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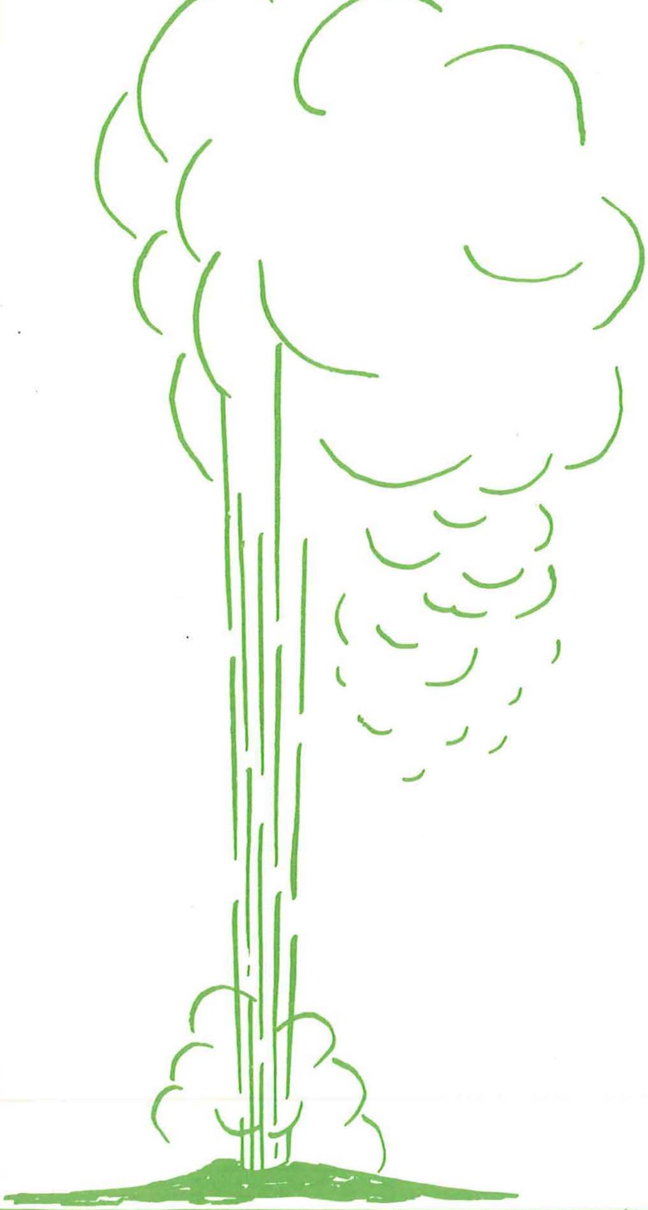

TEMPERATURE GRADIENTS IN A PORTION OF MICHIGAN: A REVIEW OF THE USEFULNESS OF DATA FROM THE AAPG GEOTHERMAL SURVEY OF NORTH AMERICA

By
Tracy L. Vaught

August 1980
Date Published

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Gruy Federal, Inc.
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Introduction

Surface manifestations of geothermal resources are uncommon in the eastern United States. Warm springs occur only in restricted areas of the Appalachian and Ouachita Mountains. No volcanism has occurred in this region for at least 20 million years. Therefore the search for geothermal resources in most of the east will depend on temperature and heat flow measurements from deep wells and from data generated through indirect methods such as geochemistry, gravity, magnetics, and regional geology.

The most readily available geothermal data base is the American Association of Petroleum Geologists' Geothermal Survey of North America (1976). This data set has been extensively used by those interested in the utilization of geothermal resources in the east. However, much of the data base is unverified, and this report has been prepared as a guide to some of the problems inherent in its use.

A thorough review of the entire data base for the eastern United States would have entailed an unjustifiable dedication of resources. Instead, a representative sample--the portion between latitudes 43.2° and 44.2°N in Michigan--was studied in detail. This area was selected because its geology is relatively simple and the well data are relatively extensive.

Temperature Gradients and Geothermal Resources

Temperature gradient measurements are useful in exploration for geothermal resources, since they allow ready detection of thermal anomalies and estimation of their areal extent. Caution must be exercised, however, in using gradients to project temperatures below the depth of measurement, for three reasons:

1. Temperature gradients vary with rock type. Shales and unconsolidated sediments have considerably lower conductivity than dolomites and well-cemented sandstones. Since conductivity affects

temperature gradients, projection of temperatures to depth must rely on a knowledge of geology.

2. In general, conductivities increase with depth because of increased compaction and cementation so that gradients decrease with depth. Thus, linear projection of gradients below observation points may predict temperatures much higher than those which actually exist.

3. Gradient measurements made in shallow holes are strongly influenced by near-surface effects such as precipitation and movement of groundwater. Geothermal workers have long recognized that anomalously high bottomhole temperatures (and thus, elevated gradients) often occur in shallow wells. Even in relatively deep gradient holes (up to thousands of feet) movement of groundwater can alter the geothermal gradient.

Petroleum exploration has yielded numerous subsurface temperature measurements which permit the calculation of temperature gradients in the eastern half of the country. Recently, the American Association of Petroleum Geologists and the U. S. Geological Survey (1976a,b) jointly published several maps showing regional variations in subsurface temperatures. One map, the Michigan portion of which is presented here as figure 2, displays average temperature gradients calculated from drill hole information; a second map shows, where data are available, the depth to various isothermal surfaces.

These maps may be of only limited use in geothermal exploration because of arbitrary corrections applied to calculated temperature gradients. Any gradient values more than two standard deviations from the mean were excluded because of suspected error. Because of these deletions, some true geothermal anomalies may not show up on the published maps. So although the AAPG-USGS maps are widely used by geothermal workers in the east, their local accuracy is questionable.

Despite these problems, the data set from which the gradient map was generated is the best currently available for study of geothermal phenomena in the eastern United States. The Los Alamos Scientific Laboratory is using the gradient data to target hot dry rock exploration in the east. Preliminary results are encouraging and suggest that some of the anomalies may be more important than the gradient map implies (Hodge and others, 1979; Maxwell, 1979).

Analysis of Michigan Temperature Gradients

This study is an analysis of temperature gradient data derived from drill holes in an east-west zone through the center of the southern peninsula of Michigan (fig. 1). The purpose of this work is to investigate possible problems in utilizing the AAPG data base, giving particular emphasis to the area of Michigan outlined in the figure. Michigan was chosen because a review of that State's geothermal potential shows inconsistencies between gradients from shallow wells and nearby deeper wells and because the geology of the State is relatively simple.

Structural complexity and variable lithology can mask the true thermal character of an area and make geothermal gradient interpretations difficult and ambiguous. The structure and stratigraphy of the Michigan basin are relatively predictable, which makes the basin ideal for a study of this type. These features are discussed in the following section because an understanding of Michigan basin geology makes it easier to predict the influence of lithology on the basin's geothermal gradients.

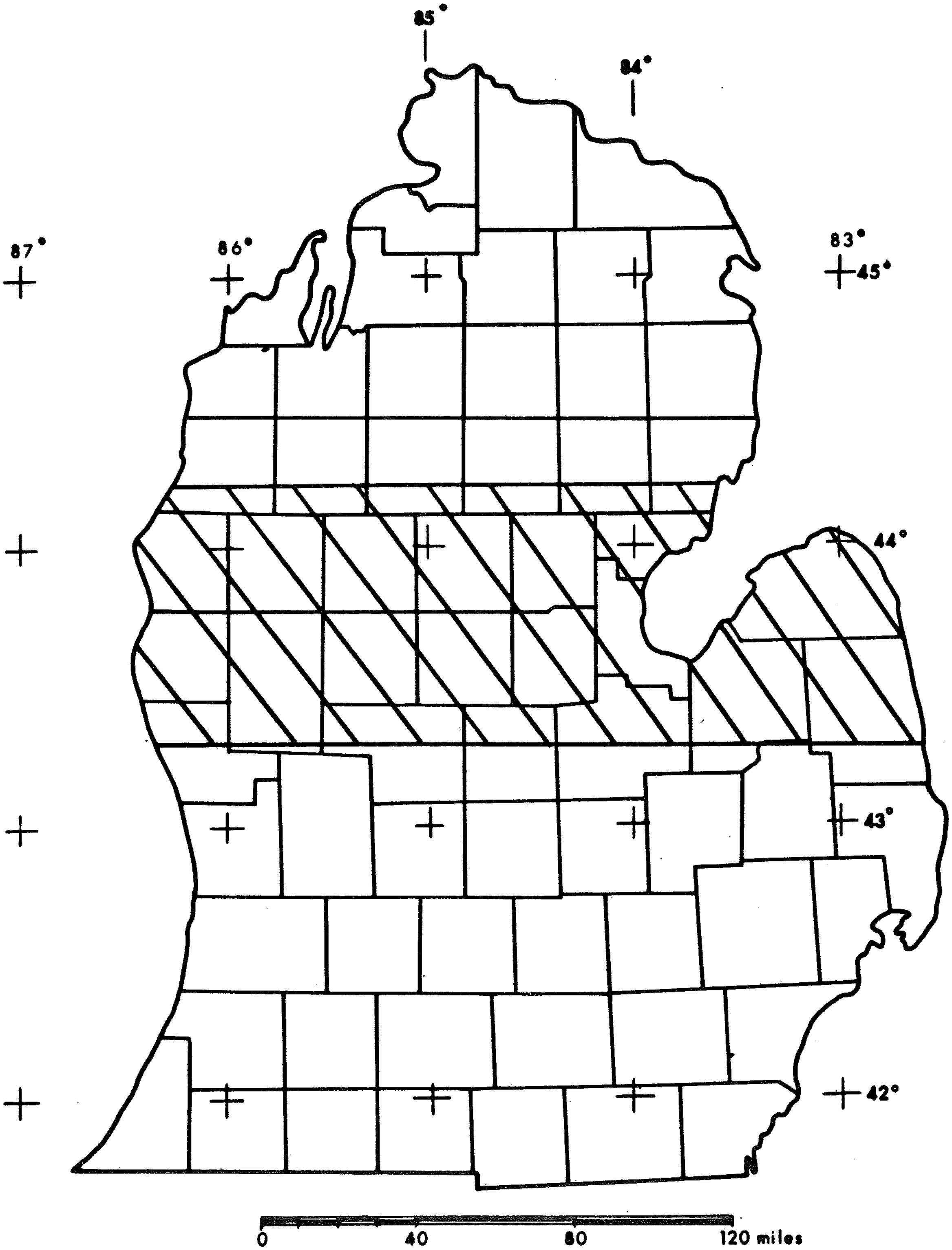


Figure 1.-- Index map showing study area (crosshatched).

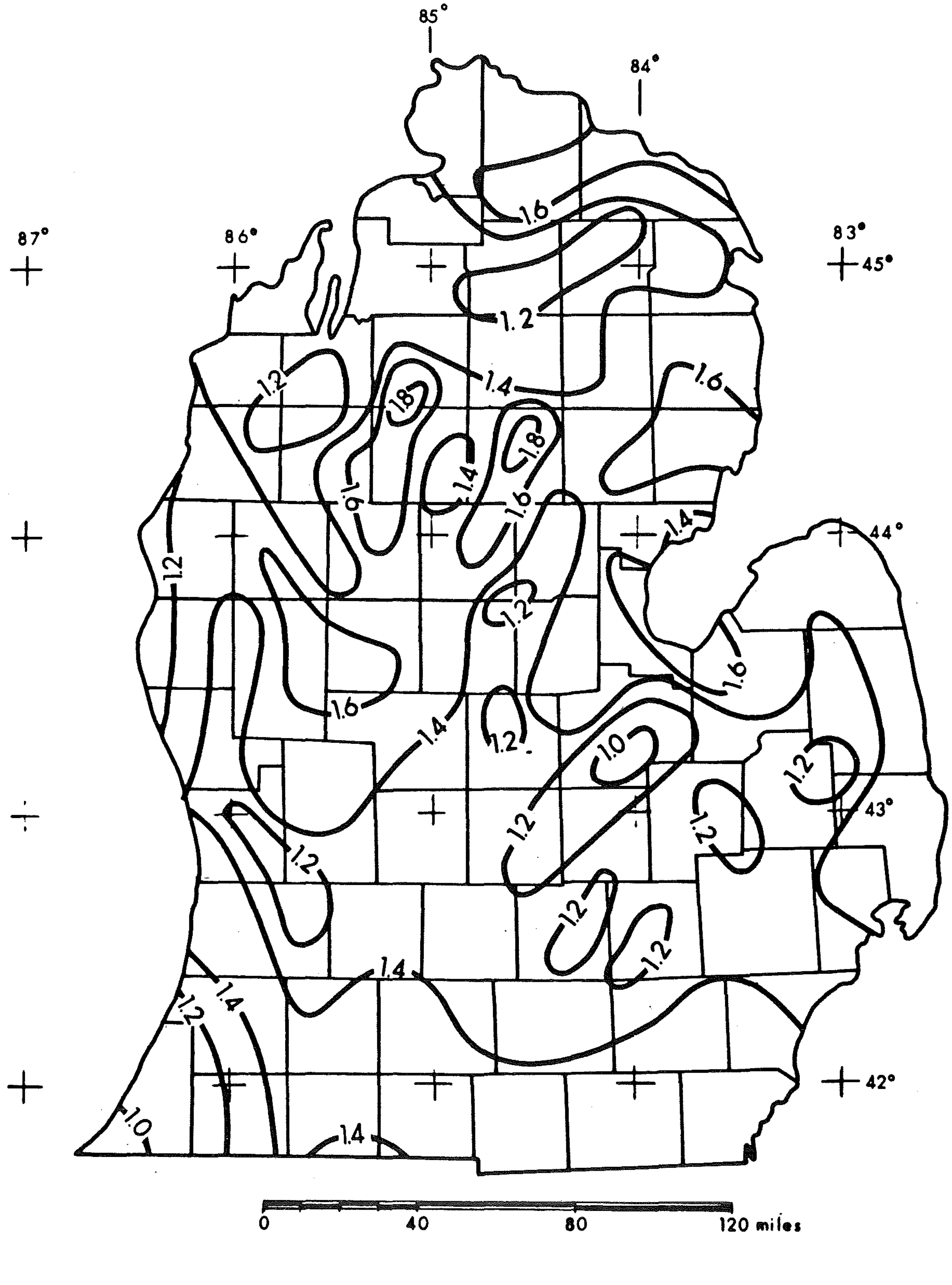


Figure 2.-- Geothermal gradient map of Michigan
Contour Interval = 0.2°F/100 Ft.
(from American Association of
Petroleum Geologists and U.S.
Geological Survey, 1976).

Geology

The Michigan basin is almost totally contained within the southern peninsula of Michigan. Its edges extend into Wisconsin, Illinois, Indiana, and the Province of Ontario.

Structural Setting

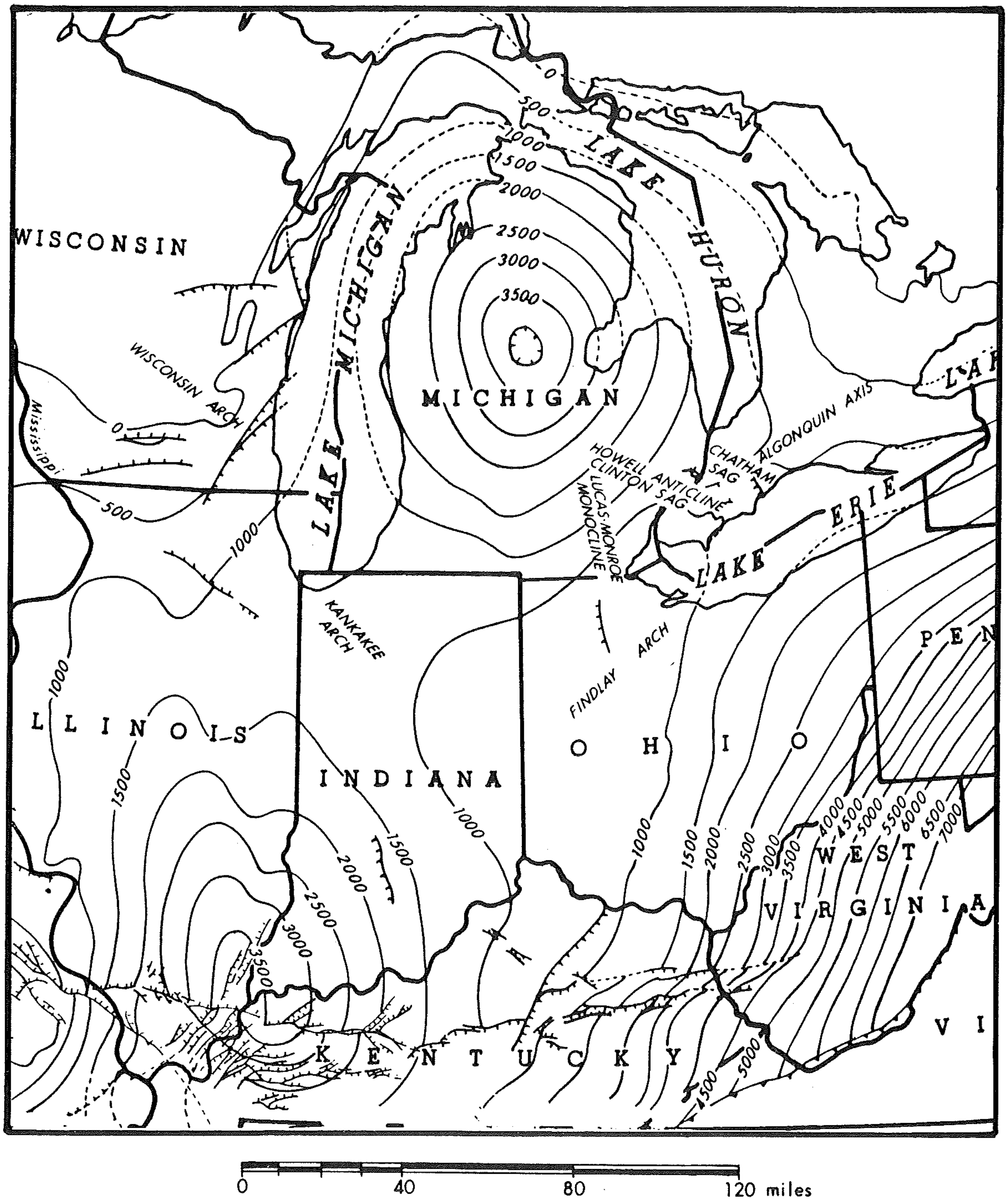
The structural boundaries of the basin are the Canadian Shield to the north, the Wisconsin Arch to the west, the Kankakee Arch to the south, and the Algonquin Arch to the east (fig. 3). The basin is nearly symmetrical in shape and is slightly elongated in a northwest-southeast direction.

Despite the presence of some subsurface faults and numerous gentle folds, the Michigan basin has been relatively stable since the beginning of the Paleozoic Era. The structure is typical of basins formed in stable regions. Since deposition was almost continuous, rocks from each Paleozoic period are represented in the stratigraphic sequence.

The basin was tectonically active from the late Cambrian to the Jurassic, but because of its cratonic location, activity was relatively gentle. In general, subsidence of the basin occurred as the result of a gentle downward flexing of the middle of the basin rather than through block faulting or intense folding. Sedimentary strata within the basin dip toward the center at about 60 ft/mile (Heinrich, 1976). Faults are not mapped at the surface in Michigan but they are known in the subsurface. Figure 4, adapted from Whitten and Beckman (1969), shows numerous folds approximately parallel to the major axis of the basin (N. 45°W.)

Stratigraphy

Most of the bedrock in the Michigan basin is mantled by 250 to 300 ft of Pleistocene glacial drift. In some places the drift is 1,000 ft or more thick.



LEGEND

STRUCTURE CONTOURS ON PRECAMBRIAN BASEMENT ROCKS DASHED WHERE INFERRED. COUNTOUR INTERVAL 500 METERS

NORMAL FAULT (TICKS ON DOWNTHROWN SIDE)

Figure 3. Structural features (from King, 1969).

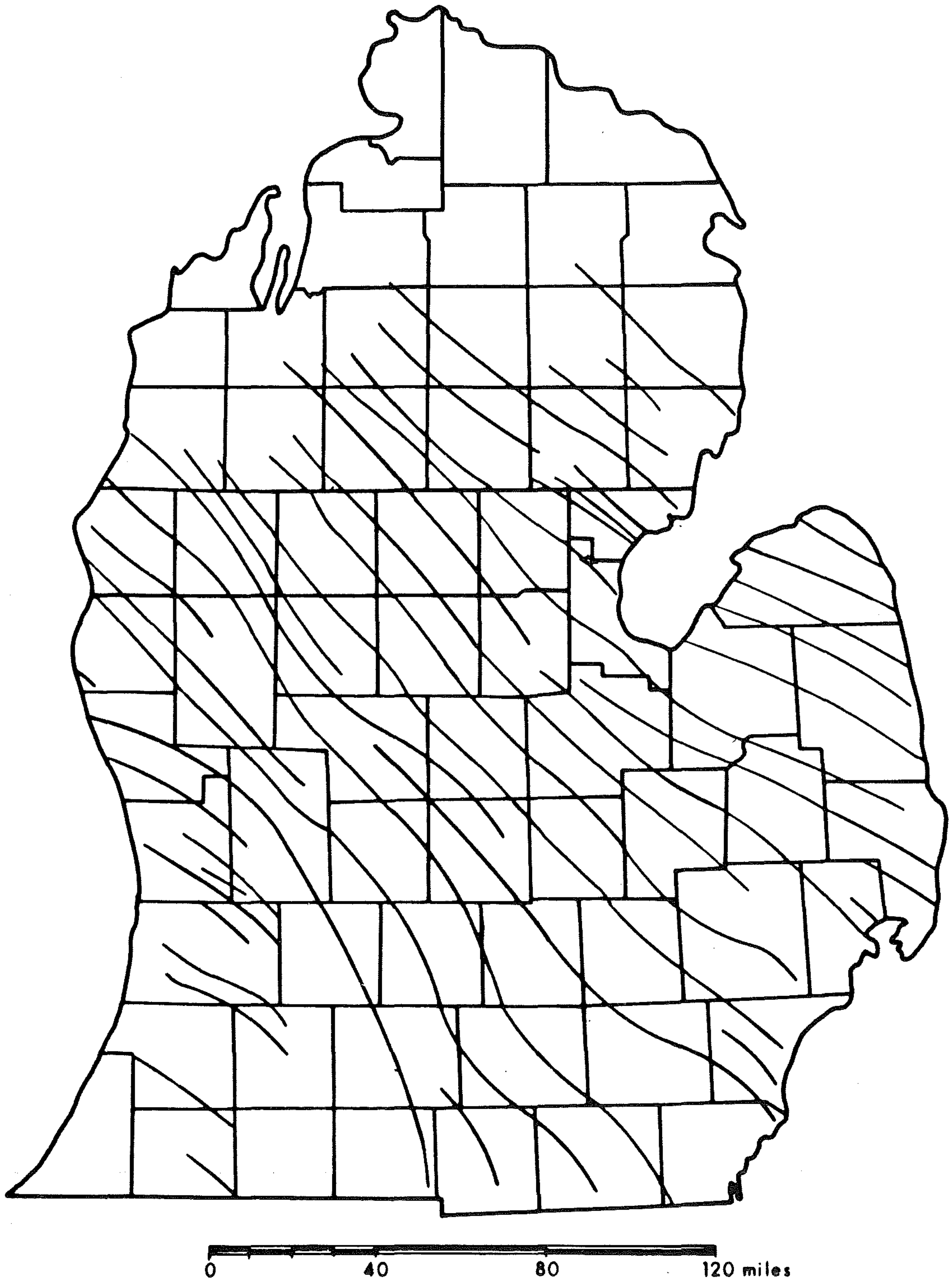


Figure 4.--Trends of anticlinal structures.
(from Whitten and Beckman, 1969).

A bedrock geologic map (fig. 5), modified from Kelley (1968), shows the bedrock forming elliptical map units with the youngest nearest the center of the basin. Sedimentary rocks, Cambrian through Jurassic in age, are present below the Pleistocene rocks (fig. 6). These sedimentary rocks are as much as 15,000 ft thick in the basin's deepest portions (Ells and Ives, 1964). Sedimentation in the basin kept pace with structural development, so that the sediments of Paleozoic age are characteristic of those deposited in a shallow epicontinental sea or a coastal environment. The Jurassic rocks are continental sands and shales.

A generalized stratigraphic column for Michigan is shown in figure 6, and a generalized cross section of the upper part of the basin, adapted from Lilienthal (1978), is shown in figure 7. The data used to construct the cross section were taken from 11 wells in a west-to-east line across the study area. This illustration is central to the understanding of the relationship between selected formations and to developing an overall picture of the structure in the subsurface.

When considering the relationship between lithology and temperature gradient, the most important formations in the cross section are the Coldwater Shale, the Antrim Shale, and the Ellsworth Shale. In the study area these units occur in the upper 3,000 ft of the basin. Their combined thickness reaches 1,400 ft. These units could be important zones of elevated temperature gradients because shales generally show poor thermal conductivity.

The appendix contains a brief lithologic description of the units found in the study area.

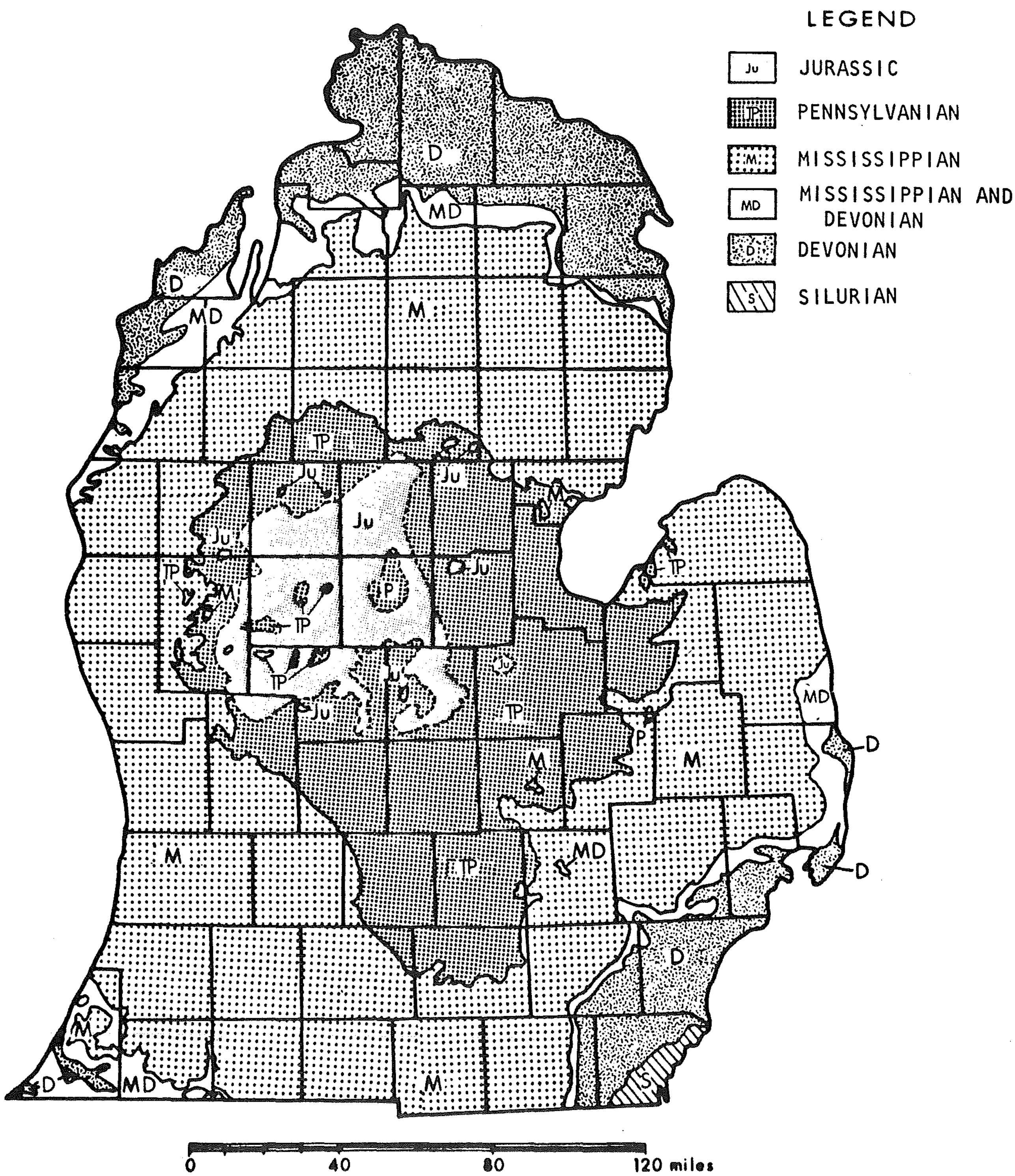


Figure 5.--Geology of Southern peninsula of Michigan below glacial drift, (modified from Kelley, 1968).

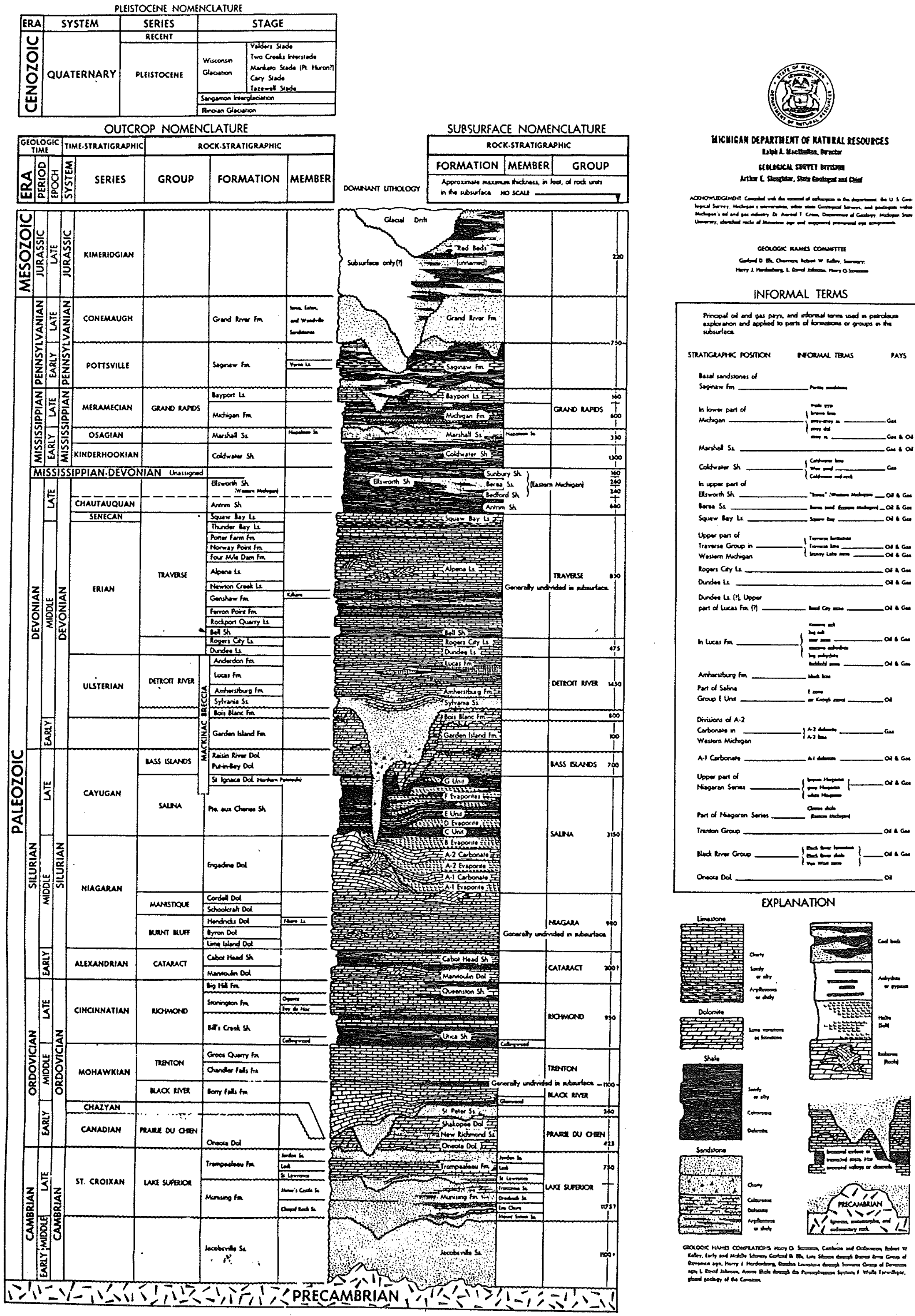


Figure 6.-- Stratigraphic succession in Michigan (from Mich. Dept. of Natural Resources, 1964).

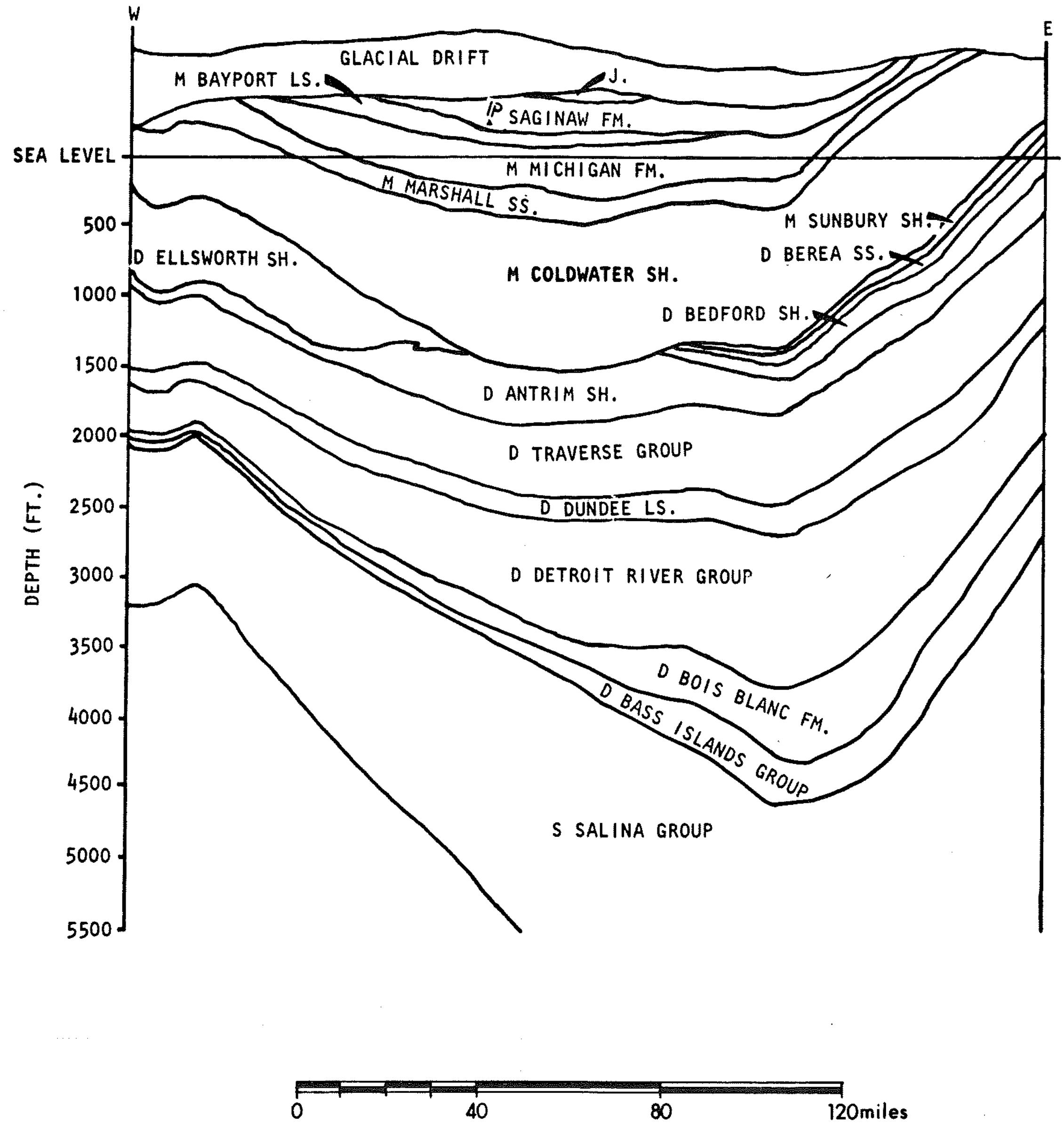


Figure 7.--Generalized stratigraphic cross section across the Michigan basin. (Rogers City Limestone and Garden Island Formation not present) (adapted from Lilenthal, 1978)

Michigan Temperature Gradients

When temperature logs are not available, geothermal gradients are calculated from the relation

$$\text{gradient} = \frac{\text{BHT - MAT}}{\text{d}/100} ,$$

where BHT is the bottomhole temperature, MAT is the mean ambient temperature, and d is the well depth in feet. Gradients are expressed as degrees Fahrenheit per hundred feet of depth.

The temperature gradient data used in this study are from drill holes in an east-west section through the southern peninsula of Michigan from latitude 43.2° to 44.2°N (fig. 1). This particular strip was chosen for study because of the relatively large number of wells drilled there and because of its proximity to the center of the Michigan basin where shale units are generally thickest.

The study area comprised all or part of 25 counties. The data were assembled from 143 wells. Twenty-seven of the wells have total depths less than 3,000 ft; 74 have depths from 3,000 to 5,000 ft, and 41 are more than 5,000 ft deep (table 1).

Most of the data in this report come from the data file that accompanies the Geothermal Gradient Map of North America (American Association of Petroleum Geologists and U.S. Geological Survey, 1976a). Some of the deep well data were gathered by the present author from the Michigan well files. Each set of well data includes location, recorded bottomhole temperature (BHT), ambient surface temperature, system of rocks, and bottomhole lithology. Despite the previously discussed problems with using AAPG data for geothermal work, the data set does provide a comprehensive, inexpensive list of wells drilled in Michigan before 1973.

The BHT's in the data file are not corrected, but corrections were applied in calculating the gradients that appear on the published gradient map. The correction factors used by AAPG are unique to specific geographical areas. The gradient values in this report are uncorrected; had the correction factor for Michigan been applied, these values would be 0.15 to 0.19°F/100 ft higher, depending on the depth of the hole.

Table 1 is a list of the wells drilled within the study area, showing BHT, location, lithology, age, depth, ambient surface temperature, and calculated (uncorrected) temperature gradient. The data are roughly ordered by depth to aid in interpreting the relationship between gradient and depth. Figure 8 shows the locations of the wells shallower than 3,000 ft, and figure 9 shows the locations of the wells deeper than 3,000 ft in the study area. It is immediately apparent that gradients in the deep wells are much lower than those in nearby shallow wells.

Figure 10 is a graph of geothermal gradient versus depth, which shows a clear inverse relationship between depth and gradient. The graph also shows a large range of gradients from wells less than about 3,000 ft in depth. If this range in shallow-well gradient values is real, a comparable range would be expected in the deep wells.

A plot of bottomhole temperature against depth (fig. 11) gives a similar picture. Superimposed on the data plot are gradient lines of 1°F/100 ft and 2°F/100 ft. Only one well deeper than 2,400 ft has a gradient greater than 2.0°F/100 ft. It should also be noted that 9 of the 14 wells with gradients greater than 2°F/100 ft have bottomhole temperatures of 80°, 90°, 95° or 100°F.

These data suggest that wells shallower than 3,000 ft may not be reliable indicators of geothermal gradient, at least in a portion of Michigan.

TABLE 1

DATA FROM WELLS IN CENTRAL MICHIGAN

(from American Association of Petroleum Geologists, 1976)

Location lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
43.2700 84.4500	17,459	243	47	1.12	ig	p€
43.5074 84.4329	9,516	176	48	1.35	carb	O
43.5439 83.1880	9,296	116	48	0.73	ss	€
43.7100 82.7700	9,068	148	47	1.11		
43.2106 83.5359	8,525	128	47	0.95	ss	O
43.7664 83.0071	7,260	128	46	1.13	sh	S
43.6386 83.9535	7,541	124	49	0.99	ev	S
43.8337 86.1739	7,088	141	47	1.33	ss	€
43.6500 84.0200	7,878	134	47	1.10		
43.7300 83.1300	7,910	122	47	0.95		
43.5389 82.9671	6,438	165	47	1.83	sh	S
43.6295 82.7136	6,011	118	47	1.18	sh	S
43.2181 82.7083	6,784	120	47	1.08	ss	€
43.2775 82.5844	6,503	122	47	1.15	ss	€
43.9793 82.9612	6,660	163	46	1.76	sh	S
43.3644 85.7301	6,518	135	46	1.37	ss	O
43.3461 85.8545	6,235	121	46	1.20	ss	O
43.6750 86.0114	6,575	130	46	1.28	carb	O
44.1461 83.9917	5,148	145	45	1.94	carb	D
43.4386 82.6107	5,028	102	47	1.09	sh	S
43.2295 82.8461	5,198	110	47	1.21	carb	S
43.4002 82.8656	5,844	112	47	1.11	sh	S
43.4003 85.9520	5,306	115	46	1.30	carb	O
43.6525 86.2798	5,528	104	47	1.03	ss	O

Location lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
43.7812 86.2014	5,981	120	47	1.22	carb	O
43.9130 85.3876	5,031	120	45	1.49	carb	D
44.1926 83.7232	5,303	112	44	1.28	carb	D
43.8792 84.5160	5,194	108	45	1.21	carb	D
43.9534 86.3022	5,170	108	47	1.18	sh	O
44.0600 84.6300	5,265	105	47	1.10		
44.1000 84.9800	5,161	122	47	1.45		
44.0800 84.9800	5.160	118	47	1.38		
44.0100 84.6500	5,250	109	47	1.18		
44.0627 84.7171	5,245	147	45	1.94	carb	D
44.1190 83.8074	5,454	108	45	1.16	carb	D
44.1033 83.6163	5,279	110	45	1.23	carb	D
43.5053 82.7253	5,669	108	47	1.08	sh	S
43.4929 82.7699	5,939	109	47	1.04	carb	S
43.5216 82.6761	5,418	114	47	1.24	sh	S
43.2388 82.8966	5,208	116	48	1.31	carb	€
43.7972 85.0810	4,116	91	47	1.07	carb	D
44.1317 84.9447	4,138	93	45	1.16	ev	D
44.0609 84.8905	4,048	91	45	1.14	carb	D
43.3261 82.6746	4,721	98	47	1.08	carb	S
43.4000 82.6187	4,994	109	47	1.24	sh	S
44.1763 83.8601	4,480	113	45	1.52	carb	D
43.4770 83.7796	4,247	96	47	1.15	carb	D
44.0402 83.9731	4,254	106	46	1.41	carb	D
43.9160 85.5633	4,689	100	45	1.17	carb	D
44.0317 85.6606	4,830	99	45	1.12	ss	D

Location, lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
44.1216 85.2906	4,192	96	45	1.22	carb	D
44.1277 85.3470	4,423	108	45	1.42	carb	D
44.0213 85.1862	4,251	110	45	1.53	carb	D
43.8335 85.3125	4,025	101	45	1.39	carb	D
43.7422 84.8755	4,064	96	47	1.21	carb	D
43.9629 84.5184	4,999	108	45	1.26	carb	D
44.1322 84.3875	4,967	104	45	1.19	carb	D
43.9019 84.3784	4,558	96	45	1.12	carb	D
43.5650 84.5265	4,510	102	48	1.20	carb	D
43.9885 85.0185	3,905	92	45	1.20	sh	D
43.9538 84.9607	3,983	105	45	1.51	carb	D
43.8186 85.0864	3,953	95	45	1.26	carb	D
43.7843 84.7012	3,774	96	47	1.30	carb	D
43.6644 85.0753	3,826	100	47	1.39	carb	D
43.6119 83.0584	3,357	103	47	1.67	carb	D
43.4806 82.9340	3,208	95	47	1.50	carb	D
43.7412 83.2805	3,800	94	46	1.26	carb	D
43.3083 84.1264	3,619	106	47	1.63	carb	D
43.2365 83.2364	3,289	86	47	1.19	ss	D
43.2515 83.2992	3,267	90	47	1.32	ss	D
43.5914 83.5920	3,472	118	48	2.02	carb	D
43.4955 83.8091	3,209	92	49	1.34	carb	D
44.0772 84.0714	3,135	85	46	1.24	carb	D
43.2773 84.7997	3,285	89	48	1.25	carb	D
43.3378 84.5665	3,232	82	48	1.05	carb	D
43.3412 84.6252	3,364	83	48	1.04	carb	D
43.6228 85.1973	3,674	91	46	1.22	sh	D

Location, lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
43.2691 85.6195	3,015	105	47	1.92	carb	D
44.0509 85.8927	3,098	80	45	1.13	carb	D
44.0756 85.8859	3,035	84	45	1.29	carb	D
43.7107 85.1351	3,933	97	46	1.30	carb	D
43.5650 85.5556	3,352	84	46	1.13	carb	D
43.6765 85.2434	3,849	98	46	1.35	carb	D
43.7412 85.1193	3,838	91	46	1.17	carb	D
43.7218 85.4348	3,567	84	46	1.04	carb	D
43.5267 85.5313	3,400	90	46	1.29	carb	D
43.3894 85.3499	3,339	90	48	1.26	carb	D
43.2910 85.1221	3,480	95	48	1.35	carb	D
43.3198 85.3800	3,388	94	48	1.36	carb	D
43.4043 85.0044	3,504	96	48	1.37	carb	D
43.3542 84.9304	3,493	93	48	1.29	carb	D
43.2982 85.0884	3,546	111	48	1.78	ev	D
43.4565 85.2571	3,550	116	48	1.92	carb	D
43.1198 86.2116	3,637	96	47	1.35	sh	S
43.4088 85.6576	3,136	100	46	1.72	ev	D
43.7546 85.6653	3,612	85	46	1.08	carb	D
43.6287 86.0131	3,400	90	46	1.29	carb	D
43.5863 85.5834	3,401	80	46	1.00	carb	D
43.9013 85.1770	3,979	100	45	1.38	carb	D
43.8257 85.5537	3,702	90	45	1.22	carb	D
43.8293 85.1532	3,956	89	45	1.11	carb	D
43.9301 85.5398	3,628	100	45	1.52	carb	D
43.8883 85.3799	3,788	97	45	1.37	carb	D
44.0168 85.4953	3,848	97	45	1.35	carb	D

Location, lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
44.1459 85.5440	3,968	101	45	1.41	carb	D
44.1711 85.5327	3,969	109	43	1.66	carb	D
43.6083 84.9318	3,896	95	47	1.23	ev	D
43.6256 84.9786	3,682	96	47	1.33	carb	D
44.1989 85.2146	3,875	90	43	1.21	carb	D
43.5095 84.3402	3,494	94	48	1.32	carb	D
43.8168 84.1806	3,534	99	48	1.44	carb	D
43.8043 84.3293	3,873	95	48	1.21	carb	D
43.6631 84.5491	3,712	80	48	0.86	carb	D
43.8819 86.1070	3,340	90	47	1.29	sh	D
43.7605 85.5391	1,579	85	46	2.47	sh	M
43.7865 85.2497	1,918	95	46	2.55	ss	M
43.6775 85.5250	1,525	100	46	3.54	sh	M
43.6170 85.3407	1,428	64	46	1.26	ss	M
43.2621 86.3195	2,196	79	47	1.46	ev	D
43.3421 86.3090	2,383	74	47	1.13	carb	D
43.4491 86.2505	2,358	80	47	1.40	carb	D
43.4279 85.8352	2,360	102	46	2.37	carb	D
43.5522 85.6180	1,406	75	46	2.06	sh	M
43.7888 86.3244	2,273	86	47	1.72	carb	D
43.5291 86.4243	1,839	100	47	2.88	carb	D
43.9823 85.2629	2,035	95	45	2.46	sh	M
44.1270 86.2816	2,189	100	47	2.42	carb	D
44.0196 86.4988	1,938	98	47	2.63	carb	D
44.0666 85.7333	1,612	69	45	1.49	ss	M
44.0490 85.4065	1,877	100	45	2.93	sh	M
44.0304 85.2474	2,058	100	45	2.67	sh	M

TABLE 1 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottomhole temp., °F	Ambient temp., °F	Gradient, °F/100 ft	Lithology	Age
43.3650 85.6776	2,472	90	46	1.78	carb	D
43.1051 83.9446	2,644	68	48	0.76	carb	D
43.5319 83.3609	2,573	99	48	1.98	carb	D
43.5164 83.3184	2,387	88	48	1.68	carb	D
43.6010 83.2958	2,900	85	48	1.28	carb	D
43.6552 83.9483	2,800	99	49	1.79	carb	D
43.6301 83.7984	2,860	92	49	1.50	carb	D
43.5434 85.2591	1,420	70	46	1.69	ss	M
43.8533 84.7544	1,409	86	45	2.91	carb	D
43.7780 86.0344	2,770	100	46	1.95	carb	D
43.4800 85.0220	1,396	80	47	2.36	ss	M
43.3432 84.7682	2,891	87	48	1.35	carb	D

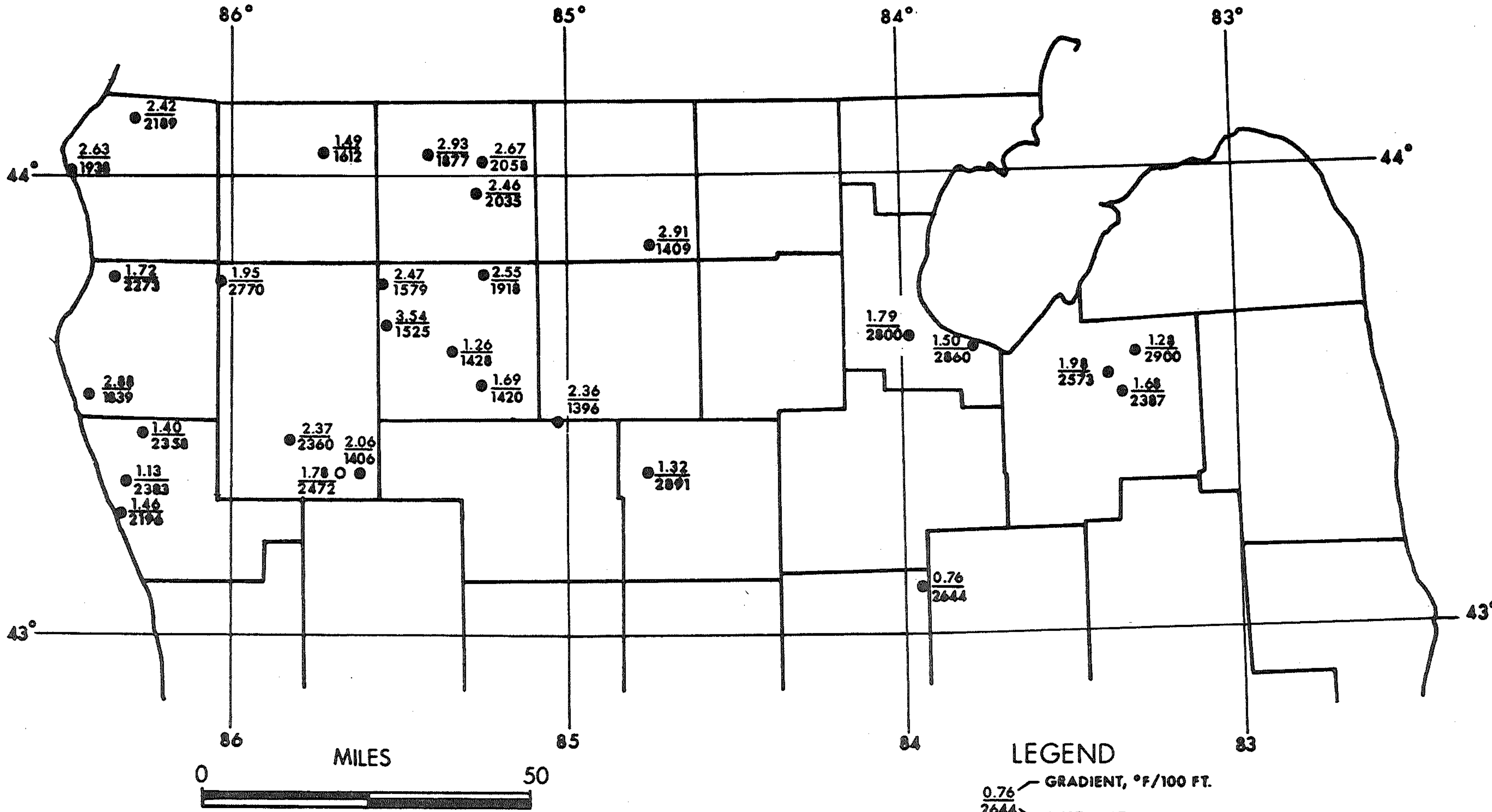


Figure 8 - Temperature gradient and depth of wells shallower than 3000 feet.

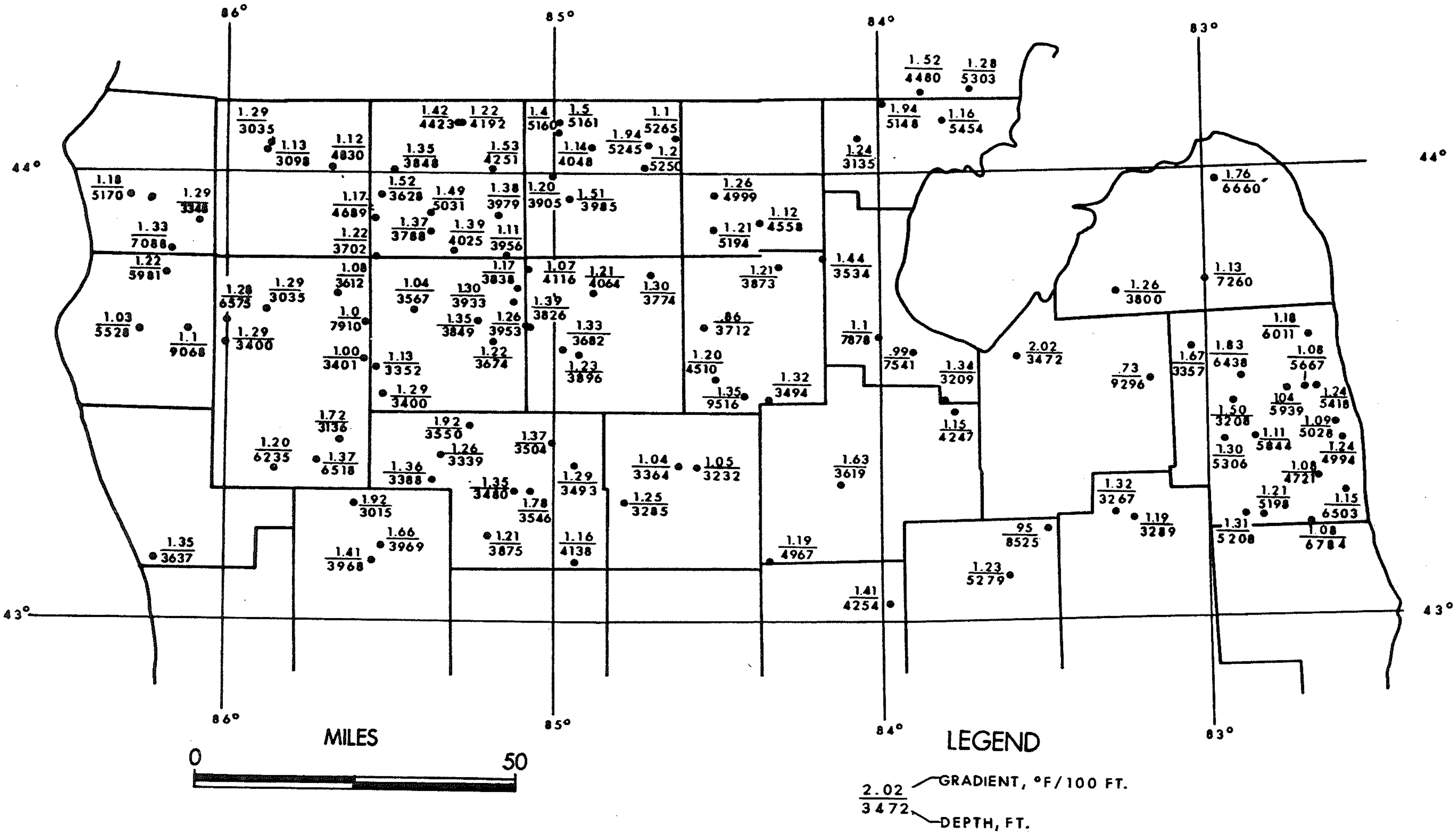


Figure 9.-- Temperature gradient and depth of wells deeper than 3000 feet.

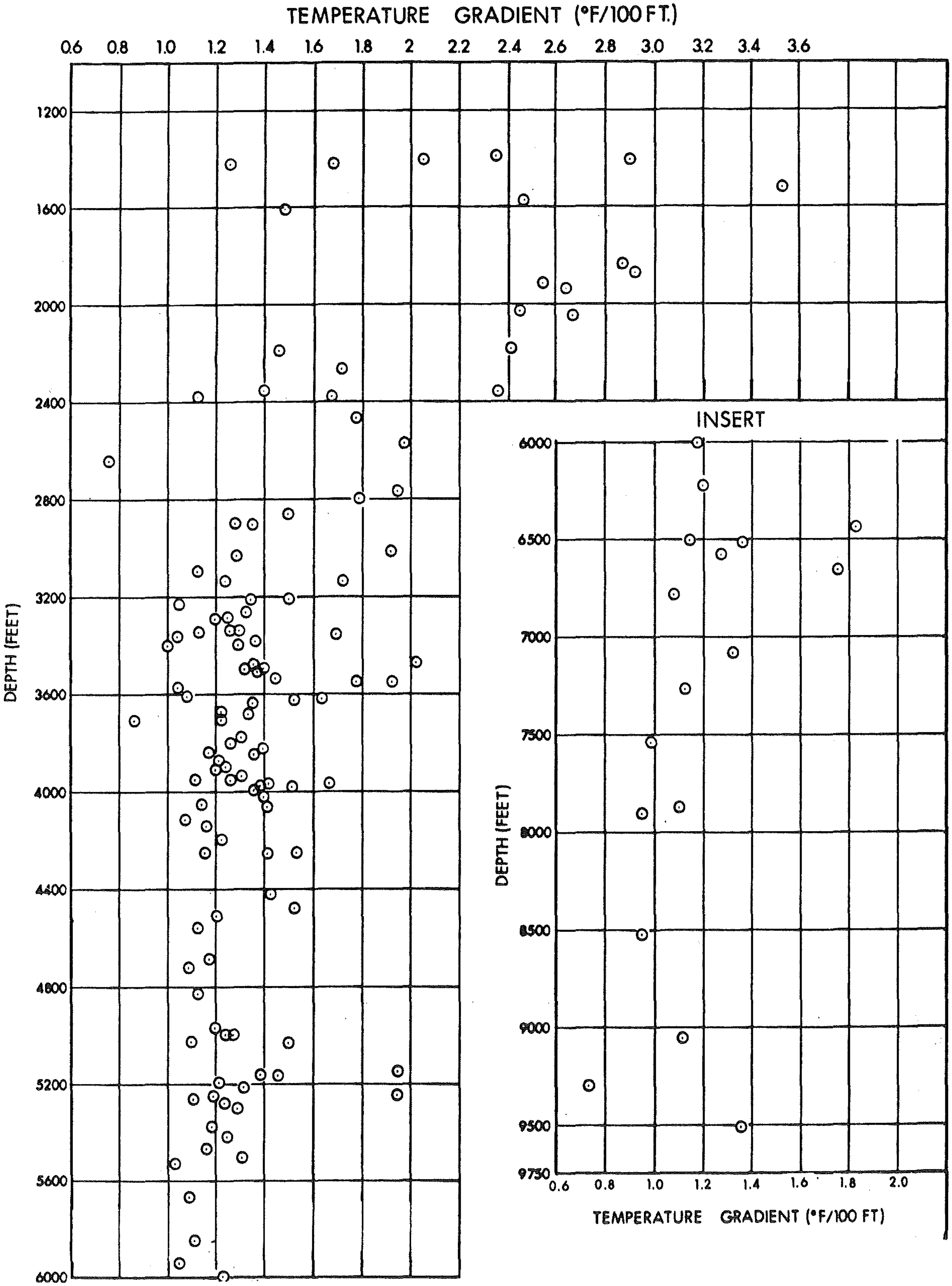


Figure 10.--Temperature gradient plotted against well depth.

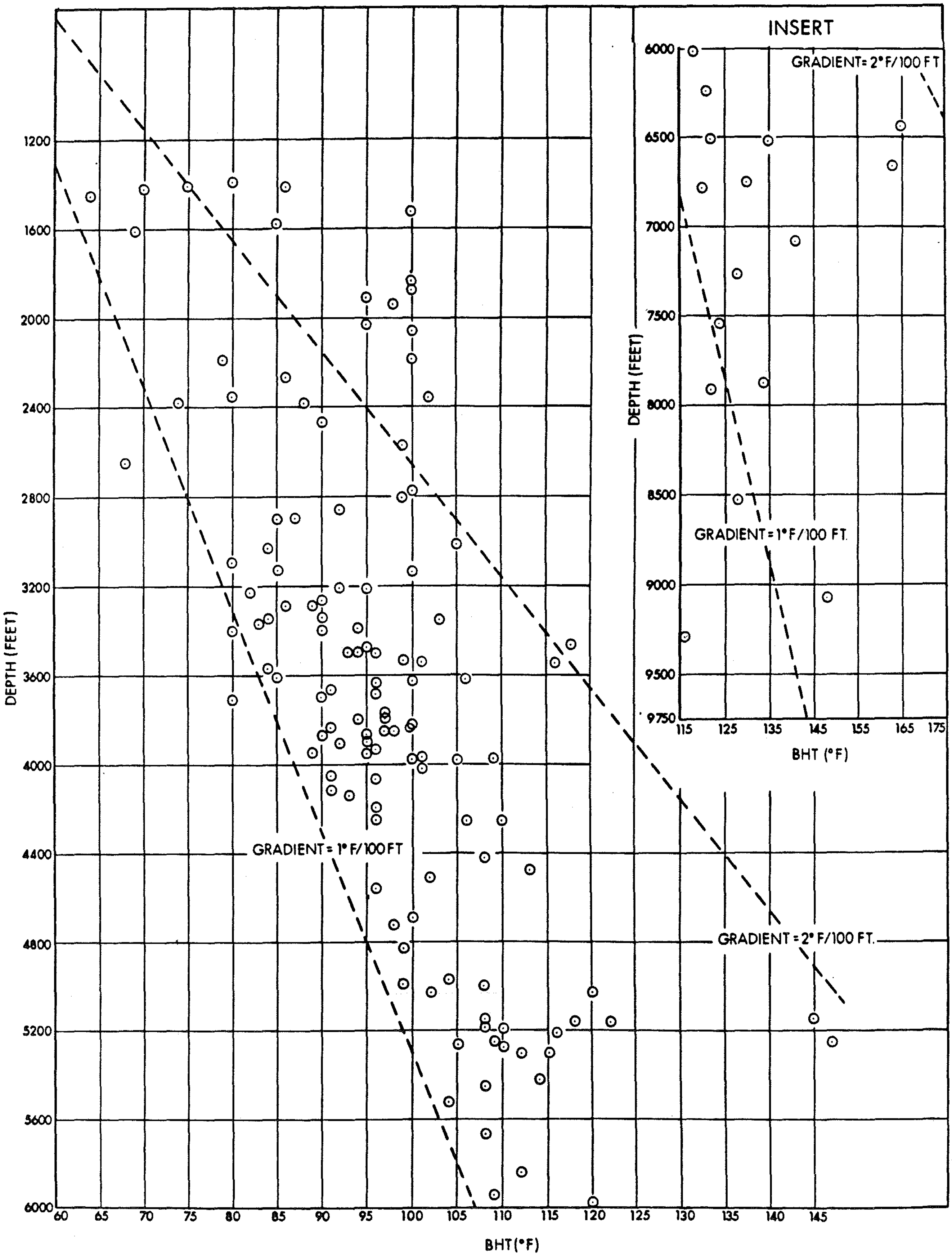


Figure 11.--Bottomhole temperature plotted against well depth (dashed lines represent a constant gradient of 1°F/100 ft. and 2°/100 ft.)

Explanations for Elevated Gradients

Bottomhole temperature measurements and temperature gradients calculated from them are subject to several sources of error. Temperatures measured in a well are affected by mud temperature and circulation rate and the time elapsed since circulation. However, these factors are generally considered to reduce indicated bottomhole temperatures below true equilibrium values and so will not be considered in the following discussion of the elevated gradients found in shallow wells in Michigan.

Temperature gradients may also be affected by movement of groundwater, errors in BHT measurement, and variation in the heat flow and thermal conductivity of the rocks penetrated by the well.

Groundwater Circulation

Elevated bottomhole temperatures occur in wells located near upward-convecting water originating in warmer, deeper strata. The geothermal gradient calculated from such a bottomhole temperature will not be representative of the region in general, and the temperature at a particular depth predicted from the gradient will be higher than the actual temperature.

In both cases, projection of these gradients for temperature determination at a particular depth will yield temperatures that are too high.

Hodge and others (1979, p. xxiii-2) used only data from wells deeper than 1,650 ft in a study of the geothermal resources of New York State, noting that "The data from wells shallower than 500 meters generally give locally variable gradients which probably reflect the temperatures of relatively shallow groundwater circulation systems rather than the temperature of the underlying strata."

If groundwater circulation is the reason for the high gradients observed in shallow wells in Michigan, the depth of circulation apparently is greater than that expected in western New York. The degree of vertical fluid migration necessary to account for the high BHT's in shallow wells in Michigan is easily calculated. The highest gradient exhibited by a shallow well in the data set is 3.54°F/100 ft from a 1,525-ft well. The BHT of this well is 100°F. The average temperature gradient in the Michigan basin is about 1.2°F/100 ft. Therefore, if groundwater circulation is at work, water at 100°F must originate at a depth of 4,417 ft and travel vertically for a distance of 2,892 ft.

Vertical movement to this degree is unlikely because there is little or no evidence of vertical permeability in Michigan. Numerous shale strata serve as barriers to upward movement of water, and there are no extensive deep fault systems in Michigan's southern peninsula that would allow vertical travel of water.

These results suggest that groundwater circulation cannot be the sole explanation for the high thermal gradients in Michigan.

Erroneous Temperature Readings

Maximum-reading thermometers have been used to measure BHT's in oil and gas wells since the 1930's. Use of this instrument ensures that most incorrect recordings will be on the high side. However, in some cases the thermometer may have a weak constriction and the mercury may be shaken down as the tool is brought up the hole, giving an incorrect reading on the low side.

Before a maximum-reading thermometer is lowered downhole, it must be reset by centrifuging. If the thermometer is then exposed to a warm environment on the surface for any significant length of time, its downhole reading will be that surface temperature when the formation temperature is lower than the surface temperature, as is the case in many shallow wells. Errors are also introduced when the mean air temperature is incorrect. Microclimatic effects can change this temperature over short distances. In Michigan, the cooling effects of the surrounding lakes is a good example.

The effect of erroneous BHT values on calculated gradients will be greater for shallow wells than for deep wells. For example, in an area where the ambient surface temperature is 47°F, a 2,000-ft well whose BHT is mistakenly read as 100°F instead of 90°F would show a calculated geothermal gradient of 2.65°F/100 ft instead of 2.15°F/100 ft, a difference of 0.50°F/100 ft. The same absolute error (10°F) in measuring the BHT of a 7,000-ft well at 150°F instead of 140°F leads to a gradient of 1.47°F/100 ft instead of 1.33°F/100 ft, a difference of only 0.14°F/100 ft.

There is persuasive evidence that some recorded bottomhole temperatures are outright guesses. Figure 11 shows BHT's from this study plotted against depth, along with temperature gradient lines of 1°F/100 ft and 2°F/100 ft. The grouping of points above the 2°F/100 ft gradient line on figure 11 contains 14 BHT's which give almost all the abnormally high gradients calculated in the study area. Five of these BHT's are exactly 100°F, a number having all the characteristics of an estimation. Four other shallow bottomhole temperature readings could well be guesses--two are 95°F, and the others are 85°F and 80°F. If these nine suspicious data points are removed from the sample, there is almost no evidence of high temperature gradients at shallow depths.

Low-Conductivity Rocks or High Heat Flow

In the absence of convection, temperature gradient (Γ) is related to conductivity (K) and heat flow (q) by the relation $\Gamma = q/K$.* Therefore a high

*One heat flow unit (HFU) = 1 x 10^{-6} cal/cm^2 sec.
One conductivity unit (CU) = 1 x 10^{-3} cal/cm sec °C.

temperature gradient requires either an elevated heat flow, a low conductivity, or both.

It is well known that in the absence of convective heat transfer, the conductive flow of subsurface heat toward the surface is constant at all depths. This heat flow can be calculated from data readily obtained by drilling: conductivity is obtained from analysis of core samples, and temperature gradient is calculated from temperature logs.

Seven heat flow values calculated in the study area (fig. 12) range from 1.0 to 1.3 HFU (Sass and others, 1976). From these values, an estimate can be made of the maximum temperature gradient that would be encountered. The conductivities of the various rock sequences that comprise the upper 3,000 ft of the study area are known approximately; they lead to the conclusion that conductivity in the area cannot be expected to be less than 4.0 CU. These values of heat flow and conductivity give a temperature gradient of 1.8°F/100 ft, significantly lower than the gradients found in many of the wells less than 3,000 ft deep.

High concentrations of radioactive elements in the Precambrian rocks underlying Paleozoic sediments can generate sufficient heat to produce local areas of heat flow as high as about 2.3 HFU. This heat flow value and a conductivity of 4.0 CU would produce a gradient of 3.2°F/100 ft, which approaches some of the highest gradient values encountered.

Therefore, it is possible that there are areas within the study region where high gradients actually exist, caused by a combination of high heat flow and low conductivity. However, it does not seem likely that this mechanism causes all the high gradients, because such an explanation would require heat flow to be elevated at each shallow well that exhibits a high gradient but not elevated in any of the areas where heat flow values have actually been determined.

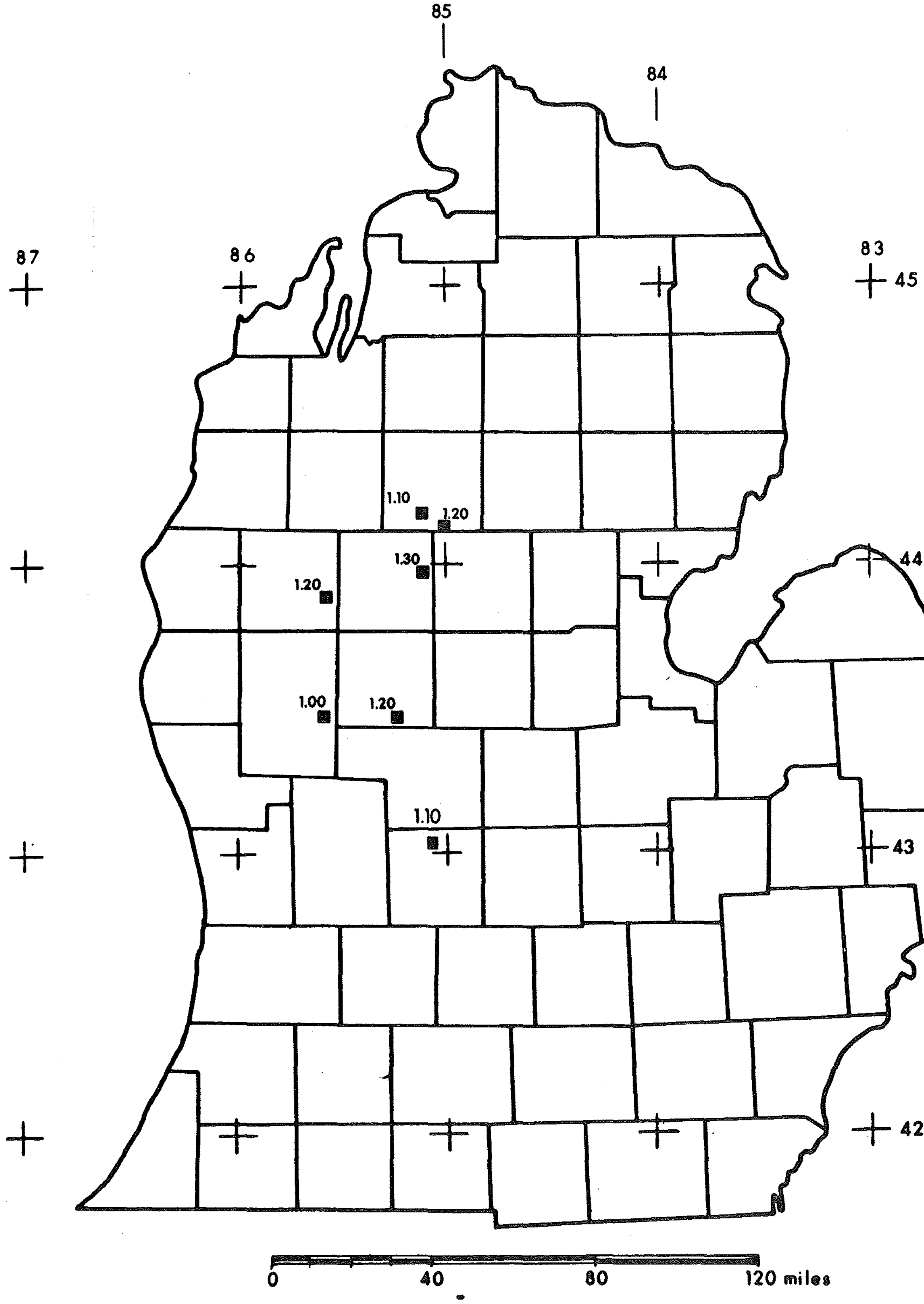


Figure 12.--Location of heat flow holes in the study area.
Heat flow valves are in HFU.
(1 HFU = 1 x 10^{-6} cal/cm^2 sec.).

Conclusion

Special care should be taken when using the data file that accompanies the Geothermal Gradient Map of North America. The BHT's recorded for shallow holes in Michigan are abnormally high. An investigation of these high BHT's shows that they may be due to groundwater circulation, elevated heat flow, sediments of low conductivity, measurement errors, or outright guesses.

Groundwater circulation may be occurring in limited areas of the basin, but there is no direct evidence of widespread deep-groundwater circulation in a subsurface fault system underlying the study area.

The combination of high heat flow and low-conductivity rocks is another possible explanation. Although heat flows measured in the study area do not exceed 1.3 HFU, there may be areas of high heat flow due to increased concentrations of radioactive elements in the basement. Shallow wells with high BHT's occur throughout the basin, but it is not likely that areas of high heat flow occur with the same frequency.

High BHT's may result from errors in measurement or from using estimates rather than actual measurements. Failure to reset the maximum-reading thermometer, or exposing it to warm air or sunlight, may cause temperature measurement errors on the high side, particularly in shallow holes. Logging engineers freely admit that BHT estimation has been common practice. Offset wells frequently serve as guides for estimating BHT's, but when an offset well of similar depth is not available, the BHT may be guessed. A large percentage of the elevated gradients are found in shallow wells whose recorded BHT's are exactly 80°, 85°, 95°, and 100°F.

The AAPG data set is valuable as a first approximation of geothermal potential because of its comprehensive nature. However, it must be used with caution and with an appreciation of the quality of the data.

Particular caution must be used in interpreting data from the shallow wells. Comparison of figures 8 and 9 clearly shows that there is little or no agreement between the gradient values in shallow and deep holes drilled near each other.

Such differentiation of shallow-hole data and deep-hole data is of utmost importance in interpreting the geothermal potential of Michigan. Even if the shallow-hole gradients are real, projected temperatures in deep wells are not likely to be high enough to provide economically usable thermal fluids.

Finally, the AAPG-USGS temperature-gradient maps can be useful guides for preliminary geothermal exploration. But this study shows that they can not be used as conclusive indicators of geothermal potential unless substantiated by other geologic data.

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APPENDIX

Lithology of Stratigraphic Units in Michigan

Quaternary glacial drift; unconsolidated clastic sediments. These sediments are characterized by sands, gravels, clays, boulders, and marl. The glaciofluvial deposits are characteristically stratified gravels, sands, and silts. Average thickness is 150 to 400 ft.

Jurassic red beds; poorly consolidated sands and shales with occasional gypsum and limestone. Maximum thickness 220 ft.

Pennsylvanian

Grand River Formation

sandstones and sandy shales; iron oxide cemented, yellow to reddish-purple.

Saginaw Formation

sandstone with some interbeds of sandy shale and shale. Combined maximum thickness of Grand River and Saginaw is 750 ft.

Mississippian

Bayport Limestone

gray to tan, dense, homogeneous, fine-grained limestone containing variegated spherical concretions of chert. The basal section is sandy limestone or dolomite and thin gray sandstones. Average thickness is approximately 50 ft; maximum thickness is 160 ft.

Michigan Formation

interbedded shale, sandstone, carbonate, and anhydrite. The shales are light to dark gray. The sandstones are fine-grained. The maximum thickness is 600 ft; the average, 150 to 200 ft.

Marshall Sandstone

sandstone and shale; the sandstone is gray to brown or red to greenish-gray with varying grain size. The top of this formation is characterized by thin units of sandy dolomite and the bottom is characterized by gray shales. Its maximum thickness is about 330 ft.

Coldwater Shale

gray to bluish-gray shale with some maroon and greenish-gray shales appearing in the upper section. In the east, siltstone and fine-grained sandstones occur near the top and the bottom, and in the west, a few thin limestone beds occur. Iron carbonate concretions occur locally. Average thickness is approximately 900 ft; maximum thickness is 1,300 ft.

"Red Rock Marker"

bed of thin red shale, sometimes calcareous.

Mississippian-Devonian

Sunbury Shale

black, highly radioactive shale that is well developed in the eastern part of the state. It is a good stratigraphic marker. The maximum thickness of this unit is 160 ft.

Devonian

Berea Sandstone

gray to grayish-white, fine-grained, subangular sandstone. Siltstone and dolomitic sandstone are also present. Occurs in eastern part of the state. Maximum thickness 260 ft.

Bedford Shale

gray shale that contains thin gray siltstone and sandstone. Present in eastern part of state. Maximum thickness 240 ft.

Ellsworth Shale

greenish-gray to gray shale that occurs only in the western part of the state. In the upper part, silty or dolomitic beds are present. It has a low radioactive response. Its maximum thickness is approximately 500 ft. The Sunbury, Berea, and Bedford in the east are represented in the west by the Ellsworth.

Antrim Shale

black to brown pyritic shale with a very high radioactive response. Limestone and siltstone beds are present near the base. Maximum thickness 660 ft.

Traverse Formation

light gray calcareous shale in western part of the state. Limestone stringers increase to the southeast. The Traverse Formation is sometimes interbedded with the Antrim Shale.

Traverse Limestone

gray to grayish-brown limestone with minor gray shales in the western part of the state. Coarsely crystalline dolomite is present near the top. Anhydrite is present in an evaporite basin on the west side of the state. Toward the east the Traverse Limestone becomes mostly shale. Average thickness is approximately 200 ft.

Bell Shale

fossiliferous, soft gray shale. Dolomitic zone found near base.

Rogers City Limestone

The Rogers City Limestone is usually included in the Dundee because it is seldom identified.

Dundee Limestone

buff-brown-black limestone, fine-grained in the east and coarsely crystalline bioclastic limestone in the west. The Dundee in the west is partially dolomitized and is underlain by anhydrite and sucrosic dolomite. Maximum thickness of Dundee and Rogers City Limestone is 475 ft.

Detroit River Group

Anderdon Formation

fossiliferous limestone rarely identified in subsurface studies.

Lucas Formation

thick carbonate sequences containing rock salt and anhydrite. It is found in the central and northern part of the basin.

Amherstberg Formation

carbonate sequence that is not readily distinguishable from the Lucas. It does not contain salt or anhydrite.

Sylvania Sandstone

clean, white, mature sandstone with frosted grains. Maximum thickness of Detroit River Group is 450 ft.

Bois Blanc Formation

gray to brown finely crystalline dolomite that contains chert and argillaceous dolomite. This formation probably think toward the south and west. Maximum thickness 800 ft.

Silurian

Bass Islands Group

gray, tan, or brown finely crystalline dolomite with local anhydrite, salt, and shale stringers. In outcrop it is divided into Raisin River Dolomite and Put-in-Bay Dolomite. Its maximum thickness is 700 ft.

Salina Group

G Unit

thin, dark gray dolomitic shale with anhydrite nodules.

F Evaporite

thick salt beds interbedded with shales and evaporitic dolomites. The top is characterized by gray to brown dolomite and anhydrite. On the periphery of the basin the upper salts may be replaced by thin beds of gray-green shale and minimal amounts of red shale.

E Unit

brown, finely crystalline dolomite interbedded with shales and argillaceous dolomite. The top is gray-green shale. Occasional anhydrite stringers are present. Average thickness is 100 ft.

D Evaporite

an upper and lower salt bed separated by an anhydritic and argillaceous dolomite. On the periphery of the basin the unit grades into anhydrite and shale.

C Unit

shale or dolomitic shale containing anhydrite nodules. It includes a layer of dolomite in the middle of the formation.

B Evaporite

the upper part contains thin dolomite beds contained in salt, while the lower part is essentially all salt. In the central part of the basin the unit is approximately 475 ft thick; it thins toward the periphery. There is a loss of evaporites toward the southern edge edge of the basin and a replacement by dolomite and argillaceous dolomite.

A-2 Carbonate

gray to dark brown limestone and dolomite. Local shale and anhydrite beds are present.

A-2 Evaporite

salt grading into anhydrite toward the periphery of the basin. Sometimes minor dolomite stringers are found near the periphery. In areas where pinnacle reefs are present, the A-2 Evaporite occurs as a thin anhydrite layer overlying the reefs. In the deepest part of the basin this formation is 475 ft thick.

A-1 Carbonate

dark brown, finely crystalline dolomite and limestone. When associated with reefs, the A-1 Carbonate is thin and may be absent over the higher parts of the reefs.

A-1 Evaporite

salt grading into anhydrite along the basin margins. The A-1 Evaporite is usually absent over pinnacle reefs. In the deep part of the basin it is 500 ft thick. The maximum thickness of the Salina Group in the center of the basin is about 3,000 ft.

Niagara Group

buff-colored carbonate. In the central part of the basin it is characterized by a pink crinoidal limestone. Biohermal and biostromal reef development occurs on the northern and southern sides of the basin. This formation is thickest near the margins and thins toward the center of the basin. Maximum thickness is 980 ft.

Clinton Formation

In the northwest part of the state the Clinton is a cherty dolomite that reaches a thickness of 400 ft. Toward the southeast it thins and grades into a gray shale separated by a thin bed of buff dolomite.

Cataract Group

Cabot Head Shale

gray, green, and red shales. Toward the north, carbonate stringers become more abundant.

Manitoulin Dolomite

buff to brown, finely crystalline dolomite interbedded with argillaceous dolomite. The maximum thickness of the Cabot Head and the Manitoulin is 200 ft.

Ordovician

Richmond Group

undifferentiated in the subsurface. Consists of red, green, and gray shales interbedded with gray to brown fossiliferous limestones and dolomites.

Utica Shale

greenish-gray to black shale grading upward into a light gray shale.

Trenton Group

generally undivided in the subsurface. The Trenton is a brown, finely crystalline fossiliferous limestone containing dolomite and dolomitic limestone associated with fractures. Black carbonaceous shale with chert nodules is also present. This unit is capped with 10 to 15 ft of dolomite.

Black River Group

tan to brown, finely crystalline limestone containing brown chert nodules. Some of the limestone is argillaceous or dolomitic. The Black River becomes clayey near the base. The maximum thickness of the Trenton and Black River is 1,100 ft.

St. Peter Sandstone

white, well rounded, medium-grained, poorly sorted sandstone. The St. Peter contains local shale beds. It is present in southwestern and western Michigan. Maximum thickness is 260 ft; average thickness is about 50 to 75 ft.

Prairie du Chien Group

white to brown dolomite containing oolitic chert. Thin interbedded shales are present at the base. Maximum thickness 425 ft.

Cambrian

Trempealeau Formation

buff to gray to light brown, finely crystalline dolomite interbedded with argillaceous dolomite. Maximum thickness, near the center of the basin, is 750 ft.

Jordan Sandstone Member

gray to orangish-pink, fine- to medium-grained sandstone with subangular to subrounded quartz grains. It is silica cemented in the top, but in the bottom the cement is dolomitic. Traces of anhydrite are present. It may reach 600 ft in thickness in the northwestern part of the southern peninsula.

Lodi Member

grayish-red to brownish-gray, dolomitic, micaceous siltstone and dark gray shale. The base is more glauconitic and dolomitic. Its maximum thickness is 170 ft.

St. Lawrence Member

dark gray, fine to coarsely crystalline dolomite. Glauconite, chert, dark shale, and sandstone interbeds are present in its upper part. In southern and southwestern Michigan the shale content increases in the lower part of the formation. Toward the southwest and west, pink dolomite is present in the body of the unit and the top portion becomes cherty. In the west central and north central areas of the southern peninsula, interbedded sandstone and dolomite predominate.

Munising Formation

Franconia Sandstone Member

fine-grained dolomitic sandstone, shale, and sandy dolomite that contains a large amount of glauconite. It may attain a thickness of 100 ft or more in southwest Michigan.

Dresbach Sandstone Member

white to olive-gray sandstone with occasional interbeds of buff, argillaceous dolomite. It is medium-grained with subangular grains and is silica cemented.

Eau Claire Member

the upper part is characterized by gray and green shales interbedded with sandy dolomite, thinly bedded siltstones, and dolomitic shales. The lower part is characterized by gray sandstone, gray and green shale, and buff-colored, argillaceous, finely crystalline dolomite. It is about 700 ft thick in southwestern Michigan, around Calhoun and Kalamazoo Counties.

Mt. Simon Sandstone Member

white to gray, medium- to very coarse-grained sandstone with subrounded to rounded grains. It is silica cemented and contains some glauconite. The base is pink or reddish and arkosic with minor amounts of glauconite, green shale, anhydrite, and dolomite cement. The top is characterized by a shaly sandstone. The unit thins toward the east and north. In southeastern Michigan, the formation is finer grained and more indurated. In western and southwestern Michigan, it is coarser grained and friable. The maximum thickness of the Munising Formation is 1,175 ft.

Jacobsville Sandstone

reddish-purple, coarse-grained sandstone with siltstone and shale. The sandstone is silica cemented and hematite-stained. Glauconite is present.

Precambrian Basement Complex

granitic igneous rocks, gneiss, schist, interbedded sediments, Keweenawan volcanics.

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