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OIL WELL TEMPERATURES IN GEOTHERMAL EXPLORATION

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INTRODUCTION

Subsurface temperature data recorded in the routine testing of wells drilled for petroleum can be used to identify areas which may contain potential geothermal resources.

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. Figure 1 shows the area covered by the search. Thermal measurements are not on file from several of the states. Nearly 7,000 wells with temperatures and associated depth appear in the file as listed in Table 1.

Table 1

Wells retrieved in the Petroleum Information Corporation thermal search by states.

State	No. of Wells	State	No. of Wells
Alaska	0	North Dakota	620
Arizona	15	Oregon	0
California	0	South Dakota	71
Colorado	1,097	Texas	243
Idaho	2	Utah	191
Montana	1,063	Washington	0
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 location of unidentified geothermal systems by examining thermal data from oil wells. It is probably 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.

Higher than normal temperatures in oil wells might be expected in the following situations:

1) Where faults extend to depth and provide routes for the ascent of flui~~e~~ds heated in the geothermal gradient.
2) Where there is an anomalous concentration of heat at the base of the crust (Diment and others, 1975).
3) Beneath layers of low thermal conductivity material.
4) Above basement rocks that contain moderate or high concentrations of radioactive minerals (Combs and Simmons, 1973).
5) In the presence of high level magma chambers (Smith and Shaw 1975).
6) In geopressurized areas.
7) Where exothermic chemical reactions are taking place in the earth (??)

(????).

Deep circulation along faults may produce large thermal anomalies relatively near the surface which could be detected in oil wells. Where heat is transferred solely by conduction, thermal anomalies related to radiogenic heat, magma chambers, and sources near the base of the crust, thermal anomalies may be more subtle, and it has been usual to rely upon more accurate temperature measurements to detect them.

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 and, with the aid fo water in heat transport, thermal anomalies may be found considerable distances from the heat source.

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 alyers 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.

BHT's in THERMAL STUDIES

All temperatures in the Petroleum Information file are listed as BHT's (bottom hole temperatures) although they are not alsways taken at the bottom of the hole. Termperatures 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 stablilize. 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 an appreciable 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. A number of investigators have used this relationship to correct BHT's for calculating geothermal gradients (Evans and Coleman, 1974; Dowdle and Cobb, 1974; Grisafi and others, 1974; Timko and

Fertl, 1972).

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 suggest that the heat flow difference they calculated for various oil fields in the Basin are related to the depth of a basement producing radiogenic heat and the presence of shale diapins.

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 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 his 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 loarge 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 2 shows the oil fields which provided the Petroleum Information data and the locations of wells tested by Heasler.

Figure 3 shows a part of the stratigraphic column at th Elk Basin field and the stratigraphic locations at which the 43 Petroleum Information tempertures were recorded. In some cases drill stem test intervals overlapped formation boundaries as shown in the figure.

Figure 4 is a depth plot of the file temperatures in Elk Basin, Silvertip and Silverti 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. 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 equilibrate and are thus lower than those of Heasler.

DATA HANDLING

Gradients to surface were calculated for all wells using as surface tempertures the climatic division averages published by the National Oceanic and Atmospheric Administration 91974). Such surface temperatures can produce reasonably good gradients to the surface if the points of temperature measurement are at appreciable depths (Heasler, 1978, p.89) but, for shallow temperatures, gradients are ususally excessively high. Figure ~~4~~5, compiled from well temperatures in Utah, illustrates this. In this figure temperature gradients, averaged over 100m intervals, are plotted against depth. The high gradients noted at shallow depths could result from using surface temperatures too low in value. It may be that the average atmospheric temperatures are lower than the average ground surface tempertures. This is speculative, but an insulating layer of snow in winter, for example, would cause the ground to be substantially warmer than the air.

The introduction of heat into a borehole by drilling fluids will have an effect on the thermal gradient calculated from the surface. The temperatures 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 ~~8~~ 6 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).

In Figure ~~#~~ 6, thermal gradients appear to have stabilized at a uniform value of about 22°C/km near 1,800 meters. 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 as low temperature energy resources.

In presenting the results, high gradient areas produced by a predominance of shallow temperatures are noted.

RESULTS

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 attractive as potential geothermal energy resources, 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.

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 difficut to establish. Also, in areas not noted for oil porduction, such as the Basin and Range Provinde, very few data points appear. In Table 1, the number of wells retrieved in the Petroleum Information Corporation thermal search are listed by state. Wtih the addition of data points in Utah from another source, six states have regions where well densities are high enough to outline concentrations of anomalous gradients. These are: Colorado, Montana, New Mexico, North Dakota, Utah, and Wyoming. well temperature data in North Dakota and Wyoming are being evaluated by state groups. The remaining four states will be discussed here.

Figures ~~6~~ 7, ~~7~~ 8, ~~8~~ 9 and ~~9~~ 10 are maps of Colorado, Montana, New Mexido, and Utah, respectively on which comparisons are made between areas of high thermal gradients and areas considered generally favorable for the recovery of thermal waters as outlined by Sammel (1978). High gradient areas appearing on these maps are those in which a large percentage of gradients exceed 35°C/km. All gradients were calculated to the surface using the mean annual atmospheric temperature. As explained earlier, gradients calculated from shallow depths are likely to be exaggerated. Anomalous areas of Figures ~~6~~ 7 through ~~9~~ 10 are listed in Table 2.

There exist isolated high-gradient wells with attractive BHT's which cannot be conveniently placed in anomalous areas. Others are sure to be found in the examination of data from state oil and gas agencies.

Colorado

Colorado wells in the Petroleum Information file are most abundant in the Great Plains, particularly in the Denver Basin. There are no wells at all lying within areas considered generally favorable for the recovery of thermal waters as outlined by Sammel (1978).

The Rico anomalous area (5) lies just west of 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 ~~g~~high geothermal gradients here arise from BHT's taken in Mississippian and Pennsylvanian rocks.

There are 13 areas of anomalous gradients shown in Colorado. Two of these, the Akron and Wray areas and contiguous, but are listed as separate areas because of the marked difference in the depths and formations from which BHT's were obtained. The anomalous area nearest to a major population center is Berthoud (7), six miles south of Loveland.

Montana

All of the Petroleum Information wells in Montana are east of the Continental Divide and none lie within areas considered generally favorable for the recovery of thermal waters. Ten anomalous areas are classified, three of which arise from BHT's at very shallow depths; the Havre (1), Malta (2), and Laurel (10) areas. The last is near the population center of Billings.

The Havre high gradient are (1) is near the Little Rocky mountains where thermal springs issue from rocks of the Madison Group in three major areas (Sammel, 1978). High gradients from Petroleum Information data here nearly all arise from shallow depths (one less than 100 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 be justifiably extended to cover some ~~much~~ of the anomalous gradient area.

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. Here 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 circualtion (Sammel, 1978). BHT's in the anomalous Chaco Mesa area are from upper Jurassic and Lower Cretaceous rocks and produce gradients up to 41°C/km.

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

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 in ~~from~~ public records.

Ninety-four percent of the data points in Utah lie in the Colorado

Plateau. As a result, in eastern Utah there is a better distribution of thermal gradient values than in most other areas of comparable size.

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 Figure 10. This one area lies in the Uinta Basin in northeastern Utah. Thermal waters here are attreibuted 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 55°C (Sammel, 1978). All of the BHT's examined in this study are at depths much greater than this (up to 5,000meters) 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. The absence of an anomalous gradient illustrates how the vertical positions of data points in oil wells can be as important as their horizontal distributions in locating thermal waters.

Ther Price anomalous area (2) is near a moderate sized population center, but BHT's here are from shallow depths and the maximum temperature recorded is only 40°C. This temperature might be useful under favorable conditions of water supply and location.

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Anomalous gradients in Grand County (4) have a close spatial relationship to outcropping Mancos shale where it crosses the Uncompahgre Uplift (see Figure ~~10~~ 11). 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 shoudl occur here. No published heat flow values are available but the geologic situation is somewhat 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 from Precambrian may be a significant contributor (Brookins, 1978).

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CONCLUSIONS

Areas of anomaoulsy high thermal gradients can be identified from bottom hole temperatures in oil wells even though these temperatures have not equilibrated with adjacent formation temperatures and are not, in themselves, very precise. In Colorado, Montana and New Mexico high gradients appear to be associated with areas generally considered favorable for the recovery of thermal waters. These are the Rico, Havre, and Chaco Mesa anomalous areas which appear in Table 2. Some other regions regarded as having geothermal energy potentials are not represented by anomalous gradients. A reason for this may be that bottom hole temperatures were measured at depths or in formations which are not closely related to the source of thermal waters. An example of this is an area in the Uinta Basin of Utah where normal geothermal gradients were calculated from deep temperatures, while known thermal waters are found at shallow depths. The conclusion here is that deep circulation in a fault zone has allowed meteoric waters to be heated in a normal geothermal gradient. Had the temperatures here been measured at shallow depths this thermal area might well have been found.

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The identificaiton of a potential geothermal resource from oil well temperatures depends upon the fortuitous location of BHT's in both the horizontal and vertical dimension. The density of data points, are hence the likelihood of finding a promising thermal area, can be increased by collecting more values from the vast store of BHT's filed with state agencies.

In the anomalous areas listed in Table 2, there are often BHT's which are especially attractive and which, if a suitable water supply exists, are possible candidates for energy production. A number of isolated wells have this same apparent potential. Anomalous areas may be indicative of thermal regions and may help direct exploration programs but it is the individual high gradient well that provides the best direct clue to a potential geothermal energy source. It is recommended that geothermal exploration based on oil well temperatures be initially directed toward the finding of individual wells with exceptionally promising thermal characteristics.

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