GL04124

INTRODUCTION

The Earth Science Laboratory has completed a preliminary study of oil and gas well temperatures gathered in routine well tests to examine their utility in geothermal exploration. It was not intended that accurate thermal maps be constructed, but rather that rapid comparisions of thermal data be made over large areas of the western United States. In the study regional trends were sought and also thermal irregularities that might directly indicate individual geothermal systems. In this regard, the primary aims were 1) to identify high temperatures in wells which in themselves are attractive as potential energy sources, and 2) to locate areas containing a preponderance of high thermal gradients which suggest the presence of geothermal systems even though they may lack temperature-depth values within the range of possible exploitation. These objectives require that all available temperatures and depths be examined, including discordant values. Temperature at shallow depths which might indicate energy sources for direct heat applications were sought as were areas with potential for electrical power generation.

The data studied is necessarily confined to areas favorable for petroleum production. In the western United States most areas now recognized as having geothermal energy potential do not correspond with petroleum provinces (see Map 1, USGS Circ. 790, 1978). The reason for this ~~may be~~ is that in sedimentary basins, where the study data were gathered, surface evidence of geothermal systems is least likely to be present. The study of oil well temperatures is an inexpensive method of extending geothermal exploration into these basins.

Higher than normal temperatures in oil wells of the western United States might be expected in the following situations:

1) Where heat is transferred by the convective circulation of water or steam.

2) Beneath layers of low thermal conductivity material.

3) Where there is an anomalous concentration of heat near the base of the crust (Diment and others, 1975).

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). Since temperatures normally increase with depth, geothermal gradients must be used to determine the presence of thermal anomalies. The principal variables affecting geothermal gradients are thermal conductivity and water movement (Birch, 1954) of the first two situations listed. The remaining situations also affect geothermal gradients but they are not always easily recognized from gradient alone.

This study was initiated with well data appearing in a computer file prepared by Petroleum Information Corporation of Denver. This is their Well History Control System (WHCS) which includes data on more than 970,000 wells drilled in the United States. The well Information used in this study was limited to the area shown in Figure 1 and to only those wells in which temperatures have been recorded. Temperatures were obtained in the following well test cycles: 1) Initial Potential tests, 2) Formation tests (drill stem tests), and 3) Productions tests. Descriptions of each well are included in the file together with geologic and production information and, where available, fluid recoveries and water analyses.

In some parts of Utah, the Petroleum Information data were augmented with bottom-hole temperatures posted on geophysical logs. These were obtained from the Utah Division of Oil, Gas and Mining.

With the well information being restricted to petroleum provinces, only portions of the following states are considered in this report: Colorado, Montana, New Mexico and Utah. Well temperature data from North Dakota and Wyoming are being evaluated by state groups.

DATA QUALITY

Temperatures measured in initial potential, formation and production tests are measured at or near the bottom of the well and are commonly termed bottom-hole temperatures (BHT's) as are temperatures posted on geophysical logs. They are not, however, 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 true formation temperature by several tens of degrees (Pirson, 1963). The thermal disturbances responsible for this instability have a number of sources; the most important, in the depths considered here, is the effect of circulating drilling fluid which tends to cool the lower parts of the hole.

Bullard (1947) recognized that when drilling fluid circulation ceases the temperature in the borehole will gradually adjust to formation temperature exponentially with time. Lachenbruch and Brewer (1959) studied temperature data collected over six years in a well in arctic Alaska and approximated drilling disturbances with a constant line heat source in a uniform medium and found a solution for true formation temperature at a fixed depth as a function of time. This is a logarithmic relationship, similar to Bullard's. If the time at which the drilling fluid ceases to circulate is known, a logarithmic projection of multiple bottom hole temperature at a certain depth can be used to approximate the equilibrium temperature. Evans and Coleman (1974) and Timko and Fertl (1972) have used this technique to estimate equilibrium temperatures in oil wells for the calculation of thermal gradients. Other methods of approximating true formation temperatures from multiple BHT's at fixed depths have been proposed by Albright (1975) and Middleton (1979). These are both based on the principle that the rate of temperature adjustment depends on the difference between the borehole temperature and the undisturbed rock temperature.

Bottom-hole temperatures appearing on geophysical logs are often repeated at a specific depth, together with the time since drilling fluid circulation ceased. This suggests that a solution for true formation temperature can be found. Where multiple temperatures appeared at fixed depths on geophysical logs studies, values were so erratic that equilibrium temperatures could not be approximated. This was due to measurement errors which cannot be distinguished from valid data in individual wells. Inaccuracies in measuring bottom-hole temperatures are common in oil well testing (Kehle and others, 1970) and the degree of error is impossible to establish.

In an oil field BHT's are measured at enough different depths so that by averaging these measurements as reasonably reliable thermal gradient over certain stratigraphic intervals can be determined. In the Recôncavo Basin of Brazin, Carvalho and Vacquier (1977) used uncorrected BHT's to arrive at average thermal gradients. With these gradients, and thermal conductivities, they calculated heat flow for various oil fields in the Basin.

A comparison of Petroleum Information thermal data with accurate downhole temperature measurements is possible at the Elk Basin oil field of northwestern Wyoming. For this field Heasler (1978) has published temperatures measured after the wells had essentially attained thermal equilibrium. These measurements were taken at discrete intervals of 5 and 10m from the surface to a maximum depth of 1,772m in five oil wells. Heasler found (~~1978, p.89~~) that least-squares thermal gradients of all data points in each well were in excellent agreement with gradients calculated using a surface temperature and "maximum depth" temperatures for each well. Average gradients for the five wells from these methods were 31.3 and 31.4 $^{o}C/km$, respectively. The Petroleum Information file contains 23 well temperatures in the Elk Basin and an additional 20 in the nearby Silvertip and Silvertip South fields (figure 2). Figure 3 is a portion of the stratigraphic column showing positions where temperatures were recorded in the Petroleum Information file.

A least-squares gradient of the Petroleum Information data over this interval cannot be expected to represent the true gradient because of the stratigraphic relief of the area. In the Elk Basin field, BHT's at the same stratigraphic position can be at depths differing by 600m. A stratigraphic position in the Silvertip field can be 1,800m deeper than the same one in the Elk Basin field. A method of comparing the Petroleum Information data with those of Heasler is to calculate a thermal gradient using a surface temperature and the average temperature-depth value of the 43 Petroleum Information data points. Figure 4 compares gradients calculated from Petroleum Information temperatures with data from well EBET 173 tested by Heasler. This figure shows that the mean temperature of Petroleum Information values is considerably less than would be a corresponding temperature in well EBET 173. A lower average temperature is to be expected because of thermal disequilibrium at the times of measurement. As a result, the average gradient to surface is also reduced. In this case it is 26.0°C/km compared with 31.4°C/km for the average surface - "maximum depth" gradient of Heasler's wells, a discrepancy 17 percent and the mean temperature is 11.1°C lower than the expected formation temperature.

The Recôncavo Basin study shows that averaging methods can be used for determining approximate geothermal gradients over certain stratigraphic intervals enough data points are available. The Elk Basin comparison indicates that average gradients to the surface will generally be less than true gradients because BHT's have not adjusted to formation temperature. In this study, averaging of gradients to the surface will be used to outline are as of high gradient wells but all well temperatures are individually considered in an effort to discover local anomalies. Temperatures are uncorrected values and errors are sure to exist but, in the immediate vicinity of geothermal areas, thermal gradients are high enough that substantial errors can be tolerated.

DATA HANDLING

Thermal gradients to the surface were calculated for all bottom-hole temperatures using as surface temperatures the climatic division averages published by the National Oceanic and Atmospheric Administration (1978). In this investigation no corrections for thermal disequilibrium were made nor was considerations given errors which may exist in the measurement. Other thermal effects which were also ignored ~~were~~ are those related to topography, climatic changes, glaciation, isostatic uplift, and erosion.

Areas having a preponderance of high gradients were outlined as areas of special geothermal interest. For the states of Colorado, Montana, New Mexico, and Utah comparisons were made between high gradient ~~areas~~ regions and areas considered generally favorable for the recovery of thermal waters as outlined by Sammel (1978).

DISCUSSION

Thermal gradients calculated to the surface from bottom-hole temperatures were found to be dependent upon the depth to the point of temperature measurement. Figure 5, compiled from well temperatures in Utah, illustrates this. In this figure thermal gradients to the surface, 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 temperatures.

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 introduced drilling fluid is more likely to be related to the seasonal 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 6 but average gradients, even for the coldest months, are anomalously high. Heat generated by the friction of drilling and the deformation of drill rod is generally insignificant (Lachenbruch and Brewer, 1959).

In Figure 5, 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.

Thermal gradients exceeding 35°C/km are considered anomalously high regardless of the depths of the BHT's from which they were calculated. Thus "anomalous" gradients of shallow wells must be viewed differently from those of deep wells. The 28 high gradient areas appearing on Figures 7 through 10 have average thermal gradients ranging from 36.0°C/km to 86.7°C/km. In eight of these areas, gradients are predominantly from temperatures at depths of less than 1km. Although gradients are likely to be exaggerated in these areas, all suggest potential for geothermal resources.

The high gradient areas of Figures 7 through 10 are clearly anomalous compared with much lower average background gradients. A number have associations which suggest geologic or hydrologic origins; others require further study before serious speculation can be made into their causes. In the following sections some of the high gradient areas will be discussed. They are all summarized in Table 1.

HIGH GRADIENT AREAS ASSOCIATED WITH KNOWN THERMAL WATERS

The Rico area (12) in Colorado and the Chaco Mesa area (24) in New Mexico (Figures 7 and 9) are two high gradient areas which correspond with areas considered generally favorable for the recovery of thermal waters (Sammel, 1978). The Rico area lies just west of the Dunton-Rico Hot Springs in Dolores County where spring waters from 28^{o}C to 46^{o}C come from deep circulation in faults (Sammel, 1978). The Chaco Mesa area (24) corresponds closely with a location where waters of 32^{o}C and 48^{o}C are encountered in two wells at 304 and 306m, respectively. These warm waters are also due to deep circulation (Sammel, 1978). In the Rico and Chaco Mesa areas it is probable that the oil well temperatures were measured at points in or near the fault zones which provide routes for the deep circulation.

The Havre high gradient area (14) in Montana (Figure 8) may be related to thermal springs in the Little Rocky Mountains several miles to the east. These springs issue from rocks of the Madison Group (Sammel, 1978). Thermal gradients in the Havre Area are from bottom-hole temperatures in Cretaceous sediments which may contain warm waters transported upward along faults from the Madison Group. Tertiary intrusive and extrusive rocks are present here, which may reflect an independent source of heat unrelated to thermal waters of the Little Rockies. Although well temperatures are from shallow depths here, some of the BHT's are attractively high.

Known Thermal Waters Not Associated With High Gradient Areas

Some regions regarded as having geothermal energy potential are not represented by high gradients even though they are in areas of good well distribution. These included an area in the Uinta Basin of northeastern Utah and two areas in the San Juan Basin of northwestern New Mexico. In the Uinta Basin (Figure 10) thermal waters are attributed to deep circulation in the Duchesne fault zone. Waters considered in outlining this favorable area are found in wells 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 gradients of 35°C/km or higher, temperatures up to 120°C were recorded. This is probably a situation in which the waters have received heat related to a normal geothermal gradient and have moved upward by convection along a fault zone. In favorable thermal areas of the San Juan Basin, where high gradient areas do not appear (Figure 9), Petroleum Information data are from deeper points than the reported thermal waters, although depth differences are not as great as those in the Uinta Basin. The absence of high gradients in these cases illustrates that the vertical positions of BHT's can be as important as their horizontal distributions in the exploration for geothermal systems.

High Gradient Areas Associated With Low Thermal Conductivity Rocks

A low thermal conductivity insulating layer occurring above points of subsurface temperature measurement is one of the major causes of elevated geothermal gradients over the interval between these points and the surface (Birch, 1954). It is probable that this situation at least contributes to many of the high gradients found in this study. Low thermal conductivity shale is present in most of the high gradient areas of Figures 7 through 10. In the Great Plains of Colorado and Montana nearly all BHT's are from points beneath thick Cretaceous shale units. The pattern of high gradients here, however, does not appear to be related to the thickness of overlying shale. The outline of the Cheyenne Co. high gradient area (13, Figure 7) corresponds very closely with outcropping Pierre Shale. In the Colorado Plateau, exposed Mancos Shale occupies most of the Rangely (2, Figure 7) and Grand Co. (28, Figure 10) high gradient areas.

High Gradients Areas Associated With Doming

In several cases high gradient areas are associated with doming. A striking example of this is the Malta Area (15) in Montana which occurs centrally over the Bowdoin Dome. Other areas associated with doming are the Havre (14), Wolf Point (15), and Laurel (23) areas of Montana. Heasler (personal communication) has found elevated BHT's associated with anticlines in the Big Horn and Powder River Basins of Wyoming. ~~They~~ These appear to be due to warm waters which have received heat related to a normal geothermal gradient rising in aquifers up the flanks of the anticlines. He has further noted that on the steep flank of asymmetric anticlines, where convection is more rapid, higher BHT's occur. The high gradients area associated with doming in Montana may similarly be the result of hydrothermal convection.

The Grand County, Utah, High Gradient Area - Thermal Data From The Utah Division of Oil, Gas and Mining

In an agreement between Petroleum Information Corporation and the Earth Science Laboratory, information on individual wells of the WHCS file cannot be released, but no such restriction applies to bottom-hole temperatures which are available from state agencies. These appear on many geophysical logs. They are measured with maximum-reading thermometers and are assumed to be the temperatures at the bottom of the logged interval. Although less convenient to use than the Petroleum Information File state agency files contain many more bottom-hole temperatures.

Approximately 1,100 bottom-hole temperatures were obtained in eastern Utah from the files of the Utah Division of Oil, Gas and Mining. It was from these data that the Grand County high gradient area (28, Figures 10 and 11) was discovered. This high gradient area lies over a portion of the Uncompahgre Uplift and corresponds closely to outcropping Mancos Shale. The Uncompahgre Uplift is a tectonic and physiographic high that extends northwestward from the San Juan Mountains in southwestern Colorado to the Uinta Basin in Utah. Precambrian rocks that form the core of the Uplift ~~are composed of~~ gneissic granodiorite which was intruded in Precambrian time by monzonite and biotite-muscovite granite (Hedge and others, 1968). Bounding the Uncompahgre high on the southwest is steep faulting with 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 which may indicate the vertical extent of faulting. To the southwest is the Paradox Basin whose subsidance was complementary to the uplift of the Uncompaghre (Stokes, 1956). The Uncompahgre high extends northwest into the Uinta Basin as shown on Figure 11.

In the high gradient area near the town of Cisco, Utah, Precambrian granite rocks are at a depth of about 2,400 feet and are overlain by the Triassic

Chinle Formation. At the surface is ~~a~~ 500 feet ~~layer~~ of Mancos Shale. Most BHT's in the high gradient area were measured in the Jurassic Morrison Formation and the Cretaceous Dakota Sandstone which, near Cisco are at depths of less than 1,500 feet (457m). The depths to the Morrison and Dakota Formations increase to the north and the amount of overlying Mancos Shale also increases in this direction up to its total thickness of about 3,500 feet (1,067m).

The association of the Grand County high gradient area with Mancos Shale is a strong indication that the low thermal conductivity of the shale has elevated the BHT's in underlying strata. To investigate this possibility, the lithologic logs of 21 wells in east-central Utah were examined and thermal conductivities were estimated on the basis of rock types overlying the points of temperature measurement. In estimating thermal conductivities rock types were assigned the following values:

Rock Type	Thermal Conductivity (10^{-3} cal/cm sec °C)
Sandstone	10
Shale and siltstone	4
Limestone and dolomite	7
Salt and anhydrite	10

These are subjective values based on ones published by Clark (1966).

Figure 12 is a plot of estimated thermal conductivities versus thermal gradients calculated to the surface for 21 wells in east-central Utah. Although there is a considerable scatter of points, this plot suggests an inverse relationship between thermal conductivities and thermal gradients. Points A, B, and C on the plot are typical values from three wells in contrasting environments. Their positions are shown on Figure 11 and a brief description of the wells appears in Table. 1.

Table 1. Descriptions of wells from three contrasting environments in east-central Utah.

Point	Location	BHT depth m	BHT °C	Thermal Gradient to Surface °C/km	General Lithology overlying BHT	Estimated Thermal Conductivity $\frac{10^{-3} cal}{cm\ sec\ °C}$
A	PARADOX BASIN	2,477	51.7	16.6	35 % salt and anhydrite 65 % sandstone, limestone, and dolomite - minor shale	8.1
B	UINTA BASIN	2926	97.8	29.8	alternating sandstones, shales, and siltstones - minor limestone	5.8
C	HIGH GRADIENT AREA - ASSOCIATED WITH UNCOMPAHGRE UPLIFT AND MANCOS SHALE OUTCROP	821	44.4	41.2	90 % Mancos Shale 10 % sandstones and shales	4.1

Table 1

In general, the three environments of table 1 are characterized by the thermal gradients listed. Gradients in the Paradox Basin are consistantly low. In the Uinta Basin they are somewhat larger but rarely equal those of the Grand County high gradient area. The differences in gradients in these three environments are ~~probably~~ related to contrasting thermal conductivities. The absences of high gradients over Mancos Shale west of the high gradient area might be explained by cooling due to groundwater introduced from the high plateaus of central Utah and from the Green River.

Despite the strong evidence that ~~contrasts in~~ high thermal conductivities are the total cause of the Grand County anomaly, there still exists the possibility of other contributing factors. It may reflect the presence of thermal waters that have ascended along the deep faulting on the southwest flank of the Uncompahgre Uplift or it may be due, in part, to radioactive heat generated in granitic rocks of the Uncompahgre Complex. Some indication of an association of high gradients more with the Uncompahgre Uplift than with the Mancos Shale resulted from an arithmetic exercise designed to diminish the effects of the unusually high thermal gradients produced by BHT's at shallow depths. This was accomplished by selecting an artificially high surface temperature in calculating gradients. In Figure 13, well temperatures in east central Utah, averaged over 100m intervals, are plotted against depth. The regression line of these averages has a surface intercept of 24.2°C. This is clearly much higher than the actual value but, if used for a surface temperature, gradients from temperatures at shallow depths will be depressed to a greater degree than those from deep temperatures. Figure 14 is a map of the same area as Figure 11 on which high gradient areas resulting from a surface temperature of 24.2°C are outlined. All gradients are reduced in this calculation and the high gradient areas shown are those averaging more than 25°C/km. More high gradient areas appear in the Uinta Basin than resulted from conventional calculations. These are generally confined to the northwest extension of the Uncomphagre Uplift and suggest that the high gradients and the uplift may be related. This technique produced no high gradients in the Paradox Basin, probably because of high thermal conductivity evaporite units present here.

CONCLUSIONS

Two high thermal gradient areas have been found which have close spatial relationships with areas containing known thermal waters. It is believed that they are produced by high bottom-hole temperatures measured within, or very near, ~~their respective~~ convection systems. Other high gradient areas which suggest temperature measurements within hydrothermal systems are those related to doming. Extremely high gradients in individual wells are clearly brought about by non-conductive processes and are prime targets for additional study.

The effects of low thermal conductivity materials are sure to be at least contributing causes to many of the high gradient areas but the extent of these contributions is not known. Thermal gradient patterns, however, do not consistantly follow lithologic distributions and other factors are ~~at work~~ involved. In sedimentary basins these are probably hydrologic in nature and may either supply heat to a given area or transport it away from.

Three areas where low-temperature geothermal waters are known to occur are not represented by high thermal gradients, although the horizontal distribution of data points in these areas is reasonably good. The thermal waters here have acquired their heat by upward convection in a normal geothermal gradient. This normal gradient is reflected by the bottom-hole temperatures which are from points appreciably deeper than the thermal waters. Had they been measured at shallower depths, the thermal waters would have been identified. This illustrates that discovering geothermal systems by examining well temperatures depends upon the fortuitous location of BHT's in the vertical dimension just as chance plays a part in discovering them from horizontal distributions.

This study of well temperatures in geothermal exploraion will have proven its worth if any of the high gradient areas are found to contain exploitable geothermal systems. There is no doubt that hydrothermal convection systems have been located, although additional study will be required to determine their utilities. These systems are obvious from ~~the~~ extremely high temperatures measured in some individual wells. Data on single wells in the Petroleum Information file cannot be released, but those wishing to identify especially attractive bottom-hole temperatures can find them in the files of state agencies. Also, because of the large number of geophysical logs containing BHT's on file with these agencies, the present study can be greatly expanded in all respects.

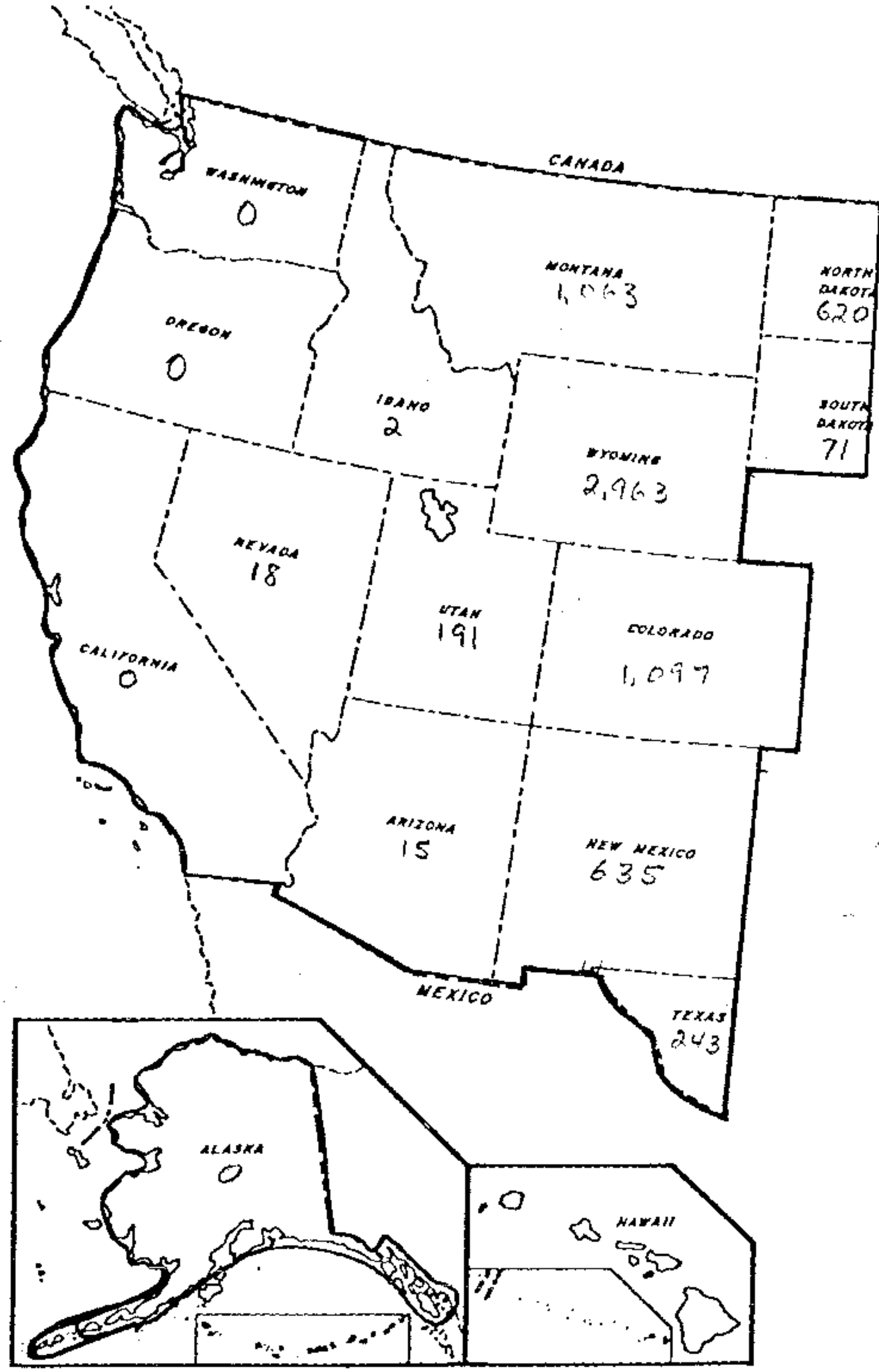


Figure 1. Retrieval area covered in the Petroleum Information Corporation file of bottom hole temperatures.
Number of wells with bottom-hole temperatures listed for each state.

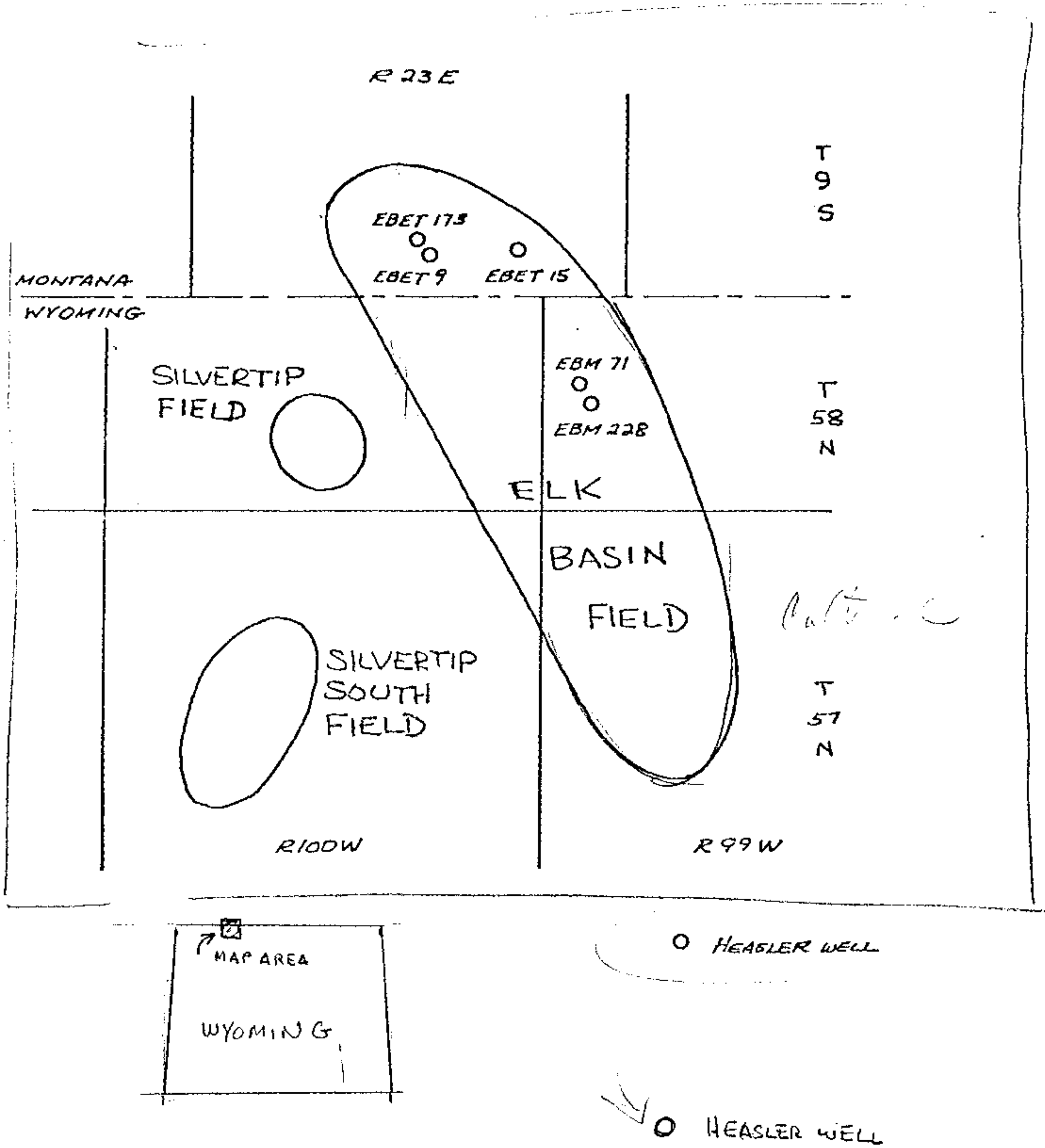
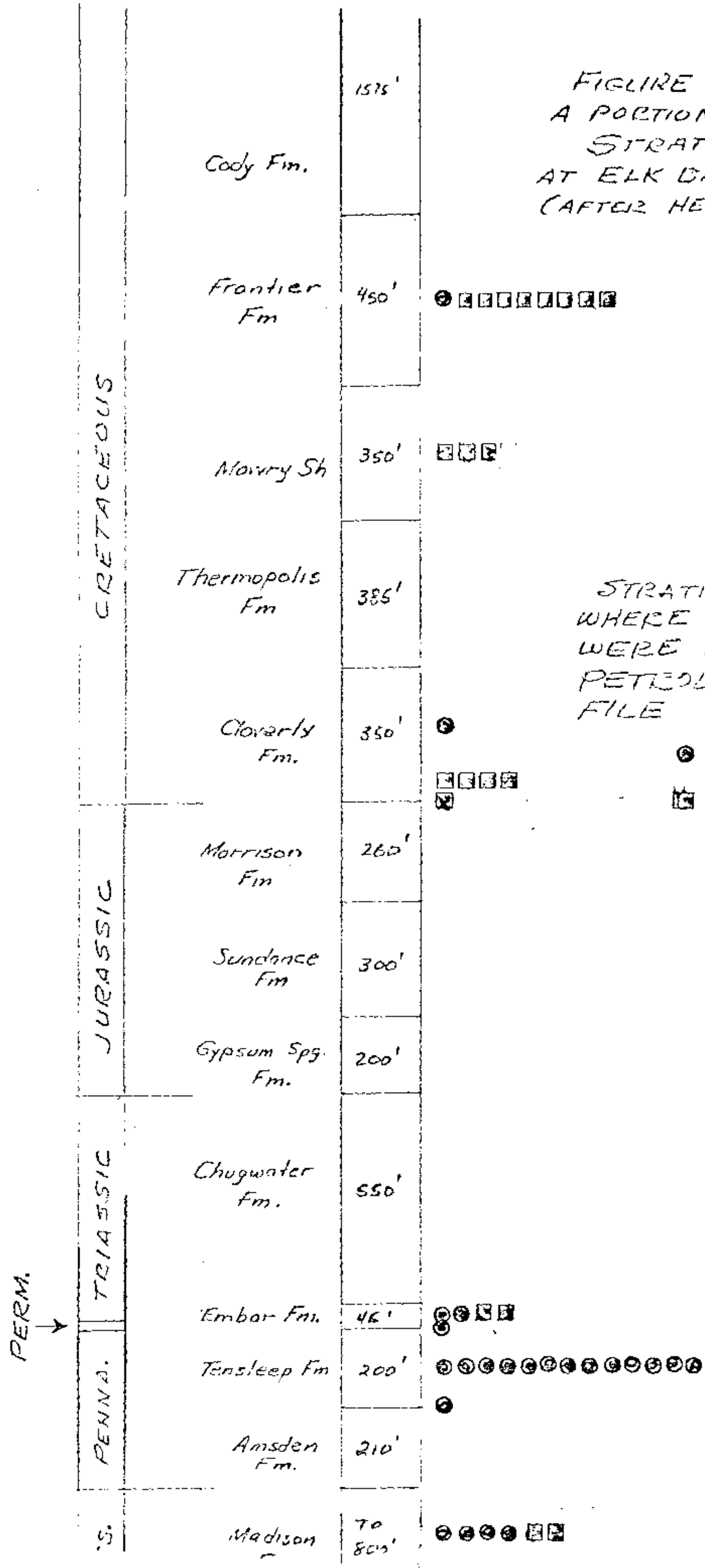


Figure 2. Locations of wells tested by Heasler and outlines of oil fields which supplied Petroleum Information data.

6-27-79

FIGURE 3
A PORTION OF THE STRATIGRAPHIC COLUMN AT ELK BASIN OIL FIELD, WYO (AFTER HEASLER).



STRATIGRAPHIC POSITIONS WHERE TEMPERATURES WERE RECORDED IN THE PETROLEUM INFORMATION FILE

- ELK BASIN FIELD
- SILVERTIP AND SILVERTIP SOUTH FIELD

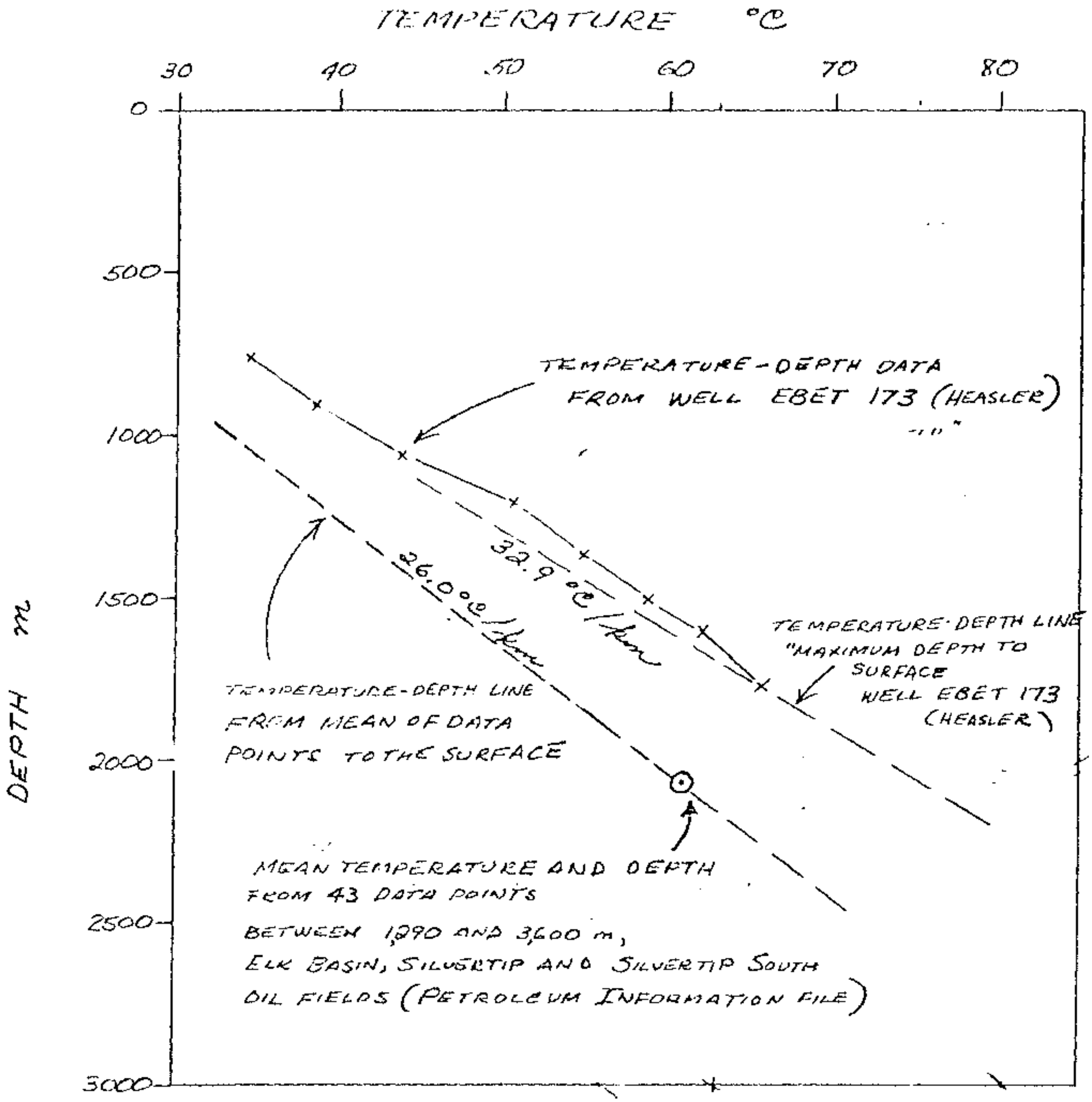


FIGURE 4. Temperature/depth relationships in the Elk Basin, Silvertip and Silvertip South oil fields, Wyoming and Montana.

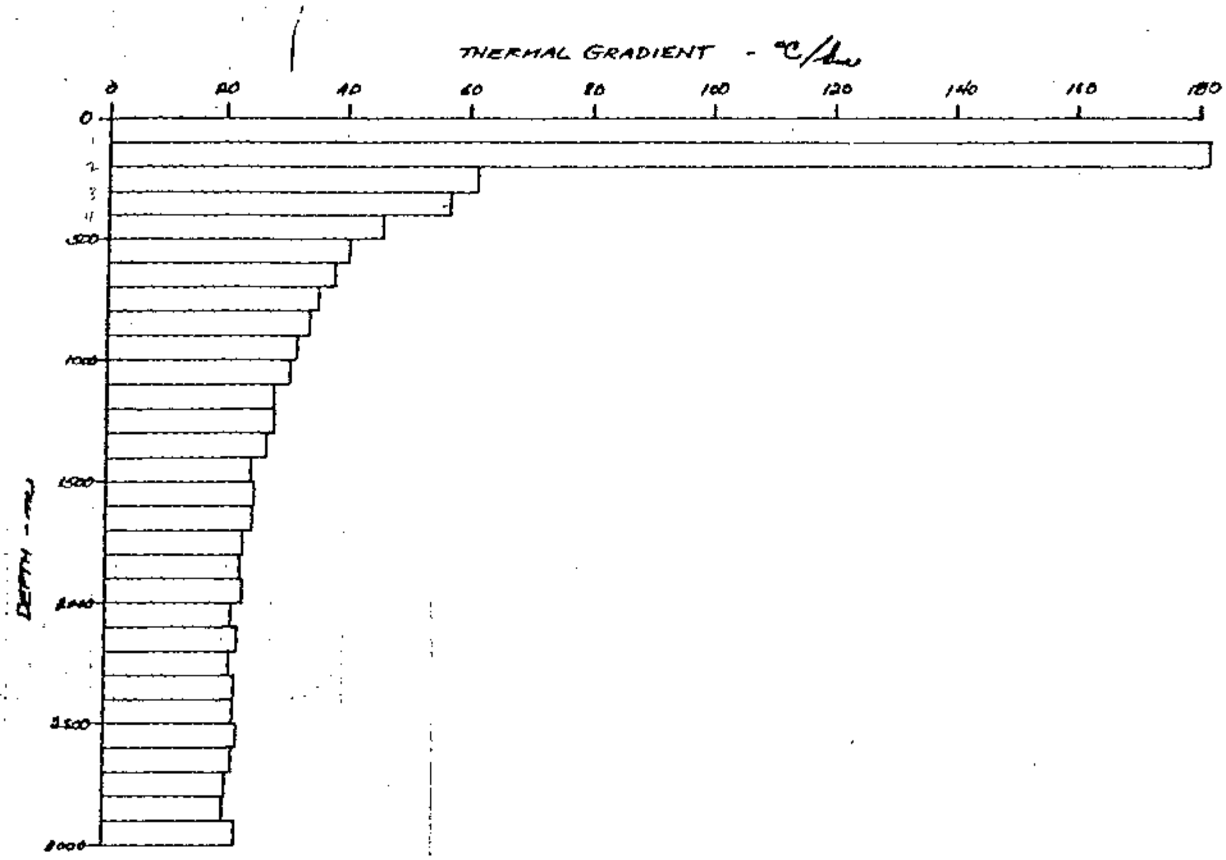


Figure 5. THERMAL GRADIENTS IN UTAH TO THE SURFACE, USING MEAN ANNUAL ATMOSPHERIC TEMPERATURES. AVERAGE GRADIENTS OVER 100 m INTERVALS PLOTTED AGAINST DEPTH

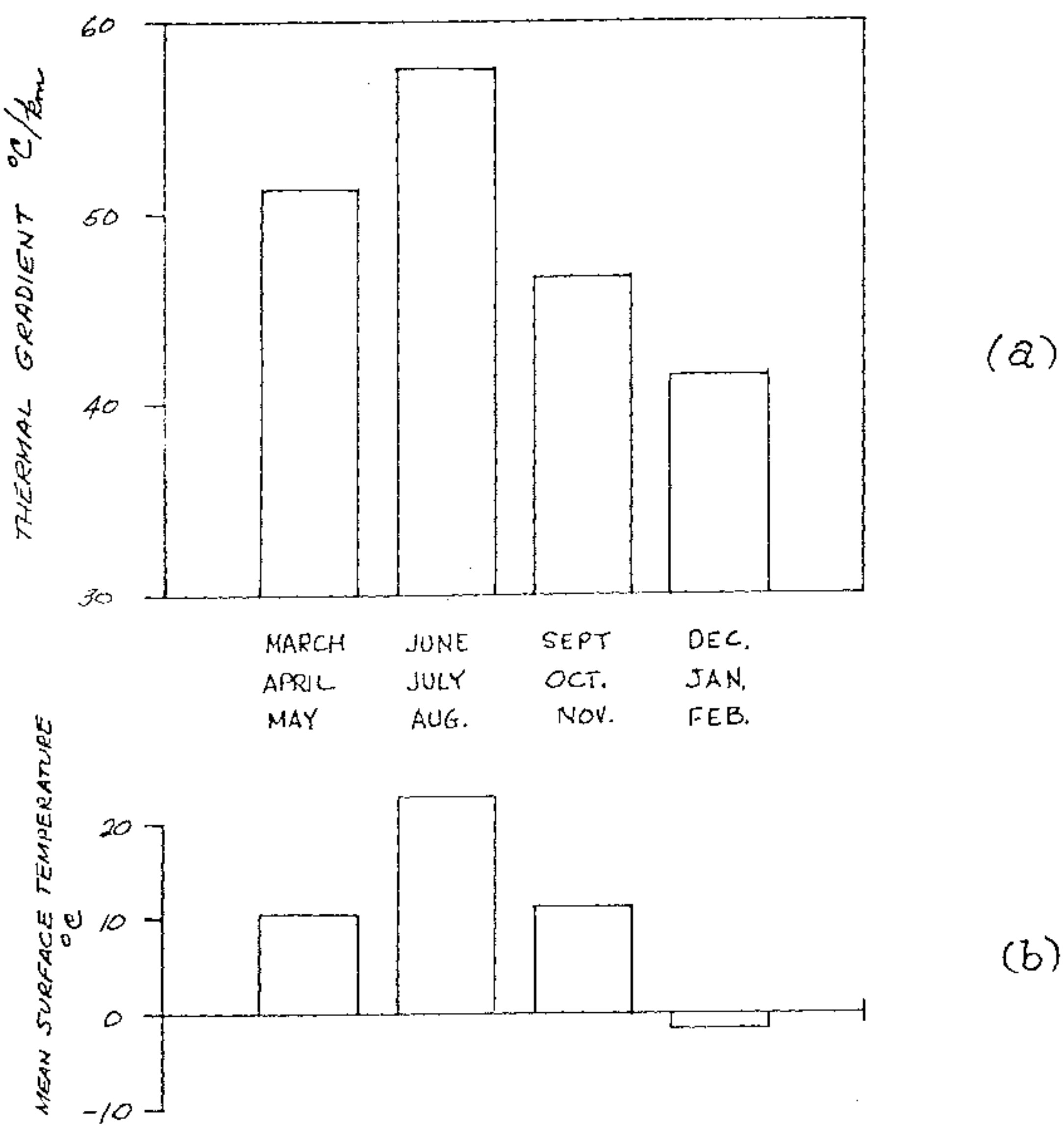


Figure 6. (a) THERMAL GRADIENTS IN UTAH FROM DEPTHS OF 500 m OR LESS TO THE SURFACE, USING MEAN ANNUAL ATMOSPHERIC TEMPERATURES. AVERAGE GRADIENTS BY SEASONS. (b) MEAN SEASONAL ATMOSPHERIC TEMPERATURES.

Figures 7, 8, 9, and 10

COLORADO, MONTANA, NEW MEXICO, AND UTAH

COMPARISONS OF THERMAL GRADIENTS IN OIL WELLS WITH AREAS CONSIDERED GENERALLY FAVORABLE FOR THE RECOVERY OF THERMAL WATERS

EXPLANATION

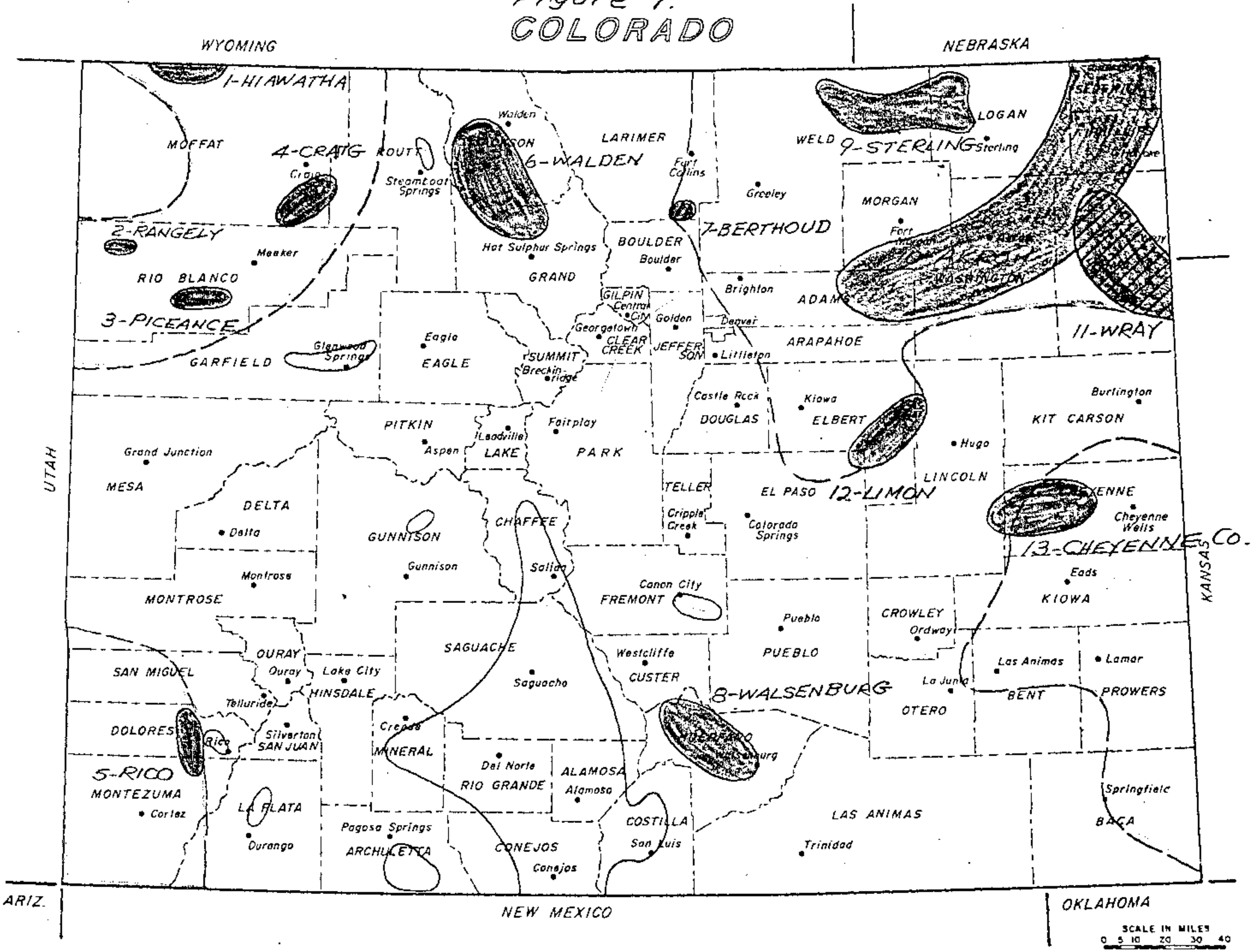
AREA GENERALLY FAVORABLE FOR THE RECOVERY OF THERMAL WATERS (USGS CIRCULAR 790).

AREA OF ANOMALOUS THERMAL GRADIENTS.

AREA OF ANOMALOUS THERMAL GRADIENTS CALCULATED TO DEPTHS PREDOMINANTLY LESS THAN ONE KILOMETER.

REGIONS OF BEST WELL DENSITY.

Figure 7.


COLORADO
WYOMING
NEBRASKA
UTAH
KANSAS
ARIZ.
NEW MEXICO
OKLAHOMA
1-HIAWATHA
2-RANGELY
3-PICEANCE
4-CRAIG
5-RICO
6-WALDEN
7-BERTHOUD
8-WALSENBURG
9-STERLING
11-WRAY
12-LIMON
13-CHEYENNE Co.
MOFFAT
RIO BLANCO
GARFIELD
MESA
DELTA
MONTROSE
SAN MIGUEL
DOLORES
MONTEZUMA
LA PLATA
SAN JUAN
OURAY
HINSDALE
MINERAL
ARCHULETTA
CONEJOS
RIO GRANDE
ALAMOSA
COSTILLA
SAGUACHE
GUNNISON
PITKIN
EAGLE
GRAND
SUMMIT
LAKE
CHAFFEE
PARK
LARIMER
BOULDER
GILPIN
CLEAR CREEK
JEFFERSON
DOUGLAS
TELLER
FREMONT
CUSTER
EL PASO
ELBERT
ARAPAHOE
ADAMS
WELD
MORGAN
LOGAN
WASHINGTON
LINCOLN
KIT CARSON
KIOWA
CROWLEY
PUEBLO
OTERO
BENT
PROWERS
LAS ANIMAS
BACA
Walden
Craig
Steamboat Springs
Meeker
Glenwood Springs
Hot Sulphur Springs
Eagle
Breckinridge
Georgetown
Central City
Golden
Boulder
Fort Collins
Greeley
Brighton
Denver
Littleton
Fort Morgan
Sterling
Castle Rock
Kiowa
Hugo
Burlington
Cheyenne Wells
Eads
Leadville
Fairplay
Aspen
Grand Junction
Delta
Montrose
Gunnison
Salida
Cripple Creek
Colorado Springs
Canon City
Pueblo
Ordway
La Junta
Las Animas
Lamar
Westcliffe
Saguache
Lake City
Ouray
Telluride
Silverton
Rico
Cortez
Durango
Creede
Del Norte
Alamosa
Pagosa Springs
Conejos
San Luis
Trinidad
Springfield
SCALE IN MILES
0 5 10 20 30 40

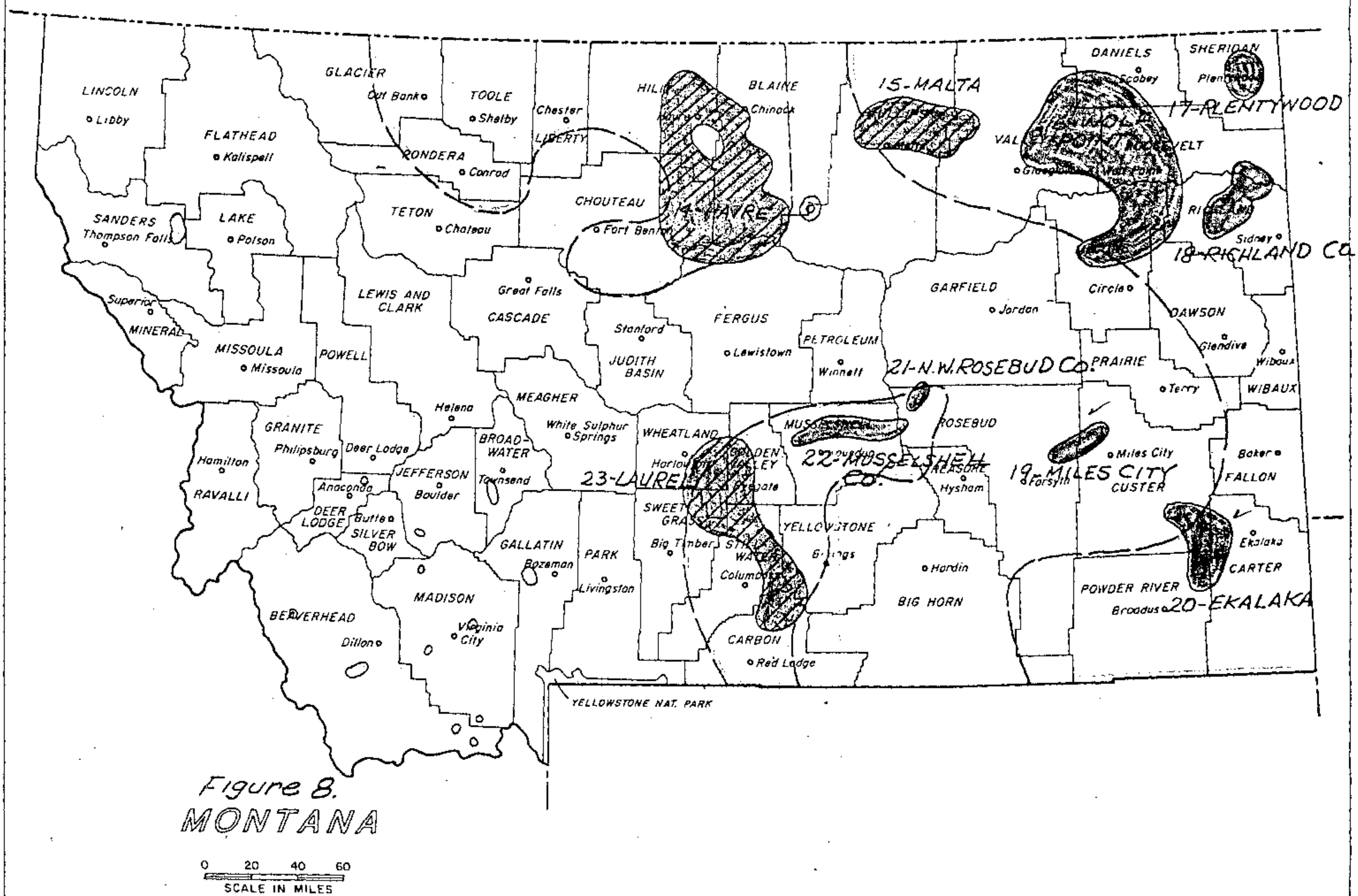
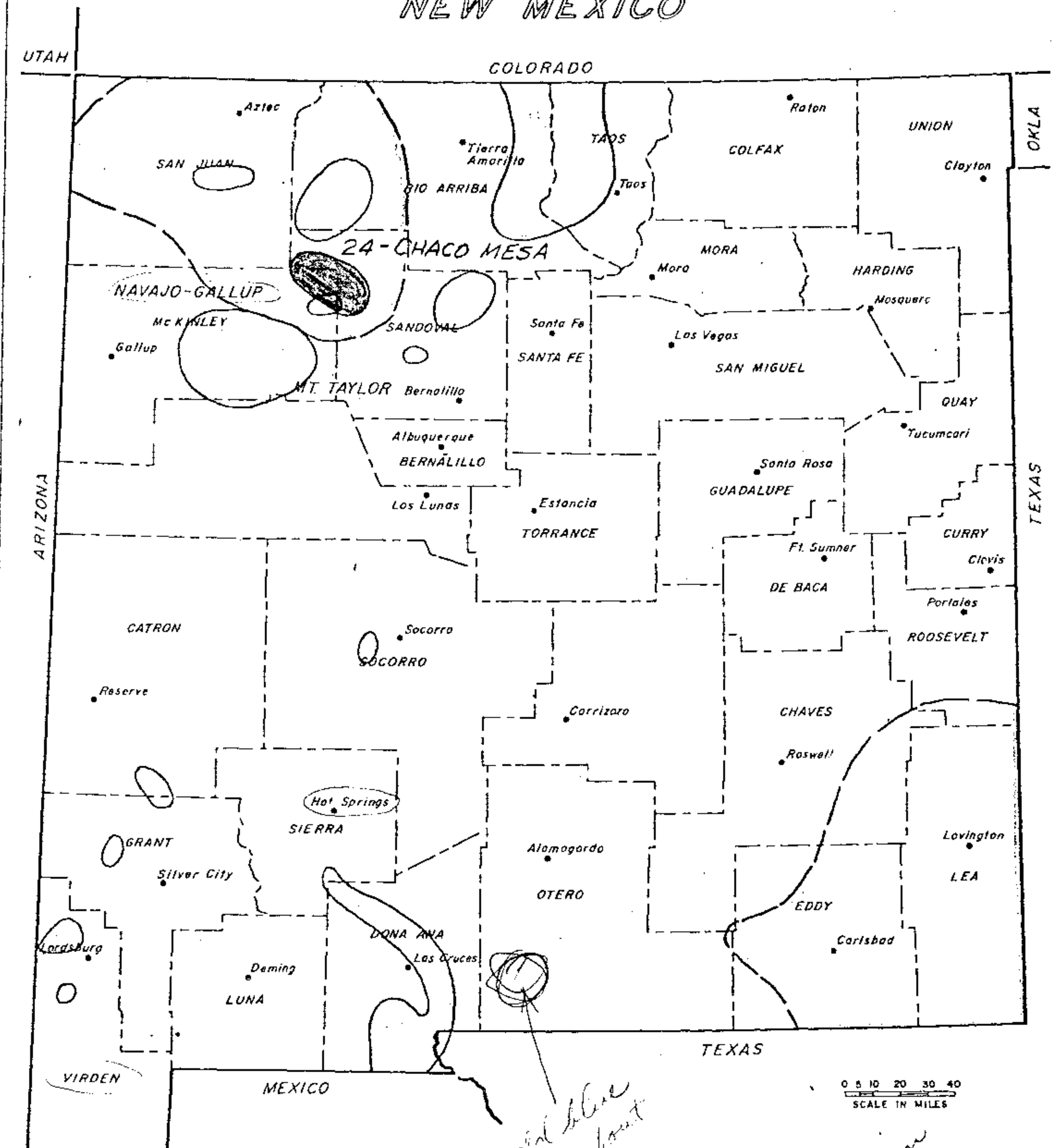


Figure 8.
MONTANA

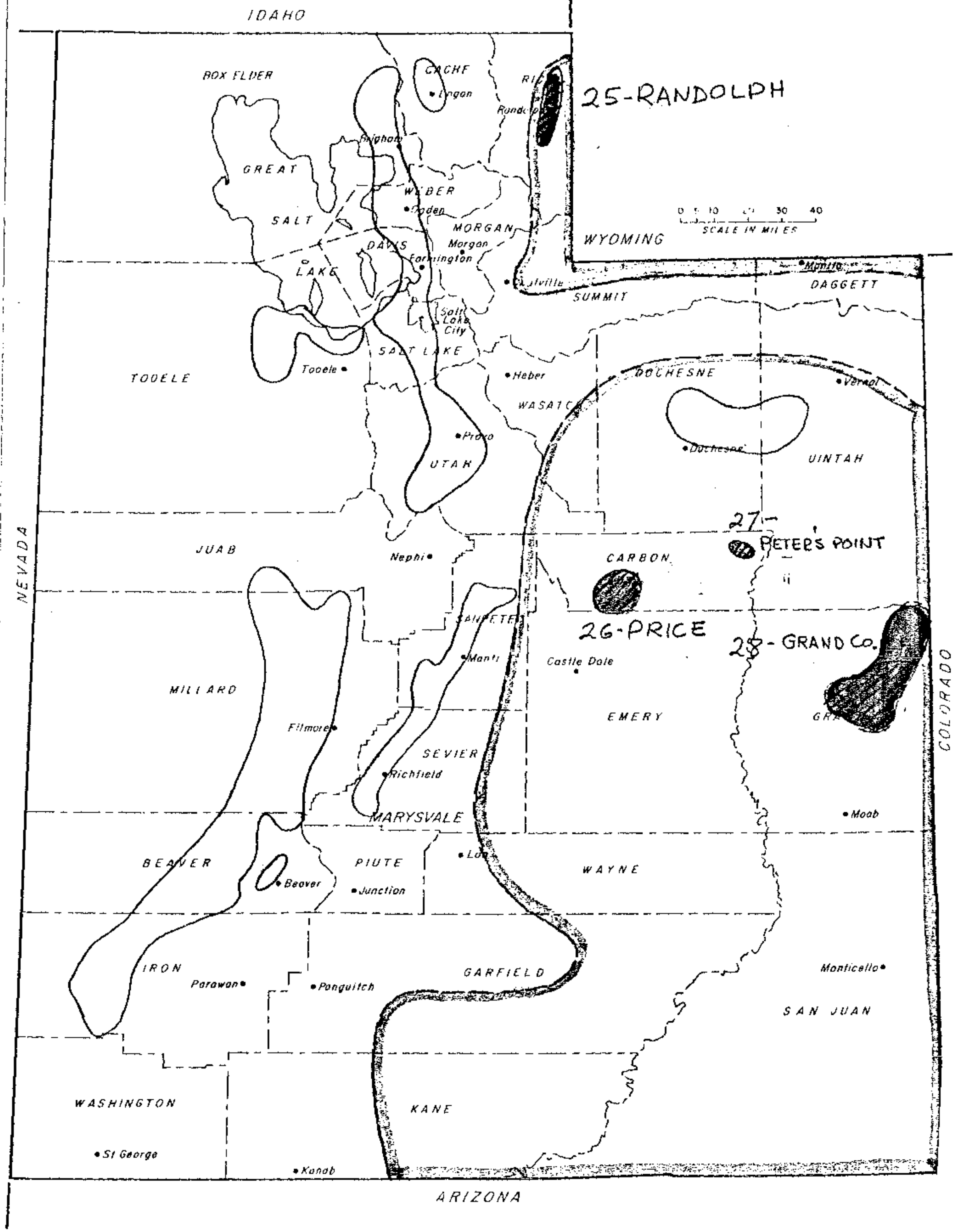
Figure 9.
NEW MEXICO



add blue spot about here

Base map needs revision

Figure 10
UTAH



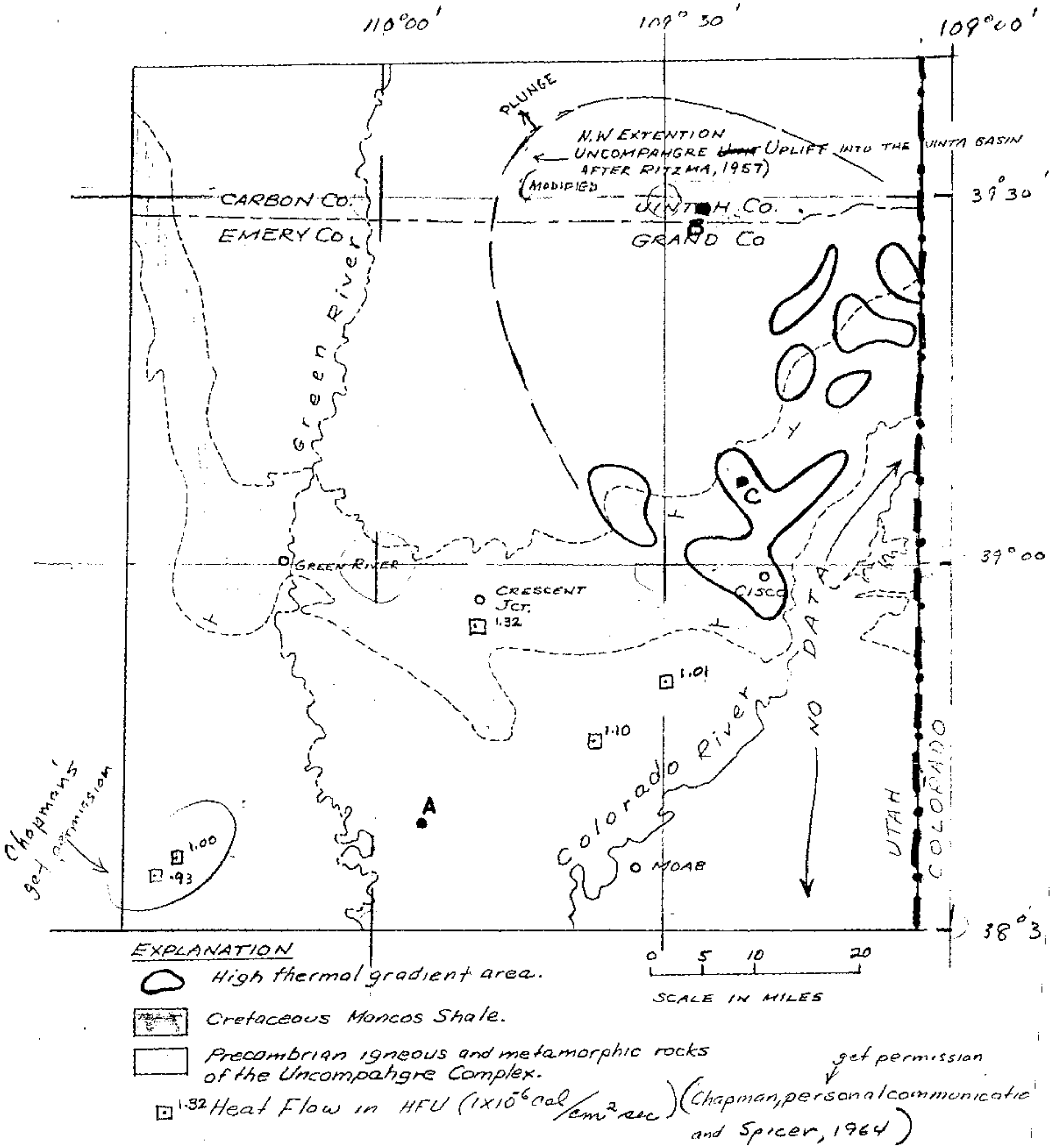


Figure 11. Detail of anomalous thermal gradient areas in Grand County, Utah.

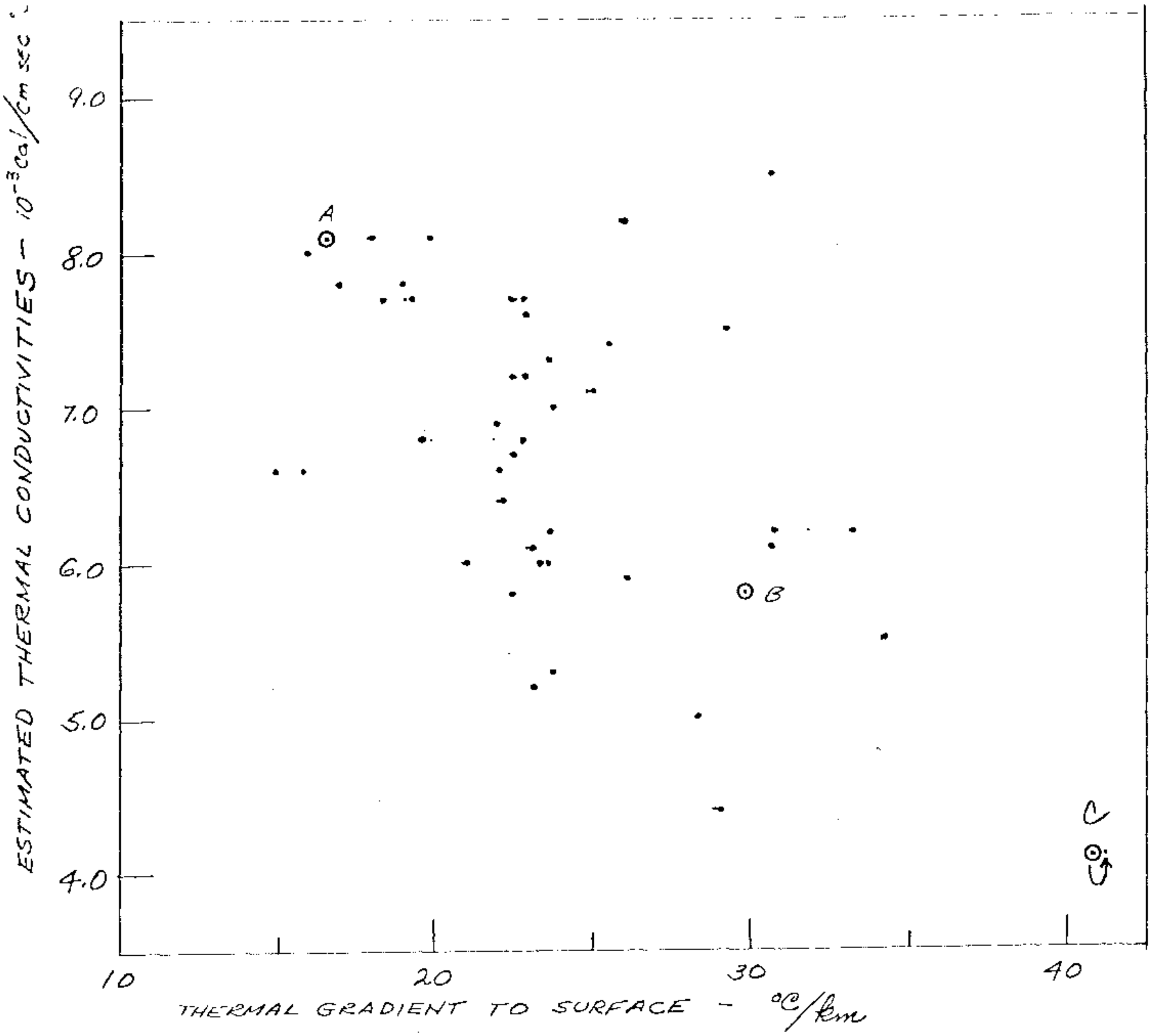


FIGURE 12 EAST CENTRAL UTAH — THERMAL CONDUCTIVITIES ESTIMATED FROM LITHOLOGIC LOGS VERSUS THERMAL GRADIENT TO SURFACE. POINTS A, B, AND C, ARE TYPICAL VALUES FROM THE PARADOX BASIN, THE UINTA BASIN, AND THE UNCOMPAHGRE-MANCOS HIGH GRADIENT AREA, RESPECTIVELY.

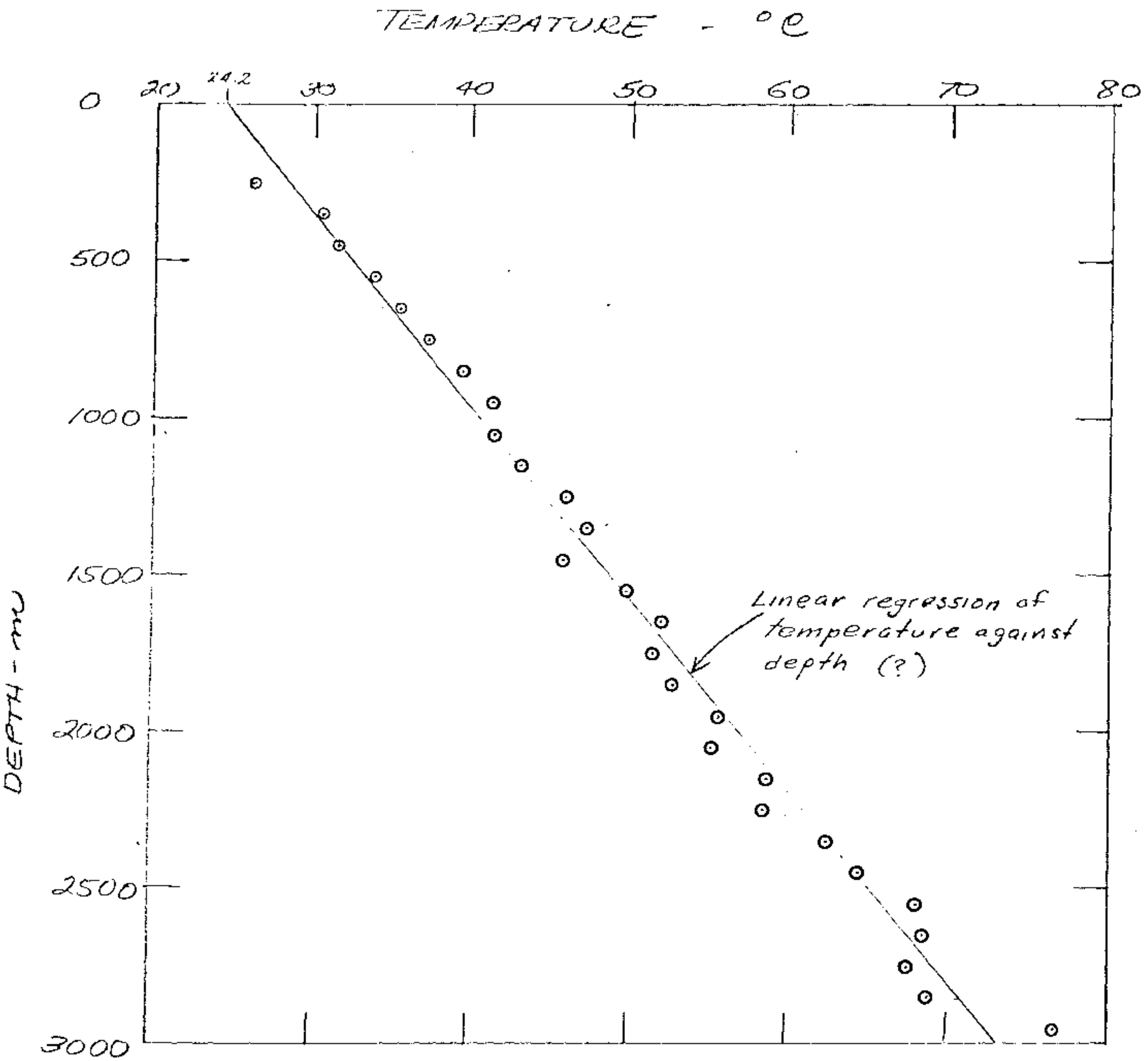


FIGURE 13. BOTTOM-HOLE TEMPERATURES IN EAST-CENTRAL UTAH, AVERAGED OVER 100 m INTERVALS AND PLOTTED AGAINST DEPTH.

9-25-79

TABLE 2. AREAS OF PREDOMINANTLY HIGH THERMAL GRADIENTS ~~(>35°C/km)~~

AREA NUMBER AND NAME	NUMBER OF WELLS: TOTAL	NUMBER OF WELLS: ANOMALOUS	DEPTH TO ANOMALOUS BHTs (m): MINIMUM	DEPTH TO ANOMALOUS BHTs (m): MAXIMUM	DEPTH TO ANOMALOUS BHTs (m): AVERAGE	MAXIMUM GRADIENT °C/km (°F)	STRATIGRAPHIC LOCATIONS OF ANOMALOUS BHTs	COMMENTS
COLORADO (FIGURE 7)								
1. HIAWATHA	5	3	957	1,807	1,490	36.6 / 48	CRETACEOUS MESAVERDE FM. TO TERTIARY WASATCH FM.	BETWEEN SAND WASH AND WASHAKIE BASINS
2. RANGELY	14	11	902	1,673	1,151	40.3 / 50	UPPER TRIASSIC TO CRETACEOUS DAKOTA SS.	ALL WELLS IN RANGELY OIL FIELD. OUTCROPPING MANCOS SHALE OCCUPIES MOST OF AREA
3. PICEANCE	5	4	1,281	2,725	1,728	38.7 / 47	CRETACEOUS MESAVERDE FM. AND TERTIARY WASATCH FM.	PICEANCE BASIN
4. CRAIG	8	5	926	1,478	1,196	36.7 / 43	CRETACEOUS - PRINCIPALLY DAKOTA SS.	WHITE RIVER PLATEAU. LATE TERTIARY INTRUSIVE ROCKS PRESENT
5. RICO	4	4	1,238	2,025	1,735	45.8 / 54	MISSISSIPPIAN AND PENNSYLVANIAN	NEAR DUNTON-RICO HOT SPRINGS — TERTIARY INTRUSIVE ROCKS PRESENT. MANCOS SHALE IN OUTCROP
6. WALDEN	9	6	270	1,974	1,364	42.4 / 109	CRETACEOUS AND TERTIARY	NORTH PARK BASIN. SURROUNDED BY PRECAMBRIAN GRANITIC ROCKS. QUATERNARY-TERTIARY ANDESITES AND BASALTS
7. BERTHOUD	4	3	934	1,107	998	41.0 / 45	CRETACEOUS	WESTERN EDGE OF DENVER BASIN. PRECAMBRIAN GRANITIC ROCKS TO WEST.
8. WALSENBURG	9	8	512	1,885	1,087	41.2 / 59	JURASSIC, CRETACEOUS, AND TERTIARY	EAST FLANK OF SANGRE DE CRISTO RANGE. PRECAMBRIAN GRANITIC ROCKS IN NORTHWEST. TERTIARY INTRUSIVES AND EXTRUSIVES. PIERRE SHALE ABUNDANT IN OUTCROP.
9. STERLING	23	17	1,496	2,361	1,855	37.2 / 48	CRETACEOUS DAKOTA SS.	DENVER BASIN
10. AKRON	83	51	1,050	2,089	1,568	36.0 / 46	CRETACEOUS DAKOTA SS.	CENTRAL AND EASTERN DENVER BASIN
11. WRAY	25	17	494	924	716	39.9 / 55	CRETACEOUS NIOBRARA FM.	EASTERN DENVER BASIN. CLASSIFIED SEPARATELY FROM AKRON AREA ON BASIS OF DISTINCTIVE DEPTHS AND FORMATION TESTED.
12. LIMON	7	7	944	1,906	1,650	38.4 / 47	CRETACEOUS - PRINCIPALLY DAKOTA SS.	DENVER BASIN
13. CHEYENNE CO.	5	5	979	1,489	1,245	41.0 / 44	PENNSYLVANIAN AND PERMIAN	EASTERN BOUNDARY OF DENVER BASIN — LAS ANIMAS ARCH. CORRESPONDS TO PIERRE SH. OUTCROP.

9-25-79

TABLE 2. AREAS OF PREDOMINANTLY HIGH THERMAL GRADIENTS (~~≥35°C/km~~) - continued

AREA NUMBER AND NAME	NUMBER OF WELLS: TOTAL	NUMBER OF WELLS: ANOMALOUS	DEPTHS TO ANOMALOUS BHT's (m): MINIMUM	MAXIMUM	AVERAGE	MAXIMUM GRADIENT °C/km (a25)	STRATIGRAPHIC LOCATIONS OF ANOMALOUS BHT's	COMMENTS
MONTANA (FIGURE 8)								
14. HAVRE	83	62	88	716	357	47.0 / 171	CRETACEOUS	WEST OF LITTLE ROCKY MOUNTAINS. SHALLOW WELLS OVER BEAR PAW ARCH AND TO THE NORTH. TERTIARY INTRUSIVE AND EXTRUSIVE ROCKS PRESENT.
15. MALTA	12	12	290	410	353	54.7 / 101	CRETACEOUS	SHALLOW WELLS. CORRESPONDS CLOSELY WITH APEX OF BOWDOIN DOME. LARGE EXPOSURES OF CRETACEOUS SHALE
16. WOLF POINT	93	78	1,158	2,844	2,064	38.9 / 66	PRINCIPALLY DEVONIAN AND MISSISSIPPIAN	CORRESPONDS, IN PART, WITH DOMING WEST OF THE WILLISTON BASIN.
17. PLENTYWOOD	12	11	2,066	3,267	2,342	36.6 / 43	ORDOVICIAN, DEVONIAN, AND MISSISSIPPIAN	NORTHWESTERN WILLISTON BASIN
18. RICHLAND CO.	24	20	2,570	3,773	2,952	37.0 / 47	ORDOVICIAN, DEVONIAN AND MISSISSIPPIAN	WESTERN WILLISTON BASIN
19. MILES CITY	7	7	1,401	1,556	1,449	37.3 / 40	CRETACEOUS KOOTENAI AND MUDDY FORMATIONS	MILES CITY ARCH
20. EKALAKA	7	7	1,255	1,444	1,357	40.3 / 53	CRETACEOUS GREENHORN AN MUDDY FORMATIONS	NORTH END OF BLACK HILLS UPLIFT.
21. NW ROSEBUD CO.	16	12	1,472	1,742	1,549	37.5 / 46	MISSISSIPPIAN AND PENNSYLVANIAN	OVER SUMATRA SYNCLINE AND SUMATRA ANTICLINE.
22. MUSSELSHELL CO	53	43	787	1,790	1,244	38.2 / 53	PRINCIPALLY MISSISSIPPIAN AND PENNSYLVANIAN	INCLUDES PARTS OF BULL MOUNTAIN BASIN, POLE CREEK ANTICLINE, AND WILLOW CREEK SYNCLINE.
23. LAUREL	23	22	202	994	513	52.0 / 90	PRINCIPALLY CRETACEOUS	SHALLOW WELLS. EXTENDS ACROSS BIG COULEE-HAILSTONE DOME TO FROMBERG FAULT ZONE.
NEW MEXICO (FIGURE 9)								
24. CHACO MESA	15	~~10~~ 12	~~[illegible]~~ 472	~~[illegible]~~ 1428	1,565	37.0 / 41	JURASSIC AND CRETACEOUS (OK)	SOUTHERN SAN JUAN BASIN. AT AREA CONSIDERED GENERALLY FAVORABLE FOR THE RECOVERY OF THERMAL WATERS.

9-25-79

TABLE 2. AREAS OF PREDOMINANTLY HIGH THERMAL GRADIENTS (~~>25 °C/km~~) continued

AREA NUMBER AND NAME	NUMBER OF WELLS		DEPTH TO ANOMALOUS BHT'S (m)			MAXIMUM GRADIENT °C/km	STRATIGRAPHIC LOCATIONS OF ANOMALOUS BHT'S	COMMENTS
	TOTAL	ANOMALOUS	MINIMUM	MAXIMUM	AVERAGE			
				UTAH (FIGURE 10)				
25. RANDOLPH	4	3	105	1,416	714	au5 228 86.7	JURASSIC TWIN CREEK FM.	WEST FRONT OF CRAWFORD MOUNTAINS IN THE GREEN RIVER BASIN. BHT OF 65.6°C AT 1,416m ONE MILE SOOTH OF RANDOLPH*
26. PRICE	4	4	370	608	480	44.7 48	PROBABLY CRETACEOUS	SHALLOW WELLS. MAXIMUM BHT, 40°C AT 608 m.* MANCOS SHALE PRESENT IN OUTCROP.
27. PETER'S POINT	11	7	405	998	789	45.3 137	TERTIARY	UINTA BASIN. ALL WELLS IN PETER'S POINT OIL FIELD.
28. GRAND CO	180	136	154	1,404	659	42.9 98	TRIASSIC, JURASSIC AND CRETACEOUS	ASSOCIATED WITH MANCOS SH. OUTCROP AND UNCOMPAHGRE UPLIFT. BHT OF 72.8°C AT 867m TWELVE MILES WEST OF CISCO.*

*TEMPERATURES AND DEPTHS FROM THE UTAH DIVISION OF OIL, GAS, AND MINING.