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AN ASSESSMENT OF THE GEOTHERMAL RESOURCES OF INDIANA BASED ON EXISTING GEOLOGIC DATA

By
Tracy L. Vaught

December 1980
Date Published

Work Performed Under Contract No. AC08-80NV10072

Gruy Federal, Inc.
Arlington, Virginia

U. S. DEPARTMENT OF ENERGY
Geothermal Energy

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Preface

This assessment of geothermal resources in the State of Indiana is part of a series of investigations concerning geothermal energy in the eastern half of the United States. These studies are being conducted by Gruy Federal, Inc. for the U.S. Department of Energy's Division of Geothermal Energy.

An initial study, completed in 1979, assessed the overall geothermal potential of the 35 states east of the Rocky Mountains. Subsequent investigations are focusing on individual midwestern states. In addition to this Indiana study, reports on Michigan and Illinois are scheduled for completion during DOE's 1980 fiscal year.

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Introduction

In the eastern United States, obvious manifestations of subsurface heat--such as geysers, recently active volcanoes, and hot springs--are far less common than they are in the west. The search for geothermal resources in the east, therefore, must be based on careful interpretation of regional and local geology, since it is the geology of a particular area that determines whether such resources are present.

General Geology of Indiana

Physiography

Indiana is located within the Interior Lowlands province, the sediment-mantled southern extension of the Laurentian Shield. The province is a part of the Central Stable region (fig. 1), which includes the oldest and most tectonically stable portion of North America. The region is bordered on the west by the Rocky Mountain system, on the south by the Ouachita Mountains and related structures, and on the east by the Appalachians. To the north it extends into Canada.

Since the beginning of Paleozoic time, only mild deformation has taken place in this region (King, 1951). It is characterized by gentle domes, arches, and relatively shallow basins, which formed during Paleozoic time (Eardley, 1951). The seas transgressed earlier and more often on to the Interior Lowlands, depositing thicker sediments there than on the shield area. Sediment thickness ranges from hundreds to thousands of feet, reaching 14,000 to 15,000 ft in the Michigan and Illinois basins. According to King, the entire area of the Interior Lowlands subsided during sedimentation; the arches and domes subsided less than the basins. Faulting appears not to have been important in the formation of most structures, although minor faults are associated with many. A geologic map of Indiana is shown in fig. 2.

Stratigraphy

Indiana is characterized by widespread thin, nearly flat-lying Paleozoic rocks (Burger and others, 1966). Long periods of stability were interrupted by episodes of sedimentation and erosion that sculptured the landscape. One of these episodes was continental glaciation, which deposited the glacial till that now covers much of Indiana. The sedimentary bedrock in Indiana ranges in age from Cambrian to Late Pennsylvanian (Patton, 1955). A stratigraphic column for the state is given in Table 1.

The oldest exposed rocks are in the structurally highest region, the Cincinnati arch, in southeastern Indiana, where Ordovician rocks outcrop in eight counties. Westward, down the flank of the Cincinnati arch and into the Illinois basin, the surface strata range in age from Ordovician to Pennsylvanian; the younger rocks outcrop farther away from the arch than

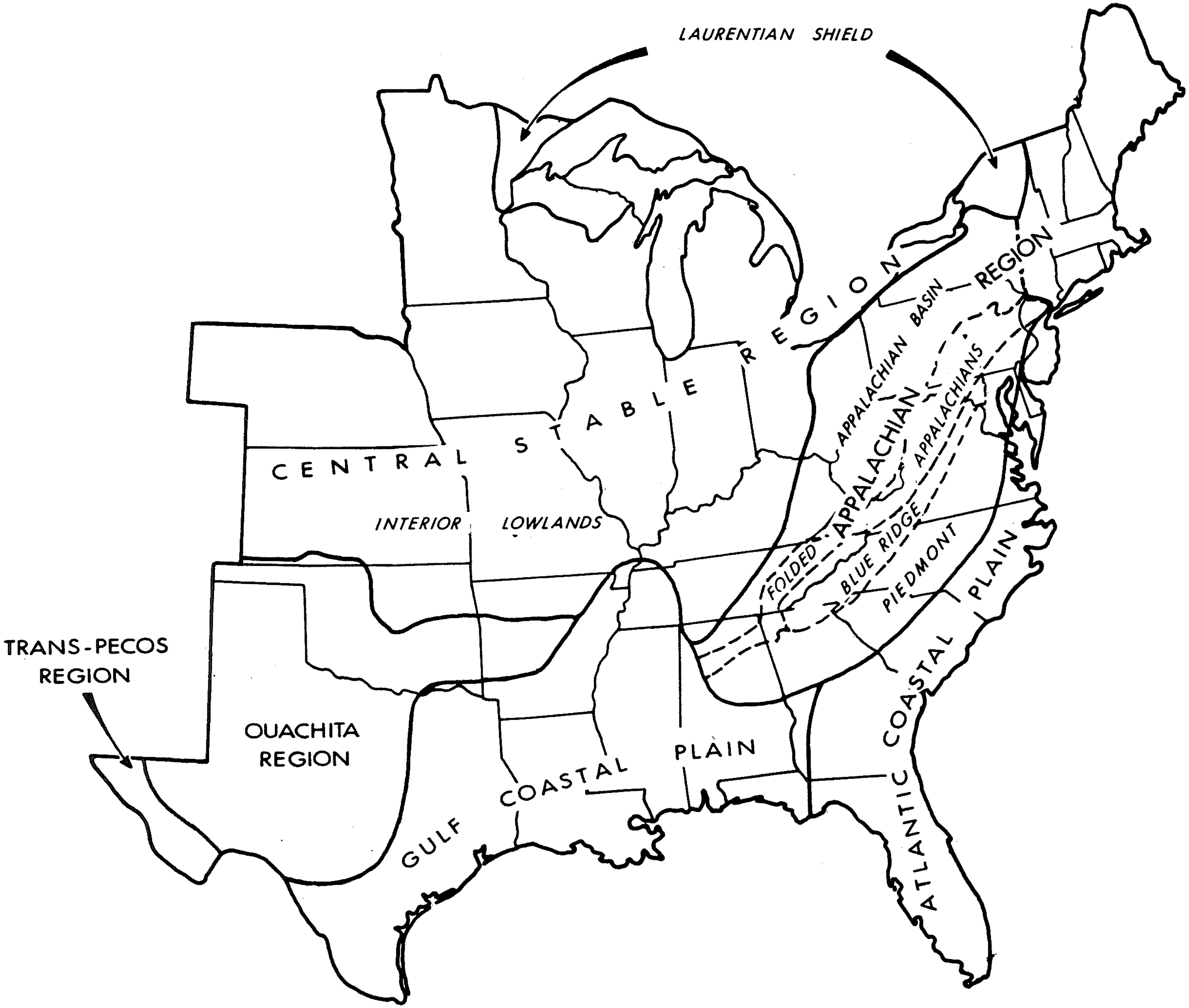

Figure 1.--Geological regions of the eastern United States.

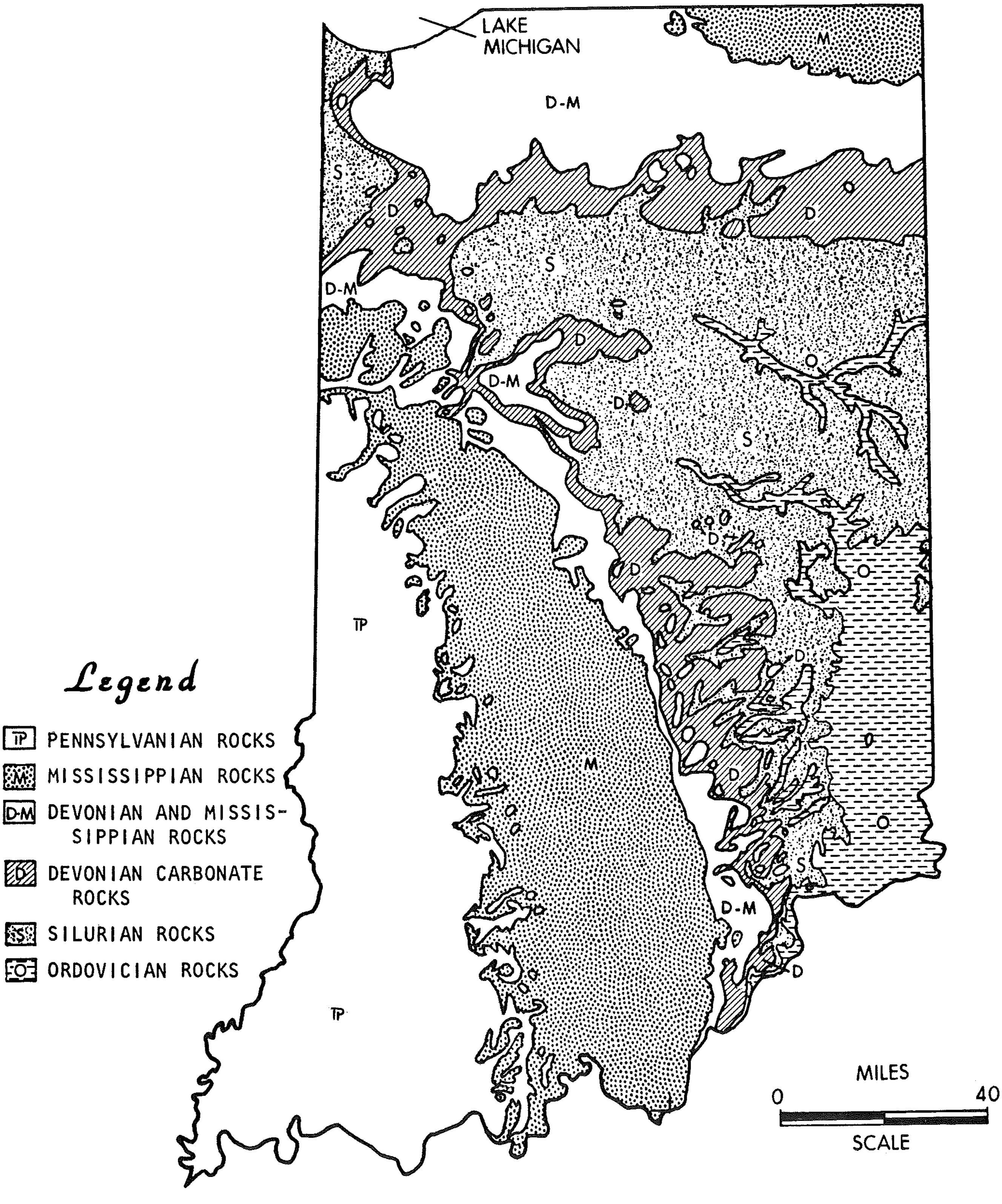

Figure 2.--Generalized geologic map of Indiana (modified from Becker, 1974).

TABLE 1

GENERALIZED STRATIGRAPHIC COLUMN FOR INDIANA
(from Shaver and others, 1970)

Era	System	Series	Group	Formation
Cenozoic	Quaternary	Pleistocene		Largo Fm
				Trafalgar Fm
				Jessup Fm
				Atherton Fm
				Martinsville Fm
				Prospect Fm
	Tertiary			Lafayette Gravel
Paleozoic	Pennsylvanian	Missourian	McLeansboro	Mattoon Fm
				Bond Fm
				Patoka Fm
		Desmoinesian		Shelburn Fm
			Carbondale	Dugger Fm
				Petersburg Fm
				Linton Fm
			Raccoon Creek	Staunton Fm
		Atokan		Brazil Fm
		Morrowan		Mansfield Fm
	Mississippian	Chesterian		Kinkaid Ls
				Degonia Ss
				Clore Ls
				Palestine Ss
				Menard Fm
				Wallersburg Ss
				Vienna Ls
				Tar Springs Fm
			Stephensport	Glen Dean Ls
				Hardinsburg Fm
				Golconda Ls
				Big Clifty Fm
				Beech Creek Ls
			West Braden	Elwren Fm
				Cypress Fm
				Reelsville Ls
				Sample Fm
				Beaver Bend Ls
				Bethel Fm
			Blue River	Paoli Ls
		Valmeyeran		Renault Fm
				Aux Bases Fm
				Ste. Genevieve Ls
				St. Louis Ls
			Sanders	Salem Ls
				Harrodsburg Ls
			Bordon	Muldraugh Fm
				Carwood Fm
				Locust Point Fm
				New Providence Sh
				Coldwater Sh (N)
		Kinderhookian		Rockford Ls
				Sunbury Sh
	Devonian	Senecan and Chautauguan		Ellsworth Sh
				New Albany
				Antrim Sh (N)
		Erian		North Vernon Ls (S)
				Traverse Fm (N)
				Detroit River Fm (N)
				Jeffersonville Ls (S)

TABLE 1 (continued)

Era	System	Series	Group	Formation
Paleozoic	Devonian	Ulsterian		Geneva Dol (S)
	Silurian	Cayugan		Salina Fm
		Niagaran		Wabash Fm
				Louisville Ls
				Waldron Sh
				Salamonie Dol
		Alexandrian		Brassfield Ls
	Ordovician	Cincinnatian		Whitewater Fm
				Saluda Fm
				Dillsboro Fm
				Kope Fm
		Champlainian		Lexington Ls
				Trenton Ls
				Black River Ls
				Joachim Dol
				St. Peter Ss
				Knox Dol
	Cambrian	St. Croixan		Davis Fm (S, NE)
				Franconia Fm (NW)
				Ironton Ss (NW)
				Galesville Ss (NW)
				Eau Claire Fm
				Mt. Simon Ss
	PRECAMBRIAN			

the older ones (Patton, 1955). The same pattern is found on the other side of the arch in northern Indiana, where Silurian, Devonian, and Mississippian rocks are present at the surface.

Figure 3 shows the structure on the Precambrian basement. The sediments thicken on both sides of the Cincinnati arch, toward the center of the Illinois basin on the southwest side and toward the center of the Michigan basin on the northeast side. Figures 4 through 8 are isopachous maps of some of the deeper units. The isopachs of Silurian and Devonian formations cover only the area southwest of the Cincinnati arch. The distribution and thickness of formations for which no isopachs are shown are given in the appendix.

The Mt. Simon Sandstone and the Eau Claire Formation underlie the entire state. The Davis Formation, known in the northwest part of the state as the Galesville Sandstone, Ironton Formation, and Franconia Formation, may be present throughout the state, but its presence in southwestern Indiana is not verified.

The appendix contains lithologic descriptions of all units that may occur at depths reasonable for geothermal exploration.

Structural Features

Structurally, Indiana is characterized by gentle tilting, mild folding, gradual subsidence, and occasional faulting. Mild crustal deformation produced arches and basins of regional proportions. On the arches, sediments are relatively thin, because younger sediments have been eroded. In the basins, the sediments are thick due to subsidence and uninterrupted sedimentation (Carpenter and others, 1975).

The state encompasses parts of four major structural features: the Cincinnati arch, the Kankakee arch, the Illinois basin, and the Michigan basin (fig. 9). On the arches, which extend diagonally across Indiana from southeast to northwest, the sedimentary rocks are less than 3,500 ft thick in places and the dips of the strata are gentle. Dips are somewhat greater on the edges of the basins than on the arches.

Cincinnati Arch. The Cincinnati arch is a broad positive structural feature that enters Indiana in its southeastern corner and extends northward and northwestward into southern Wabash and Miami Counties, where it meets the Kankanee arch (Patton, 1955). Throughout the area, dips are low and their directions are unpredictable. Westward and southwestward from the arch the rocks generally dip toward the center of the Illinois basin, from less than 10 feet per mile near the crest to 50 feet per mile in some areas near the edge of the basin. Northward from the arch, the rocks dip into the Michigan basin. The area was uplifted in Middle Devonian and again in Late Mississippian time. After the arching in Late Mississippian time, the region was submerged during the Early and Middle Pennsylvanian and sediments originating in the Appalachian region were deposited. During the Late Pennsylvanian, broad gentle arching took place once again.

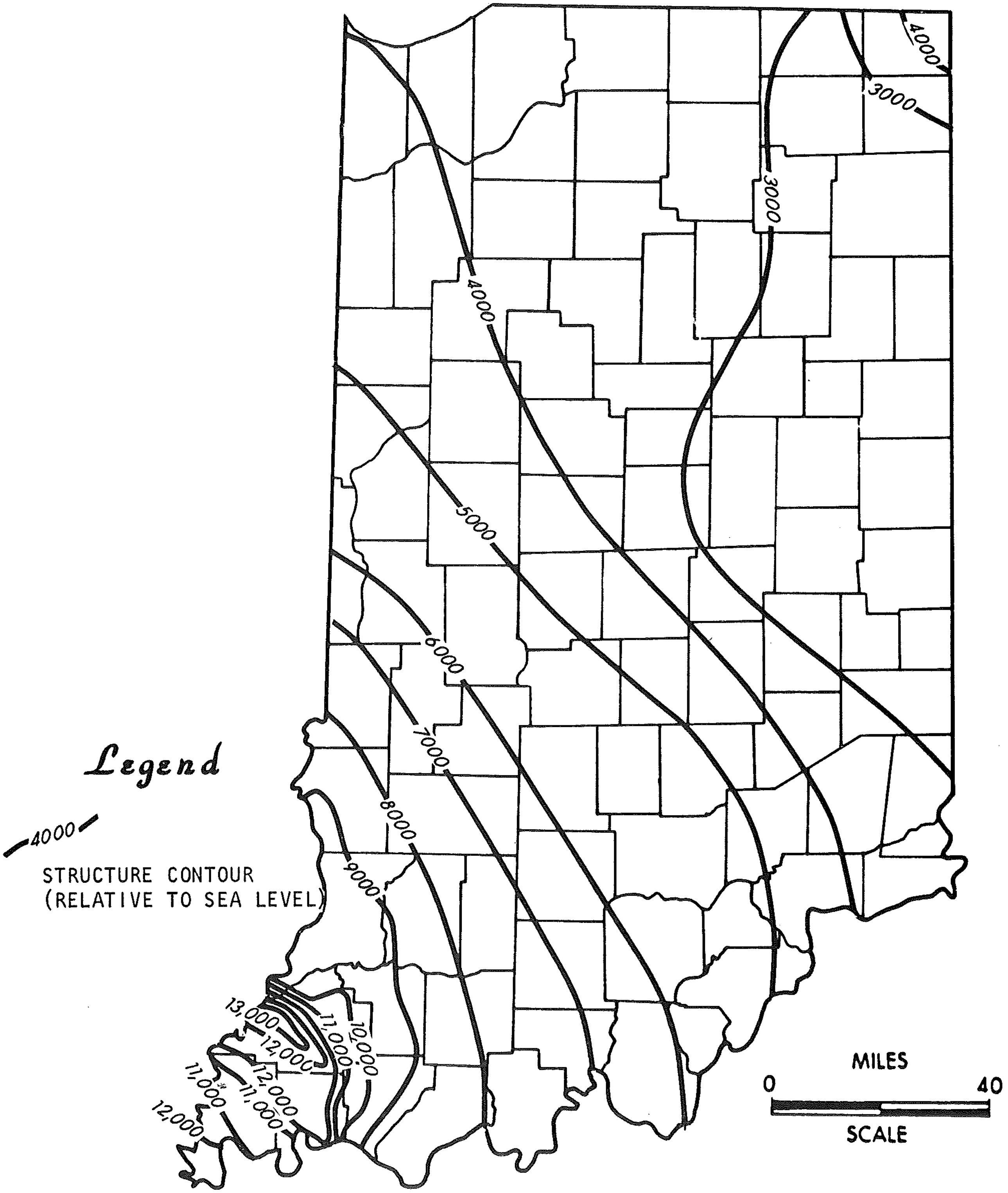

Figure 3.--Structure on Precambrian basement (after Bayley and Muelberger, 1968).

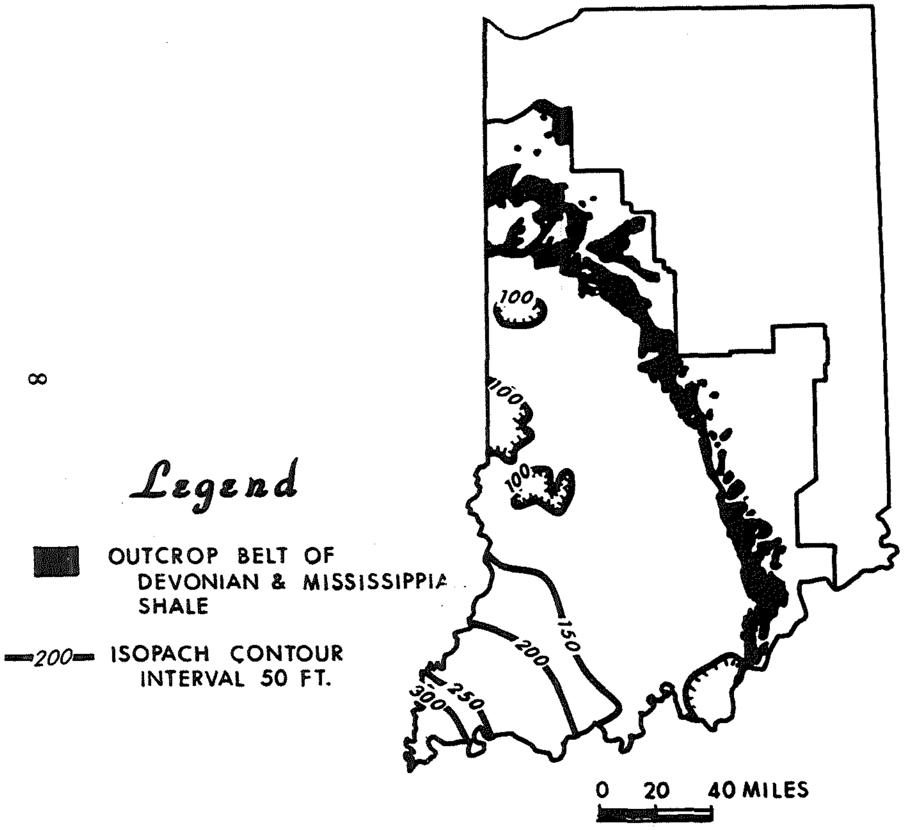

Figure 4.--Thickness of New Albany shale south of the Cincinnati Arch (from Becker, 1974).

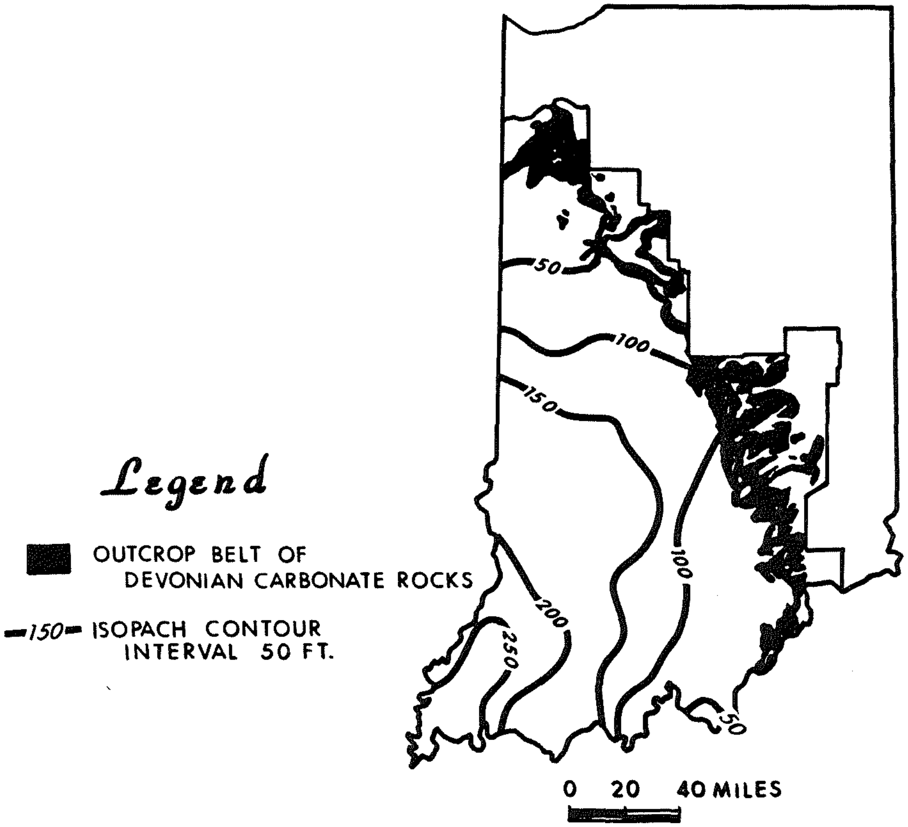

Figure 5.--Thickness of Geneva Dolomite, Jeffersonville Limestone, and North Vernon Limestone south of the Cincinnati arch (after Becker, 1974).

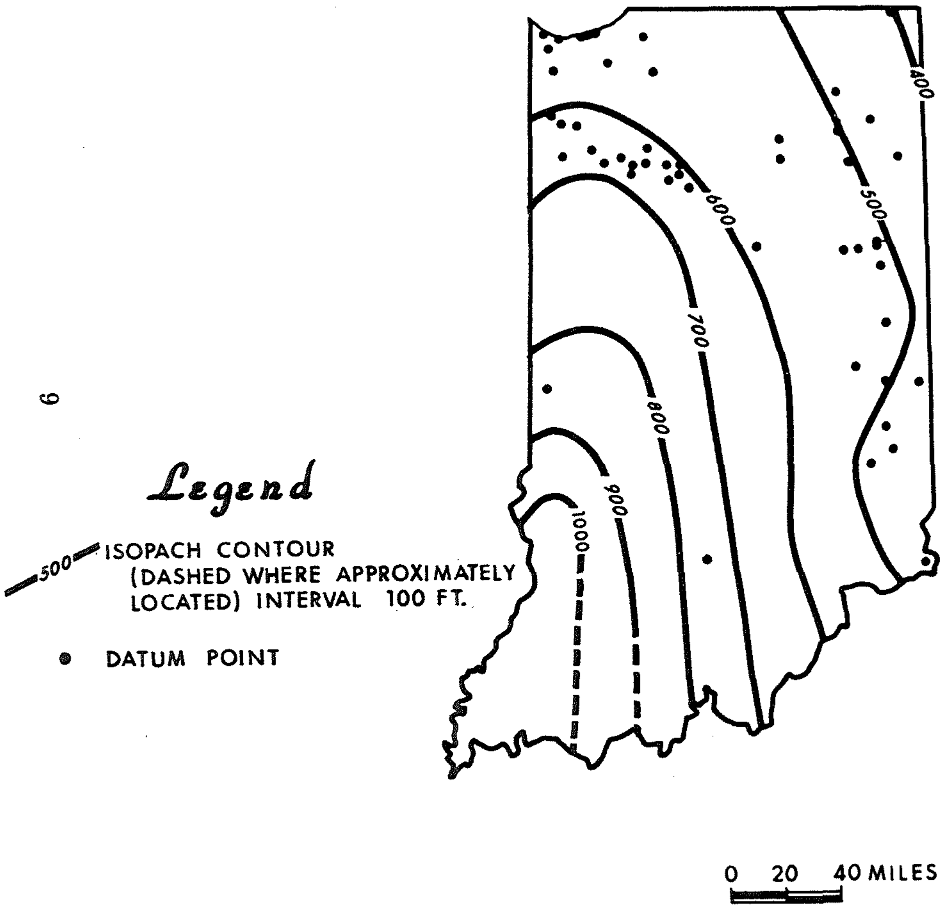

Figure 6.--Thickness of the Eau Claire Formation (after Becker and others, 1978).

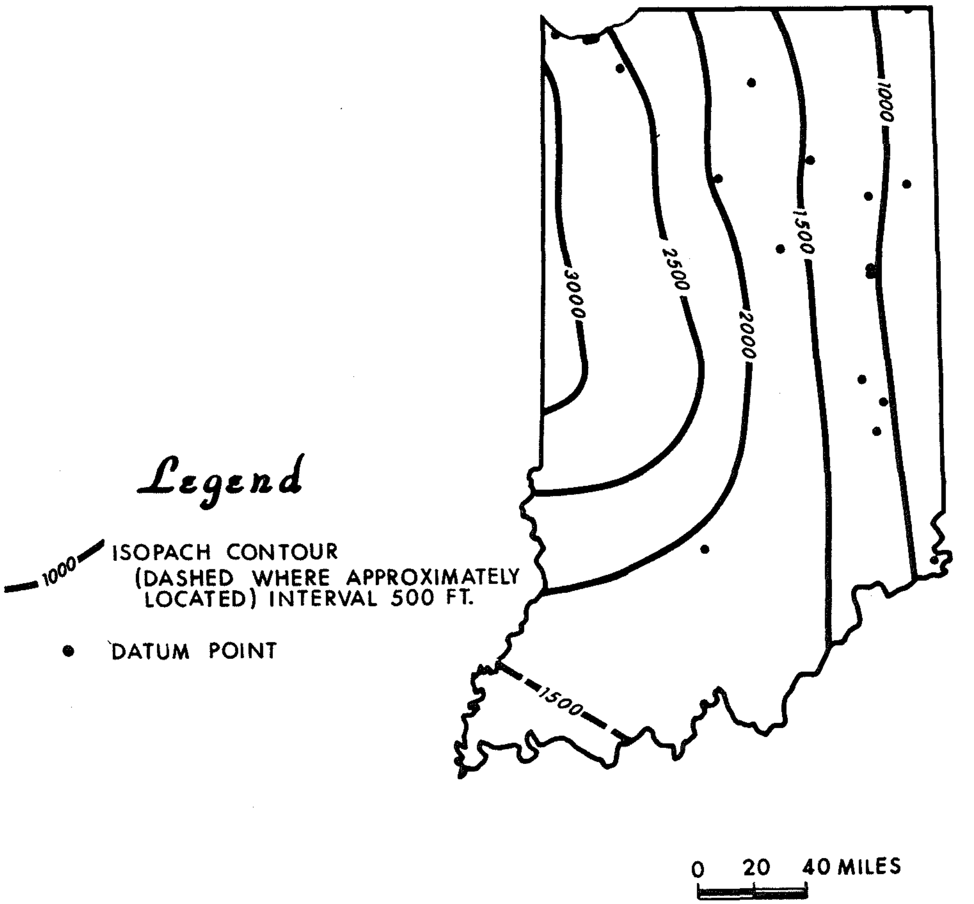

Figure 7.--Thickness of interval from base of Knox Dolomite to top of Precambrian basement (from Becker and others, 1978).

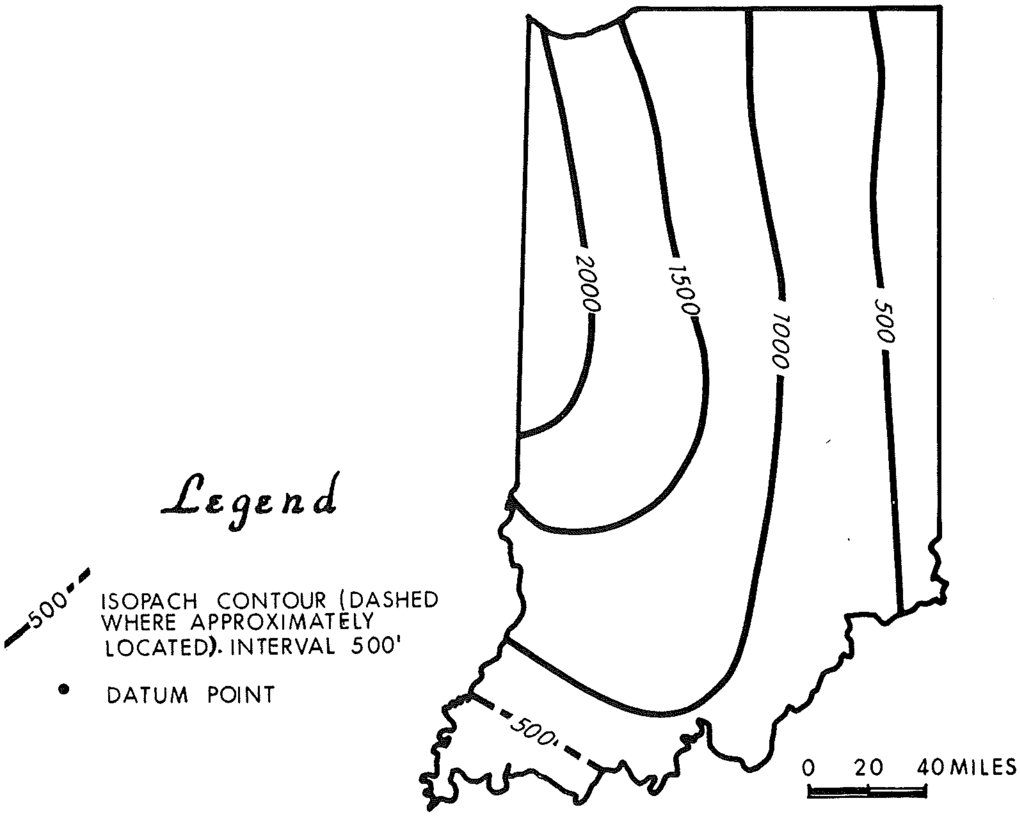

Figure 8.--Thickness of the Mount Simon Sandstone (after Becker and others, 1978).

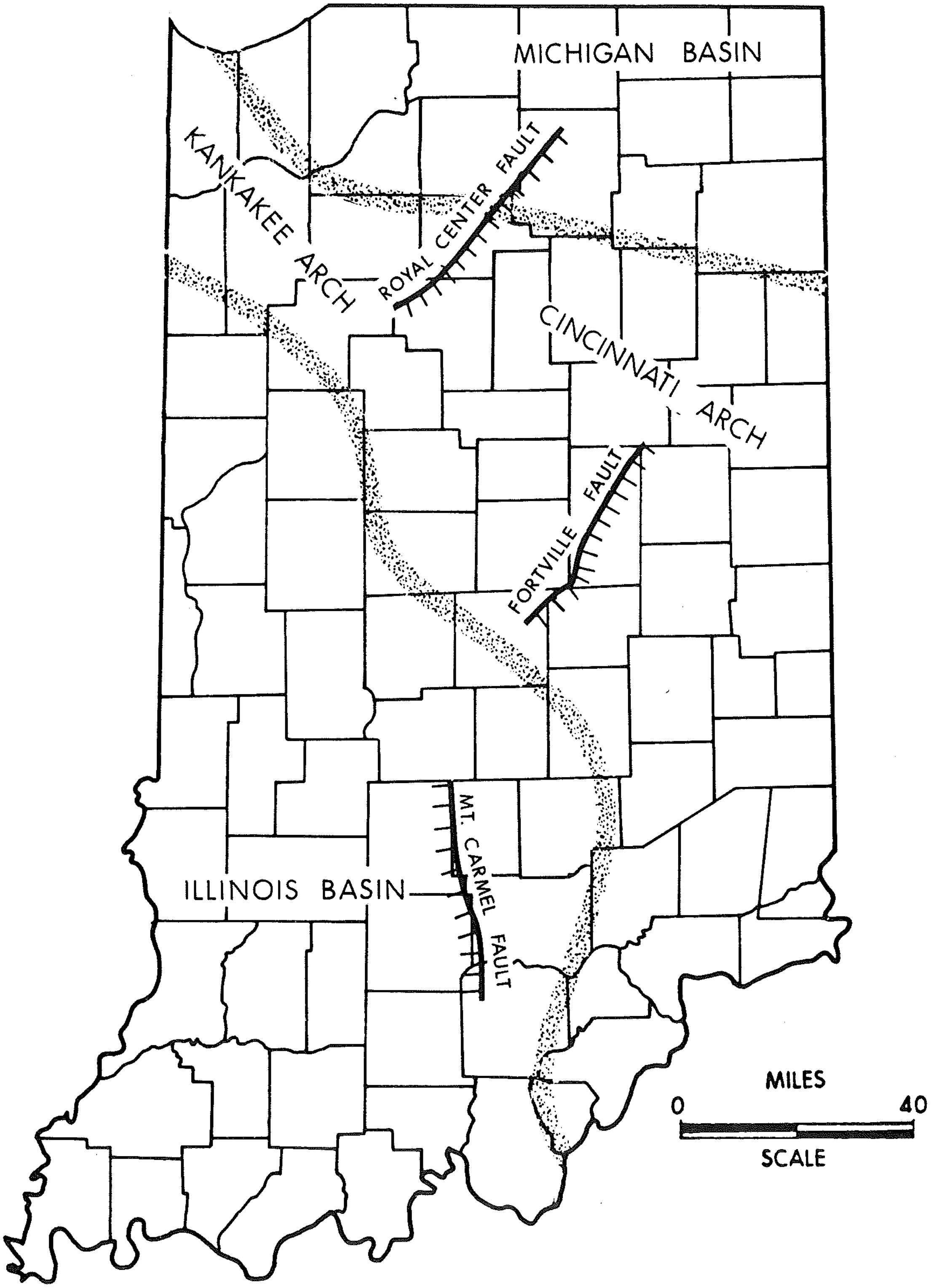

Figure 9.--Structural features (from Carpenter and others, 1975).

Kankanee Arch. The Kankanee arch is the northwest extension of the Cincinnati arch, passing northwesterly across Indiana and Illinois and connecting with the Wisconsin dome. The arch acquired its relief by greater subsidence of the surrounding basins rather than by actual uplift. Relative uplift occurred some time before the deposition of the St. Peter Sandstone in Early Ordovician time, again during Late Mississippian time, and once again during Late Pennsylvanian. The region emerged in Early Ordovician, when it locally suffered 600 feet of erosion. It emerged again in Late Mississippian during a regional uplift of the Great Lakes region, and once more in Late Pennsylvanian.

Illinois Basin. The Illinois basin is bounded on the north by the Kankakee arch, on the northeast and east by the Cincinnati arch, and on the west by the Ozark dome. Its eastern part underlies a large area in southwestern Indiana. The basin reaches a depth of approximately 13,000 feet below sea level in extreme southwestern Indiana (fig. 3). Subsidence of the basin began during Cambrian time and further deformation took place during Mississippian and Pennsylvanian time (Eardley, 1951). Sediments within the basin range in age from Cambrian to Pennsylvanian.

Michigan Basin. The Michigan basin is roughly symmetrical, with concentric bedrock outcrops of Paleozoic formations. Its southern tip underlies the area of Indiana north of the Cincinnati arch. Cambrian through Pennsylvanian sediments are represented in the basin, but Pennsylvanian rocks are not present in the Indiana portion. Nearly all formations thicken toward the center of the basin, indicating that it was a persistently negative structural feature subjected to continuing subsidence (Cohee, 1948).

Three major faults in Indiana (fig. 9) are presumed to have disturbed Precambrian basement rocks (Becker and others, 1978). The Royal Center fault in north central Indiana has a northeast-southwest trace, and the Fortville fault in east central Indiana has a northeast-southwest trace. Both are normal faults that are downthrown to the southeast. Dawson's (1971) structure map on top of the Trenton Limestone shows less than 100 feet of displacement on both faults. The Mt. Carmel fault in south central Indiana has an approximately north-south strike and is downthrown to the west. Its maximum stratigraphic displacement of the Trenton is 150 feet.

Indicators of Geothermal Energy

In the eastern United States, geothermal energy is an elusive resource. There are no geysers or recently active volcanoes, and very few hot springs. Geothermal exploration in the east must rely on clues such as geology, temperature gradients, heat flow, geochemistry, seismicity, and gravity measurements.

There are three likely sources of elevated subsurface temperatures in the eastern United States: (1) igneous intrusions enriched in uranium and thorium that produce elevated heat flow as the result of radioactive decay, (2) thick sediments of low conductivity that cause above-average thermal gradients by allowing the accumulation of heat below them, and (3) movement of deep waters upward along bedding planes or through faults and fractures to produce accumulations of warm water in reservoirs relatively near the surface or warm springs at the surface. Temperature gradients, heat flow, geochemistry, seismic activity, and regional geology are important indicators of these resources.

Heat Flow and Thermal Gradient

The temperature gradient (Γ), heat flow (q), and conductivity (K) of the rocks through which the heat is passing are related by the equation

$$q = K\Gamma . \dagger$$

Early heat flow studies showed that North America could be divided into several provinces, each with its characteristic heat flow (Roy and others, 1968a,b). Heat flow varies within a province because of differences in the heat generated in upper crustal rocks (Birch and others, 1968). There is a linear relationship between heat flow and radioactive heat generation (A) in the rocks at each site:

$$q = q^* + DA. \S$$

As further studies are made, more detailed heat flow and reduced heat flow (q^*) data will be available in addition to those provided by Sass and others (1976).

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†When q is expressed in heat flow units (1 HFU = 1 x 10^{-6} cal/cm^2 sec) and K in conductivity units (1 CU = 1 x 10^{-3} cal/cm sec °C), Γ is in °C/km if the factor 10^{-2} is included to make the units consistent.

§q^* (reduced heat flow) is the heat flow characteristic of a given province; DA is the component of heat flow due to radioactive heat generation in the upper crust; and D is related to the thickness of the radioactive crust (changes from one region to another). Diment and others (1975) suggest values of 0.8 HFU and 7.5 km for q^* and D, respectively, in the eastern United States.

The Indiana heat flow data compiled by Sass and coworkers are shown in fig. 10 and table 2. These values fall within the range of average heat flow values in the eastern United States (about 1.0 to 1.5 HFU). Coverage of the state is, however, very limited. The available data do not indicate any areas of abnormally high heat flow; but to get a better estimate of the heat flow in Indiana, more holes should be drilled, especially in the southern part of the state, where thick sediments occur and higher water temperatures might be reached in the sediments.

Temperature gradient measurements are useful in the exploration for geothermal resources because 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, limestones, and well cemented sandstones. Since conductivity affects temperature gradients, projection of temperatures to depth must rely on a knowledge of geology.

2. Conductivities generally 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.

The American Association of Petroleum Geologists and the U.S. Geological Survey (1976a,b) have jointly published maps showing regional variations in temperature gradients and subsurface temperatures. A simplified version of the Indiana portion of the gradient map is shown as fig. 11. A second AAPG map shows, where data are available, depth to various isothermal surfaces. These maps have only limited utility for geothermal exploration. They were not prepared with geothermal exploration in mind, so anomalously high gradients were disregarded. Moreover, there is evidence for substantial errors in the bottomhole temperatures used to calculate gradients for these maps (Vaught, 1980). Despite these problems, the data set (American Association of Petroleum Geologists, 1976) from which the gradient maps were generated is the best currently available for study of geothermal phenomena in the eastern United States.

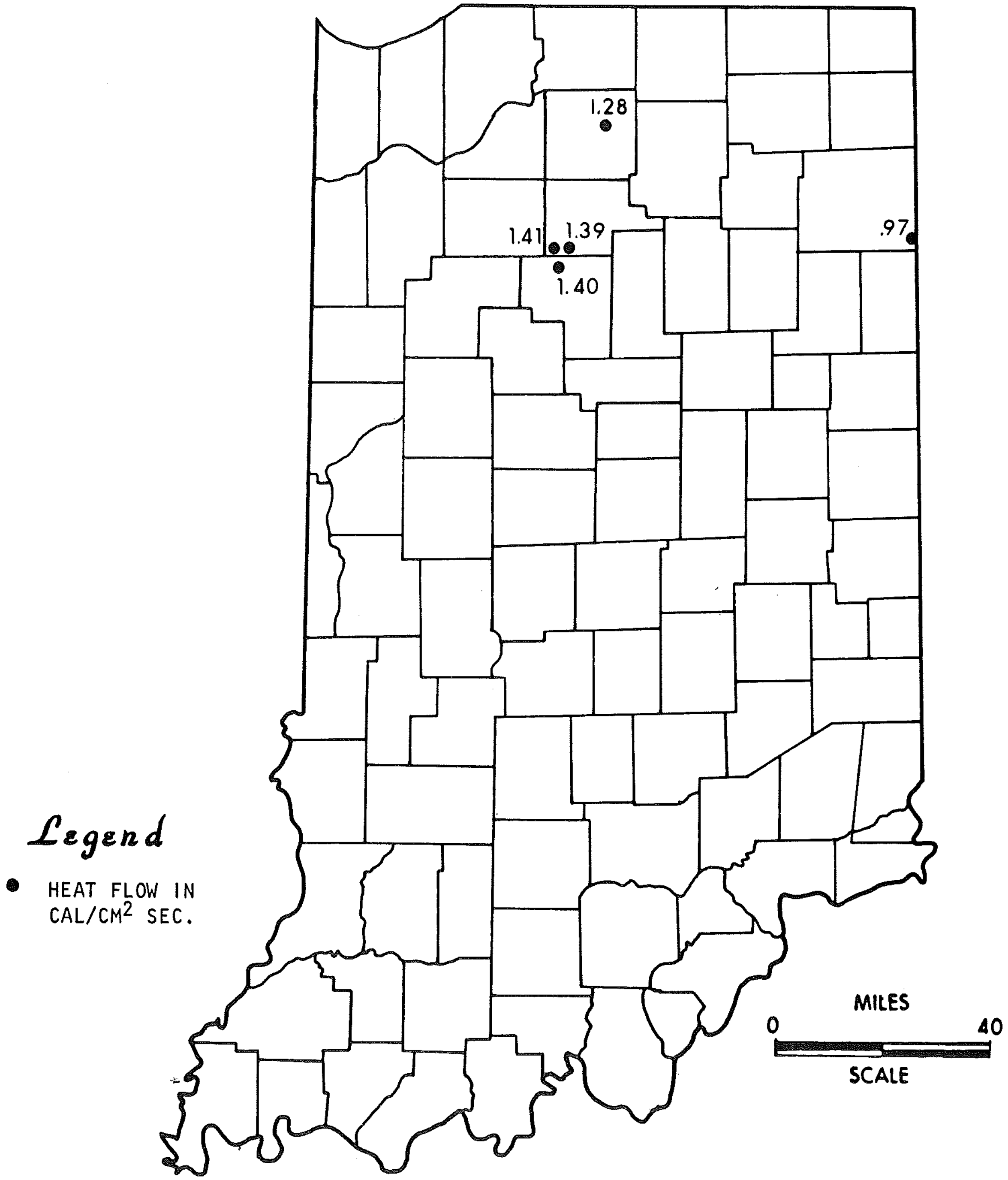

Figure 10.--Location of heat flow holes and heat flow values (from Sass and others, 1976).

TABLE 2

HEAT FLOW VALUES IN INDIANA
(from Sass and others, 1976)

Location, lat. (°N), long. (°W)		Heat Flow, cal/cm^2 sec
41°23'	86°14'	1.28
40°59'	84°52'	0.97
40°55'	86°28'	1.41
40°55'	86°27'	1.39
40°53'	86°28'	1.40

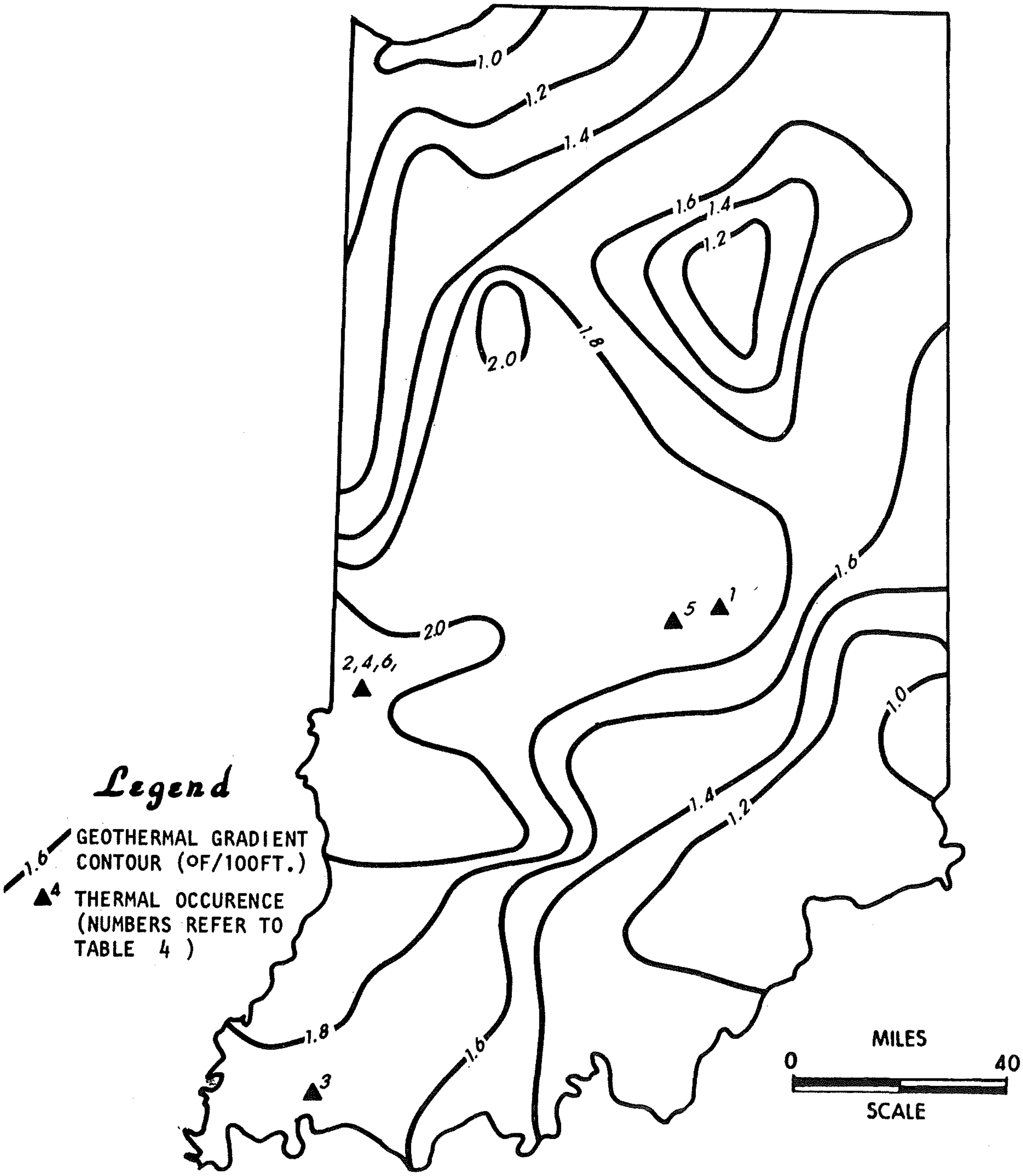

Figure 11.--Geothermal gradient (from AAPG and USGS, 1976) and thermal occurrences (from Blatchley, 1901).

Table 3 summarizes data on wells in Indiana, taken from the AAPG data file. Temperature gradients were calculated using an average ambient temperature of 55°F. The table includes 8 wells deeper than 4,000 feet, 18 from 3,000 to 4,000 feet deep, and 155 less than 3,000 feet deep. Generally, the shallow wells show much higher gradients than the deep wells, as is shown more clearly in fig. 12. The range of gradient values is considerably broader for the shallow wells; this may indicate groundwater movement, measurement errors, variable heat flow, or rocks of different conductivities. A strikingly similar pattern has been observed in Michigan for a group of wells which included many more deep wells than the Indiana group (Vaught, 1980).

Figure 11 shows that in a substantial portion of western Indiana gradients are 1.8°F or higher. But when the gradients of wells more than 3,000 ft deep are plotted on a map of the same scale (fig. 13), they rarely agree with the contoured gradients. Since both are corrected values and presumably should be consistent, the contours in fig. 11 must have been calculated primarily from shallow-well data. If this is true, the gradients represented by the contours are probably not valid for depths greater than the depth of measurement. Gradients in shallow wells may be strongly affected by groundwater circulation, variation in the heat flow and thermal conductivity of the rocks penetrated by the well, and errors in bottomhole temperature measurement.

Geothermal Occurrences

Several thermal wells have been reported in Indiana (Blatchley, 1901). Table 4 summarizes information on these wells, and fig. 11 shows their locations in relation to the thermal gradient contours. Three of the seven wells are within the 2.0°F/100 ft contour, two are within the 1.8°F/100 ft contour, and one is within 1.6°F/100 ft contour. All are shallow wells except the Terre Haute Gas Co. well, which is 2,930 ft deep but produces from a shallower interval. While these wells may indicate abnormally warm groundwaters, it is not advisable to use the indicated gradient to project temperatures at depths greater than their total depth. Furthermore, the data were published almost 80 years ago, and their validity is questionable.

Seismic Activity

Major high-temperature convective hydrothermal systems are usually associated with tectonic activity. Most major seismic events also occur in areas of major tectonic activity, such as spreading ridges, subduction zones, and continental rift zones. The eastern United States is generally considered to be tectonically stable, but some seismicity remains. Seismic activity may keep faults open, thereby allowing upward movement of warm waters. Above-average geothermal potential is probably associated with deep convection in fault zones; however, many faults in the eastern United States are inactive and are sealed by mineral deposition.

TABLE 3

DATA FOR INDIANA WELLS
(from AAPG, 1976)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
38.8412 86.3092	6,790	120	55	0.96	p€
38.2560 87.9347	6,408	145	55	1.40	O
38.6717 87.4833	5,462	120	55	1.19	O
38.3892 87.3588	4,664	110	55	1.18	O
41.6557 87.4250	4,360	105	55	1.15	p€
41.6338 87.1195	4,292	84	55	0.68	p€
41.6212 87.3672	4,276	89	55	0.80	€
38.0762 87.4398	4,020	94	55	0.97	D
38.8577 84.8858	4,000	98	55	1.08	p€
39.5353 85.0893	3,955	96	55	1.04	p€
38.3685 87.6095	3,908	118	55	1.61	D
40.9242 85.8003	3,680	90	55	0.95	p€
41.1707 87.2718	3,658	100	55	1.23	€
41.1880 85.1503	3,571	102	55	1.32	€
40.9183 85.1763	3,524	104	55	1.39	p€
38.4548 87.1182	3,506	92	55	1.06	S
39.3738 85.2063	3,470	90	55	1.01	€
41.7510 84.8057	3,435	97	55	1.22	O
38.5043 87.4918	3,408	116	55	1.79	S
39.4233 85.0715	3,336	88	55	0.99	€
38.1865 87.9228	3,250	111	55	1.72	M
38.2555 87.2187	3,207	111	55	1.75	D
38.4388 87.3423	3,141	124	55	2.20	D
30.5835 87.3368	3,070	116	55	1.99	D
38.2545 87.8702	3,010	112	55	1.89	M
38.1008 87.8353	3,009	99	55	1.46	M
38.1030 87.9690	2,992	104	55	1.64	M
37.9575 87.8743	2,985	102	55	1.57	M
38.1565 87.7757	2,980	101	55	1.54	M
38.0015 87.9913	2,979	96	55	1.38	M
38.5400 87.3038	2,978	102	55	1.58	D
37.9188 88.0258	2,917	100	55	1.54	M

TABLE 3 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
38.3032 87.8582	2,892	107	55	1.80	M
38.8082 88.0408	2.884	94	55	1.35	M
39.0667 87.5502	2,869	108	55	1.85	D
38.8597 87.4015	2,842	110	55	1.94	D
38.1093 87.7522	2,839	100	55	1.59	M
38.8048 87.4070	2,817	98	55	1.53	D
37.8738 88.0417	2,801	90	55	1.25	M
38.2367 87.7565	2,789	104	55	1.76	M
39.1240 87.5083	2,789	113	55	2.08	S
39.1428 87.6000	2,788	109	55	1.94	D
38.0195 87.7023	2,786	108	55	1.90	M
37.8900 87.8388	2,775	108	55	1.91	M
37.8503 88.0200	2,772	98	55	1.55	M
38.1557 87.7928	2,771	96	55	1.48	M
37.9040 87.7733	2,770	94	55	1.41	M
39.0428 87.4548	2,716	114	55	2.17	D
38.6517 87.6755	2,711	98	55	1.59	M
38.4535 87.1338	2,708	100	55	1.66	D
38.2245 87.6593	2,700	103	55	1.78	M
38.2917 87.7760	2,698	104	55	1.82	M
38.4678 87.1545	2,694	108	55	1.97	D
37.9925 87.6547	2,680	103	55	1.79	M
38.5882 87.2222	2,653	113	55	2.19	D
38.9755 87.3010	2,646	105	55	1.89	D
38.3192 87.1048	2,626	100	55	1.71	D
38.2090 86.9353	2,595	90	55	1.35	S
39.0850 86.9857	2,574	108	55	2.06	O
39.5755 87.2432	2,572	104	55	1.91	O
38.9840 87.3562	2,567	108	55	1.99	D
37.9092 87.6857	2,547	98	55	1.69	M
39.1408 87.4548	2,498	98	55	1.72	D
38.4168 87.6845	2,468	106	55	2.07	M
39.1878 87.4095	2,433	106	66	2.10	D

TABLE 3 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
39.1007 86.4342	2,416	85	55	1.24	O
39.1252 86.8578	2,413	110	55	2.28	O
38.1252 87.5240	2,403	96	55	1.71	M
38.1042 87.5515	2,401	86	55	1.29	M
39.0890 87.3237	2,386	113	55	2.43	D
37.8335 87.1177	2,377	90	55	1.48	M
38.8525 87.2097	2,363	109	55	2.29	D
39.3220 87.5738	2,341	104	55	2.09	D
38.5405 87.0547	2,334	111	55	2.40	S
38.6557 87.0757	2,327	96	55	1.76	S
38.4708 87.6557	2,321	98	55	1.85	M
39.0833 87.2372	2,312	99	55	1.90	S
39.3077 87.4872	2,264	98	55	1.90	D
38.1183 87.6852	2,260	82	55	1.19	M
38.2703 87.6852	2,200	98	55	1.94	M
38.5378 86.9517	2,219	90	55	1.58	D
39.3683 87.5008	2,179	103	55	2.20	D
38.2880 86.8728	2,165	98	55	1.99	D
38.8852 86.0763	2,169	83	55	1.29	O
39.3098 87.4522	2,142	96	55	1.91	D
39.0892 87.1757	2,140	92	55	1.73	S
38.7427 87.4872	2,129	108	55	2.49	M
38.4895 87.4335	2,114	94	55	1.84	M
38.3427 87.5182	2,112	92	55	1.75	M
37.9225 87.3265	2,111	94	55	1.85	M
38.4412 87.7063	2,083	98	55	2.06	M
39.5908 86.8385	2,071	102	55	2.27	O
38.9085 87.1722	2,061	100	55	2.18	S
38.4352 86.9215	2,060	85	55	1.46	D
39.2235 87.2593	2,055	91	55	1.75	D
38.1597 87.4395	2,054	82	55	1.31	M
39.4912 87.5055	2,039	98	55	2.11	D

TABLE 3 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
39.5193 87.5098	2,036	96	55	2.01	D
39.2758 87.2877	2,022	91	55	1.78	D
38.5728 87.3525	2,021	102	55	2.33	M
38.5247 86.9382	2.017	96	55	2.03	D
39.3518 87.3678	2,005	93	55	1.90	D
38.4012 87.5413	2,004	94	55	1.95	M
38.2695 87.4320	2,001	91	55	1.80	M
37.9517 87.2868	1,988	93	55	1.91	M
38.0682 87.3098	1,953	93	55	1.89	M
38.4018 86.7735	1,938	102	55	2.43	D
39.2242 87.1890	1,932	96	55	2.12	D
39.5425 87.4200	1,929	104	55	2.54	S
39.2928 87.2058	1,874	88	55	1.76	S
37.8053 87.9180	1,871	90	55	1.87	M
38.9550 87.0762	1,843	95	55	2.17	S
38.9897 87.5410	1,843	98	55	2.33	M
39.5358 87.2257	1,842	88	55	1.79	S
39.4233 87.3418	1,841	94	55	2.12	D
39.2068 87.1015	1,835	96	55	2.23	S
39.6233 87.5012	1,827	112	55	3.12	D
38.1910 87.3523	1,824	96	55	2.25	M
39.0333 87.0598	1,821	98	55	2.36	D
38.6670 87.4573	1,818	91	55	1.98	M
39.0188 86.4097	1,794	112	55	3.18	O
38.2063 87.3217	1,792	88	55	1.84	M
38.3352 87.3862	1,786	92	55	2.07	M
37.8042 87.1857	1,785	85	55	1.68	M
37.9688 87.3698	1,783	82	55	1.51	M
39.4513 85.3052	1,775	84	55	1.63	O
37.8720 87.1067	1,765	77	55	1.25	M
38.5890 87.5760	1,762	86	55	1.76	M
39.5030 87.3403	1,757	89	55	1.94	D

TABLE 3 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
38.5750 87.4858	1,721	82	55	1.57	M
38.8082 86.9350	1,686	82	55	1.60	D
38.9720 86.4253	1,671	102	55	2.81	O
38.6742 87.1430	1,662	92	55	2.23	M
39.4373 87.3573	1,660	92	55	2.23	D
39.2545 86.9880	1,656	88	55	1.99	S
39.1890 87.5518	1,648	97	55	2.55	M
39.0383 87.3503	1,644	96	55	2.49	M
39.4762 87.1695	1,619	88	55	2.04	S
37.9752 87.1858	1,602	85	55	1.87	M
37.9923 87.1252	1,600	81	55	1.63	M
39.5030 85.2095	1,594	74	55	1.19	O
38.0575 87.1693	1,576	84	55	1.84	M
39.5533 85.3180	1,565	70	55	0.96	O
38.6428 87.3407	1,555	96	55	2.64	M
38.7193 86.8670	1,550	97	55	2.71	D
39.4230 87.1712	1,540	83	55	1.82	D
39.5835 85.4543	1,525	80	55	1.64	O
38.8855 87.4922	1,516	90	55	2.97	M
38.3073 87.2707	1,503	91	55	2.40	M
39.5543 85.2043	1,500	70	55	1.00	O
39.6185 87.2688	1,489	94	55	2.62	D
38.0263 87.0698	1,480	92	55	2.50	M
37.7508 87.3177	1,458	85	55	2.06	M
39.2030 86.9412	1,448	92	55	2.56	D
37.8677 87.1392	1,433	79	55	1.67	M
39.5693 87.0858	1,402	85	55	2.14	S
38.3018 87.2353	1,385	82	55	1.95	M
38.6052 87.0877	1,363	98	55	3.15	M
38.1343 87.0733	1,337	78	55	1.72	M
38.2732 87.0247	1,318	82	55	2.05	M
38.3708 86.8675	1,308	96	55	3.13	M

TABLE 3 (continued)

Location, lat. (°N), long. (°W)	Depth, ft	Bottom-hole temp., °F	Ambient surface temp., °F	Gradient, °F/100 ft	Age of deepest unit penetrated
38.7728 87.1197	1,304	87	55	2.45	M
39.9733 87.3248	1,300	84	55	2.23	O
38.8518 87.2690	1,299	79	55	1.85	M
39.6035 87.0903	1,291	82	55	2.09	D
38.8025 87.1527	1,218	84	55	2.38	M
38.1922 87.1395	1,190	77	55	1.85	M
37.9893 86.9578	1,172	75	55	1.71	M
38.7072 86.9370	1,113	85	55	2.70	M
38.8235 87.0677	1,106	88	55	2.98	M
39.9888 87.3517	1,102	64	55	0.82	S
40.7683 85.7338	1,077	65	55	0.93	O
38.1523 86.9395	1,014	77	55	2.17	M
39.4848 86.7018	999	79	55	2.40	D
39.2232 86.4367	919	74	55	2.07	S
38.1417 86.7510	840	81	55	3.10	M
38.0066 86.8750	797	73	55	2.26	M
38.8032 86.2890	753	80	55	3.32	D
38.0722 86.6512	725	77	55	3.03	M
39.1677 86.1428	721	71	55	2.22	O
38.5058 86.8920	708	96	55	5.79	M

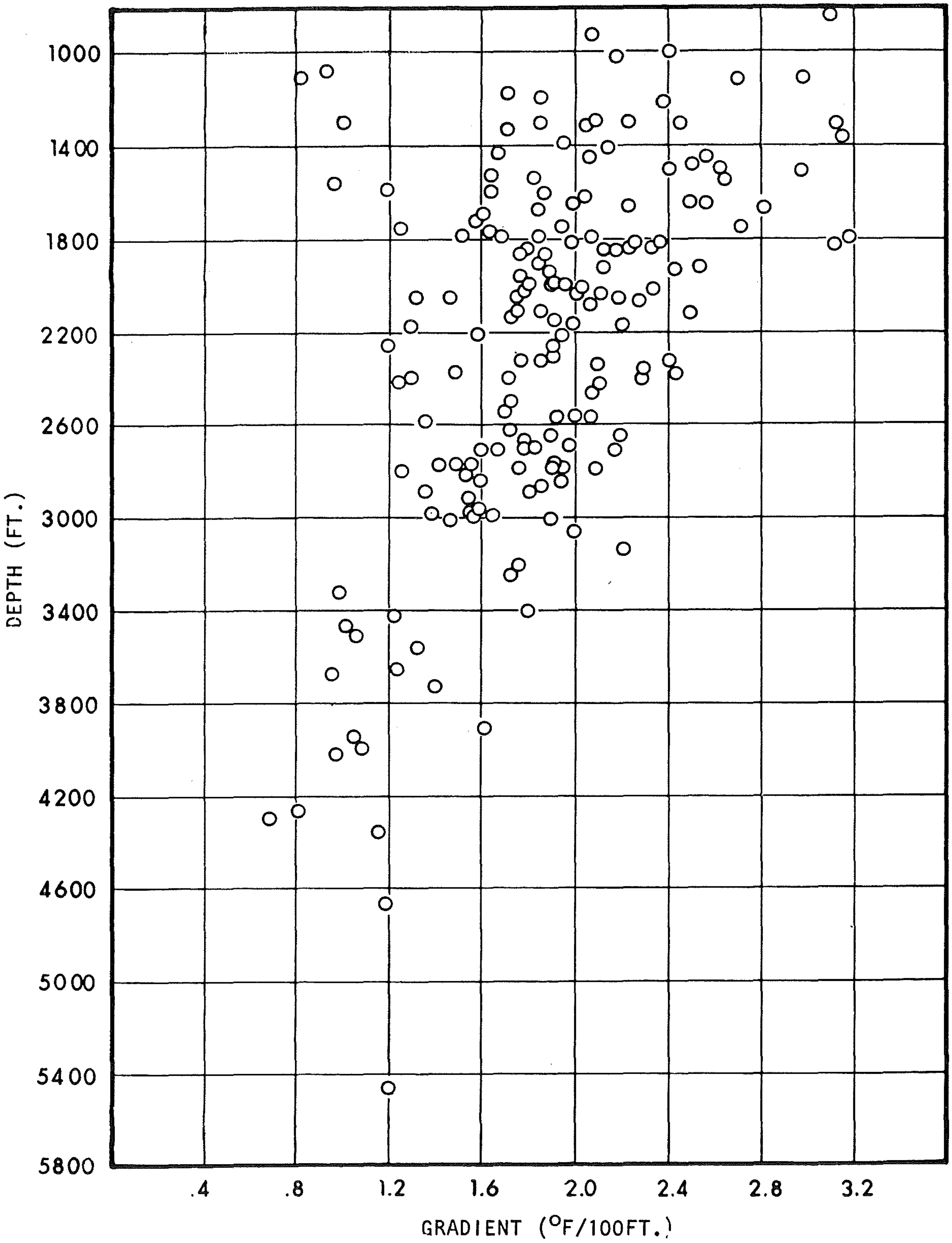

Figure 12.--Temperature gradient plotted against well depth (data taken from AAPG, 1976). Locations of holes deeper than 3,000 feet are shown in fig. 13.

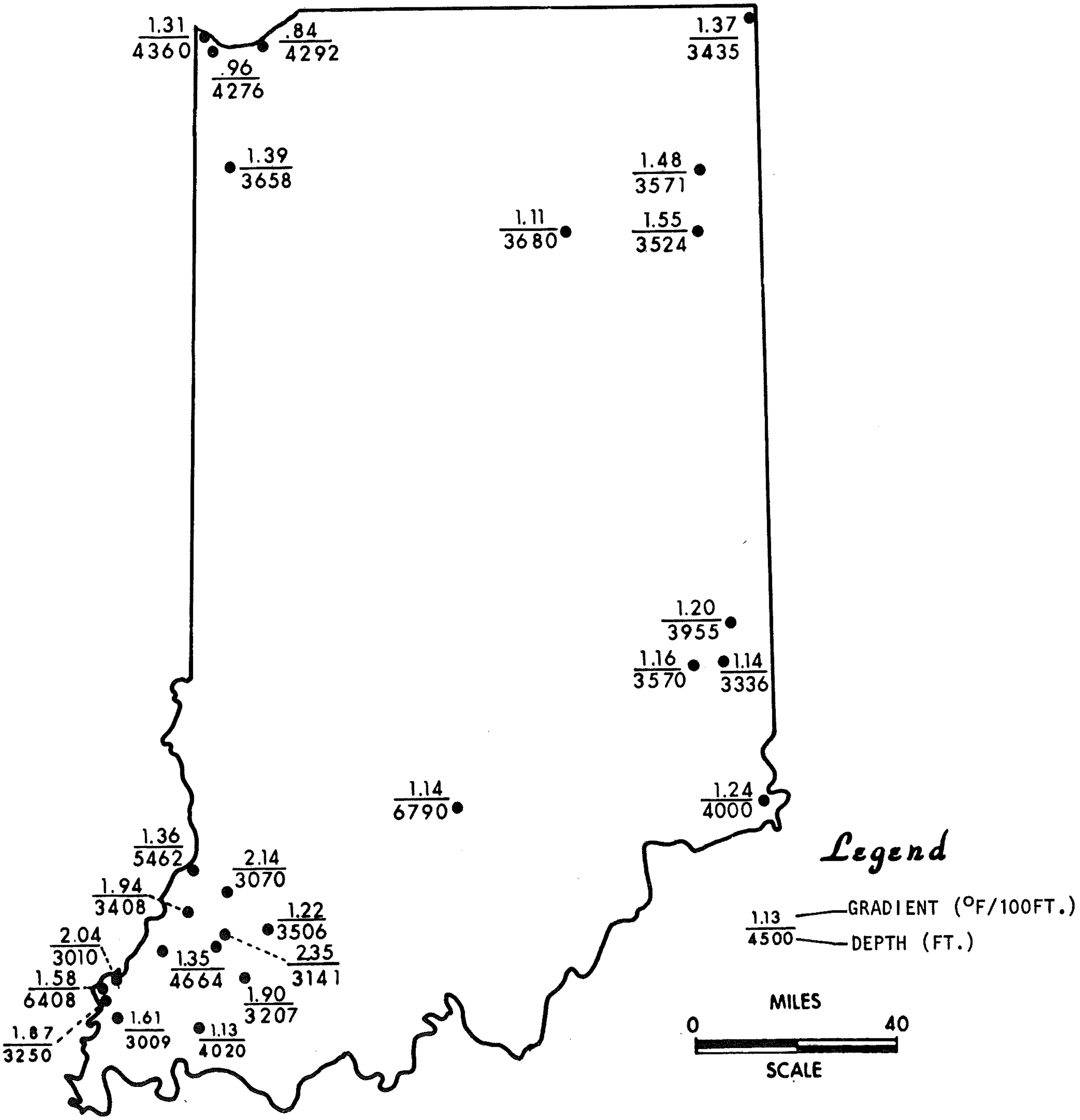

Figure 13.--Corrected temperature gradient and depth for wells deeper than 3,000 feet.

TABLE 4

THERMAL OCCURRENCES IN INDIANA (from Blatchley, 1901)

Name	Location*	Depth, ft	Temp., °F	Flow rate, gal/min	Remarks
1. Barlow thermal well	Sec. 3, T. 13 N., R. 6 E.	39	86	--	
2. Exchange mineral well	Terre Haute	1,865	80	100	Produces from a depth of 1,800 ft
3. Fritzlar mineral well	Western part of Evansville	1,830	72	--	
4. Magnetic mineral well	Terre Haute	1,912	80.5	180	Produces from depths of 1,800, 1,840, and 1,968 ft
5. Shelbyville thermal well	lat. 39°31.53'N. long. 85°45.83'W.	24	76	--	Location approximate
6. Terre Haute Gas Co. well	Terre Haute	2,930	81.5	250	Produces from the interval 1,800-1,900 ft

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*See figure 11.

Hadley and Devine (1974) have published a series of maps of the eastern United States relating historical seismic activity (1800-1972) to geologic structures. The Indiana portion of their map showing earthquake epicenters is given in fig. 14. Seismic frequency reaches 16 events per 10^4 km^2 in southwestern Indiana, but the rest of the state is essentially inactive. Along the southern Indiana-Illinois border, "movements on known faults or closely related faults have been the source of recorded earthquakes" (Hadley and Devine, 1974).

Woollard (1958) noted a northeasterly trend of earthquake epicenters from the Missouri-Kentucky area across southern Indiana and Ohio into the St. Lawrence River valley. Woollard suggests the line of earthquakes may be due to structural controls or to isostatic adjustment after glacial melting, because of its parallelism with the Appalachian trend. The trend has not been shown to correspond to any known geologic feature.

Geochemistry

Swanberg and Morgan (1978) have developed a correlation between regional heat flow and the temperature of groundwaters measured by their silica content. Their study shows that Indiana is characterized by low silica temperatures and suggests that heat flows are not likely to be anomalously high.

Deep Sedimentary Basins

The thick sedimentary sequence in the Illinois basin underlying the southwestern part of Indiana offers targets for production of high-temperature fluids. The production capabilities of many of these deep aquifers are unknown, because there has been very little deep drilling in the Indiana portion of the basin. At present it is uneconomic to drill deep geothermal wells in areas of near-normal geothermal gradient, but it may become attractive in the future.

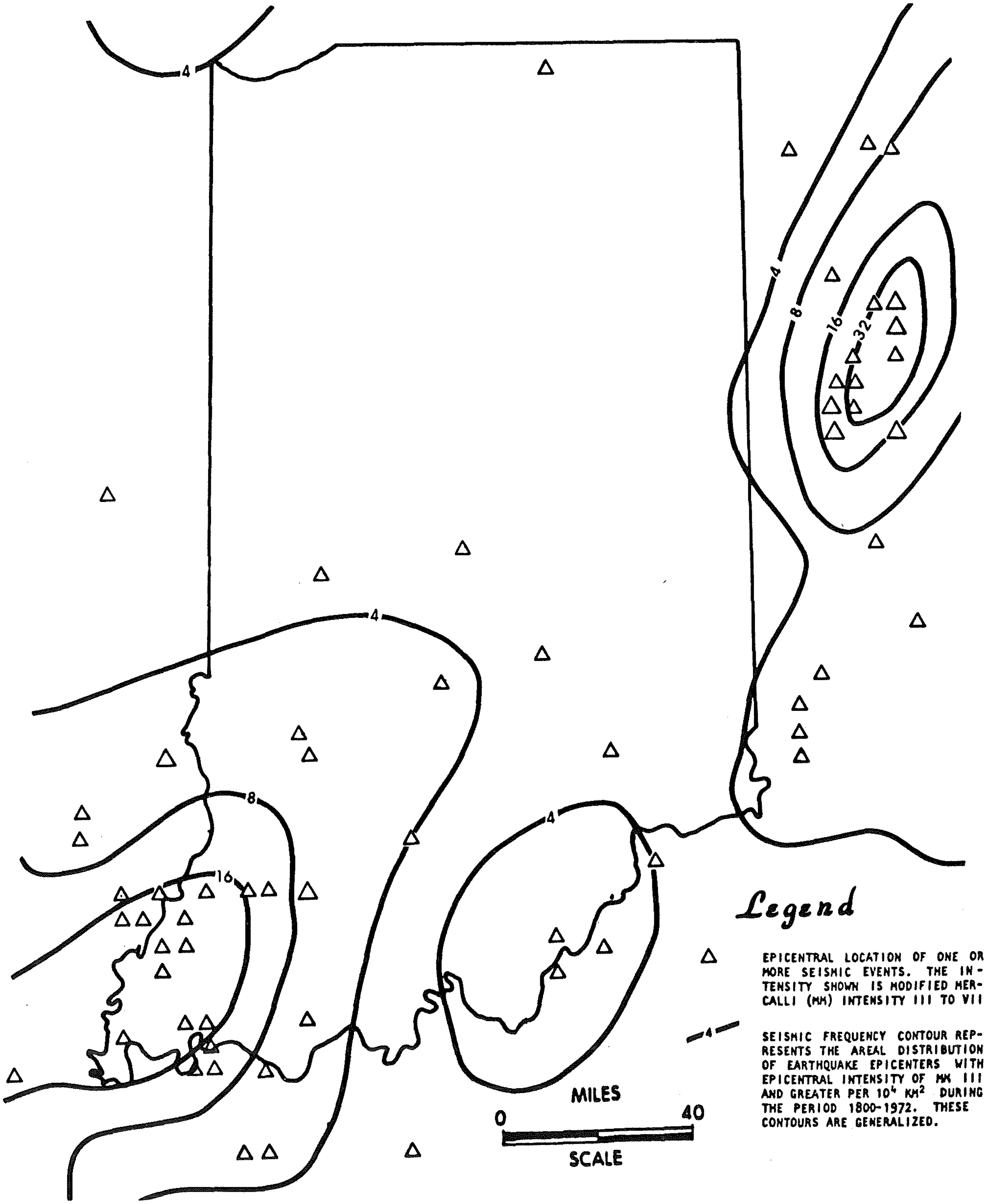

Figure 14.--Seismic activity (from Hadley and Devine, 1974).

Conclusions

In the eastern United States, known manifestations of geothermal energy occur as warm springs; radioactive, heat-producing granitic plutons beneath a thick covering of poorly conductive sediments; aquifers containing abnormally warm waters; or deep sedimentary basins with normal gradients.

Of these occurrences, only two are known to be present in Indiana. Six thermal wells in the state show that abnormally warm aquifers are present, but they are known to exist only at shallow depths; there is no indication that abnormally warm aquifers are present at depths greater than 3,000 feet. Three major faults in Indiana--the Mt. Carmel, Royal Creek, and Fortville faults--might serve as conduits for deep warmer waters to move to shallower levels; there is no evidence, however, that this process is taking place. The Illinois basin, which extends into southwestern Indiana, is a deep interior basin with a normal geothermal gradient. Temperatures as high as 190°F might be reached at a depth of 10,000 feet, but it is uneconomic at present to drill to such depths to reach fluids at that temperature. The state has no warm springs. There is no evidence that large granitic plutons are present in the basement; however, insufficient deep drilling has been done to prove or disprove their presence.

The geothermal gradients in this report were calculated from the data in the data file that accompanies the AAPG-USGS Geothermal Gradient Map of North America. This is the most comprehensive collection of well data available, but caution must be used in projecting temperatures below the depth of measurement. Calculated gradients in the shallow wells are much higher than those in the deep wells, which may be due to water circulation, measurement error, or variation in heat flow and conductivity of the rocks penetrated by the well. There is no evidence that the high gradients of the shallow wells continue at depth. Coverage of Indiana by deep wells is limited, however, and it is possible that future deep drilling may discover high geothermal gradients.

Heat flow values measured in Indiana are within the normal range for the eastern Unites States, from 0.97 to 1.41 HFU. To date, however, only five heat flow holes have been drilled in Indiana, all in the northern half of the state. To obtain a better estimate of heat flow in Indiana, more heat flow holes are needed. The southwestern part of the state would be especially interesting, since the AAPG gradient map indicates gradients of 2.0°F/100 ft and thicker sediments are present.

Further geothermal investigations in Indiana should be directed to the southwestern part of the state, where the sediments are thick enough to produce elevated temperatures and the shallow wells show above-normal gradients.

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APPENDIX

LITHOGRAPHIC DESCRIPTION OF DEEP SEDIMENTARY UNITS IN INDIANA
(from Shaver and others, 1970, and Willman and others, 1975)

Devonian

Ellsworth Shale Recognized as a formation northeast of the Cincinnati arch and as a member of the New Albany southwest of the arch. The lower part consists of alternating beds of gray-green and black shale. The upper part is a grayish-green shale bearing light-greenish limestone or dolomite lenses and in some places dark gray, thinly laminated dolomites. The formation thins eastward, from a maximum thickness of 300 feet in Elkhart County to a minimum of 60 feet in Steuben County.

New Albany Shale Dark gray shale containing much organic matter and greenish-gray shale and minor amounts of dolomite and dolomitic, quartzitic sandstone. It is widespread west and southwest of the Cincinnati arch. Its maximum thickness is 307 feet in Posey County; its minimum, 87 feet in Harrison County.

Antrim Shale Black, fissile shale containing spores. Greenish-gray shale is present in some places in the lower third of the unit. Thickness ranges from 65 to 200 feet, reaching a maximum in Steuben County.

North Vernon Limestone The upper part is a dark gray, thick-bedded, coarsely crystalline, crinoidal limestone bearing small black rounded phosphatic pebbles. The lower part is a gray, homogeneous, argillaceous dolomitic limestone. The upper and lower parts exist in a facies relationship. The lower part thins northward from Clark County as the upper thickens. Thickness ranges from 1 to 26 feet in its southern Indiana outcrops, increasing to more than 80 feet in southwestern Indiana.

Traverse Formation Limestone and dolomitic limestones that are brown, tan, and gray, very fine grained to coarse grained and biofragmented. Sandy, argillaceous, brecciated, very fossiliferous and cherty facies are present. The top of the formation is marked by light-colored to tan, fine-grained, oolitic dolomitic limestone. It thickens to more than 100 feet in Steuben County and thins southward toward the arch.

Detroit River Formation The lower part in northern Indiana consists of a gray to tan, fine-grained argillaceous dolomite containing rounded quartz sand grains. Most of the formation is composed of tan to gray limestone and dolomite and is very fine grained, argillaceous, bioclastic, sublithographic, brecciated, and mottled. Thin green and black shale beds are sometimes present. It thickens northeastward from the arch to 140 feet in St. Joseph County.

Jeffersonville Limestone Gray to brown limestone that often contains finely laminated dolomite. In central Indiana, scattered frosted, well-rounded quartz grains are found in the laminated beds. In southwestern Indiana, the formation consists mainly of yellowish to light brownish-gray, very fine grained to medium-grained limestone that may be dolomitic or cherty. Its thickness ranges from 25 to 45 feet in outcrop, increasing to 200 feet in Posey County. It may be equivalent to the Pendleton cropping out in Madison and Lipton Counties.

Geneva Dolomite Light to moderate brown, very fine to grained vuggy dolomite. Bands of carbonaceous material and crystalline calcite masses are common. It may contain rounded, frosted sand grains. Its maximum thickness is 60 feet in Vigo, Clay, and Owen Counties; it pinches out to the north in Fountain County and to the south in Sullivan County.

Silurian

Salina Formation Dolomite and dolomitic limestones that are tan, brown and gray banded, dense, fine-grained, thinly laminated, vuggy, rather pure dolomite and gray to pink fossiliferous dolomitic limestone. From a thickness of 500 feet in far northeast Indiana it pinches out in north central Indiana.

Wabash Formation There are three distinct facies: (1) dolomitic siltstone to silty dolomite, gray, dense, fine-grained, argillaceous and thick bedded to massive; (2) limestone and dolomitic limestone, light-colored, granular, fossiliferous, and cherty; (3) light-colored, granular, vuggy, massive, nearly pure dolomite, present as a biohermal, bank reef, and reef detrital facies. It is almost 300 feet thick in west central Indiana, up to 250 feet thick along its northern limit between Fort Wayne and Lake Michigan, and 150 to 200 feet thick to the south.

Louisville Limestone South of the Cincinnati arch, it is a light-colored to brown, fine-grained, thick-bedded, argillaceous limestone and dolomitic limestone. North of the arch, it is a tan to brown, fine-grained, thick-bedded dolomitic limestone and dolomite. Sublithographic facies and cherty zones are common. Thickness ranges from 50 feet in the south, except where eroded, to as much as 85 feet in the north.

Waldron Shale Shale and dark to mottled, sublithographic to fine-grained limestone and dolomitic limestone, commonly nodular and fossiliferous. In southern Indiana it is about 10 feet thick and shaly, but northward it consists of argillaceous carbonate rocks up to 30 feet thick.

Salamonie Dolomite In the northern part of the state the formation consists of three parts: (1) dolomite and dolomitic limestone, light gray to tan, dense, fine-grained, argillaceous, and commonly cherty; (2) nearly pure dolomite, light gray to white, granular, vuggy and porous; (3) limestone and dolomite, gray, tan, and brown, granular, vuggy and fairly pure. In southeastern Indiana the lower part is an argillaceous, dolomitic limestone and shale that is 30 feet thick; the upper part is a light-colored, cherty dolomitic limestone and dolomite that is 55 feet thick. The formation is 90 to 100 feet thick on and southwest of the Cincinnati arch in northern Indiana, and 180 to 200 feet thick near the Illinois line in Newton County.

Brassfield Limestone Medium- to coarse-grained fossiliferous limestone, with numerous blebs and stringers of shale, which may contain Ordovician pebbles in its lower part. Small amounts of fine-grained dolomite are present. It is yellowish-brown to salmon pink, but near Richmond the basal section is white and above this the limestone is very dark gray and has scattered yellow grains. It crops out near Richmond and Connersville and southwest to the Ohio River near Charleston, where it is 4 to 14 feet thick. Present in subsurface west and north of the outcrop area.

Ordovician

Whitewater Formation Limestone and calcareous shale. The formation thins southward from 80 feet at Richmond to 64 feet at New Point and pinches out near Madison.

Saluda Formation Dolomitic mudstone and dolomite containing a coral-rich zone in its lower part. A 25-foot zone of dolomitic mudstone underlies the coral beds in Clark and Jefferson Counties. The formation thins from 60 feet at the Ohio River near Madison to 14 feet in Decatur County to 9 feet in Wayne County.

Dillsboro Formation Argillaceous limestone and calcareous shale. Southward, more shale is present in the lower part and the middle part is characterized by rubbly limestone. The formation is about 300 feet thick in Wayne and Decatur Counties.

Kope Formation Bluish- to brownish-gray clay shale with widely scattered beds of fossiliferous limestone that are exposed in southeastern Indiana. The formation thickens to the northwest from 220 feet in Switzerland County to 550 feet in Wayne County.

Lexington Limestone Limestone interbedded with subordinate amounts of shale. It reaches a maximum thickness of 250 feet near Patriot and Switzerland Counties.

Trenton Limestone Tan fossiliferous dolomitic limestone and dolomite that becomes less dolomitic to the south. It reaches a thickness of 225 feet in the northern part of the state and thins southward. It is very thin or absent in the southeastern part of the state.

Black River Limestone Tan, very finely crystalline to lithographic argillaceous and dolomitic limestone that is recognized mainly in the subsurface. It is less than 100 feet thick in the northwestern corner of the state and more than 600 feet thick in the southwestern part.

Joachim Dolomite Light tan, finely crystalline dolomite that is recognized mainly in the subsurface. It is about 70 feet thick in most of the state.

St. Peter Sandstone Exceptionally pure quartz sand, fine- to medium-grained, well sorted, with well rounded, frosted quartz grains. It is friable and weakly cemented. It is recognized mainly in the subsurface. The formation reaches 135 in thickness in the northwest part of the state and thins to 25 feet in the southeast.

Knox Dolomite Includes strata of Ordovician and Cambrian age. It is a light gray to white, fine- to coarse-grained cherty dolomite. In southeastern Indiana there is a thick sandstone bed in the upper part of the formation. Its thickness ranges from 1,530 to 1730 feet.

Cambrian

Davis Formation Consists of (1) brownish-gray, fine to medium crystalline, glauconitic, silty, sandy, pseudo-oolitic dolomite, (2) yellowish-gray, dolomitic, glauconitic, slightly felspathic siltstone, (3) dark gray, hard, brittle calcareous shale, (4) gray to brownish gray, dense, shaly, pseudo-oolitic limestone interbedded with glauconitic siltstone and fine-grained sandstone. In northwest Indiana, the Davis is represented by the Galesville, Ironton, and Franconia Formations. Its thickness ranges from 200 feet in west central Indiana to 50 feet in southern Indiana. No wells have penetrated this formation in southwestern Indiana.

Franconia Formation Fine- to medium-grained dolomitic sandstone, usually glauconitic, shaly, and feldspathic. The formation contains more clastics in the north and grades into a more dolomitic facies to the south and east. It is present only in northwest Indiana; its maximum thickness is 125 feet.

Ironton Sandstone White, medium- to coarse-grained sandstone, dolomitic sandstone, and dolomite. The formation becomes dolomitic and shaly to the east and south. It is recognized as far east as Kosciusko and Wabash Counties and as far south as central Fountain County. The Ironton and Galesville formations reach 200 feet in thickness.

Galesville Sandstone Clean, fine- to coarse-grained, friable sandstone with dolomite cement. It is present only in northwest Indiana and is not easily distinguished from the Ironstone Sandstone. Its average thickness is about 75 feet.

Eau Claire Formation Contains beds of shale, siltstone, oolitic limestone, and dolomite. Feldspar and glauconite are important constituents. It is found only in the subsurface and is thought to underlie the whole state. Thickness ranges from 400 feet in the northeast to more than 1,000 feet in the southwest. In northern Indiana, the formation is mostly sandstone; siltstone, shale, dolomite, and limestone become more prominent to the south and east.

Mt. Simon Sandstone Poorly sorted, fine to very coarse grained sandstone with angular to subrounded quartz grains. Gray and maroon shale beds are present that range in thickness from a few inches to 60 feet.

In northern and southern Indiana, the formation is white to yellowish-gray, pale to grayish-red in the lower part; in central Indiana, it is white to yellowish-gray. The formation is thought to underlie the whole state. Thickness ranges from 300 feet in the east to more than 2,000 feet in the west.

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