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Magnetic and Gravity Features of Western Kentucky: Their Geologic Significance

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Western Kentucky is surrounded by major uplifts and depressions of the cratonic United States. To the west in southeastern Missouri, basement rises toward the crest of the Ozark Uplift where Precambrian volcanic and related epizonal intrusive rocks outcrop in the St. Francois Mountains. Precambrian basement rises on the east along the Cincinnati Arch in central Kentucky and descends deeply to the north and south beneath the Illinois Basin and Mississippi Embayment, respectively.

Western Kentucky is one of the most structurally complex regions in the craton. Four fault systems intersect this region and appear to either bound or lie along the axis of the Mississippi Valley graben, Rough Creek graben, and the Illinois Basin (fig. 1 in pocket). The northeast-trending Mississippi Valley graben (Hildenbrand and others, 1977, Hildenbrand, Kane, and Hendricks, 1982; Ervin and McGinnis, 1975) and the east-west trending Rough Creek graben (Soderberg and Keller, 1981) are thought to be extensional features formed during late Precambrian-early Paleozoic rifting. In western Kentucky where these two complex grabens intersect (fig. 1 in pocket) the crust is highly fractured and in places folded. Moreover, crustal discontinuities associated with the south-central magnetic lineament of Hildenbrand, Kucks, and Sweeney, (1982), which extends for more than 1,000 km from southeastern Tennessee to southeastern Nebraska and transects western Kentucky, may have influenced the development of several of the fault systems. As indicated by pronounced magnetic and gravity anomalies, a large number of mafic or ultramafic masses are also present in western Kentucky and are aligned generally along fault systems.

The gravity and magnetic anomaly maps reveal several prominent features that reflect the complex nature of crustal lithologies and structures in western Kentucky. Some of these features have been discussed in the literature, either individually or within a limited context. Here we bring together these anomalies and others not previously recognized and discuss their general interrelationship and possible geologic significance. The discussions pertain to a preliminary regional study of western Kentucky and do not contain details of structures and lithologics that are required to understand the tectonic evolution of this very complex region.

Aeromagnetic and gravity data

The magnetic and gravity anomaly maps shown in figures 2 and 3 (in pocket) have been compiled from data sets previously published by Hildenbrand and others (1981) and Keller and others (1980), respectively. Although a brief description of data reduction is given here, the reader is referred to these earlier publications for more detailed information on reduction procedures. The magnetic-anomaly map was compiled from data derived from 11 aeromagnetic surveys flown at elevations ranging from 500 ft (0.15 km) to 1,500 ft (0.46 km) above mean terrain and with a flight line spacing of 1 mi (0.31 km). The residual magnetic field was obtained over most of the area by removing the International Geomagnetic Reference Field (1965 and 1975) after updating to the time when the surveys were flown. An alternative reference field, POGO, was employed for the survey covering southern Indiana (Richardson, 1978). For each individual survey, an elevation of 1,000 ft (0.305 km) above the mean value of the terrain elevation was selected as the datum level. The data were continued upward or downward an amount equal to the difference between the mean terrain clearance and the selected datum level. This should not produce any significant error because surface relief over the area is low. Before merging, magnetic field values of each survey were adjusted by a constant amount, so that they were compatible with those of adjacent surveys. The data sets were then merged utilizing one-dimensional splining techniques described by Bhattacharyya and others (1979).

The gravity data were tied to the IGSN-71 gravity datum (Morelli and others, 1974) and reduced to simple Bouguer anomaly values using a reduction density of 2.67 gm/cc and the 1967 formula for theoretical gravity (Inter. Assoc. of Geodesy, 1967). No terrain corrections were applied because of the low topographic relief. Approximately 14,800 gravity stations at an average spacing of 2 km were used to construct the map shown in figure 2.

Two kilometer grids of both the gravity and magnetic values were created using a minimum curvature method (Briggs, 1974) and then contoured by machine.

Depth to magnetic basement

A magnetic anomaly map reflects structures and lithologic contrasts in the rocks of magnetic basement. Magnetic basement is defined as the upper surface of any lithologic unit having a susceptibility or remanent magnetization of sufficient magnitude to produce distortion in the magnetic field. In western Kentucky magnetic basement is interpreted as Precambrian crystalline rocks together with igneous rocks of younger age. Phanerozoic sedimentary units in the region generally lack magnetic properties and, therefore, produce little or no effect on the magnetic field.

An interpretational method developed by Vacquier and others (1951) was employed to estimate the maximum depth to magnetic basement. In this method, an observed anomaly is compared with theoretical anomalies produced by vertical prisms of various dimensions and by different orientations of the Earth's ambient field. It was assumed that the magnetic source is uniformly polarized in the same direction as the Earth's present field. When the areal shape of a theoretical anomaly closely matches that of the observed anomaly, maximum depth to the magnetic source is determined by comparing lengths of horizontal gradients associated with the two anomalies. The method yields maximum depths to magnetic sources because the theoretical models used in the curve-matching process are assumed to have vertical sides. In real geologic situations, the causative body generally has sloping sides; therefore, its actual depth of burial is more shallow than the computed depth. The estimated average error of depth to a magnetic rock body is 10 percent (Vacquier and others, 1951).

The accuracy of depth estimates depends on the validity of the geometric and magnetization assumptions. If these assumptions are reasonably valid, the method yields suitable depth estimates. Large errors occur, however, when the magnetic source is characterized by gently dipping sides or nonuniform magnetization. The probable error associated with the computed depths to magnetic basement in western Kentucky is difficult to assess because no wells have penetrated to Precambrian basement. The depth estimates reported here must, therefore, be regarded as generalized. One hundred and forty-five estimates of maximum depth to magnetic basement were determined by analyzing the anomalies shown in figure 2; the results are shown in figure 4 (in pocket).

Magnetic and gravity features

The magnetic and gravity data reveal several anomalies of varying intensities and wavelengths. Changes in depth to crystalline basement are a contributing factor in producing the wide variety of anomaly patterns. For example, long wavelength magnetic fields over the Rough Creek graben and the southwestern corner of the map area are caused, in part, by the deepening of magnetic basement (fig. 4); shorter wavelength magnetic anomalies are, however, observed in south-central and southeastern regions of the study area where basement is much shallower. The major cause of the magnetic anomalies is, however, lithologic variations in crystalline basement. Intense magnetic highs that coincide with prominent gravity highs are assumed to reflect underlying mafic or ultramafic igneous bodies; approximate horizontal extent of major interpreted igneous bodies are shown in figure 4. Gravity anomalies in western Kentucky are produced by lateral variations in the lithologies of the sedimentary sequence and variations at the crust-mantle boundary as well as by basement lithology and depth variations. Anomalously high density mantle material at the base of the crust may cause regional high gravity intensities near the southwestern corner of Kentucky (Cordell, 1977).

Because no basement test wells are available, the lithology of basement rocks must be inferred mainly from geophysical data or from known basement rocks encoutered in nearby regions. Granites and rhyolites crop out to the west in the St. Francois Mountains of Missouri and have been found in a few wells of southern Illinois. Lidiak and Zietz (1976) suggest that similar rocks generally underlie western Kentucky.

The wide variety of gravity and magnetic patterns in western Kentucky indicate the complex nature of structure and lithologies. In the following discussions we describe patterns and correlations that seem worthwhile to point out, although the nature of the source is difficult to completely understand for some anomalies. The principal features of the area are the south-central magnetic lineament, the Rough Creek graben, the Mississippi Valley graben, and numerous large inferred igneous bodies.

South-central magnetic lineament

The south-central magnetic lineament of Hildenbrand, Kucks, and Sweeney (1982) is a pronounced northwest-trending anomaly that extends at least to the New York-Alabama lineament (King and Zietz,1978) on the southeast in eastern Tennessee and may intersect the midcontinent magnetic high (King and Zietz, 1971) on the northwest in eastern Nebraska. Hildenbrand, Kucks, and Sweeney (1982) suggest that structures along the south-central magnetic lineament may have influenced the tectonic development of major geologic features in the midcontinent. The south-central magnetic lineament coincides geographically with the northern boundaries of the Mississippi Embayment, the Mississippi Valley graben, and the Ozark Uplift. The magnetic lineament seemingly reflects a structural boundary in basement rocks along which these regional features developed or their growth was impeded. It also crosses the saddle between the Cincinnati Arch in Kentucky and the Nashville Dome in Tennessee, suggesting a structural influence in the formation of the saddle.

A section of the south-central magnetic lineament (fig. 4) in western Kentucky marks an alignment of structures that probably resulted from tectonic processes along the lineament. The broad complex of magnetic highs located east of longitude 86° 30′ W. and south of latitude 37° 30′ N. (shown in fig. 2) is part of a very large anomaly pattern that extends into eastern Kentucky and Tennessee. The high-amplitude anomalies are abruptly truncated on their southwestern edge by the south-central magnetic lineament. Basement rocks encountered in drill-holes in the regions of these highs consist of mafic and felsic volcanics, amphibolites, and mafic two pyroxene granulites (Hinze and others, 1977). The mafic volcanics are similar petrologically to Keweenawan rocks observed in the Lake Superior region (Keller and others, 1975, 1982) and may represent an extension of the rift zone associated with the midcontinent gravity and magnetic anomaly system (Lyons, 1970). Hildenbrand, Kucks, and Sweeney (1982) suggest that the south-central magnetic lineament depicts a zone of deep-seated structures along which the upper crust was extended, and forming conduits for magma during Keweenawan time. The magnetic highs in the southeast corner of the study area may mark the location of large mafic plutons of Keweenawan age. The coincidence of gravity highs (fig. 3) with these magnetic anomalies supports the interpretation that the area is underlain by mafic plutonic rocks (fig. 4).

The near-surface plutonic rocks appear to have been emplaced predominantly along north-northwest trending features. The elongated distribution pattern of the igneous rocks may have resulted by emplacement along faults having a similar trend. Another plausible explanation is that the magma extruded onto an ancient irregular topographic surface with a north-northwest grain. Whatever the cause, the magnetic and gravity highs in the southeast corner of the map area indicate the presence of massive volumes of mafic material at shallow depths of about 1.5 km to 2.5 km (fig. 4).

From about 36° 50′ N. latitude and 87° 00′ W. longitude to the northwest corner of the study area, the south-central magnetic lineament is generally expressed as a 40 km-wide band of intricate magnetic highs which are elongate along the feature's principal trend (Lidiak and Zietz, 1976; Hildenbrand and others, 1982b). Near the region of its intersection with the south-central magnetic lineament, the east-northeast-trending Pennyrile fault system appears to bend to a more southerly trend and merge with the southwest-trending western Kentucky fault system. The change in fault trend may suggest that left-lateral displacements occurred along the south-central magnetic lineament. Mafic igneous bodies south of Pennyrile fault system have linear northern edges that coincide with the area of faulting. The ascension of magma which formed these igneous bodies probably resulted from extension of the faults at their intersection with the south-central magnetic lineament.

The southeastern margin of the Mississippi Valley graben also intersects the Pennyrile fault system within the region underlain by igneous intrusions, although the margin's northeastern continuation is somewhat ambiguous. Braile and others (1982) suggest that the graben is offset to the northwest by about 35 km and continues northeastward into southern Illinois. Other plausible explanations are that the southeastern margin of the graben may either bend easterly along the Pennyrile fault system or may simply terminate at its intersection with the fault system and with the structures of the south-central magnetic lineament. The latter of these possibilities is preferred here because there is no evidence that the Mississippi Valley graben crosses the east-west trending Rough Creek graben and because the Pennyrile fault system marks the approximate southern flank of the Rough Creek graben (Soderberg and Keller, 1981). Therefore, it is possible that the south-central magnetic lineament reflects an ancient structural boundary along which later growth of the Mississippi Valley graben was impeded. This would imply that structures related to the magnetic lineament developed during or before late Precambrian or early Paleozoic time, when rifting is thought to have formed the Mississippi Valley graben.

Northwestward of the Pennyrile fault system the south-central magnetic lineament crosses a highly fractured region at the junction of the western Kentucky, Wabash, and Shawneetown-Rough Creek fault systems (fig. 4). The western Kentucky fault system is a zone of normal faulting that occurs within a rift-formed graben, the Mississippi Valley graben (Heyl and McKeown, 1978; Hildenbrand, Kane, and Hendricks, 1982). The western Kentucky fault system and the Wabash fault system have the same northeasterly trend but lie on opposite sides of the south-central magnetic lineament. The break in strike at the lineament has led some (Stauder and others, 1976; Heyl and McKeown, 1978) to suggest tectonic detachment between the systems. Moreover, the Shawneetown-Rough Creek fault system bends abruptly to a southwesterly direction as it crosses the south-central magnetic lineament. Thus there appears to be an intimate relationship between the behavior of these fault systems and the structures associated with the south-central magnetic lineament.

The Illinois-Kentucky fluorspar district, located at the intersection of the south-central magnetic lineament with the western Kentucky, Wabash, and Shawneetown-Rough Creek fault systems, contains many dikes, plugs, sills, and diatremes of syenite to periodotite and also some explosion breccias (Clegg and Bradbury, 1956; Heyl and others, 1965). The intrusive rocks have Rb-Sr and K-Ar dates of approximately 260 m.y. (Zartman, 1977). Hicks dome which lies at the structural apex of the district is a crytovolcanic structure that contains mineralized breccia and kimberlite dikes (Heyl and others, 1965). A prominent magnetic and gravity high, centered about 8 km northeast of Hicks dome, has been interpreted by McGinnis and Bradbury (1964) as a reflection of a basic igneous mass that lies at depths of 3.4 to 4.6 km and encompasses a horizontal dimension of about 19 km (fig. 4). According to these data, that part of the south-central magnetic lineament in the region of the Illinois-Kentucky fluospar district delineates a region intruded by mafic igneous material which contrasts in geophysical properties with surrounding Precambrian rocks. The origin of the Illinois-Kentucky mineral district may, therefore, be closely related to the development of structures along the south-central magnetic lineament.

Farther to the northwest in southern Illinois, the Cottage Grove fault zone is coincident with the lineament. The presence of underlying mafic igneous material (fig. 4) suggests that the Cottage Grove fault acted as a conduit for ascending magma.

Rough Creek fault system and flanking features

The east-west trending Rough Creek fault system consists of many high-angle faults characterized by normal and reverse displacements. The system is expressed as steep magnetic and gravity gradients that separate relatively short-wavelength, high-amplitude anomalies to the north from anomalies with lower intensities and longer wavelengths to the south. Soderberg and Keller (1981) suggest that the change in magnetic and gravity patterns across the fault system is associated with high-angle basement faulting along which the major movement has been down to the south. The Rough Creek system represents the northern boundary of the Rough Creek graben (discussed below). Depths to magnetic basement significantly increase to the south across the fault system.

Mafic igneous bodies may have been emplaced north of and along the Rough Creek fault system. In the northwestern part of Kentucky (lat 37° 36′ N. and long 87° 48′ W.) a large plutonic mass, called the Madisonville pluton (Hildenbrand, Kane, and Hendricks, 1982), is indicated by both intense magnetic and gravity highs. The pluton, which appears to have intruded along the fault system, lies at a depth of about 3.4 km and has a diameter of roughly 20 km (fig. 4). The approximate age of the Madisonville pluton, as determined by interpreting magnetic-field data (Hildenbrand, 1978), is estimated as early Paleozoic, which includes a period of time (Cambrian) when movement occurred along the Rough Creek fault system (Schwalb, 1978). Five other mafic bodies of various shapes and dimensions (fig. 4) are apparently located north of the Rough Creek fault system between longitudes 86° 30′ and 88° 00′ W. Zones of surface faulting are observed over three of these intrusions.

Near its eastern end the Rough Creek fault system sharply bends to the southeast and briefly follows the east edge of an elongate magnetic and gravity high that protrudes from the broad complex of highs in the southeastern part of the study area. The coincidence in trend together with the linearity of the finger-like geophysical high suggest that the fault zone continues somewhat farther southeast to and possibly beyond the southern boundary of the study area at about longitude 85° 48′ W. The southeast continuation of the fault zone is highly speculative although its extension provides the means of channeling magma to form one or more of the interpreted linear igneous bodies.

The region north of the Rough Creek fault zone between longitude 85° 45′ and 86° 30′ W. is characterized by northeast-trending faults and underlying mafic igneous material. The igneous bodies appear to have intruded along these faults.

Rough Creek graben

The Moorman syncline is an east-west elongate structural depression that lies south of and parallel to the Rough Creek fault system. From models of gravity profiles, Soderberg and Keller (1981) suggest that this structure is superimposed over a graben, the Rough Creek graben, which developed on the Precambrian surface by rifting in late Precambrian or early Paleozoic time. The gravity and magnetic expression of the graben is clearly defined as long wavelength, generally low-amplitude anomalies. The graben is bounded on the north by the Rough Creek fault system and on the south roughly by the Pennyrile fault system. Magnetic basement between these two fault systems noticeably increases in depth and attains a maximum depth of over 6 km near longitude 88° W. The eastern terminus of the graben appears to lie at about longitude 85° 30′ W.; to the east, basement rises appreciably towards the Cincinnati Arch in central Kentucky. The structural high observed on the magnetic basement surface near longitude 86° 20′ W. is probably related to the emplacement of mafic igneous material. The geophysical expression of the Rough Creek graben is somewhat ambiguous to the west where it intersects the Mississippi Valley graben. Soderberg and Keller (1981) suggested that the graben narrows along trend to the Illinois-Kentucky State border and that the southern boundary of the graben in that area is alined with the south-central magnetic lineament. This is not apparent on the depth to magnetic basement map. Slight uplifting of basement beneath the south-central magnetic lineament may reflect underlying igneous material rather than the southern margin of the Rough Creek graben. Furthermore, the broad basinal feature immediately west of the south-central magnetic lineament, shown on the basement map (fig. 4) as a closed low, suggests the extension of Rough Creek graben westward beyond the lineament. However, this depression lies near the intersection of the Rough Creek graben and the Mississippi Valley graben and probably reflects structural coupling of the two grabens.

Mississippi Valley graben

The Mississippi Valley graben has been defined by geophysical studies as a 70-km-wide depression formed during rifting in late Precambrian or early Paleozoic time (Hildenbrand and others, 1977). The broad graben, with a structural relief of about 2 km, is clearly defined on magnetic-anomaly maps as a pronounced zone of subdued magnetic expression, extending over 400 km from eastern Arkansas northeastward to western Kentucky (Hildenbrand, Kane, and Hendricks, 1982).

In western Kentucky alternating zones of magnetic and gravity highs and lows trending northwest characterize the region lying within the horizontal extent of the Mississippi Valley graben. These zones or bands also lie west of and parallel to the south-central magnetic lineament. The nature of the sources of these anomalies is not completely known, although Lidiak and Zietz (1976) suggested that the northern edge of the northwest-trending band of highs represents the subsurface extension of the St. Genevieve fault zone southward from southern Illinois into western Kentucky. The zone of highs may reflect a structural high on the Precambrian surface and/or the presence of underlying intrusive bodies. The latter may be preferred as the sources of the gravity and magnetic highs because a significant volume of mafic igneous rocks are thought to lie along the trend of the highs at latitude 36° 36′ N. and longitude 87° 57′ W (fig. 4). The adjacent northwest-trending gravity and magnetic lows may then indicate the presence of rhyolitic Precambrian basement which contrasts with the highly magnetized and dense rocks lying along the northwest-trending zone of magnetic and gravity highs and the south-central magnetic lineament.

The southeastern margin of the graben appears to have been distorted along the Kentucky-Tennessee State line near longitude 88° W. Hildenbrand, Kane, and Hendricks (1982) suggest that the distortion of the margin was due to lateral southeastward movement of about 12 km of a crustal block after initial formation of the graben.

It is interesting to note that the numerous northeast-trending faults in the western Kentucky system have no apparent expression on the gravity and magnetic anomaly maps. The absence of anomalies suggests either that the faults have limited vertical extent and reflect only near-surface structural trends or that displacements on the Precambrian surface are too small to produce anomalies.

Conclusion

The magnetic and gravity data of western Kentucky reveal numerous basement anomalies that may reflect major geologic features. The intensities and wavelengths of the anomalies vary considerably within the region, suggesting that it has experienced a long and complex tectonic history. Magnetic and gravity features, which trend predominantly west to northwest, correlate well with major Precambrian and Paleozoic tectonic features and aid in delineating their lateral extent and associated structures. The major lithologic variations in crystalline rocks indicated in the gravity and magnetic data are intrusions of mafic material.

Of particular interest is the south-central magnetic lineament which trends northwestward across the region. The lineament could represent an area of structural focus, for several fault systems appear to terminate or bend abruptly in its vicinity. During late Precambrian or early Paleozoic time, the south-central magnetic feature may have acted as a structural boundary that impeded the growth of the Mississippi Valley graben. The magnetic and gravity highs along the lineament may delineate igneous bodies that intruded a fractured crust after extensional faulting. Igneous rocks in the vicinity of the south-central magnetic lineament have been dated as Permian in age. Movement along the Cottage Grove fault zone, which coincides with the lineament, occurred from Devonian through the remainder of the Paleozoic (Weller, 1940). These observations suggest that the south-central magnetic feature within the study area was active periodically during, at least, late

Precambrian and Paleozoic time.

The fault systems and mafic igneous intrusions of the region appear to be intimately related, and this strongly suggests that the fault systems are deep-seated in the crust and served as channel-ways for intruding magma. The presence of large igneous bodies, north of the Rough Creek fault system and near the southeast corner of the study area where little evidence of surface faults is present, may indicate concealed faults having large vertical extents.

The interpretation of the magnetic and gravity data point to pertinent research areas for future consideration that deal with the nature of structures and lithologies. For example, western Kentucky appears to be at a structural junction in the craton of the midcontinent, and structures in the Precambrian basement extend radially outward largely to the southwest, east, and northwest. The southwest-trending Mississippi Valley graben and the east-trending Rough Creek graben may have formed during the early stages of rifting in late Precambrian or early Paleozoic but more importantly appear to terminate in western Kentucky. Western Kentucky may be the site of a triple junction from which two arms are delineated by these grabens. The northwest-trending St. Genevieve fault zone and paralleling structures may represent the third arm along which extension was not substantial. The tectonic evolution of western Kentucky is further complicated by interpreted igneous bodies and structures associated with the south-central magnetic lineament. The understanding of the tectonic evolution of western Kentucky will require more detailed geophysical and geologic studies which deal with the interrelationship between structures and the forces that formed them.

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