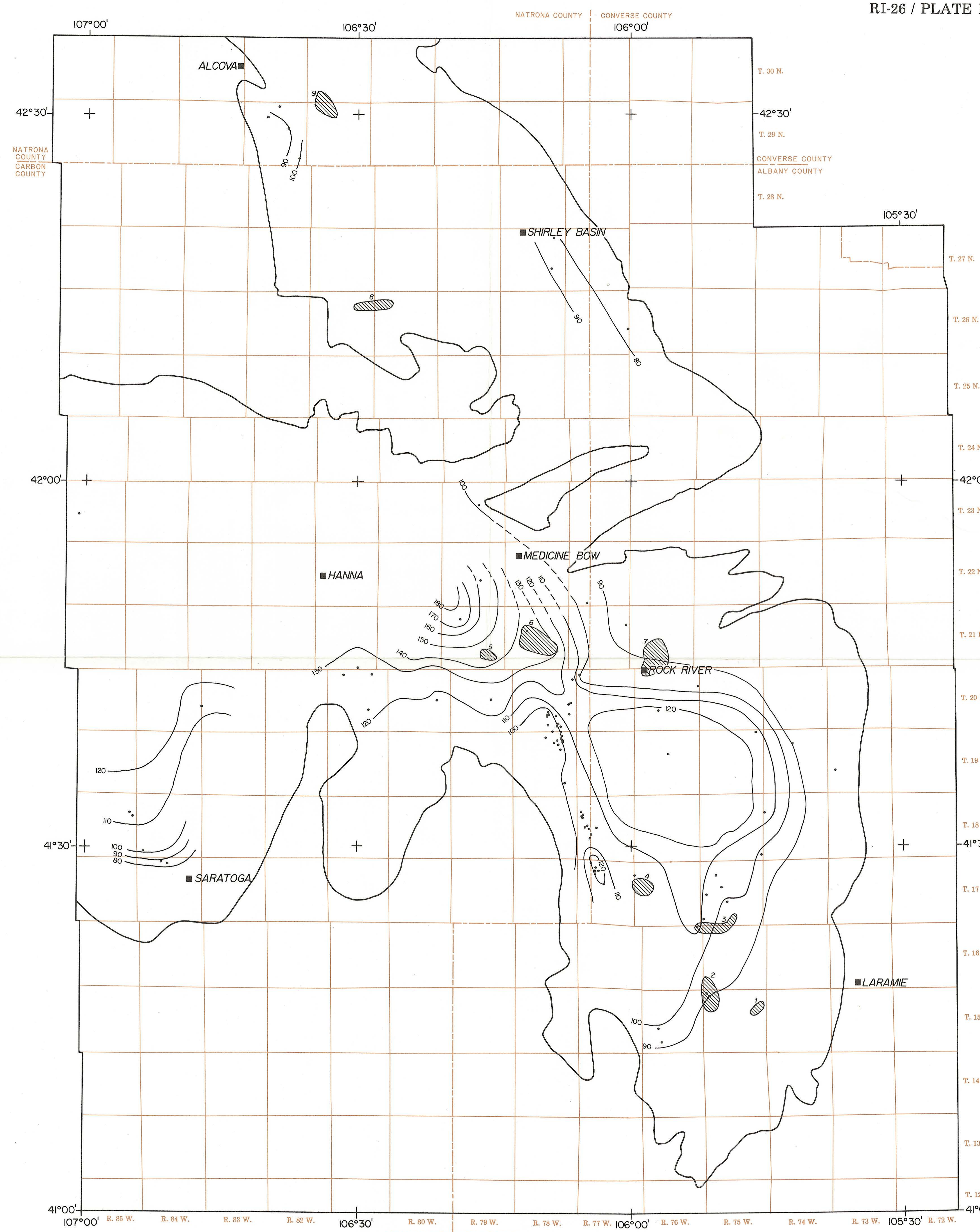
KILOMETERS
5 0 5 10 15 20

N

AREA OF THIS REPORT




COMPILED BY B.S. HINCKLEY




# GROUND-WATER TEMPERATURE CONTOUR MAP OF THE CLOVERLY AND MORRISON FORMATIONS IN THE LARAMIE, HANNA, AND SHIRLEY BASINS, WYOMING