Interpretation of an Aeromagnetic Survey of Indiana

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GEOPHYSICAL FIELD INVESTIGATIONS

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ABSTRACT

An aeromagnetic survey of the State of Indiana was conducted in 1947, 1948, and 1950 by the United States Geological Survey in cooperation with the State of Indiana. The Survey has published 92 county aeromagnetic maps on a scale of 1 inch=1 mile with a contour interval of 10 gammas.

These maps have been combined into one on a scale of 1 : 500,000 and a 50-gamma contour interval to form a regional map of the State. The aeromagnetic map has been studied in combination with a regional gravity map prepared by the Indiana Geological Survey. Most wells drilled to date (1955) have been relatively shallow and geologic information below the Trenton limestone of Middle Ordovician age has been sparse. The existence of a detailed and accurate aeromagnetic survey of the State made it possible to prepare a regional contour map of the buried Precambrian crystalline surface. This was done by analyzing 79 isolated well-defined magnetic anomalies and determining the depths at these locations. The topographic trends on the Precambrian basement rocks are in general similar to the structural trends on top of the Trenton limestone. There is also excellent agreement between the basement map and the depths to basement rocks determined by deep-well drilling. In the northeast corner of the State, the basement contours indicate the possible existence of a major northwest-trending ridge about 50 miles wide which does not appear on the structure map on top of the Trenton limestone. The existence of this ridge is partly confirmed by large gravity and magnetic anomalies at almost the same place. Seismic-reflection profiles also tend to confirm the existence of the postulated structure.

Maps showing the location of oil and gas wells have been compared with the larger aeromagnetic anomalies in several counties. A good correlation seems evident in Harrison County in southern Indiana, but in the southwestern part of the State most oil wells seem to be located along the flanks of the major magnetic anomalies.

INTRODUCTION

Much of Indiana is mantled with glacial till that has forced geologists to rely heavily on well logs for information about the areal distribution of rocks that would normally crop out. Well logs have also supplied almost all the reliable data about the subsurface. Unfortunately most wells drilled to date (1955) have been relatively shallow and geologic information below 2,000 to 3,000 feet has been sparse or nonexistent. A regional geophysical survey could be expected to yield supplemental subsurface information, and for speed and economy, mapping with the airborne magnetometer was a logical choice.

In December 1946 representatives of the United States Geological Survey and the Indiana Department of Conservation, Division of Geology, conferred on the possibilities inherent in an aeromagnetic survey of the entire State of Indiana. It was anticipated that such a survey would yield information on the configuration of the Precambrian crystalline basement rocks, on the structure and variations in thickness of overlying sedimentary rocks, on variations within the basement rocks, and on the location and approximate configuration of any younger igneous rocks which may have intruded the sedimentary strata.

A 1,500-square-mile area in the northwestern part of the State was flown in February 1947 as a test project. Data from this survey were released in open file in June 1947 as two maps. These were followed by a preliminary report also in open file. Results of the experimental survey were sufficiently encouraging to warrant proceeding with the proposed aeromagnetic mapping of the whole State. In June 1947, a cooperative agreement for such covarage was signed by the Geological Survey and the Indiana Survey.

Fieldwork was carried out from September to November 1947 under the direction of W. J. Dempsey and in September to November 1948 and August 1950 under the direction of J. R. Henderson. The magnetic survey was made with an AN/ASQ-3A airborne magnetometer flown about 1,000 feet above the ground. North-south flight lines were spaced 1 mile apart. Instrumental and diurnal drift were compensated for by means of repeated east-west base lines. Ninety-two aeromagnetic maps, one of each county, were compiled with a 10-gamma-contour interval on a scale of 1 inch=1 mile and published by the U. S. Geological Survey between April 1949 and June 1952. These are listed at the end of this report. County road maps were used for base maps because better maps of the entire State were not available. Plate 4 is a composite statewide aeromagnetic map with a 50-gamma contour interval prepared from the county maps.

Neither the 10-gamma county magnetic maps nor the 50-gamma statewide map was corrected for a normal gradient. An approximate compensation for this variation may be obtained by subtracting 8 gammas for each mile to the north and 0.5 gamma for each mile to the east. These figures were derived from horizontal intensity and inclination charts and tables of the U. S. Coast and Geodetic Survey (Deel and Howe, 1948). A large area was outlined to include all of Indiana and parts of Illinois and Ohio to insure smooth curves relatively free from the influence of local anomalies. Total intensity was determined from the formula $T=H/\cos I$ and values were computed for points equally spaced over the area. Smooth curves were then drawn through points of equal intensity.

GENERAL GEOLOGY

Indiana is part of the central stable region of North America which has undergone only mild deformation since the beginning of Paleozoic time (King, 1951, p. 3). Upper Cambrian sedimentary rocks are thought to rest directly on the Precambrian basement complex throughout the State. Sedimentary rocks representing all the Paleozoic periods through the Pennsylvanian are present. Bedrock (fig. 6) throughout most of the State is concealed by Pleistocene and Recent deposits.

As usually interpreted (Eardley, 1951, p. 29), in pre-Devonian time the Illinois and Michigan basins were a continuous unit. Beginning in the Devonian period the northwest prong of the Cincinnati arch first emerged as an area of uplift dividing the original basin into separate parts. Subsequently the depositional history of the two basins has varied. A southeastward-trending arm of the Wisconsin arch also extends into Indiana and is separated from the apparently related Cincinnati arch by the depressed area known as the Logansport sag. Ekblaw (1938) calls this fold the Kankakee arch and dates the period of maximum uplift (500–600 feet) as pre-St. Peter (Middle Ordovician).

Structurally the Cincinnati and Kankakee arches stand about 6,000 and 10,000 feet high in relation to the Illinois and Michigan basins, respectively, as measured on top of the Trenton limestone. This structural relief is attributed mainly to subsidence of the basins rather than the uplift of the arches. Subsidence is evidenced by a thickening of most individual formations toward the basin centers. The top of the Trenton limestone dips at the rate of a few feet per mile toward the central part of the basins from the center of the arches.

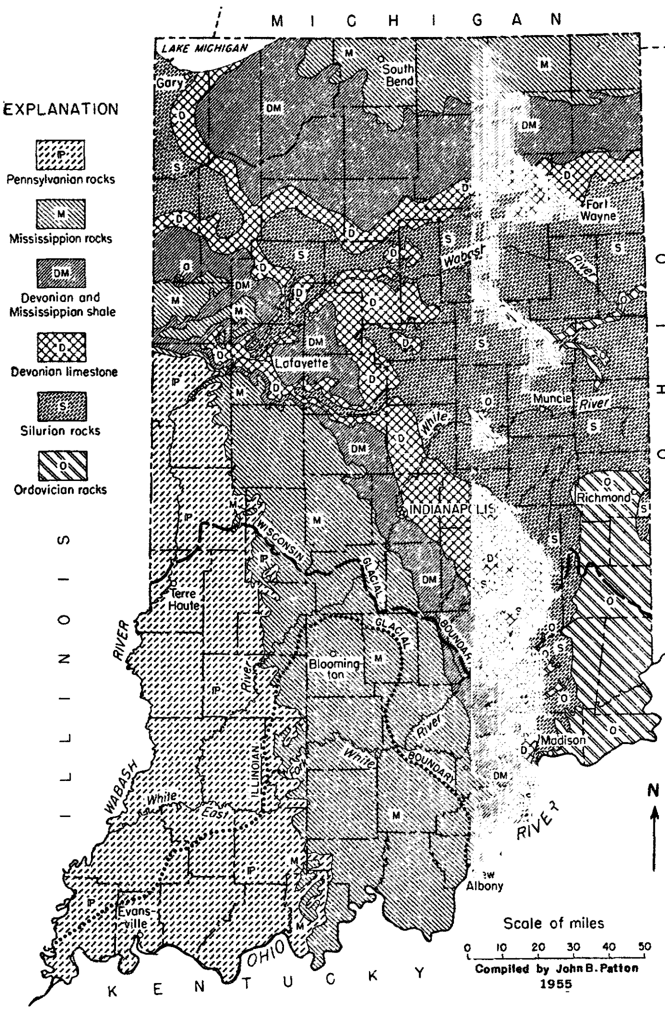


FIGURE 6.—Generalized bedrock map of Indiana.

SUBSURFACE GEOLOGY

Knowledge of the subsurface formations of Indiana has been based, for the most part, on the extensive data derived from well logs. W. N. Logan, while State Geologist, published two volumes (Logan, 1926, 1931) summarizing this information and combining it to prepare generalized subsurface maps of Devonian and Ordovician formations. Supplements to Logan's 1931 publication were issued between 193[illegible] and 1944, and structure maps of the oil-producing counties were published in 1948 and 1949 by the Indiana Gelogical Survey. Other contributors to the literature on the State's subsurface geology include Harris and Esarey (1940) and Cumings and Shrock (1928).

Below the Trenton limestone (Ordovician), subsurface data are sparse because this level marks the point below which oil and gas possibilities have been slight. Figure 7 shows the generalized structure on top of the Trenton (Dawson, 1952) in Indiana and also 7 of the deep wells that penetrate to, or near, the Precambrian basement. Stratigraphy for 4 deep wells in eastern Indiana is discussed by Bieberman and Esarey (1946); stratigraphy for 3 wells in Sullivan and Vigo Counties is discussed by Bieberman (1949). The latter group penetrate only to the Devonian.

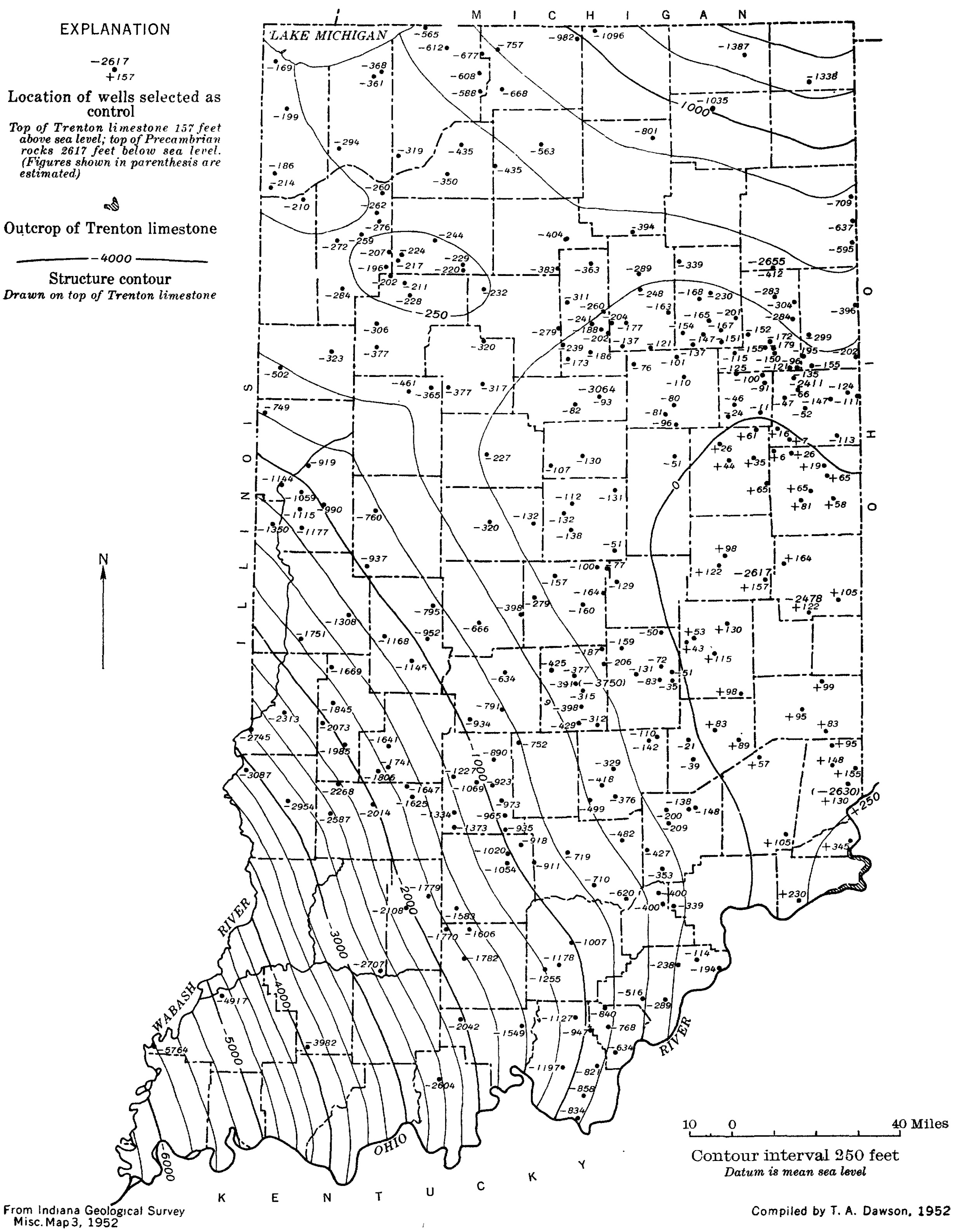


FIGURE 7.—Map showing generalized structure of Trenton limestone in Indiana.

The Trenton subsurface map graphically portrays Indiana's known major structural units. The northwest prong of the Cincinnati arch, the southeast extension of the Kankakee arch, and the dipping strata away from these positive elements toward the Michigan basin to the north and the Illinois basin to the southwest are all clearly evident. The deepest point in Indiana at which the Trenton has been reached is in southwest Gibson County, on the Wabash River, where it was found 5,764 feet below sea level.

Sub-Trenton information is mostly confined to the shallow zone above the Cincinnati arch. Below the Trenton in the basin areas much remains to be learned of the character and thickness of the sedimentary section and the controlling structures. A theoretical basement map, constructed by derivation from the magnetic data, offers an interpretation of the Precambrian basement.

AEROMAGNETIC MAP

The total intensity aeromagnetic map (pl. 4) was obtained by combining the 92 individual county magnetic maps and recontouring on a 50-gamma interval. Regional trends are more easily observed on this statewide map, but, for detailed analysis of small areas, the original county maps with their larger scale and closer contour intervals should be consulted.

Comparison of the generalized bedrock map of Indiana (fig. 6) with the statewide magnetic map reveals no apparent correlation. This was anticipated because there are neither outcrops nor known near-surface igneous or metamorphic rocks anywhere in the State. The sedimentary strata that comprise the geologic section in Indiana are for the most part nonmagnetic. Furthermore, in all the drilling in the State, no confirmed igneous intrusions have been found. There are no probable sources for the magnetic anomalies in the sedimentary rocks; therefore, it must be concluded that they arise from the crystalline basement complex.

An inherent difficulty in the interpretation of magnetic surveys is that the resultant data are seldom subject to unequivocal solutions. It is always possible to reproduce a given magnetic anomalous field by varying the parameters of magnetic susceptibility, that is, the shape and depth of burial of the magnetic mass. However, through additional geological and geophysical data, the shape and depth of the anomalous mass may be fairly accurately determined.

Depth to basement is not, in general, indicated by the strength of the magnetic field; therefore, the aeromagnetic map of Indiana (pl. 4) should not be interpreted as a topographic map of the basement. It is sometimes possible to estimate relative depths in a qualitative way. In the eastern and northern parts of the State, uplift has brought the basement rocks close to the surface. This is reflected by small- to medium-sized relatively intense anomalies. The presence of low-gradient anomalies covering large areas might imply either a thickening of the total sedimentary section or the occurrence of a different type rock within the basement, presumably less magnetic. This is well illustrated in the central and eastern parts of the State where 5 drill holes have reached the Precambrian surface. The 4 drill holes in Wayne, Henry, Allen, and Howard Counties indicate a comparatively shallow basement with depths ranging from 2,500 to 3,000 feet below sea level. In the southwestern part of the State, the magnetic pattern changes radically. This is probably caused by a thickening of the total sedimentary section. In Jay and Blackford Counties and most of Delaware County the field characteristics are not unlike those to the southwest. However, the sedimentary rocks are not thicker in Jay County, because the drill penetrated basement at a depth of 2,411 feet. Consequently, it follows that a different type rock must have been penetrated. This was verified by a study of the analysis of Precambrian cuttings at the drill holes (Kottlowski and Patton, 1953). Whereas the basement rocks at four drill holes were identified as granite, the basement rock at the fifth hole in Jay County, was found to be a dolomite marble, which is mostly nonmagnetic.

Inspection of the statewide magnetic map reveals a complex pattern with many outstanding features. Among the more striking anomalies are the roughly circular high centering on the Allen County–Whitley County border, the large well-developed high in Harrison County, the several rather isolated small- to medium-sized strong-intensity highs, such as those in Pulaski, Elkhart, Hamilton, and Grant Counties, and the diagonal southwestward-trending steep-gradient anomaly extending from eastern Randolph County to west-central Fayette County. All field values are relative to an arbitrary datum and are not absolute measurements of the earth's magnetic field. Removal of the earth's normal gradient would produce only a slight change in the size, shape, and location of the total intensity anomalies.

The Allen County–Whitley County magnetic high is the most pronounced feature on the entire map. It has a maximum amplitude of 1,500 gammas and covers a roughly circular area about 40 miles in diameter. The anomaly correlates well in position and in trend with a strong gravity high. These anomalies outline a dense highly magnetic rock mass that is probably mafic and possibly batholithic in nature.

West of this large feature is another magnetic anomaly similar in areal extent but smaller in magnitude. This occurs in Kosciusko, Marshall, Fulton, and Wabash Counties. Peculiarly, the general characteristics of this anomaly are in many ways similar to its counterpart in Allen County: the sharp gradients at the west and south borders of the anomaly with a marked reduction in slope at the east border, a pronounced negative anomaly to the northwest, and a smaller associated anomaly to the south. This suggests that the highly magnetic masses producing both anomalies have approximately the same geometry and attitude within the Precambrian rocks. The existence of a belt of gravity anomalies covering roughly the area and extending farther to the west suggests a possible zone of weakness in which the more mafic and dense rocks have intruded into the basement. The theoretical basement contour map shows about 1,000 feet of uplift in the anomalous area with the uplift offset to the north of the anomaly. In minor part, the geophysical anomalies may be associated with and represent basement uplift, but mathematical analysis has shown that the major factor must be a lithologic change in the crystalline rocks.

Scattered throughout Indiana, particularly in the northern half, are a number of roughly circular intense magnetic closures that are only a few miles in diameter. Good examples of these anomalies occur in Pulaski, Elkhart, Hamilton, and Grant Counties. The authors believe that they may signify stocks or bosses now beveled at the basement surface. This last conclusion is supported by mathematical depth estimates made on the anomalies, which show no sign of present piercement toward the surface.

There is good correlation between the strong magnetic high of about 1,000 gammas in Harrison County and a gravity anomaly of 15 milligals at approximately the same location. Again, the existence of these anomalies probably indicates the presence of a large mafic plutonic mass in the basement possibly extending well into Kentucky. Of particular interest is the close association of the magnetic anomaly with the location of gas fields in this county. This correlation is discussed on page 32.

From eastern Randolph County the sharpest magnetic lineation in the State extends southwestward for about 55 miles through Wayne County and into Fayette County. This intense feature is interrupted (trend absent) about midway, but, where present, it is strongly suggestive of a contact between different types of rock. The sharp lineation of the feature suggests that the contact is either a major fault or a linear dikelike intrusive.

The parameters of a two-dimensional structure were obtained by fitting theoretical profiles to an observed profile flown at right angle to the magnetic strike. Computations support the hypothesis that the magnetic anomaly is caused by a dike. However, the dike may have been intruded into a preexisting fault or fracture zone. The results of the calculations are shown in figure 8. Because of drill-hole information in the immediate area, the top of the dike was placed at the surface of the Precambrian, 3,000 feet below the ground. The dike was assumed to be 2,000 feet wide, extend indefinitely downward, and have a susceptibility contrast of 0.008 cgs. To account for the large negative amplitude to the northwest, a dip angle of 45° to the southeast was assumed.

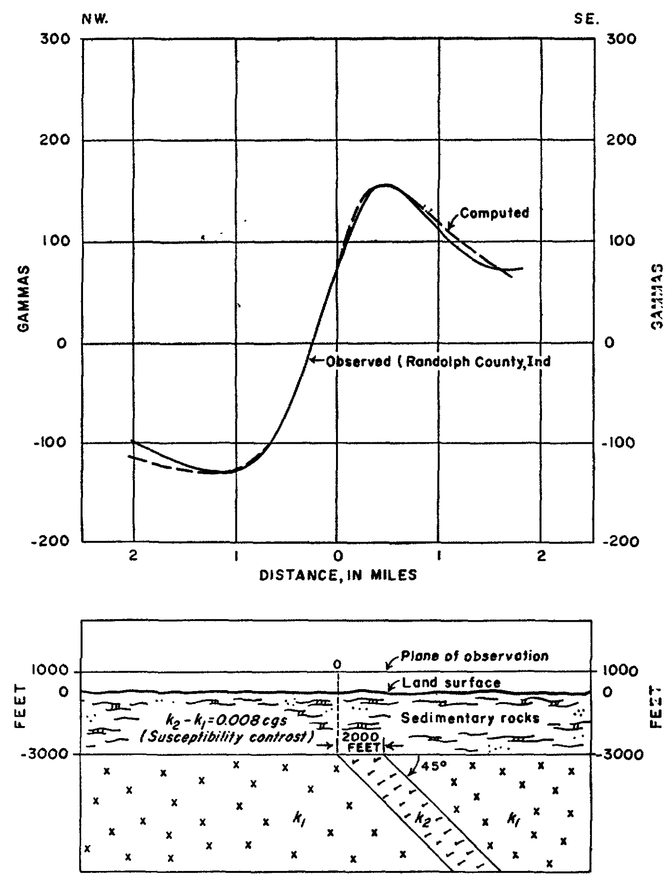


FIGURE 8.—Magnetic anomalies and geologic section over an assumed dike in Randolph County, Ind.

Other sharp magnetic gradients may be found at several locations on the aeromagnetic map. Associated with these gradients are magnetic lows covering relatively large areas. Again, they doubtless represent contacts which differentiate between rock types. A typical example is the narrow zone of small amplitude anomalies located in the western part of Rush and Henry Counties and alined in a general north–south direction.

This belt of highs is flanked to the west and east by broad negative anomalies. Sharp gradients are also evident in a zone extending through parts of Delaware, Madison, and Grant Counties and in another zone in the eastern part of Cass County. There are other less obvious regions where this differentiation of rock type is also discernible.

There is no confirming magnetic evidence of a shallow-buried intrusion in the Kentland (Newton County) "cryptovolcanic" area (Shrock and Malott, 1933). This half-square-mile area of disturbed Ordovician rocks is on the south flank of a large magnetic high. An igneous origin of the Kentland phenomenon is not entirely disproved because no aeromagnetic traverse passed directly over the structure.

AVERAGE MAGNETIC AND GRAVITY MAPS

The average magnetic map of Indiana (fig. 9) was prepared by the Indiana Geological Survey (1953a) from the series of county aeromagnetic publications. It is intended to present a regional picture of the magnetic pattern. Minor magnetic features are minimized by averaging the values of the total magnetic field for each township and plotting the arithmetic average at the center of the township. A normal gradient increasing to the north at 6.5 gammas per mile was removed.

The Indiana Geological Survey's gravitational map of the state is given in figure 10 (1953b). Control for the map is based on a density of approximately one station for each township. The contours show equal values of the Bouguer anomaly. A density of 2.6 for the upper sedimentary rocks of Indiana was used as a basis for the altitude correction. The 250-milligal contour corresponds approximately to a Bouguer anomaly of -39 milligals based on pendulum station U. S. 1092, established in 1940 by the U. S. Coast and Geodetic Survey at West Layfatte, Ind. The similarity of station density for the average magnetic and the gravity maps provides a satisfactory basis for correlating the resultant data. It must be realized, however, that the gravity data are from single station observations in each township, whereas the magnetic data are the average of nine measurements taken at the corners, the midpoints of each side, and the center of each township. The average magnetic map is, therefore, based on composite data whereas the gravity map is based on discrete points.

Many of the larger features on either map are represented by comparable features on the other map. Differences are mostly in magnitude or in the location of anomaly centers. The latter discrepancies are usually explainable by station location or are attributable to the inclination of the earth's magnetic field. Because the earth's magnetic field is inclined, total intensity magnetic anomalies are always displaced to the south of the source. Gravity anomalies, on the contrary, are located directly over their source.

The degree of correlation between the average magnetic and gravity data in Indiana varies widely. There are many obvious examples of excellent agreement, but in some areas the correlation is less satisfactory. In a few places a strong trend on one map is not reflected on the other, and in some places there are reverse correlations. In reverse correlations a positive feature on one map corresponds to a negative feature on the other.

Among the many instances of good average magnetic and gravity correlations are the positive closures along the Allen County–Whitley County border and the Lawrence County–Jackson County border high where even the southeastward-trending nose is well duplicated. Good examples of correlating negative closures are seen along the Orange County–Crawford County border and in Parke County. When correlation is good between mutually positive magnetic and gravity anomalies in Indiana the source is interpreted to be mafic igneous or metamorphic rock in the basement complex which also possesses a relatively high density contrast. Where the correlation is between mutually negative anomalies the assumption is that the underlying basement source rock is probably more felsic in nature and less dense than its environment.

The strongly developed magnetic high in Harrison County and the intense magnetic low in Franklin County are plainly duplicated by the gravity measurements but on a much less intense scale. The gravity high in southwestern Jasper County correlates in part with an elongate magnetic nose or ridge. Northern Porter County reveals a moderate-strength magnetic high with some evidence of a corresponding gravity anomaly. Interpretation of probable basement rock types in these areas of relatively poor magnetic and gravity correlation is difficult. In general it can only be assumed that the anomalies express susceptibility or density contrasts in the basement complex.

Several areas exhibit reverse correlation; two of these will serve as illustrations. A large positive magnetic anomaly centering in northeastern Delaware County corresponds in location with a negative gravity trend indicating basement rock with a high susceptibility but a low density contrast. In northwestern Fulton County a positive gravity anomaly correlates with a negative magnetic area, thereby marking a basement area where the rocks have a large density but low susceptibility contrast.

A broad belt of gravitational lows extends diagonally across the State and correlates in a general way with

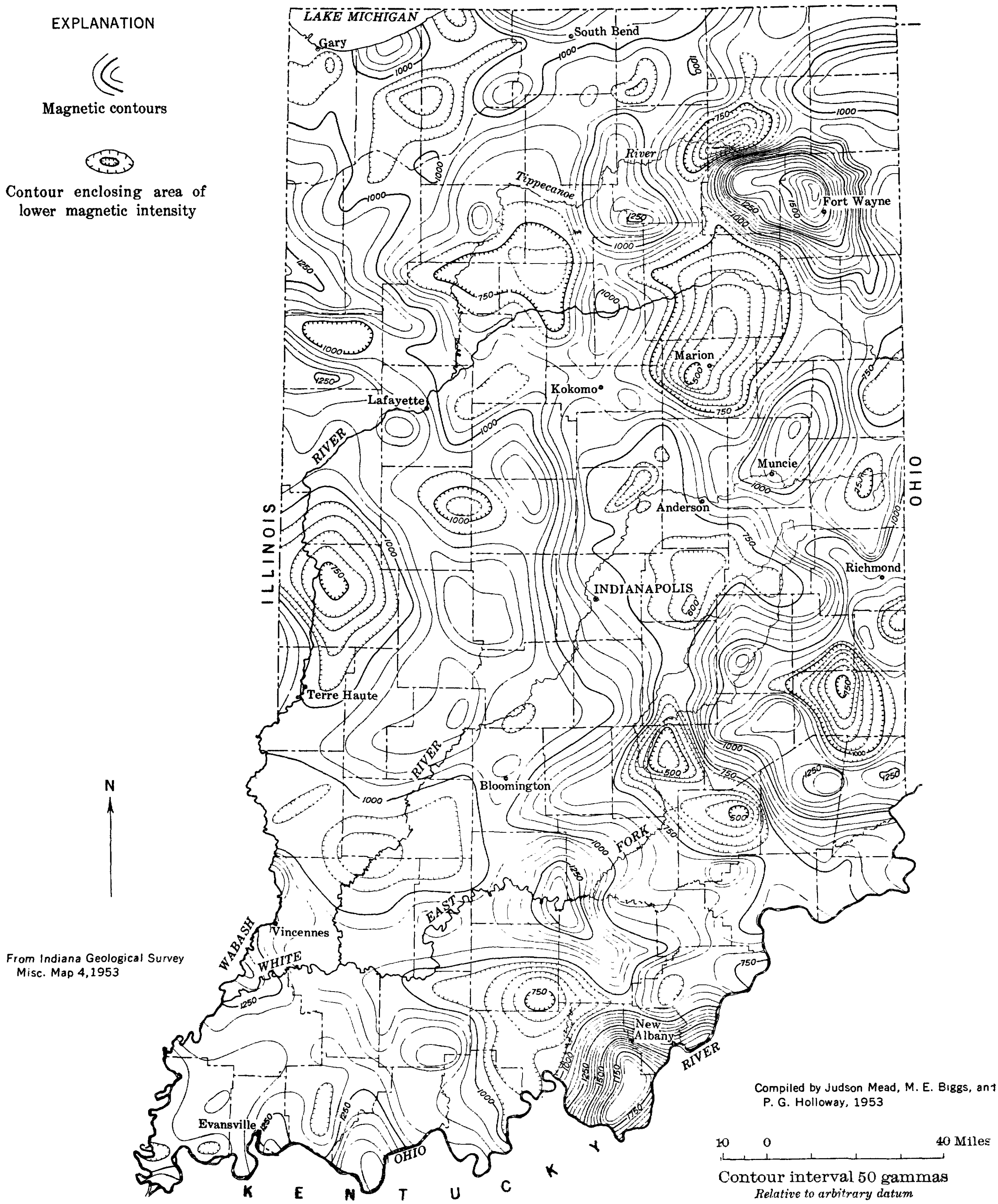


FIGURE 9.—Map of Indiana showing average magnetic intensity.

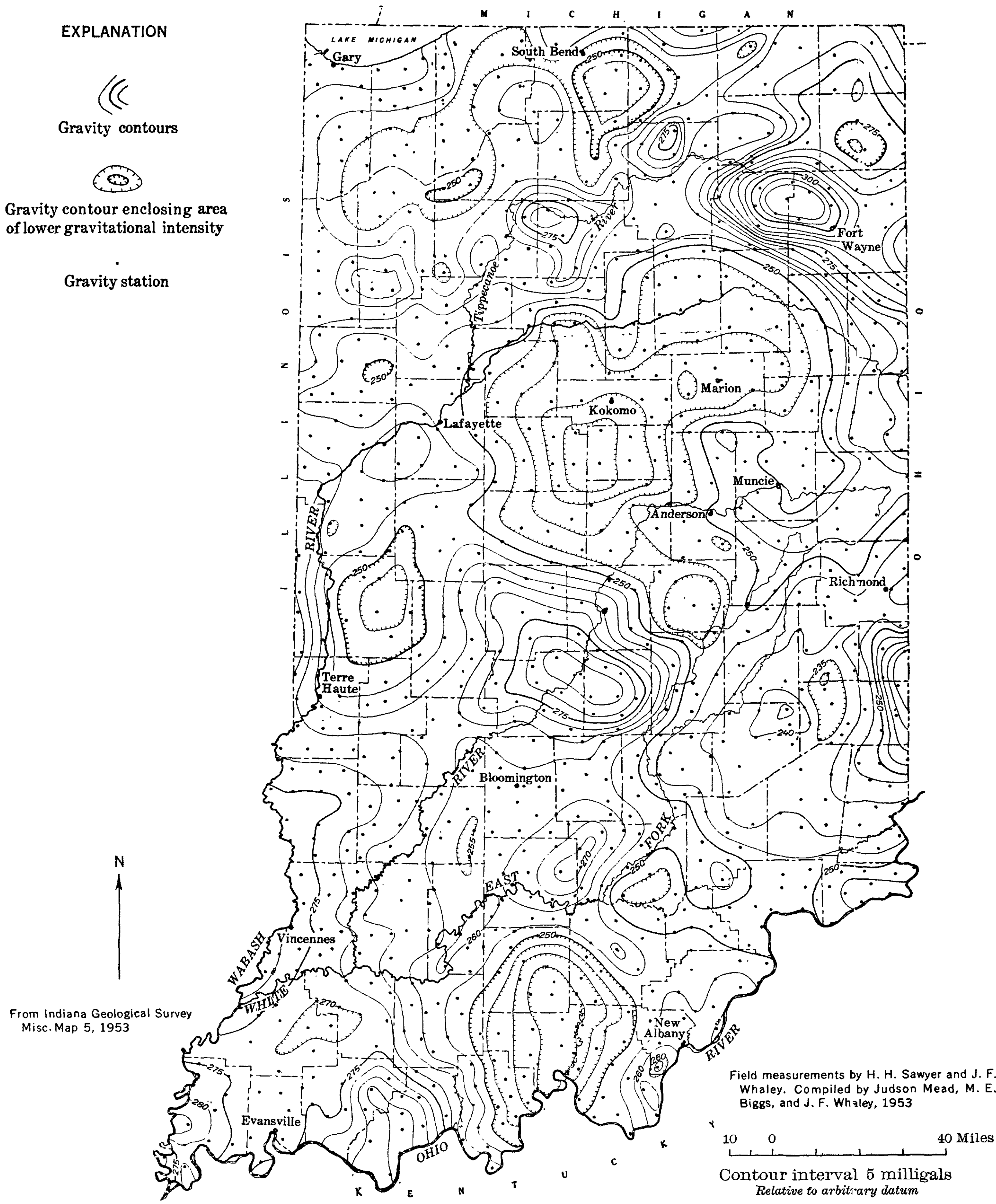


FIGURE 10.—Map of Indiana showing gravitational intensity.

the Cincinnati and Kankakee arches. This fact is interpreted to indicate a basement rock of relatively low density.

PRECAMBRIAN SURFACE MAP

The existence of a detailed and accurate magnetic survey of the State of Indiana has made it possible to prepare a hypothetical regional map of the buried Precambrian crystalline surface (fig. 11). In addition to revealing the major structural features of the basement surface, the map supplies information on the total thickness of the overlying sediments and indicates areas where additional detailed geophysical surveys may possibly outline smaller sedimentary structures.

Although many hundreds of well holes have been drilled in the State, only five have reached the Precambrian surface. All five are within a relatively small area in the central and eastern part of the State, in Howard, Allen, Jay, Henry, and Wayne Counties.

Theoretically a basement of uniform susceptibility with a topographic relief of several hundred feet at the depths anticipated in the State should yield magnetic anomalies of the order of tens of gammas. These anomalies would be so small in amplitude and so broad that they would be masked by the anomalies produced by lithologic variations within the crystalline rocks themselves and by the earth's regional gradient.

As an alternate approach, depth calculations were made interpreting individual anomalies. Only those of high amplitude and covering large areas were selected to insure that changes in rock type rather than basement relief were primarily responsible for the magnetic anomaly. The effect of the normal gradient could be ignored, for the contribution to the field is small for relatively small areas. Once the individual depths were determined a generalized contour map representing the regional configuration of the basement surface could be drawn.

The method of depth interpretation used is identical to that presented and illustrated by Vacquier and others (1951, p. 9–41). It was assumed that the basement complex is not magnetically homogeneous but is divided into lithologic units of prescribed shapes. These are prisms with horizontal rectangular surfaces, having vertical sides and extending indefinitely downward. It was assumed, further, that the rocks are magnetized by induction in the earth's field and that this magnetization is uniform and constant with depth. With these considerations the calculation of the magnetic field was made in this report for rectangular prisms of different horizontal dimensions and orientation and for different inclinations of the earth's field. The field was contoured on a map with a horizontal scale expressed in terms of the depth to the top of the model. Second vertical derivative maps of the model fields were constructed to further assist in depth interpretations.

According to Zietz and Henderson (1955, p. 308),

> The depth interpretation procedure consists of computing a second derivative map of the observed field and comparing certain diagnostic features of the anomaly for both the observed and second derivative maps with similar features of the corresponding model. When the magnetic fields are studied, the horizontal extent of the steepest slopes are compared. When analyzing the derivative anomalies one compares the horizontal distance between the maximum, minimum, and zero curvature contours.

For anomalies covering large areas, the zero curvature contour tends to outline the upper surface of the prismatic body. This fact is used to determine the proper model selected for comparison.

In addition to the general methods described above, the following factors were considered in making depth estimates: The observed as well as the derivative anomalies selected for interpretation closely resemble the computed fields; the depth indices used were, where possible, independent of the size of the model (this occurs when the anomalies are broad); because vertical sides produce sharper magnetic gradients than sloping sides, the steepest slope of an observed field was invariably selected; whenever possible, the magnetic profiles chosen for analysis were the original traverses.

It has been shown (Henderson and Zietz, 1949, p. 516) that the residual map is identical to the second derivative map except for a multiplicative constant. Consequently the critical points, such as the maximum, zero, and minimum, appear on both type maps at exactly the same position. Because residual maps require less time for computations than derivatives maps and are equally usable, only the residual fields were computed for the anomalies from which the Indiana depth estimates were made.

To illustrate the procedure used in the depth determinations, the Greentown anomaly (pl. 5*A*) in Howard County was among the ones selected for analysis. Several field profiles indicated that the depth to the prismatic mass was about 1 mile. This established that the grid spacing to be used in calculating the residual map was 1 mile. The resulting contoured map is shown on plate 5*B*. The location of the zero curvature contour suggested that a prism of strike N. 45° E. with dimensions 4(0.707)×8(0.707) depth units be selected for comparison. Using the appropriate model indices, depths obtained from the analysis of the residual and field anomalies were 2,700 feet and 2,950 feet, respectively, below sea level. These depths are in good agreement with the 3,064 feet to basement measured in the nearby well (fig. 11). On

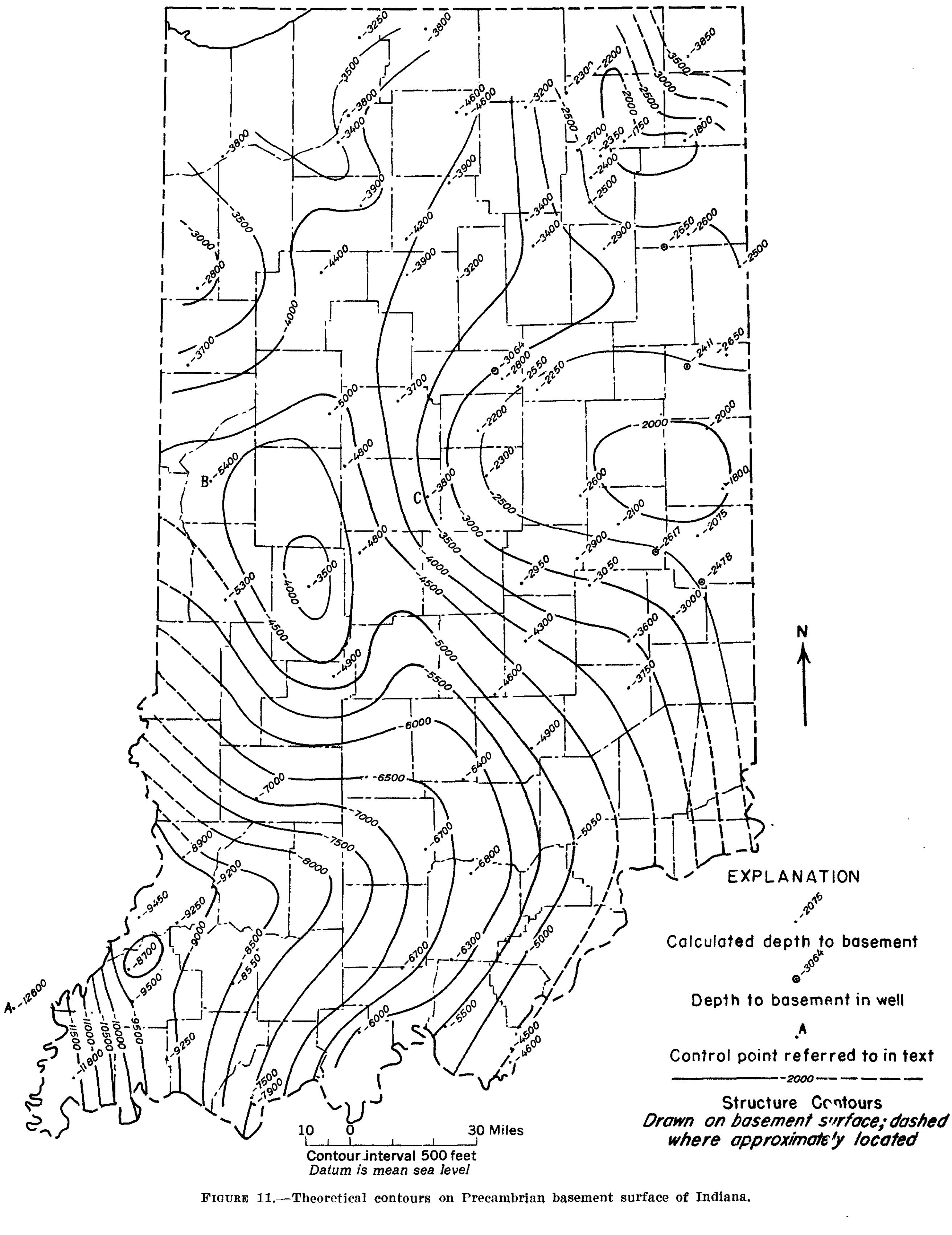


FIGURE 11.—Theoretical contours on Precambrian basement surface of Indiana.

the basement map the depths from residual and field analysis for the Greentown anomaly have been averaged and the result is 2,825 feet (rounded to 2,800 feet). All data pertinent to the depth calculations are presented on plate 5*C*. The magnetic-field profile, *F*, is shown on plate 5*D*.

Although numerous anomalies appear on the aeromagnetic map, only a few are suitable for interpretation. For an anomaly to be usable, the observed and resulting residual fields must resemble the corresponding theoretical anomalies. Also, the observed anomaly must be magnetically "clean," in the sense that the effect from neighboring anomalies is negligibly small. As a consequence, only 79 anomalies were available for depth analyses. In general, the coverage for the State was good and fairly uniform. In some areas, however, particularly in the southwest part of the State, the number of usable anomalies were few. Because of insufficient data, the construction of a detailed structural map was not justified. Instead regional contours were drawn permitting local errors of a few hundred feet in order to maintain smooth contours.

The resulting contoured map which represents the topography of the Precambrian surface is shown in figure 11. Included on the map and used in the contouring are both calculated depths and those based on drilling. The dashed lines have been extrapolated and consequently represent questionable contouring. Datum is mean sea level and the contour interval is 500 feet.

It is significant that many isolated, randomly located topographic features do not appear on the map. The smooth regional contours indicate consistency within the data themselves. Confirmation of the accuracy of the computational process is available for an area in the central and eastern part of the State. Here the comparison between the computed basement topography and the depths at the few drill holes that have penetrated to the basement indicates an average error of 10 percent.

In general, the larger features of the computed Precambrian basement surface correlate with those of the generalized structural map on top of the Trenton (fig. 7). The position of the Kankakee and Cincinnati arches and the gradual slope of the basement surface from these major ridges into the Illinois basin are consistent with the structural pattern of the area. Depths range from 2,000 feet in the east to about 11,000 feet in the southwest corner of the State. This gradual gradient is interrupted by a trough to the southwest with its axis approximately northeast to southwest and a low uplift of the basement rocks centering in Putnam County.

Quantitatively, the basement depths that were geophysically determined compare favorably at several locations with those based on geologic data alone. By extrapolation from neighboring drill holes it is estimated that the depth to basement at the deepest part of the Illinois basin is about 12,600 feet at a point about 10 miles west of the Posey–Gibson County line, (fig. 11, point A). This is in good agreement with the depth determined from the aeromagnetic survey. The basement depths at two other points in central Indiana were determined by adding the depth from sea level to the St. Peter sandstone (Ordovician) based on drilling (Am. Assoc. Petroleum Geologists, 1954), to the estimated thickness of pre-St. Peter rocks (Lower Ordovician and Cambrian) (Illinois Geol. Soc., 1951). The depths at these two points are in Fountain and Boone Counties (fig. 11, points B, and C). They are 5,400 and 3,000 feet, respectively, in good agreement with the geophysically determined depths of 4,700 and 3,500 feet.

In the northeast corner of the State, the basement relief differs markedly from the structural relief on the Trenton surface. Contrary to the attitude of the assumed Trenton surface which has a northeast dip, the calculated basement topography exhibits a large anticlinal ridge about 50 miles wide with its axis in a northwest direction and a relief of more than 1,000 feet. The validity of the existence of the structures is strengthened by the number of calculated depths in the area. Additional corroborating evidence is obtained through a comparison of several geological and geophysical maps of the same area. This is illustrated by figure 12 where the gravity map (*A*), an average magnetic map (*B*) the Trenton surface map (*C*), and the Precambrian surface map (*D*), are all presented. It is apparent that large gravity and magnetic anomalies occur at the same location. These suggest the probable existence of a large lithologic unit within the basement complex composed of a more mafic and more dense rock than its environs.

There is good agreement between the structural high on the Precambrian surface and the larger gravity and magnetic anomalies, although the structural high is displaced slightly towards the north. This shift may be explained by assuming subsequent folding to have occurred along a zone of less competent rocks parallel to the rocks causing the magnetic and gravity anomalies. If this ridge is a structural fold, then we would expect that the overlying sedimentary rocks are folded accordingly. Unfortunately, drilling and other geologic information below the Trenton is meager. It is possible that some small manifestation of this structure might even exist in the Trenton. The existence of a Trenton structure in this area would be economically

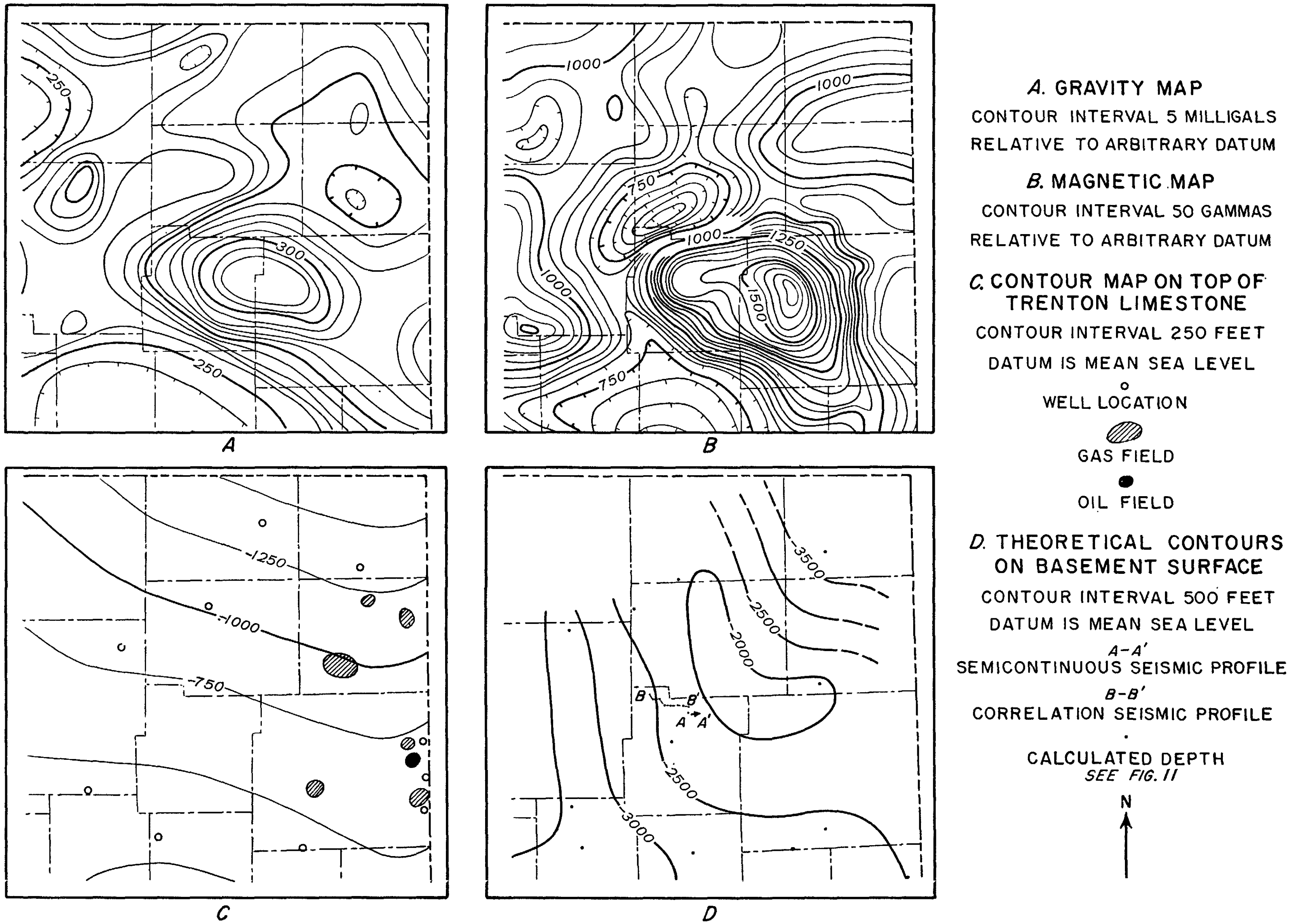


Figure 12.—Comparison of geophysical and geological maps of northeastern part of Indiana.

important because the accumulation of oil and gas from the nearby Cincinnati arch has been confined to the porous limestones of the Trenton.

It was hoped that additional geophysical evidence for the existence of the postulated structure could be obtained through the study of seismic reflections. According to Paul Lyons (1951), the reflection quality in northeastern Indiana ranges from "poor" to "no good," similar to the Michigan basin to the north. However, little seismic work has been done in this particular area in Indiana, most investigations having been carried on to the south and west. Because the standards of reflection quality for high frequency recording are not the same as those for conventional seismology, the former technique was tried experimentally in the area. In August 1955, the U. S. Geological Survey, using a high-frequency high-resolving power instrument, ran some test profiles in Whitley County southwest of the structural high to determine whether reflections of usable quality could be obtained from the Precambrian or the overlying formations. Richard E. Warrick of the U. S. Geological Survey was party chief for the fieldwork and analyzed the results.

Conventional field methods including inline, short offset geophone spreads, and single shots placed below the water table were found to yield encouraging results. Eleven-hundred-foot inline spreads with a 100-foot offset from the shot point and 100-foot spacing of the geophones were used in semicontinuous profiling, and a split-spread inline with 25-foot spacing and 100-foot offset was used in the correlation work.

Small single charges consisting of one-half pound of 50 percent ammonia dynamite were found sufficient for the reflection shots. Geophones used were of conventional design. Usually a single geophone per trace was used; at some places, however, groups of 3 geophones per trace, arranged inline and spaced from 5 to 10 feet apart, improved the records slightly.

The seismic amplifiers used were the high frequency units described by Pakiser and others (1954). The amplifiers feature variable high-frequency filters, fast automatic-volume-control action, and variable presuppression. An oscillograph equipped with high frequency galvanometers and a high-speed paper transport system completed the recording equipment.

Where there was no vertical velocity control, the time from the shot instant to the reflection was corrected for the low-velocity layer only. Care was taken to select relatively level sites so as not to introduce errors due to topography. The reflection times corrected for the low-velocity layer were plotted on time cross sections.

Generally the quality of the reflections varied from fair to very poor so that the results cannot be considered conclusive. Profile $A-A'$ (fig. 12*D*) consisted of a semicontinuous west-east line covering about 4,000 feet. The plots of the reflections yielded results which may be summarized as follows:

1. Good agreement with the depths to bedrock under the glacial deposits as determined by the refraction method.
2. A reflection occurred at approximately the time corresponding to the inferred depth of the Trenton limestone (fig. 13).
3. Three reflections appeared to correlate at times greater than the Trenton(?) reflection; the latest of these three was at a time corresponding to the inferred depth of the Precambrian.
4. The three reflectors below the Trenton all exhibit a marked dip to the west.

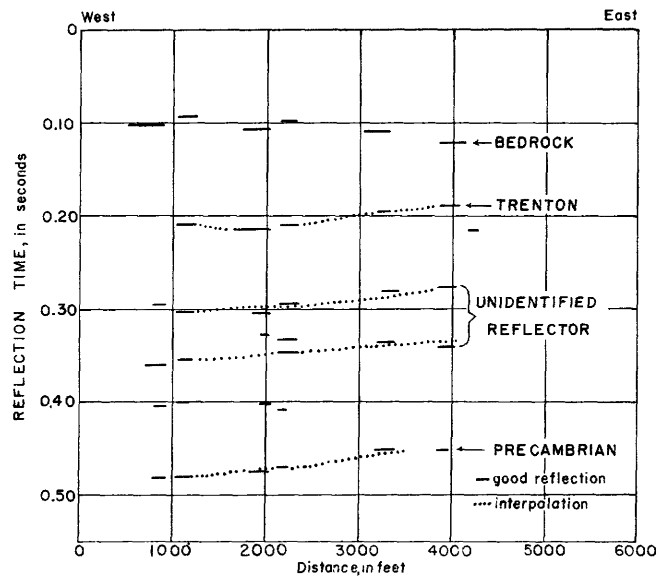


FIGURE 13.—Reflection time cross-section profile $A'-A'$, northeastern Indiana. (See fig. 12*D*.)

The second profile used groups of geophones spaced at about 1-mile intervals in a northwesterly direction from the first line (fig. 12*D*). This group consisted of split spreads and was an attempt at correlation shooting. The correlation line seems to yield the pre-Trenton reflections dipping to the northwest, but at a lower dip angle than exhibited in the semicontinuous west-east profile. However, the correlation of high-frequency reflections at 1-mile intervals is uncertain, and it is possible that the interpreted dip is not real.

The westerly dip in the first profile and the apparent northwesterly dip in the correlation records lend support to the existence of the postulated ridge in northeastern Indiana.

It is of interest to note that the reflection quality improved significantly as the filter frequencies were increased above the conventional range. No difficulty was experienced in obtaining reflections through the entire sedimentary section of some 3,000 feet.

The geophysical evidence for a structure in northeastern Indiana is supported by the conclusions of geological workers in the area. G. V. Cohee (oral communication, 1955) stated that subsurface studies in the southern part of the Michigan basin (Cohee, 1948) suggested the probable existence of a northwest-trending anticlinal fold in northeastern Indiana. The basement ridge revealed by the aeromagnetic data is consistent with these interpretations of the subsurface geology of the area.

It is perhaps significant that the small gas-producing areas which are associated with minor structural features in the Trenton occur along the flanks of the postulated ridge (fig. 12*C*). This may be analogous to the association of gas and oil production with the Cincinnati arch to the south.

RELATION OF MAGNETIC PATTERN TO OIL AND GAS PRODUCTION IN INDIANA

Indiana's oil and gas have come mainly from two large districts. In the northeast district, now largely depleted, the fields are associated with the Cincinnati arch and production is from the Trenton limestone. In the southwest district, production is obtained chiefly from Lower Pennsylvanian and Upper Mississippian rocks where the controlling structures are commonly anticlines, monoclines, and terraces of limited extent, mild amplitude, and irregular distribution (Indiana Oil Scouts Assoc. 1936, p. 96).

A detailed study has been made in an effort to associate the magnetic pattern shown on the 10-gamma Indiana county aeromagnetic maps with the location of oil and gas production in Indiana (Dawson and Lowrance, 1952). Only in Harrison County does a good correlation seem evident, but a general relationship with the larger magnetic features in the southwest district is suggested.

In Harrison County the Laconia, New Middletown, and Corydon gas fields are found to be alined along a strong north–south positive magnetic trend (fig. 14). The New Boston and Rosewood gas fields lie athwart large negative closures along the Ohio River. Although it is felt that this coincidence of gas fields with strong magnetic expressions is significant, a completely satisfactory explanation of the relationship is difficult. Harris and Esarey (1940, p. 30) have reported that this gas production is from the New Albany shale (Upper Devonian). Production is usually from minor noses and terraces on the general westward dip of the shale, but some gas has been obtained with little or no recognizable structure. It is further stated by the same authors that the New Albany shale structures decrease in magnitude with depth. These structures are recognizable on the limestone of Devonian age but are only slightly expressed on the Trenton.

All the major magnetic expressions are assumed to originate from the crystalline basement rocks (p. 22) with uplift a negligible factor except in local areas among which the Harrison County area is not included. The most acceptable theory accounting for a correlation between the minor structures in the New Albany shale and the magnetic pattern is that the reversals or interruptions in the normal dip perhaps related to zones of weakness associated with the emplacement of a large basement intrusive. We believe that the Harrison County magnetic high is but the northern part of a major tectonic element which extends a considerable distance south and east of the Ohio River into Kentucky.

When oil and gas field locations are transferred to the 10-gamma county aeromagnetic maps in the southwest district, a noteworthy feature becomes evident. This is the fact that there is a tendency for these fields to be found around the peripheries of magnetic closures rather than at or near their centers. Counties where this relation is particularly obvious include Knox and Daviess (figs. 15, 16). Minor exceptions are present; for example, the Washington field in Daviess County, which occupies the center of a magnetic low. Most of the numerous fields do apparently occur around the margins of magnetic closures, rather than in a random pattern which first inspection of the oil and gas maps might indicate. At present, no satisfactory explanation is offered for this apparent relationship of the magnetic pattern to petroleum production in the southwest district. In the absence of an understanding of the tentative correlation, direct use of the magnetic data in searching for new fields in this area may be open to question.

Production of oil and gas from the northeast district in Indiana is restricted to zones of favorable secondary porosity within the upper levels of the Trenton limestone. The Cincinnati arch has apparently controlled regional migration and accumulation. Individual fields are found on local modifications of the main anticlinal structure (VerWiebe, 1952, p. 53). No interpretable correlation is evident between the magnetic contours and the location of petroleum production in this district except to the extent that anomaly characteristics suggest a thinning of the sequence of sedimentary rocks over the arch.

The theoretical basement map of Indiana (fig. 11) shows several areas of uplift which may exert control over oil and gas accumulation in the overlying sediments. Because of its relatively shallow burial and

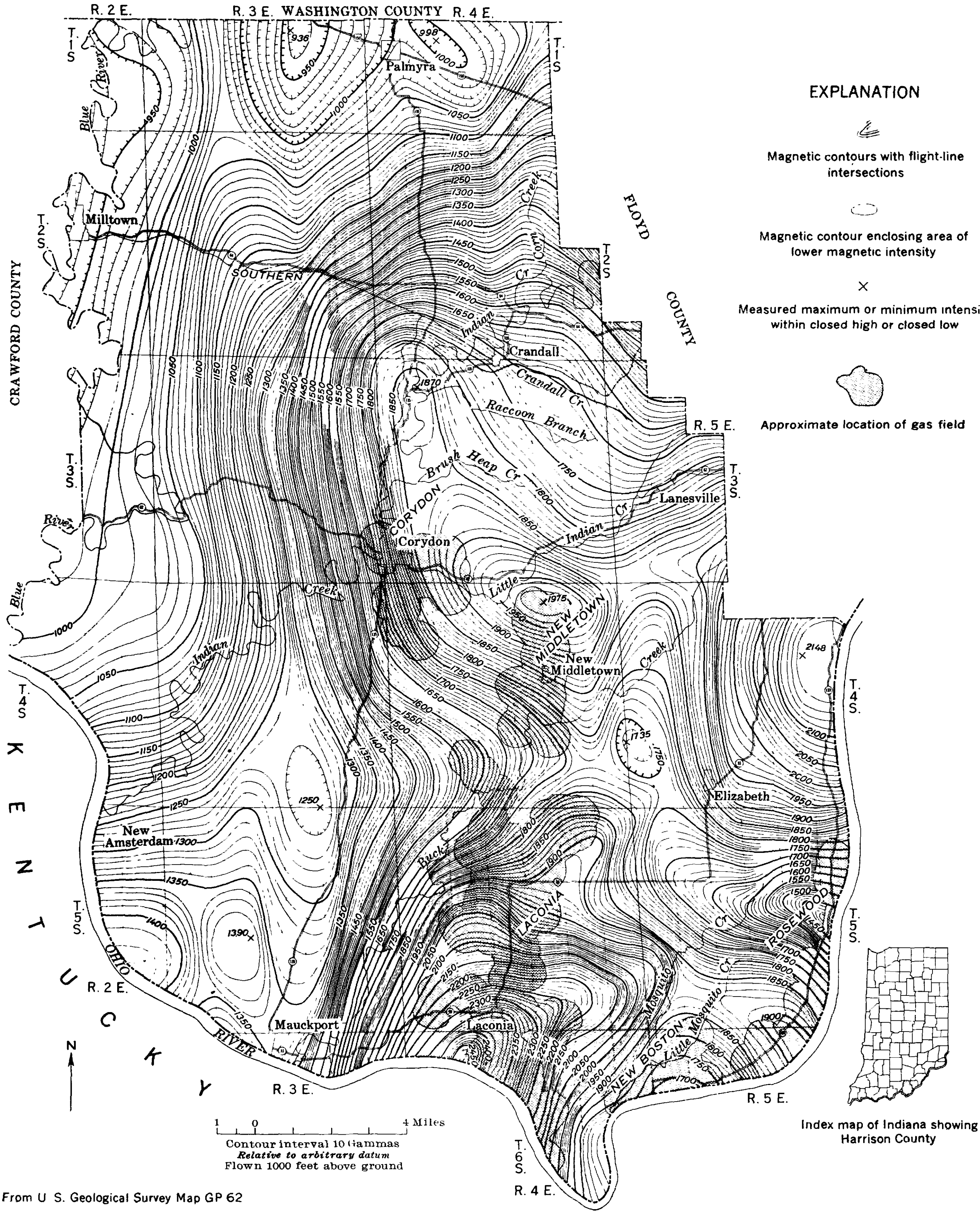


FIGURE 14.—Aeromagnetic map and gas fields, Harrison County, Ind.

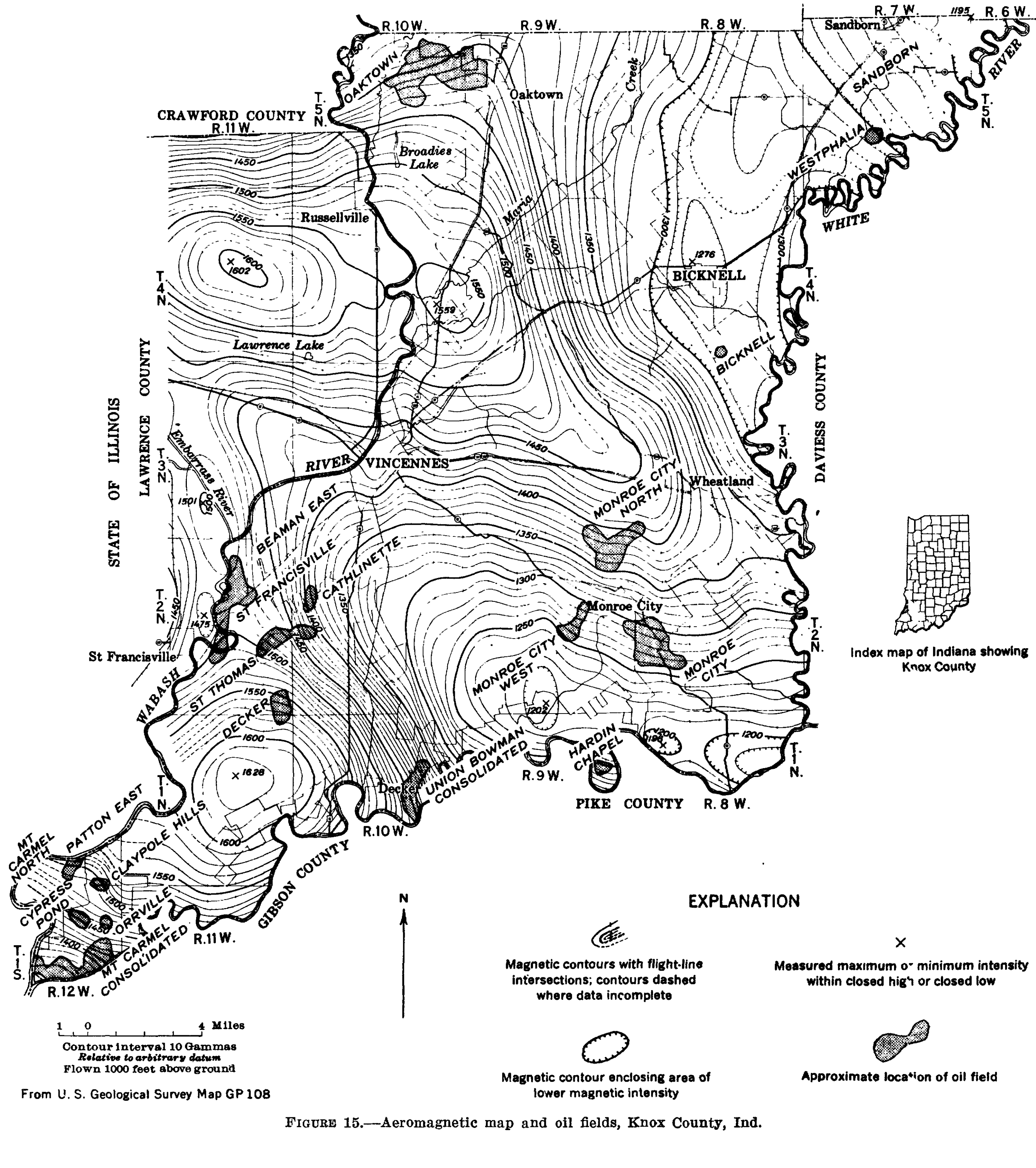
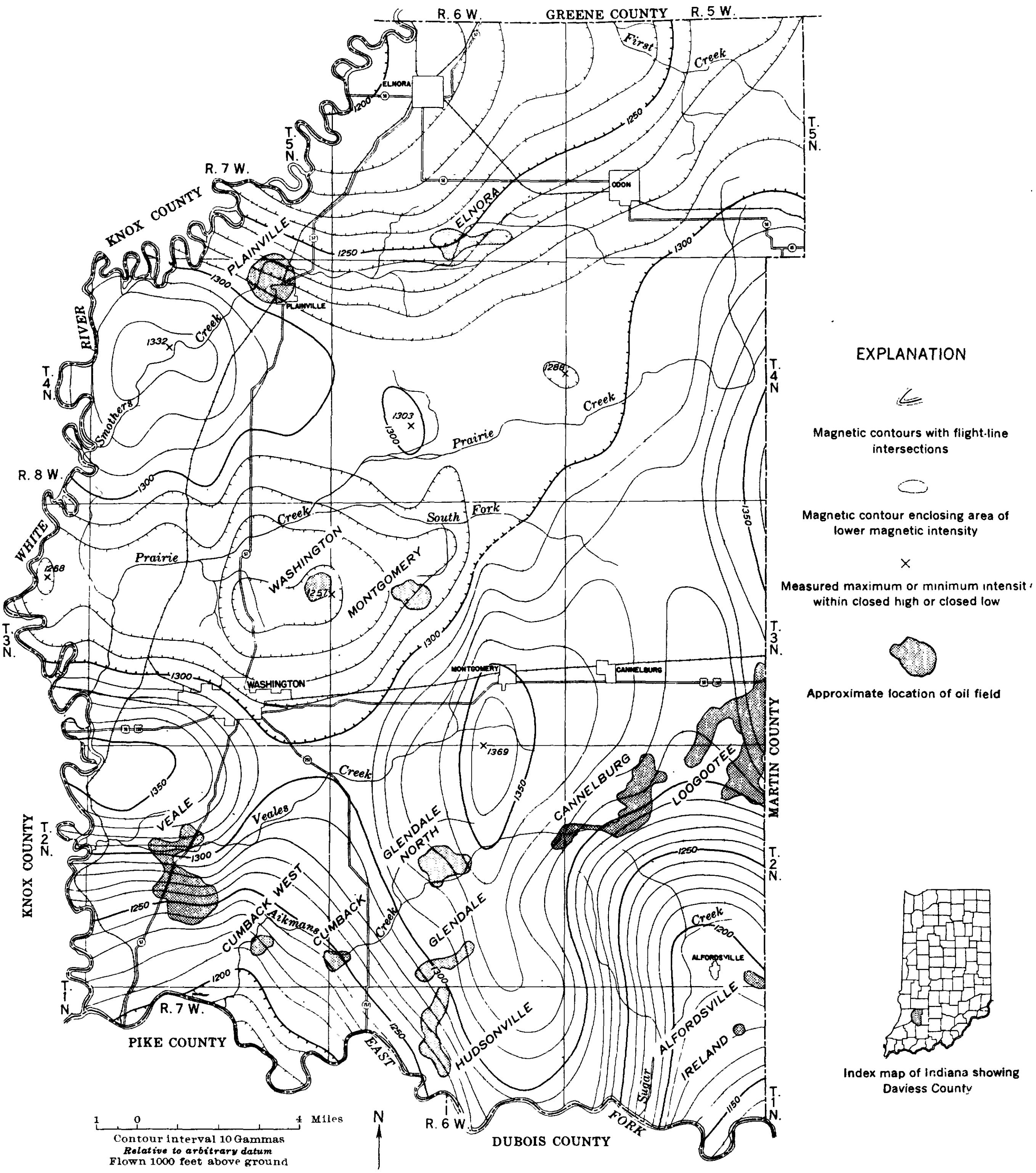


FIGURE 15.—Aeromagnetic map and oil fields, Knox County, Ind.



From U. S. Geological Survey Map GP 7

FIGURE 16.—Aeromagnetic map and oil fields, Daviess County, Ind.

comparative lack of exploration, the areas over and adjacent to the ridge in the northeast corner of the State are particularly attractive. If future subsurface exploration confirms the postulated uplift, new production of oil and gas may be expected.

CONCLUSIONS AND RECOMMENDATIONS

The primary objectives sought in the aeromagnetic mapping of Indiana have been obtained to a large extent. New knowledge of the basement-rock configuration and structures are at least implied by the contours on the Precambrian basement rocks. Thickness of the sedimentary rocks throughout the State have been calculated at 79 discrete points and interpolations made for the areas between points. Where wells to or near basement provide checks, the calculated thicknesses are correct, on the average, to 10 percent. Major basement faulting and basic intrusives into the basement can be inferred from the magnetic maps, but no evidence was found of faulting or igneous intrusions into the sedimentary rocks. The magnetic data provide subsurface information of present scientific interest and probably future economic value.

Among the areas of interest delineated by the magnetometer, the northeast corner of the State is considered paramount. The region of the postulated basement ridge should receive detailed geophysical investigation to confirm and delimit any actual uplift present. Additional aeromagnetic work in adjacent parts of Michigan and Ohio would aid in determining the extent of the trend. The calculated basement uplift, centering in Putnam County, can probably be checked with the seismograph, for the reflection quality there is better than in the northeastern part of the State.

In Newton County a detailed ground magnetic survey should be made over the Kentland "cryptovolcanic" area. This type of survey might supply a definitive answer to the type of structure present.

The Harrison County magnetic anomaly should be outlined by expanded aeromagnetic coverage to the east and south into Kentucky. A complete picture of this feature would aid in establishing its source and help in the problem of correlation of the related gas fields.

Further study of the suggested correlation of oil fields to the peripheries of magnetic anomalies in the southwest district of Indiana should confirm or disprove the importance of the relationship.

INDIANA 10-GAMMA AEROMAGNETIC MAPS

The total-intensity aeromagnetic maps published as Geophysical Investigations maps by the U. S. Geological Survey in cooperation with the Indiana Geological Survey are listed below.

Geophysical Investigations Maps

[Scale, 1 inch = about 1 mile. Contour interval, 10 gammas. Fourteen of these maps were published before numbering in the Geophysical Investigations maps series was begun]

County	*No.*	*Year*
Adams	GP 20	1950
Allen	GP 21	1950
Bartholomew	GP 82	1951
Benton	-------	1949
Blackford	GP 52	1951
Boone	GP 35	1950
Brown	GP 53	1951
Carroll	GP 22	1950
Cass	-------	1950
Clark	GP 54	1951
Clay	GP 103	1951
Clinton	GP 36	1950
Crawford	GP 55	1951
Daviess	GP 7	1950
Dearborn	GP 83	1951
Decatur	GP 56	1951
De Kalb	GP 23	1950
Delaware	GP 57	1951
Dubois	GP 8	1950
Elkhart	-------	1950
Fayette	GP 84	1951
Floyd	GP 58	1951
Fountain	GP 104	1951
Franklin	GP 105	1951
Fulton	-------	1949
Gibson	GP 37	1950
Grant	GP 59	1951
Greene	GP 106	1951
Hamilton	GP 60	1951
Hancock	GP 61	1951
Harrison	GP 62	1951
Hendricks	GP 38	1950
Henry	GP 63	1951
Howard	GP 24	1950
Huntington	GP 25	1950
Jackson	GP 85	1951
Jasper	-------	1949
Jay	GP 86	1951
Jefferson	GP 64	1951
Jennings	GP 65	1951
Johnson	GP 107	1951
Knox [1]	GP 108	1951
Kosciusko	GP 26	1950
Lagrange	GP 27	1950
Lake	-------	1949
LaPorte	-------	1949
Lawrence	GP 66	1951
Madison	GP 67	1951
Marion	GP 109	1951
Marshall	-------	1950
Martin	GP 9	1950
Miami	GP 28	1950
Monroe	GP 87	1951
Montgomery	GP 39	1950
Morgan	GP 68	1951
Newton	-------	1949

[1] Includes part of Lawrence County, Ill.

Geophysical Investigations Maps—Continued

County	*No.*	*Year*
Noble	GP 29	1950
Ohio	GP 88	1951
Orange	GP 69	1951
Owen	GP 70	1951
Parke	GP 71	1951
Perry	GP 40	1950
Pike	GP 10	1950
Porter	GP 30	1950
Posey	-------	1949
Pulaski	-------	1949
Putnam	GP 41	1950
Randolph	GP 110	1951
Ripley	GP 72	1951
Rush	GP 89	1951
St. Joseph	-------	1950
Scott	GP 73	1951
Shelby	GP 74	1951
Spencer	GP 11	1950
Starke	-------	1949
Steuben	GP 31	1950
Sullivan [2]	GP 111	1951
Switzerland	GP 90	1951
Tippecanoe	GP 42	1950
Tipton	GP 75	1951
Union	GP 112	1951
Vanderburgh	GP 43	1950
Vermillion	GP 44	1950
Vigo	GP 113	1951
Wabash	GP 32	1950
Warren	GP 45	1950
Warrick	GP 12	1950
Washington	GP 76	1951
Wayne	GP 114	1951
Wells	GP 33	1950
White	-------	1949
Whitley	GP 34	1950

[2] Includes part of Crawford County, Ill.

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