OIL WELL TEMPERATURES IN GEOTHERMAL EXPLORATION

INTRODUCTION

The Earth Science Laboratory is engaged in a systematic study of oil and gas well temperatures obtained from a file prepared by Petroleum Information Corporation of Denver. Temperatures appearing in this file are those obtained in the following well test cycles: (1) Initial Potential tests, (2) Formation tests (drill stem tests), and (3) Production tests. The file lists temperatures recorded in such tests in the western United States since December 31, 1964. ~~The~~ It file provides temperatures from nearly 7,000 wells as listed in Table 1.

Table 1

State	No. of wells	State	No. of wells
Arizona	15	North Dakota (west of 100°)	620 ✓
Colorado	1,097 ✓	South Dakota (west of 100°)	71
Idaho	2	Texas (west of 103°)	243
Montana	1,063 ✓	Utah	191 ✓
Nevada	18	Wyoming	2,963 ✓
New Mexico	635 ✓		

The Petroleum Information file contains only a small percentage of the well temperatures available. In the conterminous western states and Alaska there are approximately 150,000 wells completed since 1964 in which bottom hole temperatures have been recorded in geophysical logging. In Utah over 1,100 temperatures from geophysical logs have been added to the Petroleum Information values. This is a five-fold increase in data points here.

*

This investigation was undertaken to evaluate the possibility of discovering clues to the locations of unidentified geothermal systems by examining thermal data from oil wells. It is probable that many geothermal systems have remained undiscovered because of lack of obvious surface evidence. Renner and others (1975) believe this to be the case with water-dominated systems. It is unlikely that heat can be detected in oil provinces using oil-field measuring techniques unless mass transfer has occurred and, because of this, water-dominated systems are the most likely to be ~~detected~~ found.

Oil and gas wells are drilled in porous rock of sedimentary basins where hydrology is bound to be a significant factor in bottom hole temperatures. It is for this reason that in heat flow studies drill sites are chosen in less permeable rock, despite the more costly drilling (Lachenbruch and Sass, 1977). In some cases published values of heat flow are probably related to water circulation. Most local anomalies in high heat flow areas are "likely to come from hydrothermal convection supported by regional heat flow and modified by the forcing effects of variable topography, permeability, and precipitation" (Lachenbruch and Sass, 1977, p. 649). The Eureka (Nev.) heat flow low is believed by Sass and others (1971) to be the result of a systematic regional circulation of water to depths of a few kilometers. Norton (1977, p. 703) states that "analysis of transport phenomina in permeable media suggest that fluid circulation through fractured rock may constitute significantly to heat transfer throught the crust, at least to depths of 10-15 km."

Temperatures are taken over a wide range of depths in petroleum explorations wells and it is the usual practice to present such data as gradients; each gradient being calculated over the interval from the surface to the point of measurement. As emphasized by Birch (1954), the principal variables affecting temperature gradient in the outer layers of the crust are thermal conductivity and water movement. Hence a gradient map does not provide much information about the fundamental quantity, heat flow. This is not a serious disadvantage if the targets sought are water-dominated hydrothermal convection systems. Also, elevated temperatures resulting from a high thermal conductivity insulating layer may provide the extra margin necessary for energy extraction.

?

Hydrothermal energy can be utilized over a considerable range of temperatures. Water from springs with temperatures as low as 15°C have been used for soil warming, frost control, and livestock shelter (Bar Mettler, 1978). As thermal water becomes less accessible because it is trapped beneath the surface, more complicated and costly ~~expensive~~ procedures are required for its recovery and higher temperatures are generally needed. Boreholes of moderate depth are feasable for producing water for space heating at perhaps 90°C. Deep drilling is usually not undertaken unless temperatures suitable for the generation of electricity (> 150°C) are expected.

No arbitrary gradient value can be considered indicative of a useful geothermal system since the limiting temperature/depth ratio which separates useable from unuseable hydrothermal energy is not a constant with depth, nor even a continuous function, but is related to the temperature and the availibility of thermal waters. This is a difficulty which attends the interpretation of gradient maps assembled from data points from a wide range of depths. ~~It will be shown that~~ Areas of anomalously high gradients are ~~can be~~ found with these data but they are not necessarily of interest from an energy standpoint. In exploration, specific temperatures and depths should be examined where gradient anomalies exist. Isothermal contour maps are more useful than gradient maps in exploration for [illegible], but to construct these from oil well temperatures requires either the use of gradients in extrapolating temperatures or the elimination of all but a small number of favorable data points.

BHT's IN THERMAL STUDIES

All temperatures in the Petroleum Information file are listed as BHT's (bottom hole temperatures) although often, as in drill stem tests, they are not taken at the bottom of the hole but over an interval that may extend for several hundreds of feet. Temperatures obtained from geophysical logs are also called BHT's. These are measured with maximum-reading thermometers in logging tools and are assumed to be the temperature at the bottom of the logged interval which may or may not be at the bottom of the hole.

The BHT's measured in initial potential, formation, and production tests, as well as those recovered in geophysical logging, are not actual formation temperatures unless the well has been static long enough for the borehole and adjacent formation temperatures to stabilize. If taken immediately after drilling, the measured temperature may differ from the actual formation temperature by as much as 45°C (Timko and Fertl, 1972). However, an exponential temperature adjustment begins with the cecession of drilling fluid circulation, and the time required to lower testing equipment into the hole allows for considerable adjustment, particularly if the temperature is taken at the bottom point of the hole. The thermal disturbances responsible for this instability have a number of sources; the most important, over the range of depths considered here, is the effect of circulating drilling fluid which tends to cool the lower parts of the hole.

Lachenbruch and Brewer (1959) approximated these disturbances with a constant line heat source in a uniform infinite medium and found a solution for true formation temperature at a fixed depth as a function of time. This relationship is ~~of the form~~

$$T = T_{\infty} - A \ln \frac{t}{t-s}$$

where T = observed temperature;

T_{∞} = equilibrium temperature;

t = time elapsed since the drill bit reached the depth in question; and

s = time elapsed since the drill bit first reached the depth in question until the drilling ceased.

If only radial components of heat flow are allowed, an identical expression describes bottom-hole temperature relaxation. In this case, s is the time associated with convection and forced fluid circulation.

A number of investigators have used this logarithmic relationship to correct BHT's for calculating geothermal gradients (Evans and Coleman, 1974; Dowdle and Cobb, 1974; and Grisafi and others, 1974). A series of temperature measurements are made at a particular depth and at known times after circulation has ceased. Equilibrium temperatures can be estimated from projections of logarithmic plots.

Schoeppel and Gilarranz (1966) used temperatures from electric logs to prepare a gradient map of Oklahoma. They state that, by judicious selection of data from logs, temperature measurements can be expected to be within 5 percent of the formation temperature. They picked temperatures taken as long as possible after the circulation of drilling fluids had ceased and took the last recorded BHT's of very deep wells in which multiple logs had been run.

In the Reconcavo Basin in Brazil, Carvalho and Vacquier (1977) used uncorrected BHT's from electric logs to calculate gradients and heat flow. They recommend that in future work of this kind an attempt should be made to correct BHT's for disequilibrium conditions using time considerations. They felt confident enough of their data, however, to suggest geologic causes for heat flow differences they calculated for various oil fields in the Reconcavo Basin.

In 1975, the American Association of Petroleum Geologists, in conjunction with the U. S. Geological Survey, published a Geothermal Gradient map of North America. This map was constructed from temperature data in over 25,000 wells after the rejection of discordant values and using standard filtering and smoothing procedures. This is a regional map from which local anomalies were intentionally eliminated, Kehle and others (1970).

Data of the present study, both from Petroleum Information and geophysical logs, do not include information necessary to correct BHT's with time factors as outlined by Lachenbruch and Brewer (1959) nor is it possible to select temperatures which have closely approached equiblibrium as did Schoeppel and Gilarranz (1966). All temperatures considered in this investigation are uncorrected values. Discordant data have not been eliminated since discovering local anomalies is one of the major objectives of this study. Significant errors are sure to exist, not only due to thermal disequilibrium but to poor oil-field measuring techniques as well, but substantial uncertainties can be tolerated in the search for large local anomalies.

ELK BASIN COMPARISON

Heasler (1978) has published some reliable downhole temperatures from the Elk Basin oil field in northwestern Wyoming. These temperature measurements were made after the wells had essentially attained thermal equilibrium. They were taken at discrete intervals of 5 and 10 meters, from the surface to a maximum depth of 1,772 meters, in five oil wells. A stratigraphic interval from the Upper Cretaceous Claggett Formation to the upper part of the Mississippian Madison Formation was covered.

The Petroleum Information file contains 23 temperatures in the Elk Basin field and an additional 20 in the nearby Silvertip and Silvertip South fields. Figure 1 shows the locations of wells tested by Heasler and wells from the Petroleum file. Figure 2 shows a part of the stratigraphic column at the Elk Basin field and the stratigraphic locations at which the 43 Petroleum Information temperatures were recorded. In some cases drill stem test intervals overlapped formation boundaries as shown in the figure.

Figure 3 is a depth plot of the file temperatures in Elk Basin, Silvertip and Silvertip South oil fields. Selected temperatures from three wells tested by Heasler are also shown here. The least squares fit of 43 Petroleum Information temperature-depth values has a slope of 21.1°C/km with a correlation coefficient of 0.886. The depth range tested by Heasler covers very little of the depth region of Petroleum Information temperatures but, from Figure 3, it appears that regression analysis provides a fair approximation of the true gradient over this interval. At the time of measurement, the Petroleum Information temperatures had not equilibrated and are thus lower than those of Heasler.

RESULTS

Within major oil fields, the Petroleum Information file provides a high density of data points but, in surrounding areas, they are often so limited that regional trends are difficult to establish. Also, in areas not noted for oil production, such as the Basin and Range Province, very few data points appear. In this study, as has been mentioned, the Petroleum Information data in Utah have been augmented by BHT's from geophysical logs. As a result, in eastern Utah we have a better distribution of data points than in most other areas of comparable size in the western states. This discussion will be concerned primarily with geothermal implications in Utah.

The Petroleum Information file lists a number of individual well temperatures in the western states which are high enough, and at suitable depths, to be useful in geothermal energy production, though water availibility in these wells is not known. In an agreement between Petroleum Information Corporation and the Earth Science Laboratory, information on individual wells cannot be released, but no such restriction applies to geophysical log data collected from state agencies.

In all of the oil well data in the western states, an inverse relationship exists between thermal gradient and depth. This is a result of the computational procedure used. That is, of calculating thermal gradients between the surface and the downhole points of temperature measurement. It also requires that a rapid increase in temperature near the surface predominates. This inverse gradient-depth relationship is illustrated in Figure 4 where thermal gradients in Utah, averaged over 100 meter intervals, are plotted against depth. Average temperatures for these intervals are also shown on this figure. Linear regression of the temperature-depth values below 200 meters gives a gradient of 16.3°C/km with a correlation coefficient of 0.993. This indicates that the thermal effects which cause the gradient variation in Utah occur in the upper 200 meters and may be confined to a much shallower depth.

A rapid rise in temperature near the surface could result from a surface layer of low thermal conductivity or from heat introduced in the drilling process, or a combination of both. Anomalously warm surface waters could also produce this effect but it is not likely that such a condition predominates in all of the data.

Considering the case of a low conductivity surface layer and referring to the heat flow relationship,

$$q = k \frac{\partial T}{\partial z} ,$$

where q is the upward component of heat flux, k the thermal conductivity, and $\frac{\partial T}{\partial z}$ is the vertical component of the thermal gradient, If the gradient is considered constant between the surface and the depth of temperature measurement, z, it is equal to $\frac{T_z - T_o}{z}$.

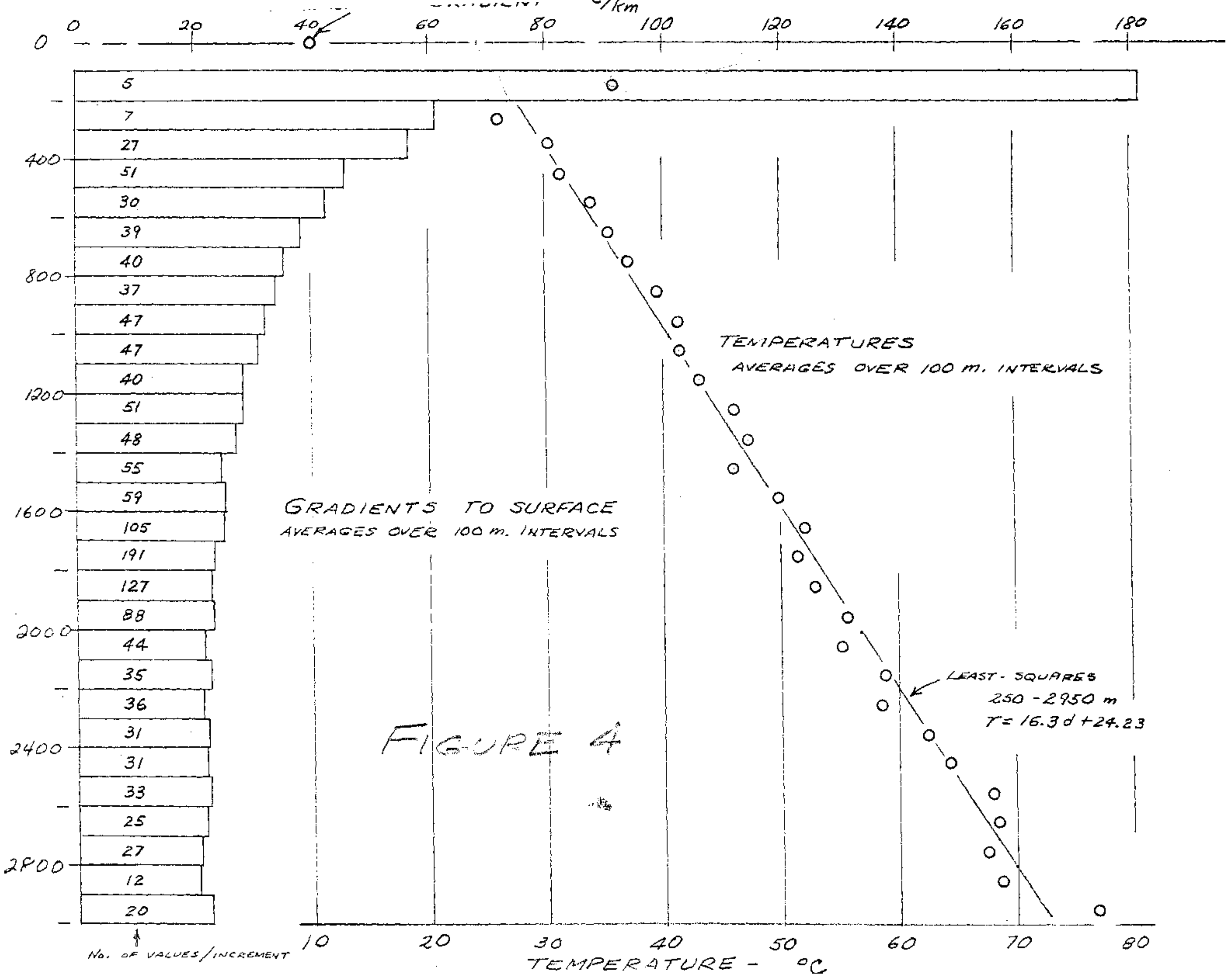

C/km
0
20
40
60
80
100
120
140
160
180
0
400
800
1200
1600
2000
2400
2800
DEPTH m
5
7
27
51
30
39
40
37
47
47
40
51
48
55
59
105
191
127
88
44
35
36
31
31
33
25
27
12
20
No. of VALUES/INCREMENT
GRADIENTS TO SURFACE
AVERAGES OVER 100 m. INTERVALS
TEMPERATURES
AVERAGES OVER 100 m. INTERVALS
LEAST - SQUARES
250 - 2950 m
T = 16.3 d + 24.23
10
20
30
40
50
60
70
80
TEMPERATURE - °C

FIGURE 4

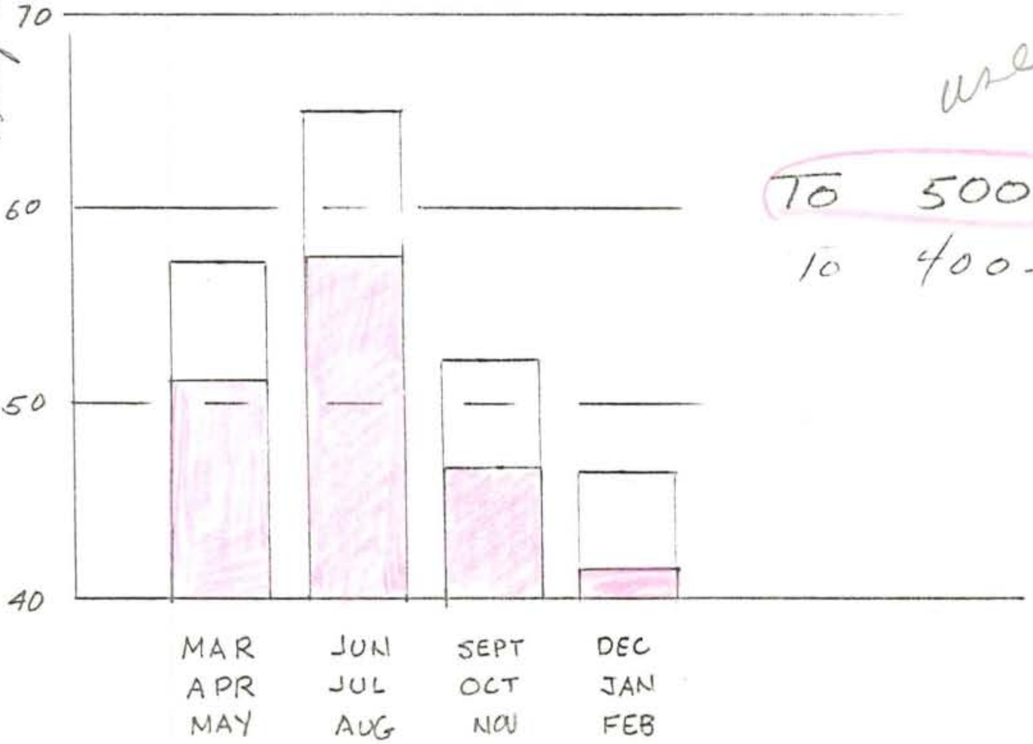
From the linear regression line of Figure 4, the temperature at 200 meters is 27.5°C. Using a surface temperature of 10.0°C and an estimated heat flow of 1.5 HFU (heat flow units, microcal/cm^2sec), then, in a conductive environment, the thermal conductivity of the upper 200 meters is

1.71 millical/cm sec °C

This value is too low for consolidated sedimentary rocks but it is typical of many moist soils and is higher than the thermal conductivity of dry soils (Clark, 1966). Some dry loams would produce an equivalent effect in a layer 40 meters thick (ibid.). Thus, if the majority of wells penetrate a moderate thickness of surface alluvium, the gradient-depth relationship of Figure 4 will inevitably occur.

The introduction of heat into a borehole by drilling fluids will have an effect on the thermal gradient calculated from the surface. The temperature of drilling fluid is more likely to be related to the seasonal surface temperature than to the mean annual temperature. Seventy-three thermal gradients in Utah to depths of less than 500 meters were compared with the seasons in which they were measured. There is a correlation between seasons and average gradients as shown on Figure 5 but average gradients, even for the coldest months, are all anomalously high. Heat generated by the friction of drilling and the deformation of drill rod is generally insignificant (Bullard, 1947, and Lachenbruch and Brewer, 1959).

°C / from average
using mean annual surface temp



To 500 m

To 400 m

use 500 meters

FIGURE 5 (?)

	MAR APR MAY	JUN JUL AUG	SEPT OCT NOV	DEC JAN FEB	TOTAL
MEAN SURFACE TEMP °C	10.3	22.8	11.3	-1.8	
No. of Samples	12	19	20	22	73
"	9	6	8	7	30

In Figure 4, thermal gradients appear to have stabilized at a uniform value of about 22°C/km near 1,800 meters. From the linear regression of temperature-depth values, this should approach 16.3°C/km if the linear relationship persists with depth. Heasler (1978, p. 89) found that gradients calculated by using surface temperatures and "maximum-depth" temperatures in five wells in the Elk Basin field were in excellent agreement with least square gradients from all data points in each well. These "maximum-depths" ranged from 1,550 to 1,775 meters.

If gradients are calculated between the surface and large depths, an acceptable gradient map might be produced from bottom hole temperatures of oil wells. In Utah, if only temperatures from depths greater than 1,800 meters were utilized, half of the data points would be eliminated and an important part of this study is the identification of anomalously warm waters at shallow depths which might be useful for low temperature energy. A method of utilizing all of the data can be achieved by assuming the surface temperature to be the surface intercept of the regression line through all temperature-depth points within a geologic subdivision. With the density of data in the Petroleum Information file, such a subdivision must be large to supply enough data points for a reliable regression line. The data of Figure 4 are restricted by political, not geologic,boundaries but approximately 94 percent are from the Colorado Plateau. The surface intercept of the regression line in Figure 4 is 24.2°C and its slope is 16.3°C/km. Clearly 24.2°C/km is much greater than the actual mean annual surface temperature but, by using it for the surface temperature, gradients in excess of the average gradient at any depth can be isolated.

In east central Utah, gradients to the surface have been calculated using surface temperatures of both 24.2°C/km and 10.6°C/km. The latter is the regional value of mean annual surface temperature published by the National Oceanic and Atmospheric Administration (1974). Plate I is a comparison of the locations of predominantly high gradient areas arising from the two calculations. Using a surface temperature of 24.2°C/km, gradient values above 20°C/km are considered anomalous and using 10.6°C/km, gradients greater than 35°C/km. Geologic features which may have a bearing on the anomaly patterns are also shown on Plate I. These are the Mancos Shale and the Uncompahgre Uplift. Precambrian rocks of the Uncompahgre Complex are shown where exposed.

Of the areas considered anomalous on Plate I, there is a marked correspondence between those produced in the two different calculations. Anomalous gradient areas derived from a surface temperature of 10.6°C have a close spatial relationship to outcropping Mancos Shale where it crosses the Uncompahgre Uplift. Anomalous gradient areas from a surface temperature of 24.2°C are also spatially related to the Uncompahgre Uplift but are less closely associated with the Mancos outcrop. They extend up to 25 miles northwest of the outcrop in a downdip direction but many of the BHT's here are from beneath the Mancos Shale. High gradient areas are produced in both calculations at the Peter's Point oil field in northeastern Carbon County.

It is possible that the low thermal conductivity of the Mancos Shale contributes to the anomalous gradients. The absence of an anomaly over Mancos on the west might be explained by cooling due to groundwater introduced from the high plateaus of central Utah and from the Green River.

Precambrian rocks which form the core of the Uncompahgre Uplift are composed of gneissic granodiorite which was intruded in Precambrian time by quartz monzonite and a biotite-muscovite granite (Hedge and others, 1968). Bounding the Uplift on the southwest is a steep fault of large vertical displacement. From a gravity survey, Case and Joesting (1972) estimate the total relief of the Precambrian surface to be of the order of 19,000 feet. The anomalous gradients could reflect the presence of thermal waters ascending along this fault. Another possible cause of the anomalous gradients is radiogenic heat from the granitic rocks of the Uncompahgre Complex. If this true, a heat flow high should exist here. No published heat flow values are available here but the geologic situation is similar to that of the Zuni Uplift in

New Mexico. There, high heat flow has been reported by Reiter and others (1975) to which radiogenic heat may be a significant contributor (Brookins, 1978).

COMMENTS ON THERMAL RESULTS BY STATE

Colo I Mont II III N Mex IV

Plates II, III, IV, and V are maps of Utah, Colorado, Montana and New Mexico on which comparisons are made between areas of high thermal gradients and areas considered generally favorable for the recovery of thermal waters as outlined in U. S. Geological Survey Circular 790 (1978). High gradient areas appearing on these maps are those in which a preponderance of gradients exceed 35°C/km. All gradients were calculated from the point of temperature measurement to the surface using the mean annual surface temperature for climatic divisions published by the National Oceanic and Atmospheric Administration (1974). As explained in <u>Results</u>, gradients calculated from shallow depths are likely to be exaggerated when using these surface temperatures.

No attempt is made to interpret gradient data which do not have some relationship to areas considered favorable for thermal waters by the USGS. The high gradient areas which do not correspond with these are believed to have good potential for geothermal energy development and all deserve further study.

BHT's from geophysical logs have been added to the Utah data. In other states, data are from the Petroleum Information file only.

Utah

The Petroleum Information file lists 191 wells in Utah. An additional 1,100 temperatures have been added from geophysical logs obtained from Utah State agencies. This is not a complete assemblage of well temperatures in Utah. Several thousand additional data points are available from public records.

Only one area in Utah, considered generally favorable for the recovery of thermal waters by the USGS, lies in a "region of best well density" on Plate II. Outside of these regions, data points are few and no gradient correlations can be made between wells. This one area lies in the Uinta Basin in northeastern Utah and thermal waters here are attributed to deep circulation in the Duchesne fault zone. Thermal waters considered in outlining this favorable area are found in well at depths of less than 400 meters with a maximum temperature of 56°C (Sammel, 1978). All of the BHT's examined in this study are at depths much greater than this (up to 5,000 meters) and, although none produced anomalous gradients, temperatures up to 120°C were recorded. This is a situation in which the waters are heated in a normal geothermal gradient and have moved upward by convection along a fault zone. It illustrates how the vertical positions of data points in oil wells can be as important as their horizontal distributions in locating thermal waters

The anomalous gradient area in northeastern Grand County has been discussed. Here, as with other anomalous areas, interpretations can only be tentative with the data on hand.

Colorado

In Colorado, one high gradient area is associated with an area considered generally favorable for the recovery of thermal waters. This is at the Dunton-Rico Hot Springs in Dolores County. These spring waters, ranging from 28°C to 46°C are believed to come from deep circulation in faults (Sammel, 1978). The four high gradients here (there are only four wells) arise from depths of from 1,240 to 1,800 meters with a mean value of 46°C/km. BHT's are in Mississippian and Pennsylvanian rocks. This good correspondence between thermal surface waters and gradients from appreciable depths is encouraging.

Montana

The high gradient area in Hill, Blaine, Chouteau, and Fergus Counties is near the Little Rocky Mountains where thermal springs issue from rocks of the Madison Group in three major areas. High gradients from Petroleum Information data here nearly all arise from shallow depths (~~some~~ one less than 100 meters) (~~as little as 150 meters~~) in Cretaceous rocks. Many BHT's are higher than the maximum temperature measured in the springs of the Little Rockies. The outline of the area considered generally favorable for the recovery of thermal waters might well be extended to cover much of the anomalous gradient area.

On Plate IV, anomalous gradient areas which arise primarily from BHT's at shallow depths are distinguished from others.

New Mexico

In New Mexico, good data density from the Petroleum Information file exists only in the San Juan Basin in the northwest and the Delaware Basin in the southeast. Three areas, considered generally favorable for the recovery of thermal waters, lie in the San Juan Basin but only one is associated with a high gradient area. This is at Little Blue Mesa where water of 32°C and 48°C are encountered in two wells at 304 and 686 meters, respectively. These waters are found in Early Tertiary sedimentary rocks and are believed to be due to deep circulation (Sammel, 1978). BHT's in the anomalous Chaco Mesa area are from Upper Jurassic and Lower Cretaceous rocks and produce gradients up to 40°C/km.

The Delaware Basin contains a large number of wells but very few anomalous gradients.