STATE OF ILLINOIS
DEPARTMENT OF REGISTRATION AND EDUCATION

AEROMAGNETIC STUDY OF THE HARDIN COUNTY AREA, ILLINOIS

Lyle D. McGinnis
James C. Bradbury

ILLINOIS STATE GEOLOGICAL SURVEY
John C. Frye, *Chief* URBANA

CIRCULAR 363 1964

AEROMAGNETIC STUDY OF THE HARDIN COUNTY AREA, ILLINOIS

Lyle D. McGinnis and James C. Bradbury

ABSTRACT

As a part of the Illinois State Geological Survey's program to develop basic data of value in exploration for and development of mineral resources, an aeromagnetic survey was made of Hardin County and parts of Gallatin, Pope, and Saline Counties in southeastern Illinois. This study has produced evidence that intrusive activity may be associated with the major Cottage Grove-Shawneetown Fault trend. A broad magnetic high, with maximum intensity $5\frac{1}{2}$ miles northeast of the apex of Hicks Dome, and oriented at an angle of 15° to the long axis of Hicks Dome, is thought to outline a stock of basic intrusive rocks at a depth of 11,000 feet or greater that has a magnetic susceptibility of 3.83×10^{-3} cgs units. The stock may be either Precambrian or Cretaceous in age and probably is similar mineralogically to shallower intrusives encountered in the area. Due to the great depth and inferred mineralogy of the stock and basement rocks (as interpreted from the magnetic map) further exploration for highly magnetic iron-ore minerals in the Hardin County area does not appear to be warranted. The absence of a magnetic anomaly directly under Hicks Dome indicates that uplift of the dome is not a result of laccolithic intrusion. Measurable magnetic anomalies that can be attributed to faulting occur only for faults having major displacements.

INTRODUCTION

As one of the first steps in the geophysical study of southern Illinois, the Illinois State Geological Survey initiated an aeromagnetic survey of Hardin County and parts of Gallatin, Pope, and Saline Counties (fig. 1) in 1962. For several years, such work has been recommended by representatives of the fluorspar industry of southern Illinois as a means of evaluating additional mineral resources in the area. The investigation was directed at the Hardin County area because it contains the most complex system of faults and is the only known area in Illinois where intrusive rocks have been encountered near the surface. Such conditions offer a favorable setting for the use of anomalous magnetic fields in the analysis of the geologic framework, since igneous rocks generally have extremely high magnetic susceptibilities compared to those of sedimentary rocks. It was thought that an aeromagnetic study would reveal information on the configuration and nature of the igneous rocks and their relation to the structural history of the area. As a direct economic objective, it was hoped that the aeromagnetic study would discover what, if any, possibilities exist for the occurrence of iron-ore deposits similar to those recently found in southeastern Missouri. A further possibility was that magnetic anomalies might indicate faults with which fluorspar mineralization is associated. The economic aspects of the study are discussed at the end of this report. The absence of local anomalies of high intensity should discourage exploration for magnetic iron-ore deposits in the area covered by the survey.

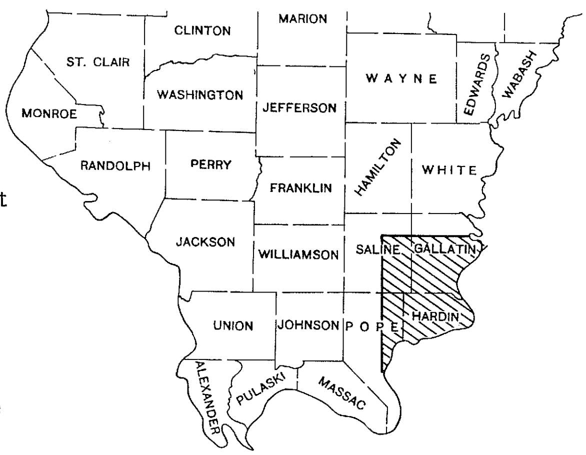


Figure 1 - Index map of Illinois showing the Hardin County area.

The authors wish to express their appreciation to Professor Otto Nuttli of St. Louis University for his discussion covering magnetic anomalies due to faulting. Interpretations and analyses are solely the responsibility of the authors.

MAJOR STRUCTURAL FEATURES

The area covered by this report is in the deepest part of the Illinois Basin and is part of the most complex, structurally disturbed region in the state. In the northernmost part of the area, although faulting is known, the beds are not greatly disturbed and exhibit a gentle northward dip. From the Shawneetown Fault Zone southward, however, the beds are warped and are intricately faulted. The most conspicuous structural features in the area are Shawneetown Fault Zone, Eagle Valley Syncline, Hicks Dome, and Rock Creek Graben (fig. 2).

The Shawneetown Fault Zone is a belt of sheared and crushed rocks that appears to be a high angle thrust fault. A maximum throw of 3,000 feet or more has been noted just west of the Saline-Gallatin County line where beds of early Mississippian age crop out south of the fault zone. Strata of the Carbondale Formation of middle Pennsylvanian age lie on the north side of the fault. Throw diminishes to the east, and strata of the Caseyville Formation of early Pennsylvanian age are the oldest exposed by the fault in Shawneetown. The fault zone has been traced eastward as far as central Kentucky where it is known as the Rough Creek Fault Zone.

The Eagle Valley Syncline is a deep asymmetric trough with steep northern and western flanks formed by the steeply dipping beds adjacent to the Shawneetown Fault Zone and a much more gentle southern flank formed by beds dipping to the north and northeast from Hicks Dome. The syncline deepens eastward and contains in its eastern part strata of the late Pennsylvanian McLeansboro Group. These are the youngest Paleozoic rocks in the area. The syncline also continues eastward across western Kentucky where it is known as the Moorman Syncline.

Hicks Dome is a sharp domal uplift in western Hardin County. Middle Devonian limestones, now represented chiefly by cherty residuum, crop out in the central part of the dome. A ring of New Albany Shale encircles the dome. Several igneous exposures, including mafic dikes and intrusive breccias, occur within a radius of two miles from the apex of the dome.

The Rock Creek Graben is a northeast-trending fault block. Downfaulting brings Pennsylvanian strata into contact with the middle Mississippian Ste. Genevieve Limestones, representing a displacement of over 1,000 feet. The boundary faults of the graben, as well as all the other faults cutting the area inside the curving Shawneetown Fault Zone, are largely of the normal or gravity type. Weller et al. (1952) reported possible thrusting along the northwest side of the Rock Creek Graben.

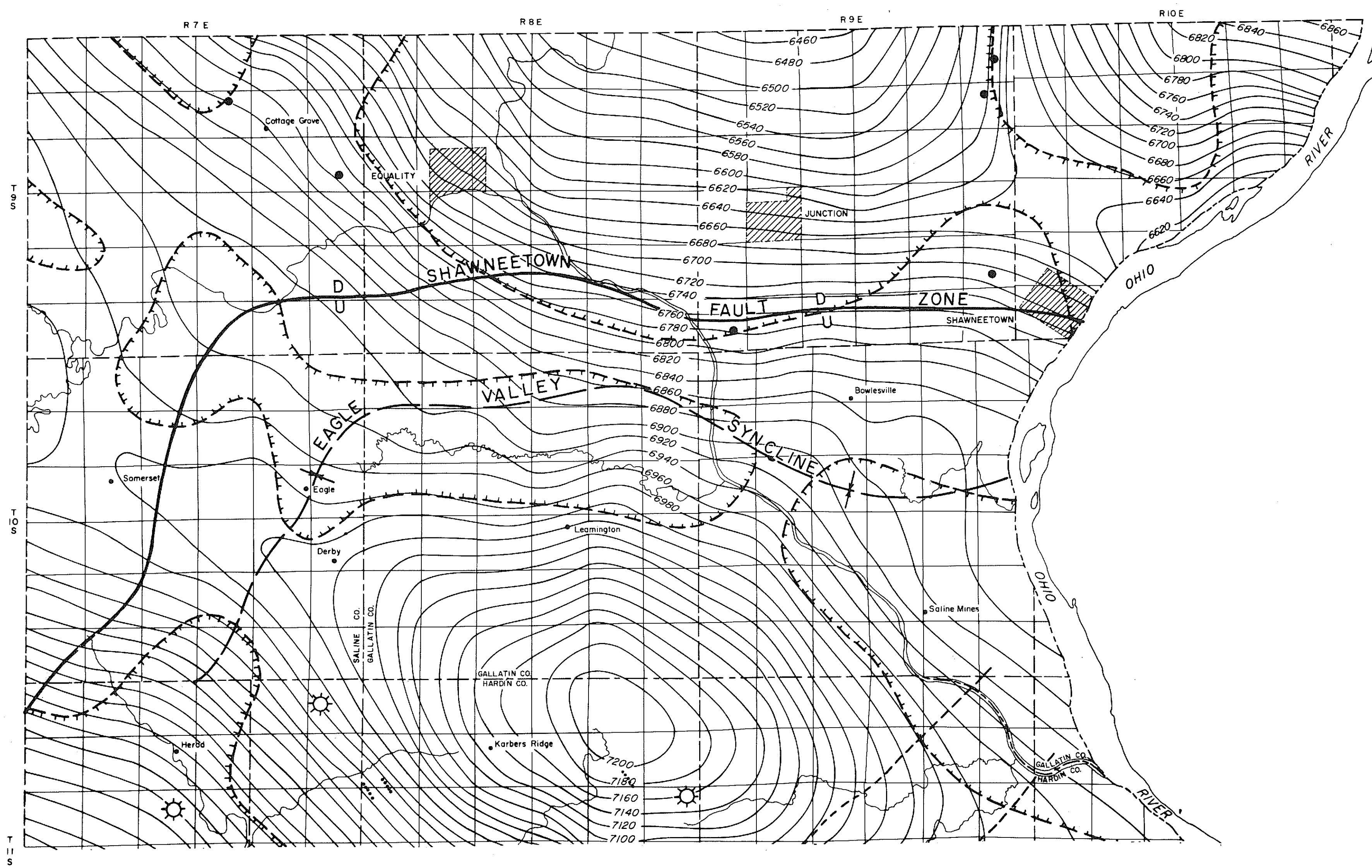
The area southeast of the Rock Creek Graben is relatively unfaulted, and the outcrop pattern (Baxter et al., 1963) shows that the strata dip northward from Tolu Dome, the apex of which is just across the Ohio River from a point between Elizabethtown and Cave in Rock.

INTRUSIVES AND TECTONICS

Intrusive igneous rocks in this area occur as dikes and sills of mica peridotite and lamprophyre and as plugs of explosion breccia (Bradbury et al., 1955; Clegg and Bradbury, 1956; Bradbury, 1962). Their distribution is shown on figure 2. The dikes are generally narrow, ranging from less than one to a few feet in width, and, with one exception, strike in a northwesterly direction. Sills have been observed chiefly as offshoots of dikes and are generally less than a foot thick. However, mica peridotite encountered in several oil tests in the Omaha pool, about 5 miles north of the mapped area, may represent sills several feet in thickness (English and Grogan, 1948).

The breccia plugs, consisting of rock fragments in a matrix of finely broken rock and mineral fragments, appear to be roughly circular or elliptical. Their actual dimensions are not determinable because of inadequate exposures, but in terms of outcrop area the largest measures 400 by 800 feet.

The role of igneous intrusion in the rather complex structural history of the area is not clear. Weller et al. (1920), J. M. Weller (1940), and Heyl and Brock (1961) postulated that igneous intrusion caused arching and fracturing of the strata. Faulting and development of northeast-trending grabens took place as the arch partially collapsed on withdrawal of magma. Although the existence of a broad, domal anticline is suggested by outcrop patterns on the geologic maps of the Illinois-Kentucky fluorspar district (Weller et al., 1952; Baxter et al., 1963; Baxter and Desborough, 1964; Weller and Sutton, 1951) the almost exclusive northwest strike of the mafic dikes indicates that the anticline was not the result of igneous intrusion. If intrusion had caused the arching, fractures of various orientations should have been opened up, and dike emplacement would not have been limited to fractures with a northwest strike. The only exception to the northwest strike of the mafic dikes is the northeast strike of the dike just east of the apex of Hicks Dome. This is apparently a special case as Hicks Dome was the site of a concentration of tectonic and igneous activity, of which some was explosive in nature (Brown et al., 1954; Bradbury et al., 1955).


R7E
R8E
R9E
R10E
T9S
T10S
T11S
OHIO RIVER
SHAWNEETOWN FAULT ZONE
EAGLE VALLEY SYNCLINE
D
U
Cottage Grove
Equality
Junction
Shawneetown
Bowlesville
Somerset
Eagle
Leamington
Derby
Saline Mines
Herod
Karbers Ridge
SALINE CO.
GALLATIN CO.
HARDIN CO.
6460
6480
6500
6520
6540
6560
6580
6600
6620
6640
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
6900
6920
6940
6960
6980
7100
7120
7140
7160
7180
7200

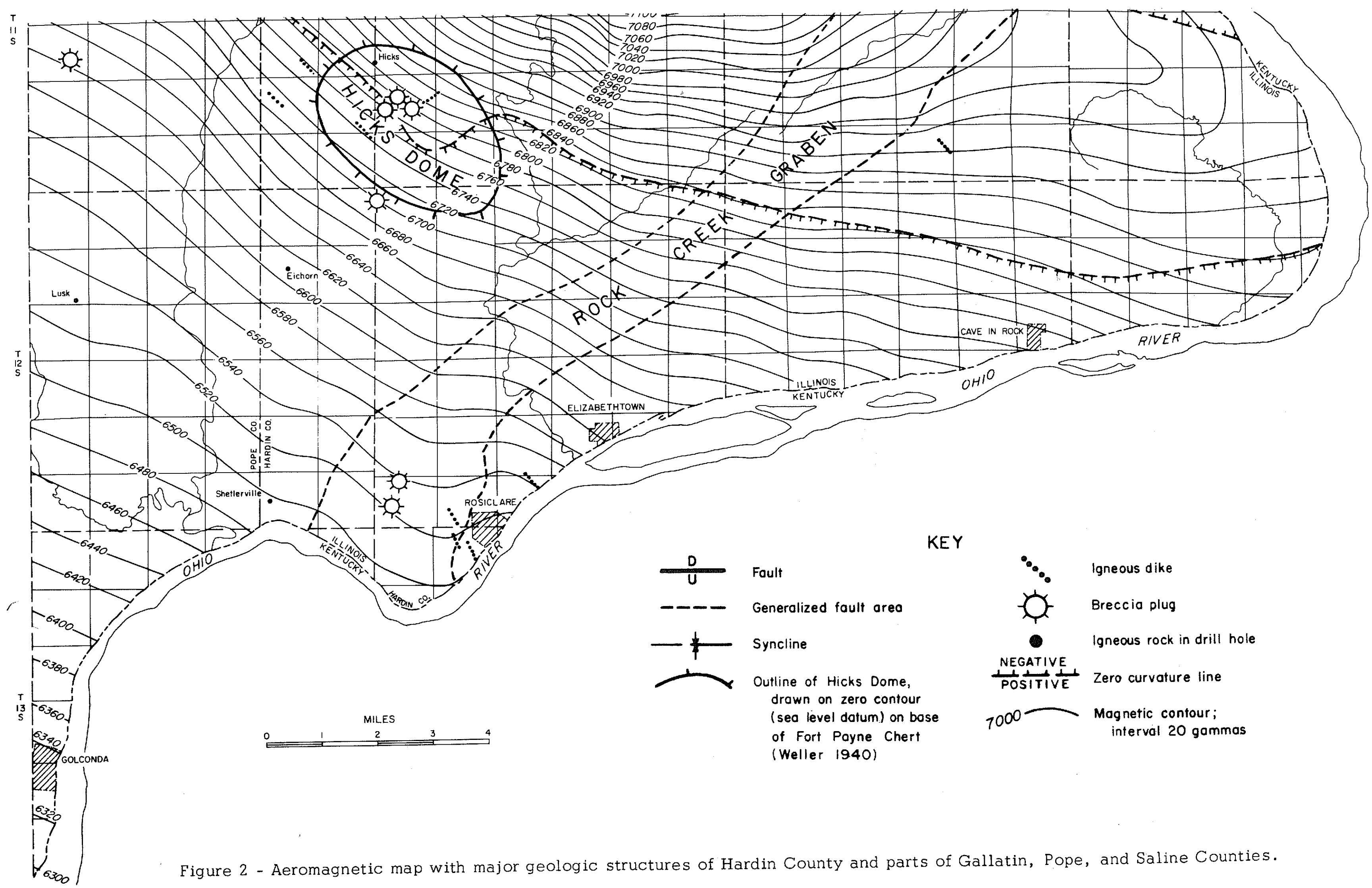


Figure 2 - Aeromagnetic map with major geologic structures of Hardin County and parts of Gallatin, Pope, and Saline Counties.

Nackowski (1959), noting the absence of dikes in the northeast-trending faults, proposed that a northeast-southwest compressive force in late Paleozoic time created northeast-trending tension fractures, along which gravity movements caused normal faulting and graben formation at a later date; in late Mesozoic time a compressive force acting in a N10-20° W direction opened tension fractures with a N10-20° W strike, into which were intruded igneous dikes. It is apparent that by this scheme the northeast-trending faults would have been held tightly closed by compressive forces at the time that the N10-20° W fractures were acting as channelways for dike emplacement. Late Mesozoic compressive forces from a more westerly direction would seem to fit the data shown in figure 2. Displacement of the dikes by the northeast-trending faults, noted by Weller et al. (1952), could have taken place during the renewed movement on the faults that affected Cretaceous strata in southern Illinois southwest of Hardin County (Ross, 1963).

AEROMAGNETIC INTERPRETATION

The magnetic survey was flown in 24 north-south profiles one mile apart and at an elevation of 2,000 feet above sea level. Two east-west cross profiles were flown for correlation purposes. The data were corrected for diurnal variations with records from a monitor flux-gate magnetometer at the University of Wisconsin, although there was little magnetic activity during the flights. The data also were corrected for regional variations: $+7\gamma$/mile to the south and $+3\gamma$/mile to the west.

Although the region contains complex structures, diatremes, and sills and dikes, the magnetic map (fig. 2) is free of small, local anomalies. The dominant magnetic feature, located in Hardin County, is a broad, elliptical high of fairly large amplitude with the long axis of the ellipse trending N65°W. The center of the magnetic high is $5\frac{1}{2}$ miles to the northeast of the structural high point on Hicks Dome.

Depth to Top of Anomalous Magnetic Body

An unpublished, vertical intensity magnetic map of western Hardin County (McClure, 1930), on open file at the Illinois State Geological Survey, was used to calculate the depth to the anomalous magnetic body. Although the ground survey was not carried far enough north to establish closure over the high, it was sufficient, with the aid of the aeromagnetic map, to determine a depth to the top of the anomalous body, utilizing the method described by Peters (1949). This method and all others to be discussed later are derived assuming negligible remanent magnetism. The calculations pertinent to the depth determination are shown in figure 3. The calculated elevation of the top of the anomalous body (approximately 11,000 feet below sea level) is roughly equivalent to basement elevations determined from magnetic anomalies in southwestern Indiana (Henderson and Zietz, 1958), about 30 miles northeast of the Hardin County anomaly. By analyzing only those anomalies of high amplitude covering large areas, Henderson and Zietz assume that the resulting depths are representative of the basement surface. The shape and size of the southern half of the Hardin County anomaly satisfies these requirements. Rudman (1963), in a recent seismic study in southwestern Indiana has found that aeromagnetic depths may be as much as 30 percent shallower than seismic depths.

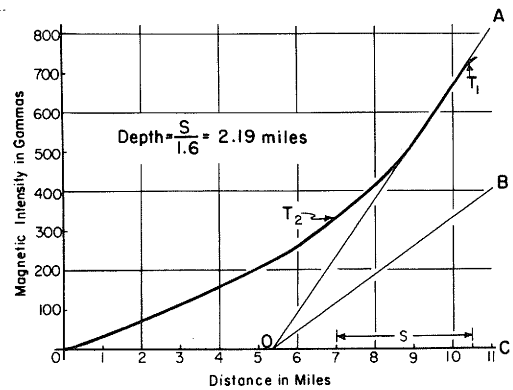


Figure 3 - Determination of depth from Peters (1949) construction. Line OA is a line of maximum slope. Line OB is drawn so that one-half the tangent of angle AOC equals the tangent of angle BOC. T_2 and T_1 are points of tangency of line OB on the magnetic profile. S is the horizontal distance between points of tangency.

Observed and Theoretical Anomalies

As a first approximation of a theoretical anomaly to the observed anomaly in Hardin County, figure A75 of Vacquier et al. (1951, p. 139) bears the closest resemblance. Profiles drawn through the center of the observed and theoretical anomalies (fig. 4), parallel to the small axes of the ellipses, fit extremely well except on the northern limb. Here the profiles diverge, with the theoretical anomaly decreasing at a faster rate than the observed anomaly. The divergence may be partially explained by the fact that the bodies causing the anomalies are not oriented at the same angle in the magnetic field. The discrepancy due to this difference in alignment is probably small. The theoretical anomaly strikes N45°E and is computed at a magnetic inclination of 75° (the contours would be simply a mirror image at N45°W), whereas the magnetic strike of the observed anomaly is about N68°W and the inclination is about 68.63° (McGinnis and Heigold, 1961). The width of the model producing the theoretical anomaly is about six miles. If the model were placed in the correct position on the observed map, the southwestern edge of the model would be located about two miles north of Hicks Dome and the northeastern edge would be in the same location as the zero curvature line south of the Eagle Valley Syncline (fig. 2).

The susceptibility contrast between the body producing the observed anomaly and common basement rocks in Illinois is obtained from the relation between the theoretical and observed anomalies in a derivation by Vacquier:

$$k = \Delta Tm/\Delta TcT$$

where k is the susceptibility contrast, ΔTc is the total amplitude of the theoretical anomaly intensity from the model, ΔTm is the total amplitude of the observed anomaly and T is the intensity of the earth's main magnetic field. Magnetic susceptibilities of basement samples collected in Illinois have been determined by Rudman (personal communication) and in southern Illinois average about 1.4×10^{-4} cgs units. Thus, the susceptibility contrast derived from the above relation is 3.69×10^{-3} cgs units, and the susceptibility of the anomalous body is 3.83×10^{-3} cgs units. Warren (1956) has published susceptibilities from western Kentucky dike rocks as determined by direct measurements that range from $.045 \times 10^{-3}$ to 9.0×10^{-3} cgs. The average susceptibility estimated from six field traverses was 3.80×10^{-3} cgs units. Although granites and allied rocks occasionally have susceptibilities of this magnitude (less than 17 percent have susceptibilities as great or greater according to Birch et al., 1942, p. 296), it is more likely that the observed anomaly represents a basic intrusive similar mineralogically to the dikes surveyed by Warren since approximately 49 percent of the basic intrusives examined by Birch et al. have susceptibilities this great or greater.

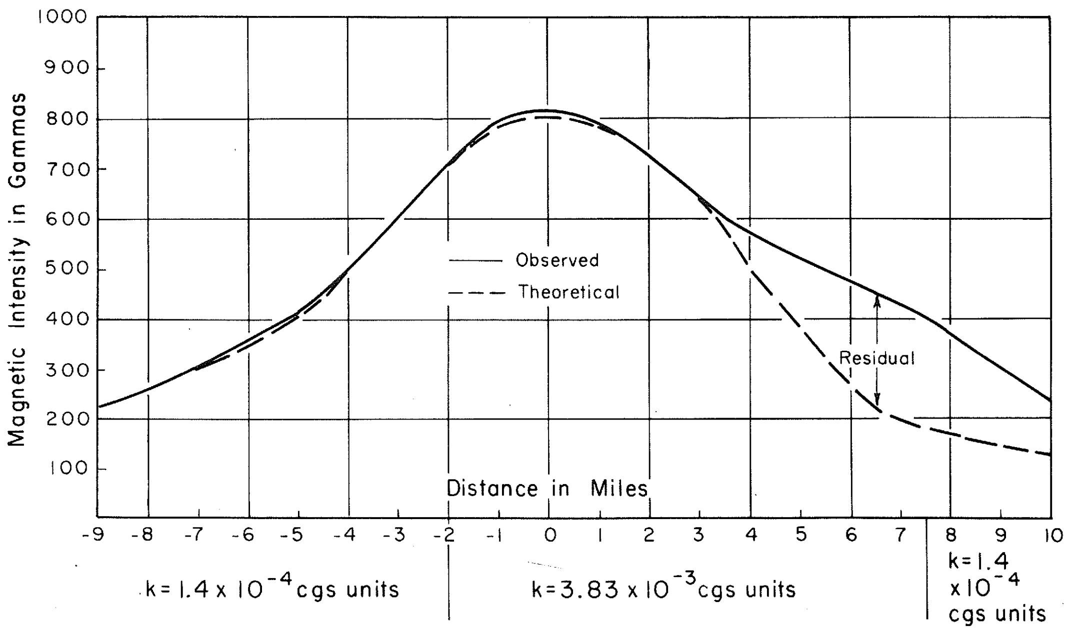


Figure 4 - Determination of width of the anomalous body. The observed profile is taken from figure 2. The theoretical profile is from a model of Vacquier et al (1951, fig. A75, p. 139).

The observed magnetic profile diverges from the theoretical profile in the general vicinity of the Shawneetown Fault Zone giving a residual anomaly of about 230γ. If the material causing the observed anomaly thinned or terminated to the north and then thickened again near the fault zone and if the anomalous material extended 3000 feet above the general basement surface in the vicinity of the fault zone, the magnetic anomaly would be due to both basement relief and a variation in basement lithology. A vertical fault with east-west strike, displacement of about 3000 feet (roughly a maximum for the Shawneetown Fault Zone) upthrown to the south, with a magnetic susceptibility contrast of 3.83×10^{-3} (assuming the sediments have zero magnetic susceptibility), would have a total anomaly of about 110γ and maximum amplitude of the anomaly would be located about two miles south of the fault (fig. 5) as derived from equations by Nuttli (1955). It is assumed here that susceptibilities of the igneous rocks are the same on the upthrown and downthrown sides of the fault. The magnetic profile of the theoretical fault is shown in figure 5. A susceptibility greater than zero for the sediments would tend to decrease the theoretical fault anomaly, whereas if the material to the north (down side) were granite and of lower susceptibility, the anomaly would be increased.

To take into account the possibility that intrusives as well as faulting contribute to the residual anomaly, another theoretical anomaly of Vacquier et al. (1951, fig. A67, p. 131) is utilized. The width to length ratio of the new model is 1/6, and when its theoretical anomaly is fitted to the residual anomaly (fig. 4), a susceptibility contrast of 4.37×10^{-3} cgs is derived, which is somewhat greater than that derived for the larger body to the south. Subtracting the magnetic anomaly due to the fault described in the preceding paragraph from the residual anomaly and again fitting the new model of Vacquier et al., a closer approximation to the first susceptibility is obtained, although it is then too low. If the anomalous body

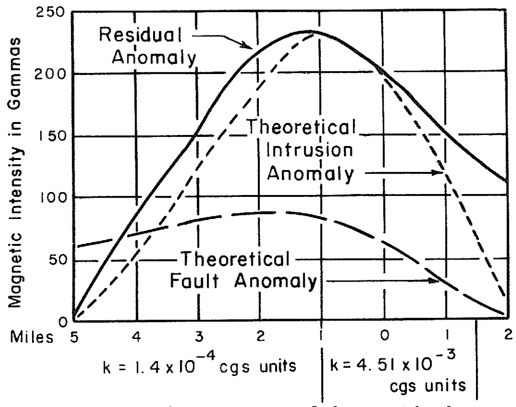


Figure 5 - Comparison of the residual anomaly and theoretical anomalies derived from models of faults and intrusions.

were sill-like and did not extend to infinity at depth, it would more closely approximate the residual anomaly. The residual anomaly is probably caused by a combination of basement relief and a change in rock type in the basement. The residual, fault, and theoretical anomalies are shown in figure 5.

Zero Curvature Line

An approximation of the size, shape, and location of the anomaly-producing body was made utilizing the method of Henderson and Zietz (1949). This is a second derivative analysis that aids in defining more sharply the outline of the anomalous body. The zero curvature line is shown as a dashed and hachured line on figure 2. According to Vacquier et al. (1951, p. 18), who also discuss the second derivative method, the zero value of the curvature (second derivative) tends to outline the top surface of the source of the magnetic anomaly. The depth indices of Vacquier were not helpful in the present study because of the deviations from an ideally shaped anomaly on the northern flank of the high and an undulating zero curvature line on the south. In the present survey, the magnetic values of consecutive north-south flight lines tend to deviate from the true field by $\pm 10\gamma$ in some portions of the area because of too few cross correlation flight lines. This results in slightly undulating contour lines. In the determination of the second derivative values, the undulations caused greater oscillations of the zero curvature line; thus, the zero curvature line shown on figure 2 has been smoothed so as to be more realistic when related to geologic features.

The magnetic high on figure 2 is enclosed by the zero curvature line. Positive, second derivative values are contained within the zero line, and negative values are found outside the line. An elongate trend of negative, second derivative values is located within the major positive area and coincides roughly with the axis of the Eagle Valley Syncline. The configuration of the zero curvature line in the Eagle Valley Syncline area suggest a thinning or perhaps splitting of the anomalous material with the greater portion of material emplaced to the south. A sill of anomalous material is suggested by the residual anomaly discussed previously and by the zero lines north of the syncline, roughly paralleling the Shawneetown Fault Zone. The narrow band of positive second-derivative values may be associated with basement faulting or with intrusives parallel to the Shawneetown Fault system or with both.

In figure A76 of Vacquier the zero line is about one mile too far south of the south edge of the model. Adjustment of the corresponding line on the observed map would place the southern edge of the major part of the anomalous body about one mile north of the apex of Hicks Dome. The width of the area between the corrected zero lines varies from seven to eight miles.

The band of positive second-derivative values paralleling the Shawneetown Fault Zone does not turn south with the surficial expression of the Fault Zone but crosses the zone and continues on to the northwest, which may indicate that basement faulting or intrusives also continue along this trend. The zero lines suggest that the major anomaly may be joined locally by sill-like connections. Sills of anomalous material are suggested by highs north of the town of Shawneetown and northwest of Equality. A small high probably related to Rock Creek Graben also is evident to the south, near Rosiclare, but the zero line was not drawn in here since this area is at the southern limits of the survey, where the data begin to show some evidence of error. The configuration of the zero curvature line indicates that the anomalous material is not confined to the area of the survey but is only a part of a major anomalous zone extending WNW and ESE.

DISCUSSION

In studies of the history of faulting and intrusions in the southern Illinois region (Ross, 1963; Weller, Grogan, and Tippie, 1952), it has been shown that the basic igneous intrusives are commonly of about the same composition and, therefore, that they probably represent a common parent body. It has also been shown in a preceding discussion that magnetic susceptibilities of dike rocks in the area are similar to the susceptibility determined for the anomalous body. Intrusions both occupy fault planes and are cut by faults, which suggests that the intrusions occurred after the fault pattern was established but before movement ceased (Ross, 1963). Recent publications (Ross, 1963; McGinnis, 1963) suggest movement along the faults is still active, which could mean that the intrusives were quite recent; however, a lead-alpha date on monazite from an intrusive breccia from the Hicks Dome area (Heyl and Brock, 1961) gives a middle Cretaceous age (90-100 million years), which suggests the Cretaceous Period was a time of intrusive activity.

Two interpretations concerning the age of the intrusion can be made. The anomalous intrusion could be Precambrian. The borders of the intrusion may merely outline a zone of crustal weakness around which major faulting has occurred intermittently since Precambrian time. The possibility that the elevation of the top of the body is less than -11,000 feet and, due to limitations in the magnetic method, may be as deep as -15,000 feet cannot be ignored. This elevation would correspond to Precambrian elevations based on previous geological and geophysical predictions. A smooth Precambrian surface would imply that the intrusion had been beveled by post-Precambrian erosion and that the intrusion was therefore Precambrian. This interpretation would necessitate a later source of intrusive igneous material outside the area covered by the survey since the near surface, peridotite dikes have been shown to be Cretaceous in age.

A second and possibly more likely interpretation is that the intrusion is Cretaceous in age and is the source of most of the dike rocks in the area. The comparable magnetic susceptibilities of dike rocks and the intrusion are significant. The configuration of the zero curvature line has more than a coincidental relation with post-Precambrian structural features; however, the fact that upward movement of an intrusion or stock of this size must have ceased shortly after penetration through Precambrian granitic rocks would require a gentle movement upward, involving stoping as its mechanism.

It is quite conclusive that a large mass of basic intrusive igneous rocks is located in the position indicated by the zero curvature lines in figure 2. The aeromagnetic data indicate that the main body of an intrusion is not located directly beneath Hicks Dome as previously suggested. This would suggest that Hicks Dome was not produced by a laccolithic intrusive uplift-a condition that may apply also to other domal structures in the region. Cretaceous intrusive activity may have modified pre-existing zones of weakness resulting in the areas of explosive brecciation surrounding Hicks Dome. Brecciation would then be contemporaneous with dike emplacement. The major intrusion is flanked by three structurally negative areas (north and west by the Eagle Valley Syncline and east by the Rock Creek Graben) and by one positive area (Hicks Dome).

Trends of the long axes of Hicks Dome and that of the anomalous magnetic body are not parallel but converge and intersect at a point northwest of Hicks Dome in the region of the Shawneetown Fault Zone. The magnetic trends in the Hardin County area appear to be more closely related to dike and major fault trends. The widespread occurrence of mafic dikes in regions lying outside the area covered by the intrusive body would suggest that material from the intrusive source has been injected outward away from the source material. It is also possible that other intrusives lying outside the surveyed area may account for some of the outlying dikes and sills. Because of the configuration of the magnetic anomaly, the lack of definite arching in the Paleozoic rocks over the inferred intrusion and because of the widespread distribution of basic rocks in the area, it is suggested that the magnetic anomalies in Hardin County are caused by a deeply buried oval stock (six to eight miles wide, twelve miles long and extending to non-magnetic depths) and sills that finger out away from the main source, covering the Precambrian crystalline rocks with a thick, undulating mantle.

Continued aeromagnetic surveying in southern Illinois is encouraged in light of the above results. The magnetic trends and anomalies are of value in delineating major structural features that have been associated with igneous activity. The correspondence of the Eagle Valley Syncline with negative second-derivative values may be of major importance in the reconstruction of the structural history of the area. The positive second-derivative values, trending parallel to the major fault system, may indicate that sills were intruded along the fault. Hicks Dome is not underlain by a laccolithic intrusion and may therefore have been caused by pre-Cretaceous NE-SW compressional forces. The relation between intrusive activity and the Cottage Grove-Shawneetown Fault System in south-central Illinois could be examined beneficially with further aeromagnetic exploration.

SIGNIFICANCE OF RESULTS IN RELATION TO MINERAL DEPOSITS

1. The aeromagnetic map of Hardin and adjacent counties (fig. 2) reflects structures involving igneous rocks. A broad magnetic anomaly of relatively low intensity centered about $5\frac{1}{2}$ miles northeast of Hicks Dome and the featureless configuration of contour lines around the anomaly suggest a large igneous body overlain by a thick sedimentary rock section. Depth to the body is estimated to be 11 to 15 thousand feet. The body probably is composed of basic rock generally similar in mineralogy to that of the dike rocks in the area. As a consequence of the great depth and the inferred mineralogy of the igneous body, further exploration for economic minerals that may be associated with the body does not appear to be warranted.

2. Shallow intrusives in the Paleozoic rocks are too small to produce significant aeromagnetic anomalies. Hicks Dome is not underlain by a laccolithic intrusion and no large bodies of magnetic iron ore are indicated in the region of the survey. However, the absence of large, shallow intrusives suggests that the area may be more favorable for oil exploration than was previously considered.

3. Minor faults, either in the basement or in the sedimentary rocks, do not produce measureable magnetic anomalies. Therefore, magnetic mapping is not likely to afford clues for locating mineralization along faults.

REFERENCES

Baxter, J. W., and Desborough, G. A., in preparation, Areal geology of the Illinois fluorspar district. Part 2-Karbers Ridge and Rosiclare Quadrangles: Illinois State Geol. Survey Circ.

Baxter, J. W., Potter, P. E., and Doyle, F. L., 1963, Areal geology of the Illinois fluorspar district. Part 1-Saline Mines, Cave in Rock, DeKoven, and Repton Quadrangles: Illinois State Geol. Survey Circ. 342, 43 p.

Birch, F., Schairer, J. F., and Spicer, H. C. (eds.), 1942, Handbook of physical constants: Geol. Soc. America Spec. Papers no. 36, 325 p.

Bradbury, J. C., 1962, Trace elements, rare earths, and chemical composition of southern Illinois igneous rocks: Illinois State Geol. Survey Circ. 330, 12 p.

Bradbury, J. C., Ostrom, M. E., and McVicker, L. D., 1955, Preliminary report on uranium in Hardin County, Illinois: Illinois State Geol. Survey Circ. 200, 21 p.

Brown, J. S., Emery, J. A., and Meyer, P. A., Jr., 1954, Explosion pipe in test well on Hicks Dome, Hardin County, Illinois: Econ. Geology, v. 49, no. 8, p. 891-902.

Clegg, K. E., and Bradbury, J. C., 1956, Igneous intrusive rocks in Illinois and their economic significance: Illinois State Geol. Survey Rept. Inv. 197, 19 p.

English, R. M., and Grogan, R. M., 1948, Omaha pool and mica-peridotite intrusives, Gallatin County, Illinois: Illinois State Geol. Survey Rept. Inv. 130. (Reprinted from Structure of Typical American Oilfields, v. III, Am. Assoc. Petroleum Geologists, p. 189-212.)

Henderson, J. R., and Zietz, I., 1958, Interpretation of an aeromagnetic survey of Indiana: U. S. Geol. Survey Prof. Paper 316-B, p. 10-37.

Henderson, R. G., and Zietz, I., 1949, The computation of second vertical derivatives of geomagnetic fields: Geophysics, v. 14, no. 1, p. 508-516.

Heyl, A. V., Jr., and Brock, M. R., 1961, Structural framework of the Illinois-Kentucky mining district and its relation to mineral deposits: U. S. Geol. Survey Prof. Paper 424D, p. D3-D6.

McGinnis, L. D., 1963, Earthquakes and crustal movement as related to water load in the Missisippi Valley region: Illinois State Geol. Survey Circ. 344, 20 p.

McGinnis, L. D., and Heigold, P. C., 1961, Regional maps of vertical magnetic intensity in Illinois: Illinois State Geol. Survey Circ. 324, 12 p.

Nackowski, M. P., 1959, Structural environment of the Illinois-Kentucky fluorspar district [abs.]: Mining Eng., v, 11, no. 1, p. 43

Nuttli, O. W., 1955, Determining depth of faulting from magnetic field intensity measurements: Mining Eng., June, 3 p.

Peters, L. J., 1949, The direct approach to magnetic interpretation and its practical application: Geophysics, v. 14, no. 3, p. 290-320.

Ross, C. A., 1963, Structural framework of southernmost Illinois: Illinois State Geol. Survey Circ. 351, 27 p.

Rudman, A. J., 1963, A study of seismic reflections from the surface of the basement complex in Indiana: Indiana Univ. [Bloomington] unpublished Ph.D. dissertation.

Vacquier, V., Steenland, N. C., Henderson, R. G., and Zietz, I., 1951, Interpretation of aeromagnetic maps: Geol. Soc. of America Mem. 47, 151 p.

Warren, J. R., 1956, A study of magnetic anomalies associated with ultrabasic dikes in the western Kentucky fluorspar district: Kentucky Geol. Survey ser. 9, Bull. 19, 38 p.

Weller, J. M., 1940, Geology and oil possibilities of extreme southern Illinois: Illinois State Geol. Survey Rept. Inv. 71, 71 p.

Weller, J. M., Grogan, R. M., and Tippie, F. E., 1952, Geology of the fluorspar deposits of Illinois: Illinois State Geol. Survey Bull. 76, 147 p.

Weller, Stuart, Butts, Charles, Currier, L. W., and Salisbury, R. D., 1920, The geology of Hardin County and the adjoining part of Pope County: Illinois State Geol. Survey Bull. 41, 416 p.

Weller, Stuart, and Sutton, A. H., 1951, Geology of the western Kentucky fluorspar district: U. S. Geol. Survey, Mineral Inv. Field Studies, MF2, map and discussion.

Illinois State Geological Survey Circular 363
12 p., 5 figs., 1963

Printed by Authority of State of Illinois, Ch. 127, IRS, Par. 58.25.

CIRCULAR 363

ILLINOIS STATE GEOLOGICAL SURVEY

URBANA