A MAGNETIC PROFILE ACROSS THE NEMAHA ANTICLINE
IN POTTAWATOMIE AND WESTERN JACKSON COUNTIES, KANSAS

by 6791

MICHAEL KÖNIG

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Approved by:

J. R. Chelikowsky
Major Professor

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INTRODUCTION

Review of Geophysical Publications

Despite the considerable amount of geophysical work that has been conducted in Kansas (Hambleton and Merriam, 1957; Merriam and Hambleton, 1959a) only little has been published. However, there are many comments in literature pertaining to magnetic anomalies associated with the Nemaha Anticline.

Jenny (1932) studied local magnetic vectors and their spatial relationship to geologic structure. He suggested that in eastern Kansas magnetic highs correspond with structural highs and magnetic lows with structural lows. A possible shift of the magnetic axis of the anomaly to the west may be explained by the asymmetric shape of the Nemaha Anticline giving rise to a westward displacement of the center of mass with respect to the crest of the ridge.

Jakosky (1940), referring to Jenny's (1940) paper, states that the Nemaha Anticline gives rise to a positive magnetic anomaly due to its proximity to the surface which outweighs influences from sedimentary rocks.

Heiland (1940) reports that the magnetic method has been successfully applied to the delineation of buried structural features such as the Nemaha Anticline, thus implying structural control on magnetic anomalies.

Woollard (1943) conducted a transcontinental gravimetric and magnetic profile from New Jersey to California. The Kansas portion of the traverse passed through Kansas City, Lawrence, Topeka, Manhattan, Beloit, and Colby. Magnetic and gravity measurements were made at intervals of seven miles. Only a very small gravimetric high was recorded over the Nemaha

Anticline; lack of contrast between the density of the granite basement complex and that of the overlying Paleozoic sedimentary rocks accounts for this. No magnetic pattern at all was observed to correspond to the subsurface topography although the value obtained at the station located approximately on the fault trace was suggestive of an inflection point of curvature. Both east and west of the Nemaha Anticline conspicuous magnetic highs were recorded; they were interpreted as the effect of lithologic variations in the basement complex probably involving gabbro to the west and other basic rocks to the east of the ridge. Woollard stated, however, that his interpretations have to be regarded as suggestive rather than conclusive because of the uncertainties arising from the large spacing used and the measurement of only one single traverse.

In his review of Woollard's paper, Nettleton (1943) reported that positive gravity anomalies associated with the Nemaha Anticline had been observed in more detailed surveys in other areas of Kansas, thus pointing out the limitations of conclusions based on only one profile.

Jensen (1949) presented the results of a magnetic profile flown above the 40th parallel from eastern Colorado to western Indiana. He did not elaborate on the findings.

Merriam and Hambleton (1956) constructed a geologic cross section along the Kansas-Nebraska border and interpreted the Kansas portion of Jensen's traverse in terms of subsurface geology. They ascribed the general eastward rise of magnetic intensity as displayed by the profile to the eastward thinning of the sedimentary rock sequence. The Nemaha Anticline was found to be magnetically low relative to adjacent basins because of lithologic variations. A small positive anomaly superimposed on the regional low was believed to be due to the nearness of the granite to the surface. Local positive anomalies adjacent to the east and west of the uplift were thought to be produced by metamorphic rocks of high magnetic susceptibility.

Agocs (1959) used Jensen's magnetic data to determine the depth and structure of the Precambrian basement rocks. He also analyzed the anomalies with respect to geologic causes in the subsurface. He related sharp magnetic anomalies superimposed on the regional magnetic low over the Nemaha Anticline to differences in lithology of the basement complex. No correlation of known structural features and broad magnetic anomalies could be established. Calculated basement depths and well depths did show relatively good agreement in places.

Agocs (1959a) interpreted aeromagnetic profiles flown in Morris and Wabaunsee Counties across the Nemaha Anticline. He concluded that the general structural configuration could be determined from the profiles; a marked change of magnetic level on the western approach of the Nemaha Anticline was attributed to a change of basement lithology from mafic west of the ridge to granitic at the location of the uplift.

Merriam and Hambleton (1959) presented a compilation of several east-west magnetic and aeromagnetic profiles conducted in eastern and northern Kansas and including Jensen's traverse and Woollard's survey. Three magnetic profiles had been flown by the U.S. Geological Survey across the Nemaha Anticline in eastern Kansas.

The traverse from Doniphan to Marshall County showed no magnetic anomaly associated with the Nemaha Anticline or other structural features of the crystalline basement. The observed anomaly was rather assumed to be related to near-surface causes or changes in basement lithology.

A maximum difference in magnetic readings of about 200 γ was reported in southern Pottawatomie County. Here, the sharp decrease of magnetic intensity close to the eastern edge of the Nemaha Anticline was interpreted as being indicative of a possible fault in the subsurface. In conclusion it was stated that fair correlation between basement topography and magnetic values along the profile was observed.

The profile from Lyon to Dickinson County showed a 600-γ anomaly over the crest of the Nemaha Anticline. Anomalies of comparable magnitude, both east and west of the ridge, however, could not be correlated with structural features in the basement.

Baysinger (1963) investigated an area in Wabaunsee, Geary, and Riley Counties. Readings were taken every half a mile. The area of investigation is underlain by the Nemaha Anticline. His magnetic contour map shows general agreement of basement structure and magnetic intensity. Five profiles based on the contour map were constructed so as to demonstrate the relationship between magnetic anomalies and structure. The northern profiles generally show good agreement and suggest a fault on the east flank of the Nemaha Anticline. Very little conformity is indicated by the southernmost profile, however. Baysinger concluded that considerable conformity exists between magnetic anomalies and structural relief of the Nemaha Anticline in the area of investigation.

Dowell (1964) conducted an areal survey in northern Riley County. The grid spacing was half a mile; the area covered the Abilene Anticline and the Irving Syncline. He concluded that considerable agreement of magnetic anomalies and geologic structure can be observed in that area.

Nature and Purpose of Investigation

It is evident from the study of previous investigations that no clear-cut relationship between structure of the Nemaha Anticline and magnetic anomalies could as yet be established.

A deficiency common to all surveys reviewed above appears to be their lack of detail due to the fact that they were either carried out from the air or based on large spacings of half a mile or more. Therefore, it was believed that a study consisting of readings taken at short intervals should furnish valuable information on the subject.

Since the structural configuration of the Nemaha Anticline is fairly well known the measurement of a magnetic profile at right angles to the strike of the subsurface ridge was thought to be permissible as a source of useful data in accord with Hahn's (1961) statements.

Furthermore, uniform conditions--ideally extending to infinity--on both sides of the profile should exist to render the interpretation valid for the structure as a whole (Nettleton, 1943).

In view of these requirements a magnetic profile was measured in Pottawatomie and Jackson Counties. The traverse leg was 100 m (110 yards).

It was realized that this short distance of magnetic stations would not be feasible for investigations on a commercial scale or for future areal surveys. However, it was expected that once data from closely spaced stations were obtained the variation of the leg and its effect on the shape and magnitude of the anomaly would suggest the most reasonable distance for future studies.

Several investigators reported a subsurface fault on the east flank of the Nemaha Anticline (McClellan, 1930; Moss, 1936; Nelson, 1952; Gasaway, 1959). Ratcliff (1957) found evidence for a surface fault in northeastern Pottawatomie County. In his opinion the fault is an extension of what is termed the "Humboldt Fault" in Nebraska (Jewett, 1951). Rieb (1954) was not in favor of a fault in the area traversed by this profile; Thomas (1927) believed that a long fault scarp extends generally northeast and southwest across the entire state of Kansas. In a later study Koons (1955) supported this viewpoint.

It was thought that if a relationship of subsurface structure and magnetic anomaly exists at all this would be most clearly indicated in the vicinity and above the supposed fault.

Thus this investigation was undertaken to serve a three-fold purpose, namely (1) to provide evidence, if possible, for the correlation of magnetic anomalies and the configuration of the Precambrian basement, (2) to delineate a possible fault on the east flank of the Nemaha Anticline, and (3) to determine the spacing that seems to be most adequate for future magnetic investigations in this area.

Geographic Location and Physiographic Characteristics of the Area Traversed

The area through which the traverse passed comprises the northern half of Pottawatomie County and a small portion of central western Jackson County (Plate I).

The first reading was taken at a distance of 578 m (1,895 feet) in a W 1° S direction from benchmark 1354 in Section 7, T. 6 S., R. 8 E.

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EXPLANATION OF PLATE I

Fig. 1. Location of profile in Pottawatomie and western Jackson Counties (solid line). Extensions of the profile are indicated by dotted lines.

Fig. 2. Index map of Kansas showing area of investigation.

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PLATE I

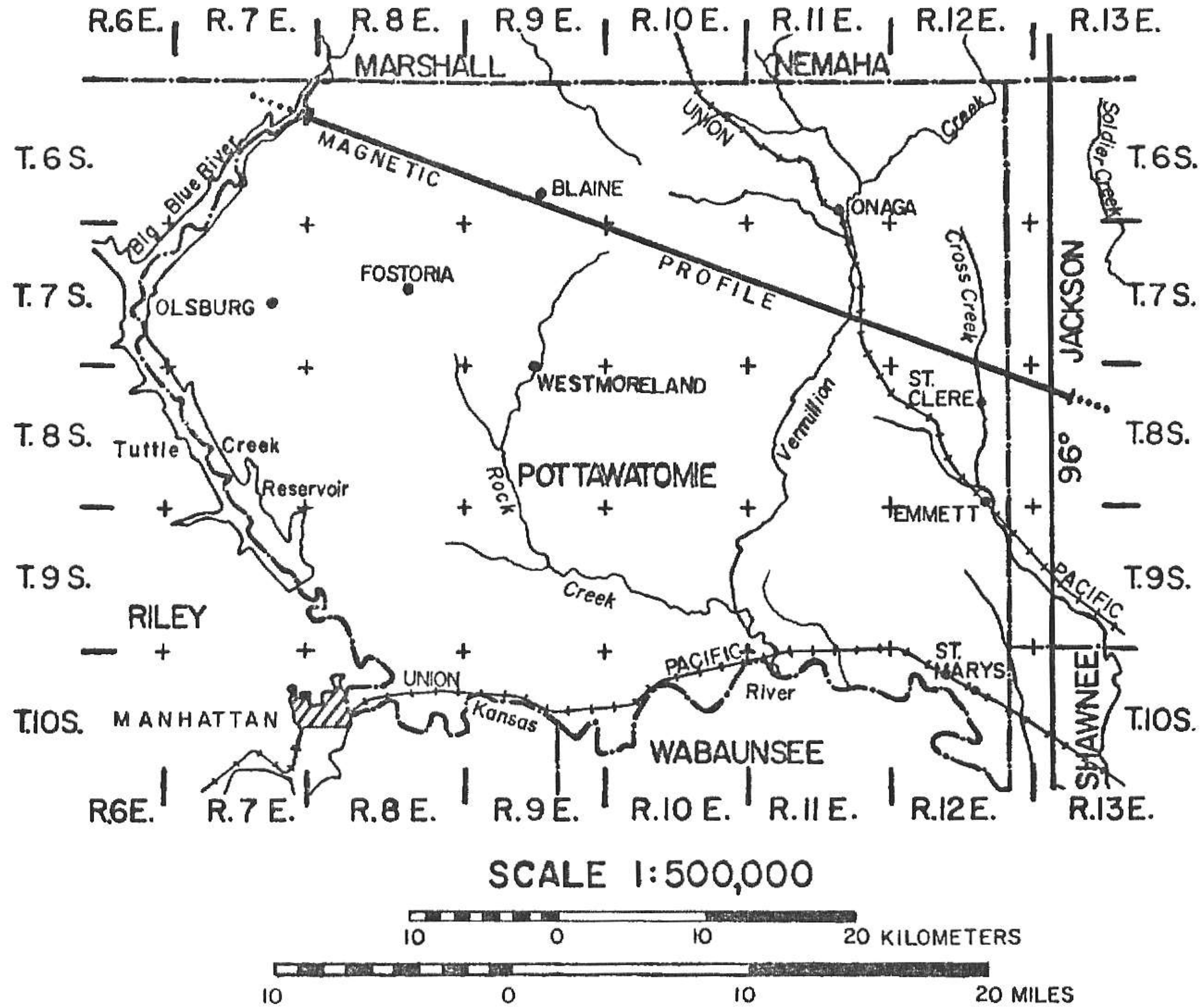


Fig. 1.

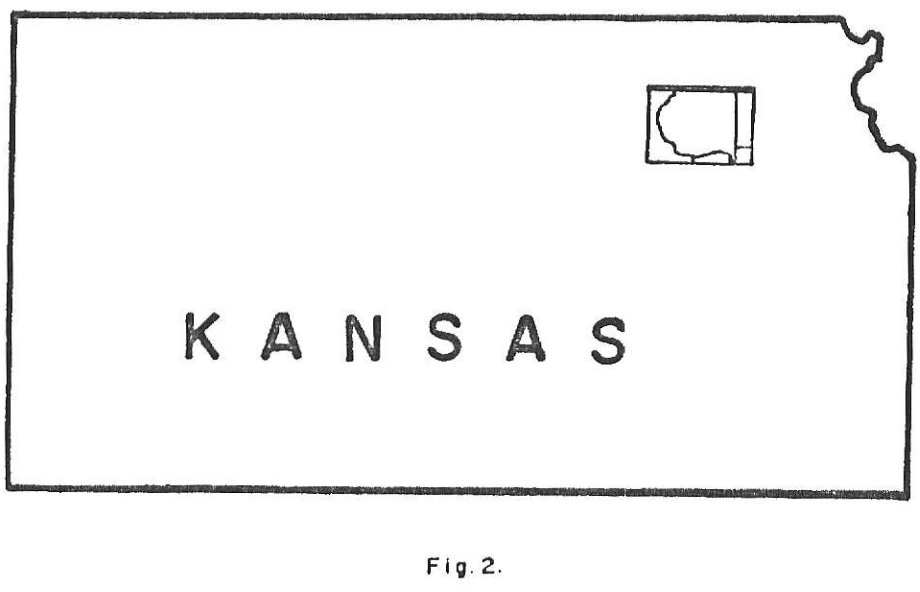


Fig. 2.

From there the profile extended through T. 6 S., Ranges 8 E., 9 E., and 10 E., T. 7 S., Ranges 10 E., 11 E., and 12 E., T. 8 S., R. 12 E. to the last station of the survey which was located at a distance of 84 m (275.4 feet) to the north, 84 m (275.4 feet) to the west from the southeast corner of SE 1/4, NE 1/4, NW 1/4, Section 8, T. 8 S., R. 13 E.

The direction of the traverse was S 70° E., which is at right angles to the approximate strike of the Nemaha Anticline (McClellan, 1930; Rieb, 1954). The total length amounts to 55 km (about 34 miles); the total number of stations equals 551 with a 100-m (110-yard) leg. According to the physiographic subdivision as discussed by Frye and Schoewe (1953) the profile passed from the "Flint Hills Upland" in most of Pottawatomie County to the "Dissected Till Plains" region bordering the Flint Hills to the east.

The Flint Hills are characterized by a parallel series of cuesta scarps and dip slopes developed on resistant cherty limestone of early Permian age (Frye and Leonard, 1952). The eastern face of the region is well defined, consisting of a steplike succession of stratigraphically controlled benches. The western part exhibits a relatively smooth series of gentle dip slopes on the resistant limestones. The fairly close spacings of the Flint Hills cuestas is a characteristic feature of the region (Frye and Leonard, 1959).

The Dissected Till Plains comprise much of northeastern Kansas. They display a well-rounded rolling surface, and are well drained and of mature topography. Most of this region is developed in glacial till with Pennsylvanian or Permian rocks exposed along the lower parts of the deeper valleys.

The area crossed by this investigation is drained by tributaries of the Big Blue River to the west and the Kansas River to the south (Plate I). The relief is moderate; along the profile it amounts to 144 m (470 feet); elevations range from 318 m (1,045 feet) at Vermillion Creek in T. 7 S., R. 11 E. to 462 m (1,515 feet) near Blaine.

GEOLOGIC SETTING

Tectonic Framework and Areal Geology

The area of investigation is part of that vast tectonic province of the North American continent which is termed the Central Stable Region (Moss, 1936). It is the buried southern extension of the Canadian Shield and, representing the continental nucleus, has undergone only slight deformation. Oscillatory movement of the crust gave rise to cyclic inundation and emergence, and gentle warping in conjunction with differential uplifts produced the major structural features: arches, domes, basins, and localized lines of faulting.

In comparison to the indefinite thickness of the crystalline basement the sediments accumulated in the course of time form but a thin veneer.

Paleozoic rocks ranging in age from early Permian to late Pennsylvanian crop out in Pottawatomie and Jackson Counties. The general northwesterly dip is about three meters per kilometer (fifteen feet per mile), i.e., less than one-half degree (Lee, 1943). A pronounced interruption of the gentle homoclinal dip constitutes the structural reflection of the Nemaha Anticline. The west dip is steepened and the east (reverse) dip locally reaches as much as twenty-three to forty meters per kilometer (120 to 200 feet per mile) (Powers, 1922).

Along the profile, the thickness of the sedimentary sequence varies from about 300 m (1,000 feet) at the crest of the Nemaha Anticline to almost 1,100 m (about 3,500 feet) in the adjacent Brownville Syncline.

In some places, Kansan glacial drift is present on upland areas, and unconsolidated alluvium occurs in major stream valleys.

Stratigraphic Succession

Precambrian Rocks. The Precambrian crystalline basement rocks include a metamorphic group and a suite of igneous rocks which intruded the metamorphic sequence (Farquhar, 1957).

The metamorphic rocks underlie most of north-central and northeastern Kansas. The continuity of their extent is broken along the crest of the Nemaha Anticline, although some outliers of metasediments occur along the trend or on higher parts of the uplift (Merriam et al., 1961).

Thus the profile traversed an area resting upon granite at the crest and on the flanks of the Nemaha Anticline whereas quartzite and schist are found at some places along the anticline and in neighboring areas.

The following description of the sedimentary sequence is largely based on Jewett and Merriam's (1959) presentation of the subject.

Cambrian-Ordovician Rocks. Cambrian and superposed rocks lie unconformably on the Precambrian base. They consist chiefly of dolomite but include some limestone and sandstone. Prominent subdivisions are, in ascending order, "Arbuckle Group," Simpson Group (including St. Peter Sandstone), Viola Limestone, and Maquoketa Shale. The combined thickness of the rocks in this division is about 450 m (1,500 feet) but large variations occur. Cambrian-Ordovician rocks are absent from higher parts of the Nemaha Anticline.

Silurian-Devonian Rocks. Rocks of Silurian and Devonian age are predominantly limestone and dolomite which lie unconformably on older rocks. The term "Hunton Group" refers to them collectively. They attain a maximum thickness of 200 m (650 feet) but have been removed by erosion from the crest of the Nemaha Anticline.

Mississippian Rocks. The Mississippian rocks are underlain by a sequence of shale termed Chattanooga Shale and Boice Shale, sometimes also called "Kinderhook Shale" separately or collectively. The known thickness of the Chattanooga Shale, probably of Devonian age, reaches about 75 m (250 feet); the maximum thickness of the Boice Shale, probably of Mississippian age, is about 35 m (110 feet).

Both formations have been removed from the highest part of the Nemaha Anticline and are also missing on its western flank in all of Pottawatomie County west of the uplift.

Prominent unconformities separate Mississippian rocks from older and younger portions of the sedimentary sequence. They are characterized by the dominance of limestone. In the area of investigation, they are absent from the crest of the Nemaha Anticline and its western flank. Elsewhere, the average thickness amounts to a few tens of meters (some hundred feet).

Pennsylvanian-Permian Rocks. Rocks of Pennsylvanian-Permian age constitute a structural unit with a wide range of thickness across the state of Kansas. In the area of investigation, both Pennsylvanian rocks and Lower Permian Series cover older sediments and the basement complex except for the highest part of the Nemaha Anticline; their compound thickness ranges from about 300 m (1,000 feet) to some 750 m (2,500 feet). Pennsylvanian rocks are exposed at the crest of the Nemaha Anticline, whereas Permian rocks crop out in the remainder of the area.

The lower Permian deposits and outcropping Pennsylvanian beds are similar in many respects; they consist chiefly of alternating layers of shale and limestone. Lenticular or channel sandstone bodies and coal beds make up a considerable part of the Pennsylvanian section and represent numerous cyclothems (Lee, 1956). Lower and Middle Pennsylvanian Series are lacking in the lithologic record at the crest of the Nemaha Anticline. Due to uplift of the basement and erosion during Mississippian and early Pennsylvanian times they have been stripped off their foundation.

Quaternary Sediments. Locally the outcropping units are concealed by glacial deposits and alluvium.

The glacial drift transported and laid down during Kansan glaciation is composed of till, clay, silt, sand, gravel, and boulders of limestone, igneous rocks, and pink quartzite (Frye and Leonard, 1952). The maximum thickness attained is in excess of 30 m (100 feet). Where present, erratic pink quartzite boulders are the most conspicuous rocks of the sedimentary sequence in Pottawatomie and Jackson Counties. Deposits of alluvium occur in some of the major valleys. In large part they are of postglacial origin (Lee, 1943).

Principal Structural Features

The most prominent feature of the Precambrian basement in Kansas is the Nemaha Anticline. It is named after Nemaha County in northeast Kansas where the deformation of the surface rocks is most pronounced (Lee, 1943). It extends across the entire state in a general N 18° E direction and into Nebraska as far as Omaha; its southern terminal is located in the vicinity of Oklahoma City (Lee, 1956).--Deviations from the general trend occur locally; in Pottawatomie County its strike is approximately N 20° E.--The anticline plunges to the south.

The Nemaha Anticline, a deformed erosion surface, exhibits an asymmetrical cross section with a much steeper east flank. A normal fault on the east limb with the upthrown part on the west is generally assumed although some controversy as to the existence of the fault still exists (Rieb, 1954; Lee, 1956).

Two topographic divisions of the Nemaha Anticline are recognized by Rieb (1954). The province north of T. 10 S. is characterized by a well-defined crest and smooth east and west sides without re-entrants.

The southern part consists of more irregular features like numerous hills, domes, and valleys.

Farther to the west, outside the area of investigation, the Salina Basin forms the basement floor.

East of the Nemaha Anticline the Forest City Basin extends from northeastern Kansas and southeastern Nebraska into Missouri and Iowa.

The deepest part of the Forest City Basin lies at its western margin. It parallels the Nemaha Anticline and deepens northward.

This structural low is commonly referred to as Brownville Syncline (Jewett, 1951).

The profile measured across the Nemaha Anticline thus comprises the gentle rise of the western flank, the sharp crest, the steeply dipping eastern slope cut by a fault, and the deep of the adjoining Brownville Syncline.

Structural History

Five periods of regional structural deformation affecting the area of investigation are recognized by Lee (1956). Three of these culminations of structural activity occurred during Paleozoic time (Lee, 1943). Prior to accumulation of Paleozoic rocks the surface of the Precambrian was subject to extensive erosion as evinced by the basal Upper Cambrian Lamotte Sandstone, which was derived from quartzite along the transcontinental arch (Anderson and Wells, 1968). Mostly marine sediments were deposited during Upper Cambrian and Lower Ordovician times. At the end of this period and prior to St. Peter deposition the first of the five periods of structural deformation was concluded: the Ozark Basin in central and eastern Missouri and the Southeast Nebraska Arch in northeast Kansas and southeast Nebraska had developed. All or parts of Riley, Pottawatomie, and Jackson Counties were included in the area of general uplift (Jewett and Merriam, 1959) because the rocks of the "Arbuckle Group" and older strata are missing. The structural pattern changed markedly after the deposition of the St. Peter Sandstone. Until the beginning of Mississippian time the Southeast Nebraska Arch subsided to form the North Kansas Basin whereas the Ozark Uplift took the place of the former synclinal basin. With the close of Chattanooga deposition these structural features were fully developed.

A new structural trend, represented by the Nemaha Anticline, the most conspicuous structural feature to arise, came into existence early in Mississippian time. It culminated at the end of Mississippian time and the beginning of Pennsylvanian deposition, and continued with decreasing intensity until Middle Permian time. The Nemaha Anticline bisected the North Kansas Basin producing the Salina Basin on the west and an unnamed basin, the precursor of the Forest City Basin, on the east. Peneplanation followed the first stage of folding. Subsequent events included the elevation of the area west of the Nemaha Anticline associated with the formation of an eastward-facing escarpment probably due to faulting, and the depression of the peneplain east of the anticline, which gave rise to the Forest City Basin. This was achieved before the invasion of the Pennsylvanian sea took place.

The contribution of faulting to the formation of the escarpment has been a subject of debate. Fath (1921) visualized the process of faulting for the elevation of the Nemaha Anticline, Thomas (1927) clearly advocated the same mechanism; Lee (1943) was convinced that faulting, at least on a local scale, did produce the displacement, and Koons (1955) concluded that a fault origin is inferential though not proved beyond doubt. Rieb (1954) argued against a fault origin of the Nemaha Anticline, and in a later paper, Lee (1956) revised his previous attitude.

In Pottawatomie County the inundation of the Nemaha Anticline was not completed until Kansas City time (Upper Pennsylvanian).

Further structural activity occurred during Mesozoic and Cenozoic times. Post-Permian, pre-Cretaceous tilting towards the west gave the Permo-Pennsylvanian rocks a westerly inclination. Apart from a general uplift of several hundred meters post-Cretaceous structural deformation superimposed a northward tilt on the rock sequence. The combination of these two structural deformations accounts for the slight northwesterly dip of the Permo-Pennsylvanian strata that is observed today. The last tilting occurred in Tertiary time when the present eastward slope of the land surface was established (Jewett and Merriam, 1959).

MAGNETISM OF THE EARTH

Geomagnetic Field and Secular Variation

The earth acts like a huge magnet in that it is surrounded by a magnetic field. A magnetic field is the spatial distribution of magnetic force (Chapman and Bartels, 1940). In order to describe this distribution the magnitude and direction of the magnetic force have to be determined at any location in space.

There are several ways of resolving the vector $\vec{F}$, representing the geomagnetic field intensity, into its components (Fig. 3): H, always considered positive, is the projection of $\vec{F}$ on a horizontal plane; at any point H may be resolved in components X (positive northward) and Y, pointing eastward when positive. Z is the projection of $\vec{F}$ on a vertical plane; it is measured positive downward. The angle made by H and the meridian is termed declination D, reckoned positive to the east. The angle of inclination or dip I is the angle made by the total magnetic intensity vector with the horizontal and is considered positive if $\vec{F}$

points downward. Three of the six elements H, X, Y, Z, D, and I are sufficient to determine $\bar{F}$ completely; thus only three of them are independent. F, H, Z, and I may be called intrinsic magnetic elements, whereas D, X, and Y may be referred to as relative magnetic elements (Chapman and Bartels, 1940).

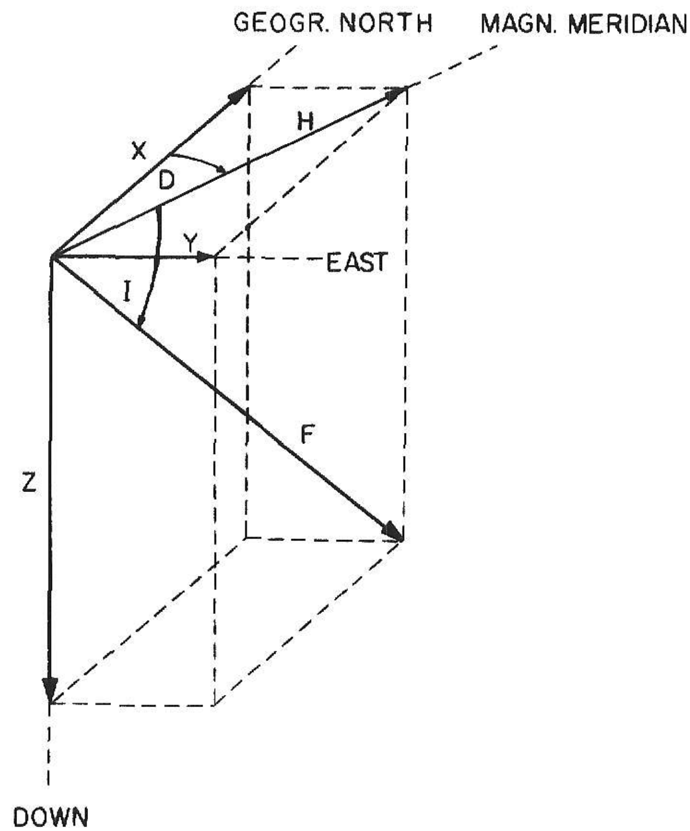


Fig. 3. The geomagnetic force F, its rectangular components X, Y, Z, and the elements H, D, I.

For mainly historical reasons geophysicists use the unit gauss for the magnetic intensity; since 1930 it has been officially called oersted among physicists (Kertz, 1969). A smaller more convenient unit is the gamma (γ): 1 gamma = 10^{-5} gauss. Both units are defined in the physical cgs (Gaussian) system.

When the magnetic field is measured on the earth's surface points are found where the vertical magnetic intensity vanishes, that is, the magnetic field is horizontal. An imaginary line passing through these points is the magnetic equator; it differs markedly from the geographic equator (Nelson et al., 1962).

A magnetic pole of the earth is a point at which the field is vertical, i.e., the dip is 90° and the horizontal intensity zero. This pole is more appropriately called a dip-pole; there are many of them associated with local anomalies on the earth's surface, and the principal dip-poles are located in the vicinity of the geographic poles at a distance of a few degrees of latitude (Chapman and Bartels, 1940). Dip-poles and geomagnetic poles as defined below are not identical.

Measurements of the geomagnetic field all over the world have revealed its general characteristics. They are most conveniently represented on magnetic charts as isomagnetic lines which are drawn through places having the same value. Thus isogonic lines connect points of equal declination, isoclinic lines pass through locations of equal dip, and places of constant intensity (e.g., horizontal, vertical, or total intensity) lie on isodynamic lines (Chapman and Bartels (1940), p. 97-101; Burmeister and Bartels (1952), p. 411-413).

The distribution of magnetic intensity is not uniform over the earth's surface (Nettleton, 1940). From the magnetic positive or north pole near the geographic south pole lines of force emerge. In the vicinity of the poles they are close together giving a relatively strong field. Near the equator the field has about half its intensity at the poles, is parallel to the surface, and points north. At the magnetic negative or south pole close to the geographic north pole the lines of force are crowded again and point inward to the center of the earth.

Towards the north or south from the magnetic equator the angle of magnetic dip increases until it is 90° at the poles.

Both the rise of magnetic intensity and growing dip angles towards the poles contribute to an increase in vertical intensity from the magnetic equator where it is zero to the north and to the south.

The earth's magnetic field is not confined to the surface. It extends far out into space diminishing to one-eighth its surface strength at a height of 6,440 km (4,000 miles) (Fleming, 1949).

It is one of the consequences of potential theory that the magnetic field of the earth can be described by spherical harmonics. It is possible to separate the permanent field into portions of internal and external origin. A non-potential part of the field, formerly postulated, would require electric currents flowing from the earth into the air and vice versa across the surface (Dobrin, 1960). It is now believed to be due to errors of observation. The externally originating portion probably comprises less than one percent of the permanent field (Nelson et al., 1962). It augments the horizontal magnetic intensity in equatorial regions and decreases the vertical intensity in polar regions. An ionospheric electric current flowing in an eastward direction around the earth's axis produces the same effect and constitutes a proper physical model (McNish, 1949).

Further analysis by spherical harmonics enables the observed internal field to be expressed as arising from a number of fictitious magnetic dipoles, each with different orientation, located at the center of the earth (Dobrin, 1960). As much as eighty percent of the main field can be exactly duplicated by the field of a short bar magnet located at the center of the earth. The dipole meeting these requirements best is directed toward a point at the surface at 79° North latitude, 290° East (70° West) longitude; its magnetic moment is presently 8×10^{25} gauss·cm^3 (Kertz, 1969).

The surface points associated with the axis of the centered dipole are called the geomagnetic poles; a system of geomagnetic co-ordinates hinges on them.

A slightly better representation of the actual field can be achieved when the dipole is located at a point shifted by 436 km from the center of mass toward a point at 74.3° North latitude, 150.8° East longitude according to Kertz (1969). The location of the eccentric dipole within the earth is called the "magnetic center."

As to the existence of the theoretically postulated sources of the earth's field it has been found that the internal field undoubtedly exists; according to McNish (1949) the external field is also very likely to be a physical fact, and Burmeister and Bartels (1952) express the same opinion. Runcorn (1956) does not believe in the reality of an external field and Kertz (1969) reports that--due to inaccuracy of measurement--its magnitude is too small to be detected.

It has also been established by observation that the earth's magnetic field is not a pure dipole field. The non-dipole or residual field, as the observed deviations are called, represents a number of large-scale or regional anomalies reaching values of several thousands of gammas. As far as the general characteristics of the residual field are concerned it is immaterial whether the normal field is produced by a centered dipole or a dipole located eccentrically in the earth's interior (Burmeister and Bartels, 1952).

Superposed on the regional anomalies there are local ones of much smaller extent. Some of them are limited to areas of a few hundred square kilometers while others cover only a few square meters (Chapman and Bartels, 1940). They constitute heterogeneously magnetized parts of the earth's crust above a depth of about twenty-five kilometers. In contrast, the regional anomalies are produced by some mechanism seated within the mantle or still deeper parts of the earth's body. This is inferred from the absence of anomalies intermediate between those of some thousands of kilometers as depicted on world maps and the local ones (Runcorn, 1956).

The dipole field is not the only one that is physically possible. A uniformly magnetized sphere would cause an identical distribution of magnetic intensity in its surroundings; a slightly greater magnetization of the earth's substance in the region toward which the dipole is assumed to be shifted would duplicate the field characteristic of an eccentric dipole. Likewise, earth currents flowing westward about the axis of uniform magnetization parallel to circles of latitude would generate the very field emanating from a centered dipole; proper modification of flow density would create the field of an eccentric dipole. The depth of the earth currents would be 1,000 to 3,000 km (Burmeister and Bartels, 1952).

The magnetic field as described above is subject to variations with time. These variations can be divided into several portions depending upon the intervals of time involved.

Secular variations are progressive for decades or centuries. Transient variations, in contrast, exhibit much shorter periodicities.

The secular variation partakes largely of the character of the main field itself. It affects all the elements of the magnetic field including the earth's magnetic moment. Since 1835 its magnitude has decreased by about six percent (Kertz, 1969). The rate and pattern of secular variation are constantly changing with time; they are unpredictable.

One of the means of illustrating the secular variation is the isoporic map, isopors being lines of equal annual change. In some places the isopors form closed curves known as isoporic foci (Chapman and Bartels (1940), p. 115-119, 123-128).

The most obvious manifestations of the secular variation are the apparent revolution of the earth's magnetic poles about the axis of rotation and the westward drift of the geomagnetic field. A planetary or world-wide nature of the secular variation should not be inferred, however, from these observations, most of which, especially the old ones, were made on only one continent. According to Runcorn (1956) it is now evident that the secular variation is a regional rather than planetary phenomenon.

The secular variation seems to be related to large-scale geologic structures in that the regional anomalous poles are shifting westward at a smaller rate than the corresponding isoporic foci (Burmeister and Bartels, 1952). This observation is interpreted as being indicative of a distinctly different behavior of the dipole and residual fields with respect to long-range variations. In fact, only about one-third of the secular variation rates at any one time seem to be due to the non-axial components of the main field (Runcorn, 1956).

An external part contributing to the secular variation is related to the eleven-year cycle in the frequency of magnetic disturbance and chiefly affects the horizontal and vertical magnetic intensities (Chapman and Bartels, 1940).

Various hypotheses have been proposed to explain the existence of the earth's main field and its secular change.

It is not reasonable to assume that permanent magnets representing the dipole and multipole models of the spherical harmonics are the cause for the earth's magnetic field. The increase of temperature with depth precludes any ferromagnetic property of matter beyond a depth of only fifty kilometers (Kertz, 1969). Furthermore, the average iron content of the crust and its magnetization are far too low to give the model of a uniformly magnetized sphere physical significance. Runcorn (1956) thinks that the inner (solid) core of the earth could be magnetized although laboratory experiments point to a decrease in the Curie temperature with pressure. On the other hand, the extreme pressures of the earth's core have as yet not been reproduced in the laboratory; they could modify magnetic properties of matter decisively.

The self-exiting dynamo theory is the most promising one (Nelson et al., 1962). It involves currents flowing in the outer portions of the core close to the mantle. Convection currents due to radioactive heat or perpetual gravitative settling and convection cells stabilized and oriented by the earth's rotation are other elements of this model

(Kertz, 1969). It would account for the secular variation and its most conspicuous feature, the westward drift of the isoporic foci if it is assumed that the earth's core rotates at a slightly lower speed than the mantle. The westward drift, in turn, would result in the observed apparent revolution of the earth's magnetic poles about the axis of rotation (Runcorn, 1956).

Furthermore, there are indications that this model could provide a solution to one of the prime problems of paleomagnetism, namely the frequent reversals of the earth's magnetic field during the last few million years (Kertz, 1969).

Transient Variations

The transient variations, characterized by much shorter periodicities compared to the slow process of secular variation, may be classified according to the periods of time involved. Small systematic variations from month to month are called annual variations; diurnal variations are more pronounced and have a periodicity of one day, and irregular fluctuations vary in amplitude and periodicity.

The overall effect of transient variations consists of a decrease of the horizontal intensity (Chapman and Bartels, 1940), and their cause is a complex of changing currents in the ionosphere and beyond.

Variations of external currents induce currents in the earth's crust; their contribution to the phenomenon amounts to one-fourth to one-third of its magnitude.

The transients are definitely known to be associated with solar effects and with conditions in the upper atmosphere. There, ionizing radiation from the sun consisting of both wave radiation (ultraviolet light) and corpuscular radiation gives rise to electric conductivity. The ionosphere, as this portion of the atmosphere is appropriately called, displays four principal conductive regions, denoted by D, E, F_1 and F_2, in variable heights between 65 and 1,300 kilometers above the earth's surface (Nelson et al., 1962).

The intensity of the sun's magnetic field is perhaps fifty times greater than that of the terrestrial field; because of the tremendous distance of 149 million kilometers, however, its influence on the geomagnetic field is negligible (Fleming, 1949).

Diurnal Variations. Like the secular variation, these short-time changes with a periodicity of approximately twenty-four hours affect all elements of the geomagnetic field.

The main features of the variation occur during daytime; the daily range is greater in summer than in winter and greater in high latitudes than toward the equator.

In the southern hemisphere conditions are reversed with respect to the northern hemisphere, and a portion of the tropics constitutes an inversion zone in which the northern type of diurnal variation predominates in June and the southern type in December (Nelson et al., 1962). The average range of this variation in magnetic intensity is of the order of thirty gammas according to Dobrin (1960). The characteristics of the diurnal variation indicate its strong dependence on the change of the earth's position relative to the sun.

Two components produce the observed changes, (1) that originating from the sun, and (2) the variation which responds to the moon's position in relation to the earth. The lunar diurnal variation represents not more than one-tenth of the total effect and can be derived only by careful analysis from very many observations. Unlike the solar variation it undergoes a progressive change in character throughout the lunar month, in a regular relation with the moon's phases. A further difference is the length of the lunar day of almost twenty-five hours.

Two-thirds to three-fourths of the daily variation is of external origin. Both external and internal components are represented by electric currents flowing above (ionosphere) and below (conductive portions of the crust) the earth's surface. Their combined effect enhances the horizontal magnetic intensity in the equatorial belt and weakens the vertical intensity in the vicinity of the poles. In the northern hemisphere the external currents are directed from east to west in the polar regions and from west to east at the equator. In the internal loop, to which the external currents give rise by induction, currents circulate in the opposite direction. In the southern hemisphere these conditions are reversed.

The distribution of the northern and southern current systems is subject to seasonal changes because of the periodic variation of the earth's position relative to the sun.

The external current systems producing the lunar diurnal variation are very similar to those just described. There is, however, a characteristic change in extent, shape, and magnitude of the systems in regular relation with the moon's phases (Bartels (1952), p. 750, 758).

The Stewart-Schuster dynamo theory has gained general recognition in providing a mechanism for the generation of external currents.

These currents are created, according to the theory, by the movement of ions across the lines of magnetic field intensity. It is the wave radiation from the sun, confined to the daylight side of the earth that is responsible for the ionization, and the required movement of the ions is due to lunar and solar tidal oscillations. Owing to resonance and solar heating of the atmosphere the solar tide outweighs the lunar atmospheric tide in contrast to the gravitational tide-producing forces on the earth's surface (Nelson et al., 1962).

Possibly the lunar daily variation originates in even higher layers of the atmosphere than the solar diurnal changes do because of the extreme sensitivity to alterations in magnetic activity (Fleming, 1949).

Annual Variation. The evaluation of magnetic observations of several years shows an annual variation of the magnetic field intensity. It seems to be related to the annual variation of magnetic activity and, apparently, has its origin outside the earth (Fleming, 1949). According to Chapman and Bartels (1940) its amplitude is of the order of ten gammas.

Magnetic Activity. The term "magnetic activity" refers to the frequency and intensity of marked irregular deviations from the normal diurnal variation during any given interval. Disturbances are more violent in polar regions; they have a tendency to recur after twenty-seven days, the period of solar rotation. A possible explanation is afforded by the observation that a stream of solar particles is often being ejected from one spot of the sun's surface for a period of several months. Thus, upon completion of every rotation of the sun, these particles sweep over the earth giving rise to the observed periodicity (Bartels, 1952).

It seems to be an established fact that magnetic disturbances vary in frequency with the number of spots upon the sun. These so-called sunspots are relatively dark spots on the face of the sun associated with strong magnetic fields. The sunspot cycle designates the interval between years of sunspot minimum and sunspot maximum; the average period is 11.2 years (Nelson et al., 1962).

A higher rate of occurrence of magnetic disturbances at the times of the equinoxes has also been recognized (McNish, 1949).

Magnetic disturbances may be classed into two groups, (1) world-wide magnetic storms and (2) smaller more restricted magnetic disturbances generally progressing haphazardly.

Magnetic storms, especially when of high intensity, often commence suddenly at the same time all over the earth. They show a tendency to oscillation and continued unrest during intervals varying from ten hours to several days; they rarely end abruptly (Bartels, 1952; Fleming, 1949). During these periods of pronounced magnetic activity the daily variation is much greater in intensity than on quiet days and markedly different in type, known as the disturbance-daily variation. Magnitudes of 100 γ or more are not uncommon under these circumstances (Dobrin (1960), p. 302). As in the case of the diurnal variation current systems in the upper atmosphere can account for the observed effects.

Disturbances of the storm type are produced by currents flowing around the earth in a ring several thousands of kilometers away and coplanar with the geomagnetic equator; the direction is either west to east (sudden commencement) or east to west (negative phase: residual disturbance). Corresponding currents are induced in the earth's crust; they diminish the magnetic flux entering the earth's body (McNish, 1949).

To account for the disturbance-daily variation, however, a much more complex current system in the ionosphere is necessary (Chapman and Bartels (1940), p. 302, 308, 310; Nelson et al. (1962), p. 29).

Spectacular auroral displays occurring predominantly in higher latitudes and severe disturbance or even disruption of radio communication are the most conspicuous manifestations of world-wide magnetic storms. Despite the similarities in nomenclature no relationship exists between magnetic storms and atmospheric weather conditions, the meteorological phenomena being too local in character and so different all over the world (Fleming, 1949). Apart from magnetic storms several other more localized magnetic disturbances occur, some of which are solar flare effects, bays, and pulsations (Bartels, 1952).

No general agreement as to the ultimate cause of magnetic disturbances has as yet been achieved. According to McNish (1949) most of the numerous theories attribute the various effects to the interaction of corpuscular solar radiation, the earth's atmosphere, and the geomagnetic field; thus they postulate a close correlation of these phenomena with the sun.

Magnetic Properties of Rocks

Local magnetic anomalies are caused by magnetized rock bodies or concentrations of magnetized minerals in the earth's crust. Inasmuch as rocks are aggregates of minerals their magnetic properties depend on the concentration and nature of the mineral constituents.--The following brief review of some of the physical facts connected with the magnetization of minerals and rocks makes use of a text written by Angenheister (1959).

The magnetic field surrounding a magnetized body can be thought of as resulting from the vector sum of the dipole fields of small magnetized volumes of the body. Each of these volumes dV possesses a magnetic moment $d\vec{m}$, and its magnetization equals $\vec{M} = d\vec{m}/dV$. If homogeneous magnetization is assumed magnitude and direction of $\vec{M}$ are constant throughout the body.

In the demagnetized state the individual dipole fields are oriented in a random fashion and neutralize each other so that there is no resultant field and no magnetic influence outside the body (Nettleton, 1940).

If placed in a magnetic field a magnetizable body assumes a magnetization which consists of two components, (1) the induced or reversible magnetization, and (2) the remanent (also permanent) or irreversible magnetization.

In many cases there exists a connection between the induced magnetization of the body and the external field. The simplest physically significant relation is linear and the proportionality factor is called magnetic susceptibility. It may be considered as a measure of the magnitude of the magnetic moments present in the material and of their mobility or the ease with which they can be oriented by the external field (Nettleton, 1940).

The reversible magnetization disappears as the magnetic field diminishes whereas the remanent portion persists without any external field. Both the induced and the remanent magnetization depend on the kind of constituent ions and the structure of the body; in addition, the irreversible magnetization is also determined by the preexisting magnetic, thermal, mechanical, and chemical conditions to which the body was subjected.

A magnetized geologic body gives rise to a magnetic field in its surroundings which can be detected on the earth's surface as the magnetic anomaly $\Delta\vec{F}$. It is permissible to assume homogeneous magnetization of the rock; in this case there exists a linear relationship between $|\Delta\vec{F}|$ and the magnetization M, given by $\Delta F = g \cdot M$, where the dimensionless factor g is determined by the geometry of the body.

The magnetization of a rock is the vector sum of the magnetic moments of its constituent diamagnetic, paramagnetic, and ferromagnetic (ferrimagnetic) mineral grains. Since the magnetization of ferromagnetic and ferrimagnetic minerals outweighs that of diamagnetic or paramagnetic material greatly it is justified to regard the magnetization of rocks as determined primarily by their content of ferromagnetic (and ferrimagnetic) constituents.

The chief minerals occurring in rocks which account for their magnetic properties are those oxides of the system $FeO - Fe_2O_3 - TiO_2$ shown in Fig. 4 (Runcorn, 1956a, p. 470).

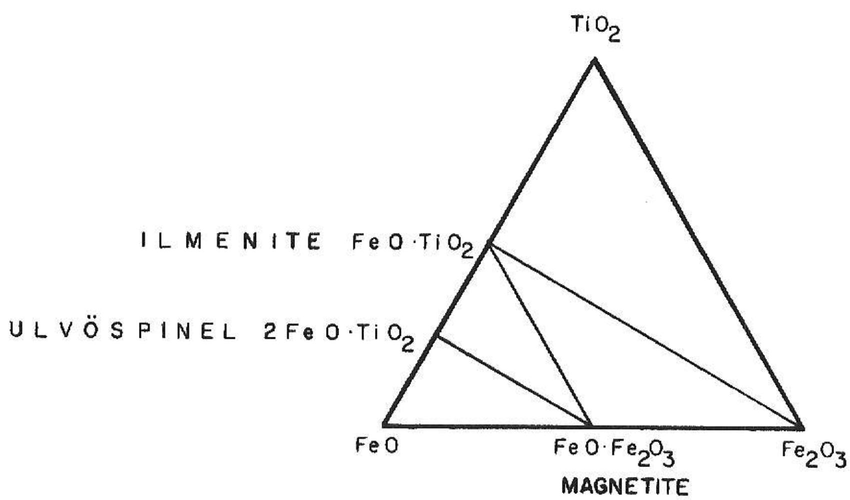


Fig. 4. Ternary diagram for the system $FeO - Fe_2O_3 - TiO_2$.

Magnetite is by far the most common and most important magnetic mineral (Chapman and Bartels, 1940), its susceptibility being very much greater than that of any other mineral (Haalck, 1934; Rössiger, 1952). It is therefore more meaningful to assume that the magnetite content determines the magnetization of rocks than to attribute the magnetic properties of geologic bodies to their overall iron content (Heiland, 1940).

There are several factors determining the magnitude of the magnetization of rocks and minerals the most important of which is temperature. A rise in temperature decreases the intensity of magnetization first slowly and then more rapidly until a critical point, the Curie temperature, is reached, where the minerals lose their ferromagnetic properties (Haalck, 1934). The Curie point is 348°C for pyrrhotite, 580°C for magnetite, and 645°C for hematite. Considering the rise of temperature with depth no rocks could be magnetized beyond a depth of about twenty kilometers (Heiland, 1940) or less than fifty kilometers according to Kertz (1969). However, it is quite possible that such tremendous pressures as occur in the earth's interior may alter this behavior unexpectedly.

Since the magnetization of rocks consists of two components it is important to know the relative proportion of induced and remanent magnetization. A change of attitude as to the value of this proportion can be observed in literature (Haalck, 1934; Chapman and Bartels, 1940). Today it is believed that the remanent magnetization generally exceeds the induced magnetization (Rössiger, 1952), and this seems to be especially so in the case of igneous rocks. They acquire their remanent magnetization largely upon cooling from above the Curie point in the magnetic field existing at the time of formation. In this manner the direction of the geomagnetic field in ancient geologic times may be preserved, which is an important subject of study in paleomagnetism (Kertz, 1969).

Intense local anomalous fields due to magnetization by lightning are also encountered in nature. Usually they do not extend beyond a distance of a few meters (Rössiger, 1952), but, according to Heiland (1940), the effect of lightning on rock magnetization is generally underestimated.

COLLECTION OF MAGNETIC DATA

Magnetometer

The magnetometer used in this investigation is the Varian Model M-49A Portable Magnetometer, a direct-reading instrument for measuring the absolute value of the total intensity of the earth's magnetic field.

It consists of a transistorized electronic package and a sensing head and weighs less than nine kilograms (twenty pounds).

The instrument, a nuclear precession magnetometer, utilizes only nuclear physical constants without being affected by external influences (Kertz, 1969); it is based on the phenomenon of nuclear magnetic resonance the accurate description of which involves quantum mechanics.

The following derivation of the equation of precession and its brief discussion are taken from Angenheister and Helbig (1965).

Most atomic nuclei have a magnetic moment $\vec{\mu}$ and an angular momentum $\vec{\ell}$ (spin). Thus they behave as if they were tiny spinning bar magnets. In a magnetic field $\vec{F}$ a torque $\vec{T}$ is exerted on the atomic nucleus owing to its magnetic moment $\vec{\mu}$. The torque, given by $\vec{T} = \vec{\mu} \times \vec{F}$, tends to align the magnetic moment with the direction of the magnetic field vector. According to the laws of mechanics this torque is equivalent to the change with time of the nuclear angular momentum; hence $\vec{T} = d\vec{\ell}/dt = \vec{\mu} \times \vec{F}$. In atomic physics a linear relation is known to exist between the magnetic moment and the spin of a nucleus, namely $\vec{\mu} = \gamma\vec{\ell}$, where γ is the gyromagnetic ratio, an atomic constant for a given substance. Thus, using the last equation one arrives at the final relation

$$\frac{d\vec{\ell}}{dt} = \gamma(\vec{\ell} \times \vec{F}).$$

It embodies the change with time of the vector representing the angular momentum and its spatial relation to $\vec{F}$, the acting magnetic force. In a small time interval Δt the vector $\vec{\ell}$ changes its position in space by $\Delta\vec{\ell}$, which may be expressed as $\Delta\vec{\ell} = \gamma(\vec{\ell} \times \vec{F})\Delta t$. Since $\Delta\vec{\ell}$ is perpendicular to both $\vec{\ell}$ and $\vec{F}$ (vector product) the vector of angular mementum--and because of $\vec{\mu} = \gamma\vec{\ell}$ also the magnetic moment $\vec{\mu}$ --moves about the vector $\vec{F}$ sweeping out a conical surface. This motion is called precession. Its angular frequency is known from theoretical considerations; it is termed "Larmor frequency" ω_L and given by $\omega_L = \gamma F$. Thus, if the constant γ is known and ω_L has been measured the quantity F, i.e., the magnitude of the total intensity $\vec{F}$, is accurately determined.

The simplest nucleus having the described properties is the proton, or hydrogen nucleus. Since the oxygen nucleus has no resultant magnetic moment responding to the phenomenon of nuclear resonance, the hydrogen in water serves as the assemblage of protons (Dobrin, 1960). The properties of this system of protons show features in addition to those of a single nucleus. They have to be considered if the magnetometer and the functions of its various elements are to be understood. In their normal state the protons in water are continually interacting because of thermal agitation. This precludes a uniform orientation of the nuclear magnetic moments of the system. Upon application of a polarizing field at an angle to and many (about 100) times stronger than the earth's magnetic field the system reaches a new equilibrium at a higher energy level after a certain time of relaxation (Waters and Francis, 1958). In this state the magnetic moments of the protons are uniformly oriented parallel to the strong polarizing field. The relaxation time termed spin lattice thermal relaxation time (Whitham, 1960) necessitates the application of the polarizing field for a period of several seconds before the new equilibrium is reached.

When the external field is suddenly removed, so that only the geomagnetic field remains, the magnetization vector of the hydrogen protons will precess about this field direction due to the inherent gyromagnetic properties of the nuclei. This precession movement gradually subsides because of the mutual interference of the protons; the time necessary for this fading of precessional motion is termed the transverse or spin-spin relaxation time (Waters and Francis, 1958; Whitham, 1960). The Larmor frequency of precession is about 2,000 c.p.s., the exact value depending on the magnitude of F (owing to $\omega_L = \gamma F$). The accurate measurement of this frequency requires a reasonable period of signal for observation, and it is only because of the relatively long decay times that this method of measurement has real practical value (Waters and Francis, 1958).

The rotating flux associated with the precessing magnetization vector induces a small electromotive force whose magnitude, also decaying exponentially as the precessional movement subsides, is of the order of a few microvolts for a few hundred cubic centimeters of water.

The direction of the polarizing field relative to the earth's magnetic field does not affect the frequency of the signal; its amplitude, however, is proportional to $\sin^2\theta$ if the external field is at an angle θ with the direction of the geomagnetic field (Whitham, 1960). Thus a polarizing field at right angles to the geomagnetic field furnishes the strongest signal. In order to produce a precession movement of the nuclei in the sample it is necessary that the external field be removed in an extremely short time interval of perhaps thirty microseconds or less (Waters and Francis, 1958).

The Varian Model M-49A magnetometer contains water in a plastic bottle surrounded by an induction coil. This coil has two functions; (1) upon passage of a heavy direct current through the wire it provides the strong magnetic field necessary for orienting the protons in the water, and (2) it acts as sensing coil to detect the precession signal caused by the protons after the polarizing field has been removed abruptly.

The signal is processed by means of electronic devices; it is amplified and its frequency then measured by comparison with a generated oscillation frequency. It is indicated as reed vibration on the reed meter calibrated directly in gammas. The reed meter consists of a total of fifty-three reeds spaced in twenty-gamma steps and gives a full range of more than thousand gammas. A twelve-step range selector makes it possible to register values through a total range of 12,000 γ.--By interpolation of the reed meter it is possible to distinguish values only five gammas apart.

Two factors determine the accuracy with which the magnetic field can be measured, (1) the nuclear constant (the gyromagnetic ratio), and (2) the frequency of precession.

The gyromagnetic ratio of the proton in water has been determined with high accuracy; it puts a limitation on absolute measurements of the total field intensity to $\pm 1\gamma$ (Waters and Francis, 1958). The overall accuracy of the magnetometer is $\pm 10\,\gamma$, and allows for possible temperature effects on components of the instrument.

Several major advantages of the magnetometer are evident. It is relatively simple in concept; it is a rugged instrument that allows absolute measurements of the total field intensity to be made accurately but does not require careful leveling or orientation. This increases the speed of operation greatly. Due to the principle of operation, external influences (temperature) and effects due to changes in properties of mechanical components (instrumental drift) are virtually nonexistent.

The precautions to be observed and the careful manipulation necessary in conducting surveys with a mechanical type of magnetometer (Alexanian, 1931) strikingly illustrates the progress made in the design of the nuclear magnetometer.

One disadvantage is that the time taken for an observation is at least one second, and hence the method cannot be used to investigate very short-period phenomena (Whitham, 1960). The fundamental deficiency based on the principle of operation is the extremely high sensitivity of the instrument to field inhomogeneities. The effect of a field gradient across the sample of the sensing head is to de-cohere the signal more rapidly effectively reducing the spin-spin relaxation time. According to Whitham (1960), a difference of ten gammas across the sample should de-cohere the signal within about one second. Artificial disturbing fields in populated areas but also naturally occurring gradients can cause a complete loss of the signal.

A minor disadvantage arises from the fact that the absolute value of the total intensity vector lends itself to interpretation less readily than any of its components (Kertz, 1969).

Field Procedures

Beginning at 578 m (1,895 feet) from benchmark 1354 (with the distance measured in a W 1° S direction) in Section 7, T. 6 S., R. 8 E., the profile was measured all through Pottawatomie County and into Jackson County where the southeastern terminal was chosen at 84 m (275.4 feet) to the north, 84 m (275.4 feet) to the west from the southeastern corner of SE 1/4 NE 1/4 NW 1/4 in Section 8, T. 8 S., R. 13 E.

To maintain the S 70° E direction of the traverse a Brunton compass was used, compensated for a magnetic declination of 10° E. In addition, the sites of stations were checked for spacing and alignment for the entire 55-km (34-mile) length of the profile on topographic maps of the 7.5 Minute Series (scale 1:24,000) published by the U.S. Geological Survey.

The profile consists of 551 stations separated by a traverse leg of 100 m (110 yards); this distance was measured by pacing. Thirteen base stations located along the profile were established in order to measure the diurnal variation during every day of field work.

Four readings were taken at every station, two of them each at different locations in the immediate vicinity of the station. It was believed that this procedure would assure the required reproducibility of the magnetic data.

Several precautions were observed to avoid influences from stray magnetic material. Personal iron-containing items other than those indispensable to conduct the field work were removed before entering the field. The disturbing influence of the necessary items (e.g., wrist watch) was reduced to a minimum by keeping them away from the sensing head as far as possible. The distances from cultural features given by Heiland (1940) and determined by Dowell (1964) for the Varian Model M-49A magnetometer were observed. Special attention was given to the location of the base stations; in order to make them easily accessible they were generally chosen close to roads without, however, ignoring the influence of the car used for the field work.

At some locations stations were too close to disturbing cultural features, whereas in other less obvious cases local inhomogeneities of the magnetic field could only be inferred from the broad and short-lived reed vibrations. In both cases the readings were discarded and new stations established. Where possible these stations were chosen perpendicularly to the direction of the traverse, and the data then obtained were substituted for the original ones. In this way no station had to be sacrificed.

Twice the traverse line was translocated at right angles to the original profile in order to escape the influence of farm buildings. Readings taken along the line of shift showing no change in intensity justified the procedure. When the buildings had been passed parallel to the direction of the profile the original traverse line was resumed. Thus a 300-m (330-yard) portion of the profile was shifted to the south by about 250 m (275 yards) at the borderline of Section 1, R. 9 E., and Section 6, R. 10 E., T. 7 S.; a northward translocation of 200 m (220 yards) took place at the west boundary of Section 6, T. 8 S., R. 13 E.; again 300 m (330 yards) sufficed to by-pass the obstacle.

Apart from disturbances due to man-made features natural field gradients occurred in places. Generally, they were confined to areas covered with glacial till. Raising of the sensing head higher than normal (i.e., about 1.2 m or four feet) could reduce the effect in some cases whereas in others it was not possible to obtain a sharp vibration on the reed meter.

In order to get an impression of the field intensity beyond the range of investigation the profile was extended by four stations on the southeast and by three stations on the northwest. Their locations were determined by the direction of the traverse line and their accessibility. Thus extension stations 1, 2, 3, and 4 were established in Jackson County, T. 8 S., R. 13 E. at distances of 850 m (0.53 miles), 1,050 m (0.65 miles), 2,525 m (1.57 miles), and 2,700 m (1.68 miles), respectively, from the southeast end of the profile; extension stations 5, 6, and 7 were chosen in Riley County, T. 6 S., R. 7 E., at 2,100 m

(1.30 miles), 2,950 m (1.83 miles), and 4,025 m (2.50 miles), respectively, from the northwest traverse terminal (Plate I). These stations as well as those of the profile proper are arranged on a line running N 70° W at right angles to the strike of the Nemaha Anticline.

Thirteen base stations were distributed along the profile. The total number of stations being 551 an average distance of only 4.2 km (2.6 miles) corresponding to 43 stations was assigned to every base station, with a minimum distance of 0.9 km (0.56 miles) and a maximum spacing of 6.3 km (3.91 miles). In fact, a much smaller number of base stations would have been sufficient for the entire length of the profile (Nettleton, 1940; Dobrin, 1960) but due to the then larger separation and the frequent checks necessary this was impracticable.

In order to obtain a sufficiently accurate measure of the diurnal variation readings were taken at the base stations at regular intervals of one hour. It was believed that this frequency would assure the registration of the diurnal variation with an error not greater than that of the instrument, that is, $\pm 10\ \gamma$. According to Nettleton (1940), readings taken at two-hour intervals could miss details of the diurnal variation (in vertical field intensity) of as great as ten gammas.

When two or three base stations were used during any one day of field work the difference in intensity between these stations was measured at the end of the day. The time required to move from one base station to the other did not exceed twenty-five minutes in any case, and it was assumed that during that time no change of intensity occurred.

The field work was conducted in eleven days during the month of April, 1971. The average number of stations per day was 53 corresponding to a distance of 5.2 km (3.23 miles); the minimum distance covered on one day was 3.3 km (2.05 miles), the maximum 6.5 km (4.04 miles). On the average ten and one-half hours per day were spent in the field.

About one month after the profile had been completed and the preliminary evaluation was under way several small portions of the profile were checked in the field. These stations represented either obvious local disturbances or crucial sections of the profile. Except for most of the local deviations excellent agreement with the original data was obtained. Readings were re-taken at the first forty-six stations of the profile in Sections 7, 18, 17, T. 6 S., R. 8 E., and at other stations located in Townships 6 S., 7 S., Ranges 9 E., 10 E., 11 E., and in T. 8 S., R. 13 E. The extensions of the profile in Jackson and Riley Counties were also measured during this second period of investigation.

INTERPRETATION OF FIELD DATA

Construction of Geologic Cross Section

Several sources were used in constructing the geologic cross section. A series of structural contour maps published by the State Geological Survey of Kansas provided most of the information needed. Thus, the configuration of the Precambrian basement, and structure and subsurface distribution of Cambrian-Ordovician (Arbuckle Group) sediments, Silurian-Devonian ("Hunton Group") strata, Mississippian rocks, and Pennsylvanian (Lansing Group) formations were obtained from these maps. (They are enumerated under "References.")

Details regarding the thickness and distribution of these and other rocks were taken from papers written by Lee (1943, 1956) and from a publication of the State Geological Survey of Kansas on the stratigraphic succession in Kansas (Zeller, 1968). Use was also made of the most recent Herndon maps issued by the Herndon Map Service, Oklahoma City, Oklahoma.

The structural maps referred to have a scale of less than 1:600,000. It was evident that the geologic cross section had to be based on a larger scale because of the amount of detailed magnetic information available. A scale of 1:250,000 was considered a good compromise although it was realized that by simply magnifying maps of a small scale inherent errors would be enlarged rather than additional information gained.

Due to scarcity of data from wells drilled into the subsurface the areal extent of the rocks, especially the exact location of the zero edge is perforce conjectural; thus, as new information becomes available the geologic cross section will undoubtedly have to be modified. It is believed, however, that the distribution of subsurface rocks is sufficiently accurate as to enable a conclusive interpretation of the magnetic profile to be made.

The surface elevations along the traverse line were taken from topographic maps used for the field work. The outcrop pattern of the section, determined from thicknesses of subsurface strata and topographic relief was compared with the areal geology as shown on the Geologic Map of Kansas; good agreement was found to exist.

The Precambrian basement was assumed to be faulted (as on the published map). For comparison a section of the Precambrian rocks was also drawn utilizing Rieb's (1954) structural contour map which shows no fault in the subsurface. This profile was discarded, however, because of lack of correlation with the magnetic data.--The location of the subsurface fault will be discussed later.

A twenty-five fold vertical exageration was chosen for the cross section. It was believed to permit a good representation of the principal rock units without too pronounced a distortion of dips.

The geologic profile shows at a glance the broad characteristics of the subsurface (Plate III). The gentle rise of the Precambrian basement on the northwest is reversed at the crest and suddenly interrupted at the site of the fault. The adjacent structural low to the east is known as Brownville Syncline, the deepest part of which lies eastward beyond the small intervening swell.

Rocks belonging to the Arbuckle Group and older strata--now missing in most of the area--have been removed by erosion prior to the deposition of the St. Peter Sandstone (Simpson Group). Due to the development of the Nemaha Anticline and ensuing erosion, rocks of Mississippian age were removed from the crest and the western limb of the uplift.

A local reversal of the gentle northwestward dip of Permian and Pennsylvanian strata is the surface expression of the underlying Nemaha Anticline. Pennsylvanian outcrops breaking the continuity of the uppermost Permian rock cover also reflect the conditions in the subsurface.

Reduction of Magnetic Data

Before magnetic readings could be plotted, several correction factors were applied, compensating for the variations with time and the spatial variations of the earth's magnetic field.

Diurnal Correction. Because of their magnitude diurnal variations have to be taken into account in reducing data taken with field magnetometers.

Readings that had been obtained from several base stations during any one day in the field were referred to one of the stations by compensating for the difference in magnetic intensity between them. This difference had also been determined in the field.

It was then assumed that the variation at the base of reference was valid for the entire length of the profile completed during that particular day. According to Nettleton (1940) and Dobrin (1960) a given diurnal correction curve can be used quite safely for corrections to a few gamma for distances of eighty kilometers (fifty miles) or more from the point at which it is determined.

The error introduced into the determination of the diurnal variation was almost exclusively due to the technique applied, i.e., the hourly return to the base stations instead of continuous recording, which, however, would have required simultaneous operation of two magnetometers.

Since the total error of the magnetometer readings ranges up to ten gammas it would have been of little value to determine the diurnal variation with higher accuracy. The variation curves based on hourly readings were therefore assumed to serve the purpose adequately, as is demonstrated by the curves shown in Jakosky (1940, p. 106) and Nettleton (1940, p. 192, 193).

With the measurements thus connected to one base station a curve was plotted by joining the values linearly. An arbitrary line of zero time was then chosen, and the measured magnetic data were corrected by adding or subtracting the amount by which, at the time of the field reading, the daily variation curve was below or above its value at the zero time.

Most of the curves show the general characteristics of a minimum in intensity approximately at noon but in detail they differ appreciably both in magnitude and shape of the peaks.

Fortunately, they do not provide evidence for the occurrence of major magnetic disturbances.

Annual and Secular Corrections. Because of their small magnitude annual and secular correction factors were not applied to the magnetic data in accord with Alexanian's (1931) recommendations. With a total amplitude of ten gammas (Chapman and Bartels, 1940) it is obvious that the effect of the annual variation during the time of investigation is completely negligible. This also holds true for the secular variation. It has to be taken into consideration, however, when absolute values from magnetic charts are needed in the process of evaluation. Due to their continuous change isomagnetic lines are only valid for a specified date but can be corrected since the change may be considered steady for a period of several years.

Normal Corrections. The geomagnetic field varies over the surface of the earth. Its intensity changes in relation to latitude and longitude but this relationship is not constant and cannot be established theoretically (Jakosky, 1940) because of the deviations of the earth's field from the ideal dipole field.

The normal corrections applied to the magnetic data were determined from the "Total Intensity Chart of the United States, 1965.0" published by the U.S. Coast and Geodetic Survey.

The extent of the profile made normal corrections necessary (Haalck, 1934). Since the area traversed was deemed sufficiently small it was permissible to determine them by linear interpolation (Nettleton, 1940).

The profile almost parallels the isodynamic lines so that the variation in intensity from station 1 (northwest Pottawatomie County) to station 551 (Jackson County) amounts to only -20 γ with absolute values of 57,165 γ and 57,145 γ, respectively.

The total intensity chart used was published in 1965, and its isodynamic lines refer to January 1, 1965. In addition to isodynamics, lines of equal annual change (decrease in total magnetic intensity) are shown which enable the required correction for secular change to be made easily.

Linear interpolations were made between the sixty-gamma and fifty-gamma isopors. Thus the total intensity was found to diminish by 59.4 γ annually at station 1 and by 58.1 γ at station 551. Assuming a constant rate of decrease for six years and four months (thus obtaining values for May 1, 1971) one determines a total decrease of 376 γ for station 1 and 368 γ for station 551. The resulting total intensities are approximately 56,790 γ for station 1 and 56,775 γ for station 551; the difference of 15 γ between these stations was distributed linearly among the data of the profile.

There is no uniform classification of magnetic anomalies. Chapman and Bartels (1940), Runcorn (1956), and Dobrin (1960) distinguish regional and normal anomalies superposed on the normal field originating from a centered or from an eccentric dipole in the earth's interior (Burmeister and Bartels, 1952). Jakosky (1940) recognizes major, continental, regional, and local anomalies, and Jenny (1940) also classifies magnetic anomalies as continental, regional, and local. Inasmuch as these regional and local anomalies arise from inhomogeneously distributed magnetization of rocks in the upper portion of the earth's crust it seems appropriate to call them "local anomalies" collectively. Correspondingly, the second class of anomalies will be referred to as "regional anomalies."

Regional anomalies are responsible for the irregular trend and distribution of isomagnetic lines and are, therefore, already included in the U.S. Coast and Geodetic Survey maps (Heiland, 1940). Regardless of the classification preferred it is sufficient to form the difference of the field data corrected for diurnal variation and the normal values as determined from the chart in order to obtain the anomaly measured along the profile. It would be termed "regional" according to Jakosky's and Jenny's classifications whereas in Chapman and Bartels' terminology it would be referred to as "local" anomaly.

Other Corrections. Corrections of topographic effects are usually negligible in magnetic surveys. Only if the uppermost surface rocks are magnetic themselves and only if the separation of stations is of about the same order as the depth of the disturbing mass are terrain corrections permissible (Haalck, 1934). Since these conditions were not expected or observed no correction of this kind was applied to the field data.

Standard corrections in connection with mechanical magnetometers are instrumental-drift and temperature corrections. Owing to the principle of operation of nuclear magnetometers they are unnecessary for data collected with these instruments.

Determination of Optimum Spacing

The magnetic field data, corrected for diurnal variations, were plotted as total magnetic intensity curve (Plate II). A scale of 1:50,000 was used to provide sufficient separation of the 551 stations.

Two broad characteristics of the curve may be distinguished. Adjacent to the central part there are two relatively smooth sections displaying fairly constant or only gradually changing field gradients. In contrast, the central portion of the profile, from about station 202 to station 420 is more rugged and consists of several major peaks due to rapid variations of field gradients.

Spacings of 200 m (1/8 mile), 400 m (1/4 mile), 600 m (3/8 mile), 800 m (1/2 mile), and 1,000 m (5/8 mile) were established by connecting only those stations of the profile that were separated by the fitting distances. The stations were joined by straight lines; it was believed that this method would show deviations from the 100-m profile distinctly. Error bars attached to every plotted value show the overall accuracy and were also intended to serve as a measure of the expected deflections.

It can be seen at a glance that only slight deviations occur on the eastern and western limbs of the profile. Where gradients are constant or nearly so the lines differ from the original curve by only slightly more than ten gammas. In these portions of a moderate, more or less uniform gradient numerous small deflections occur. They consist of irregular oscillations and are greatest in amplitude for lines of large spacings. In the vicinity of station 173, for example, the 600-m line deviates by about 13 γ whereas 20 γ are found for the 800-m line.

Despite its ruggedness the central portion of the profile shows stretches with good agreement but also the most conspicuous deflections of the entire profile.

It may be seen by inspection that the steepness of field gradients alone does not cause marked disagreement. The peaks in the central part of the profile display steep gradients yet the accuracy obtained from widely spaced readings on the flanks of the maximum peak at station 312, for example, is only slightly lower than that from sections with much shallower gradients.

A change or reversal of gradients, however, does result in pronounced divergence; this effect is enhanced where the change is abrupt, i.e., gradients are steep, while in sections of smooth gradients only slight deflections are observed. This is very well demonstrated by the minima at stations 293 to 298 and 528 to 533. In both magnetic lows the gradient is reversed over a distance of 500 m yet the departures from the original profile differ markedly in magnitude. In the vicinity of station 530 the 1,000-m line deviates by only slightly more than 10 γ but at station 298 a difference of as much as 65 γ occurs. Where the reversal of gradients is performed more gently as is the case at the maximum of station 312 no such great contrast in values results.

It is also evident that larger spacings give rise to greater deflections: thus near station 295 the 1,000-m line reaches the maximum value of 65 γ, a difference of 35 γ is obtained for a separation of 800 m, 40 γ are recorded for the 600-m spacing yet 20 γ for a distance of 400 m. Further examples are the minimum at station 365 (25 γ for 1,000-m, 15 γ for 800-m, 13 γ for 600-m lines) and the maximum at stations 282 to 286 (50 γ for 1,000-m, 40 γ for 800-m, 35 γ for 600-m, and 15 γ for 400-m lines).

A shift of magnetic extreme values depending on the spacing used is also observed. Examples are the maximum at stations 281 to 285 and the adjacent minimum (stations 294 to 298).

It is realized that the effects attributed to variable spacings also reflect the choice of stations. Most of the deviations will undoubtedly be modified as to magnitude and location if lines of equal distances connect a different set of stations. Even then it is very unlikely, however, that given a certain traverse length or an area of investigation large spacings will not lead to deflections of the order of magnitude just described.

The range of observed differences is also related to the width of maxima and minima. In general, as the extremes approach the spacings in width agreement of data will improve.

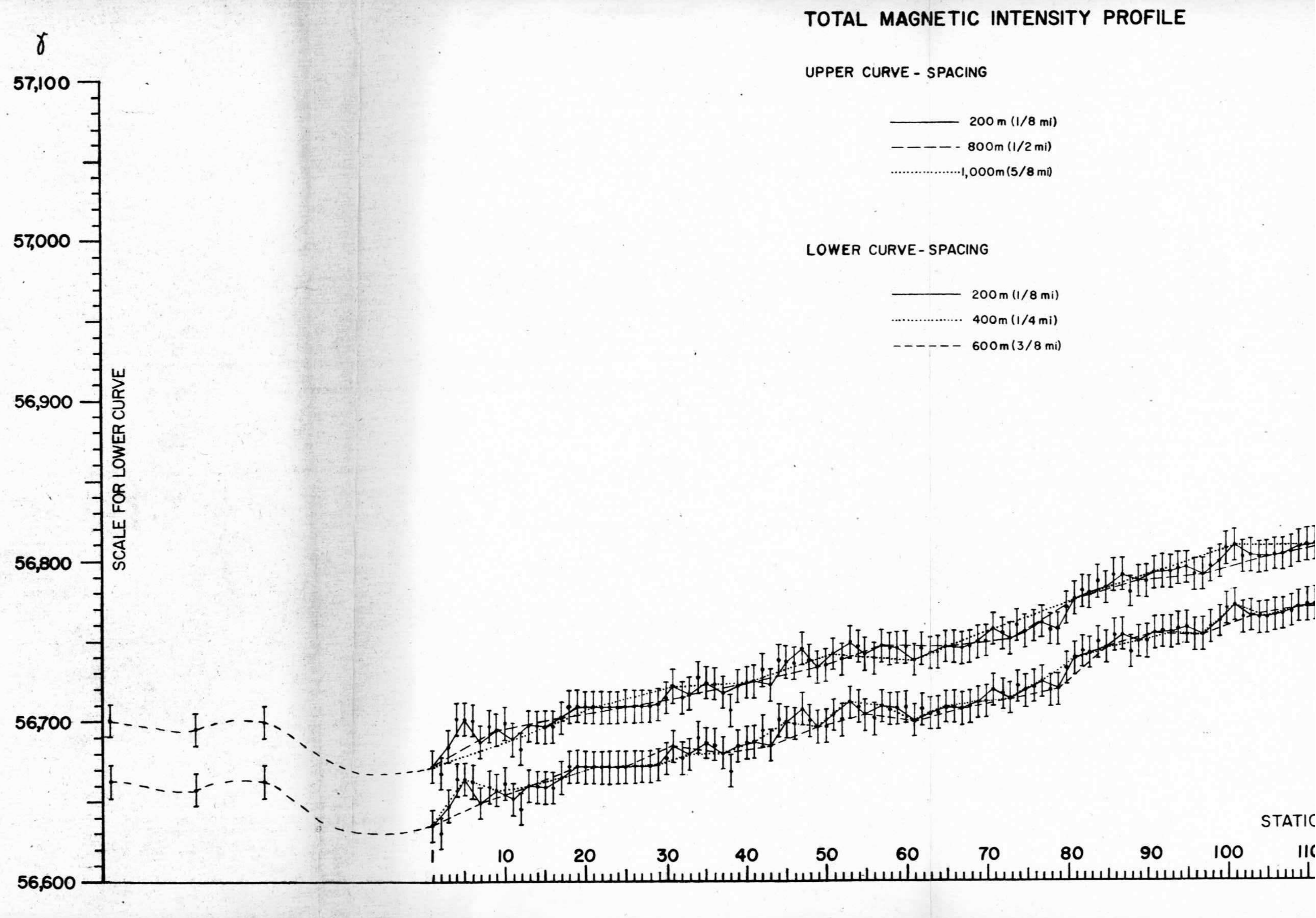
Essentially, large spacings have a smoothing effect on magnetic profiles and maps. In areas of constant gradients, notably if these are not steep, spacings of, say, 1,000 m may be used quite safely without losing much detail. In fact, larger spacings iron out local anomalies and are desirable if regional rather than local features are to be investigated.

EXPLANATION OF PLATE II

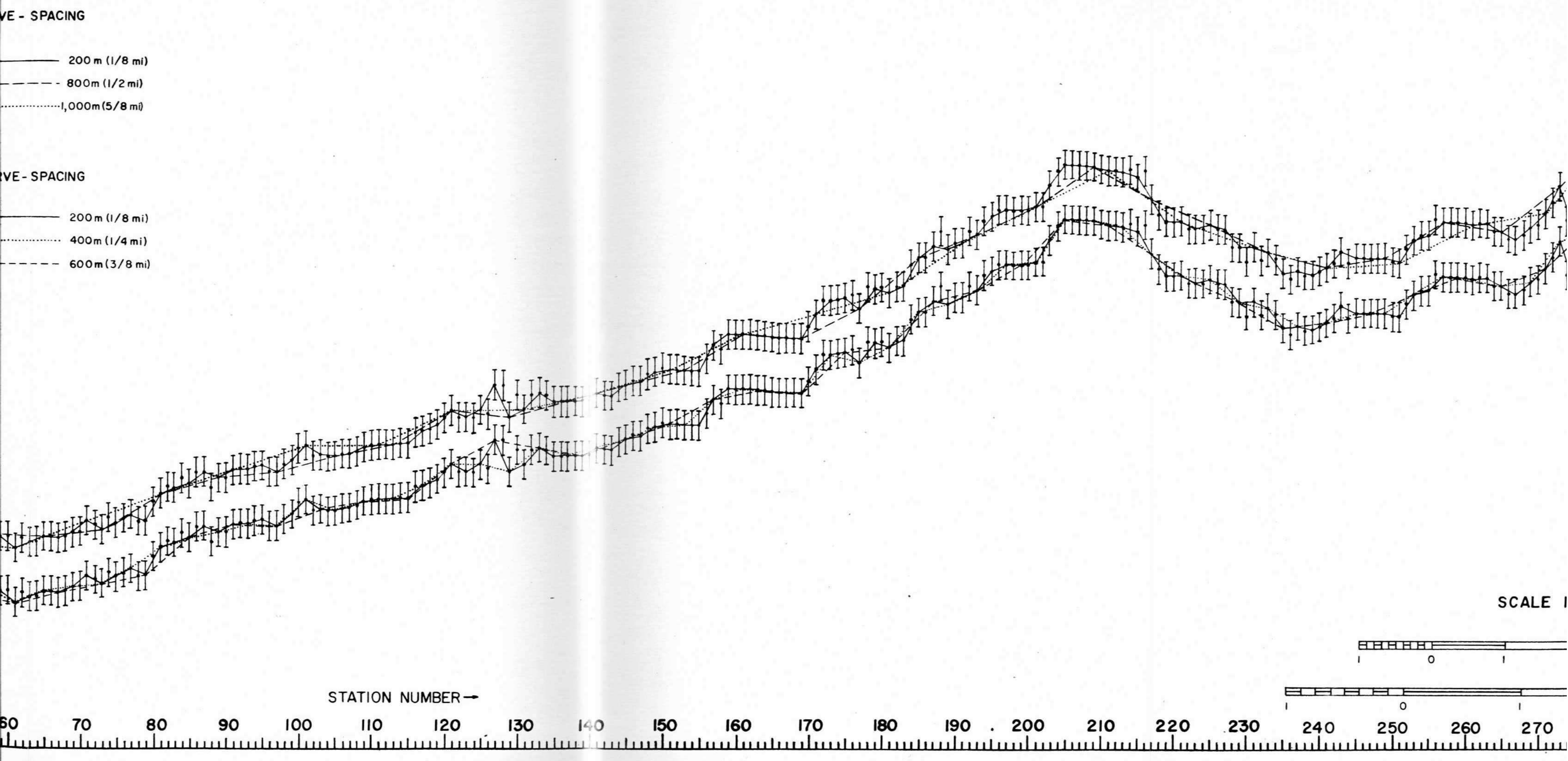
Total magnetic intensity profile across the Nemaha Anticline in relation to variable spacings. Different spacings are indicated by solid, dashed, and dotted lines.

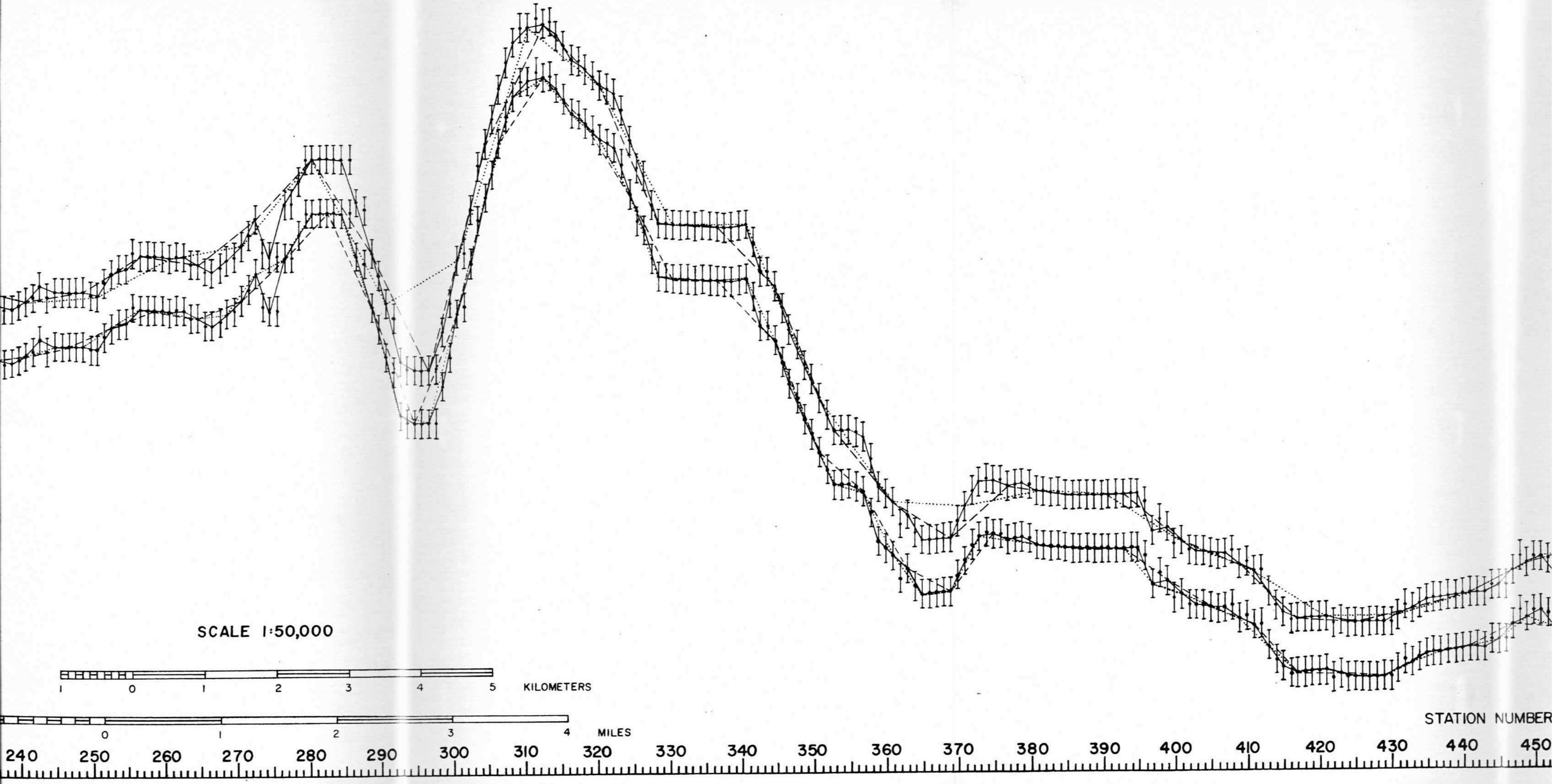
Accuracy of magnetic data is represented by error bars with a range of $\pm$ 10 γ.

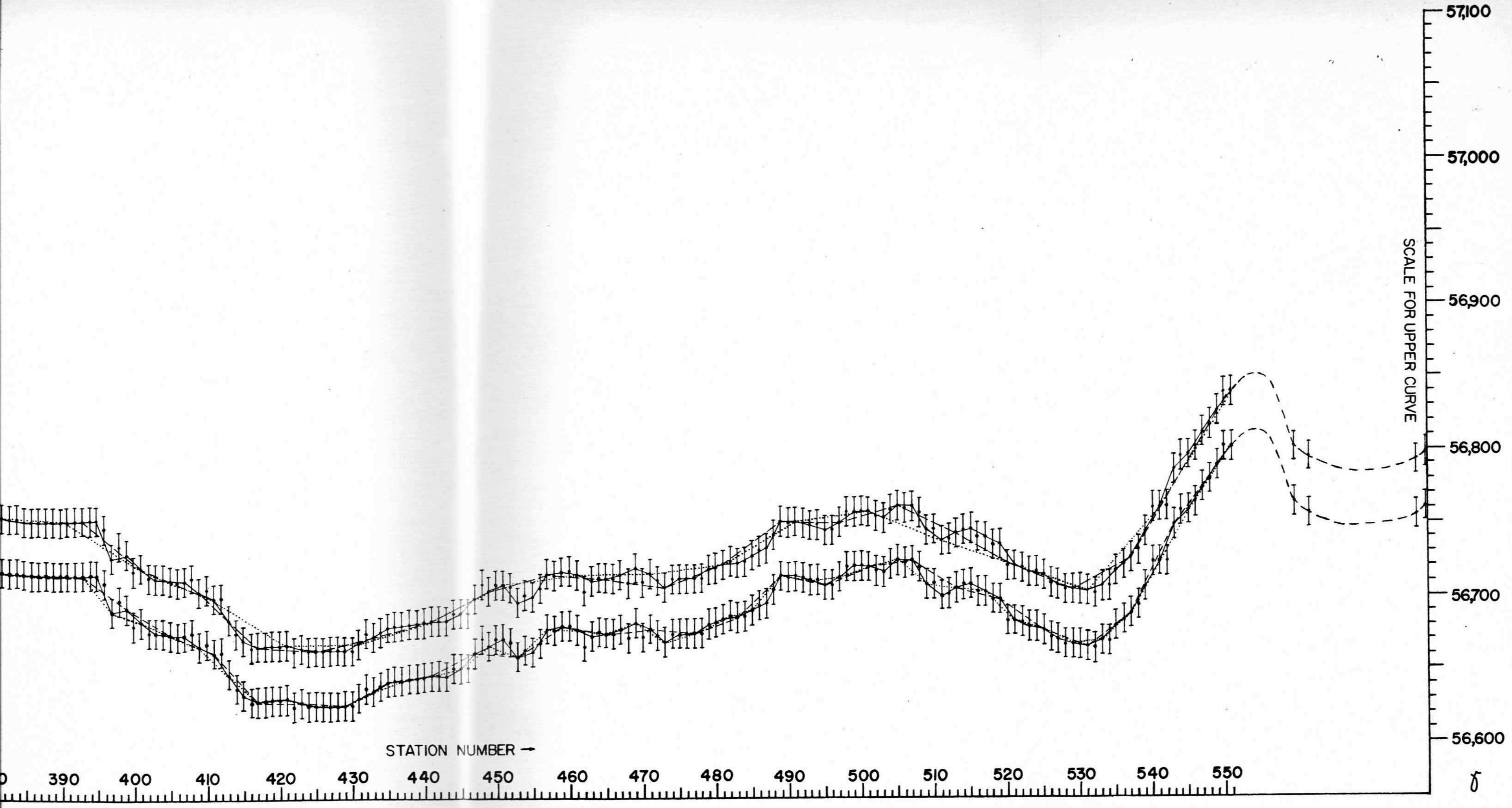
THE FOLLOWING DOCUMENT(S) IS OVERSIZED AND IS BEING FILMED IN SECTIONS TO INSURE COMPLETENESS AND CONTINUITY


TOTAL MAGNETIC INTENSITY PROFILE
UPPER CURVE - SPACING
200 m (1/8 mi)
800m (1/2 mi)
1,000m (5/8 mi)
LOWER CURVE - SPACING
200m (1/8 mi)
400m (1/4 mi)
600m (3/8 mi)
γ
57,100
57,000
56,900
56,800
56,700
56,600
SCALE FOR LOWER CURVE
1
10
20
30
40
50
60
70
80
90
100

AGNETIC INTENSITY PROFILE




SCALE 1:50,000
1 0 1 2 3 4 5 KILOMETERS
1 0 1 2 3 4 MILES
STATION NUMBER
240 250 260 270 280 290 300 310 320 330 340 350 360 370 380 390 400 410 420 430 440 450



57,100
57,000
56,900
56,800
56,700
56,600
SCALE FOR UPPER CURVE
STATION NUMBER →
390
400
410
420
430
440
450
460
470
480
490
500
510
520
530
540
550
δ

END

OF

OVERSIZE

DOCUMENT(S)

As may be seen from the curves, in areas where gradients change rapidly or are so steep as to indicate an imminent reversal, spacings of about 500 m should provide sufficient information to enable conclusive interpretations to be made. Locally, even smaller distances may prove necessary.

Calculation of a Weighted Profile

A scale of 1:250,000, recognized as geologically appropriate, seemed to necessitate the sacrifice of much of the geophysical information obtained. Yet with a spacing of 500 m, and by calculating weighted average values the problem could be solved without difficulty. A formula, given below, was used which permitted all field data to be taken into consideration at the optimum spacing of 500 m:

$$\bar{F}_\nu = \frac{1}{10} \left(F_{\nu-2} + 2F_{\nu-1} + 4F_\nu + 2F_{\nu+1} + F_{\nu+2} \right)$$

$$\nu = 3, 8, 13, \ldots\ldots, 543, 548$$

where F_ν : corrected magnetic reading at station ν

$\bar{F}_\nu$: weighted value derived from data of five consecutive stations.

This formula is one of a general type often used in geophysics to level off local fluctuations and to arrive at smooth contours or profiles (Angenheister and Helbig, 1962).

The weighting factors emphasize the key position held by value F_ν but also allocate considerable influence to the adjacent data $F_{\nu-1}$ and $F_{\nu+1}$. Their contribution gains importance when F_ν happens to deviate appreciably from an established trend but the adjacent data do not. They will then tend to reduce the effect of F_ν. A case in point is station 188 (Plate II); its original value of 56,917.5 γ was modified to 56,911 γ.

Convenience and ease of calculation also influenced the choice of the weighting factors.

Description of Magnetic Anomaly

The weighted average values had been derived from data already corrected for the diurnal variation. Consequently, the normal correction had to be applied to them before the final data were plotted as total magnetic anomaly curve at the scale of 1:250,000 (Plate III).

The anomaly is composed of four major sections, two of which are positive and two negative. The negative portion on the western limb of the curve extends eastward from outside the range of the profile to a location at 750 m (0.47 miles) east of the borderline of Ranges 8 E and 9 E., T. 6 S. It is characterized by a steady decrease in magnitude. The largest part of the anomaly is positive and comprises most of the profile in Ranges 9 E., 10 E., and the western half of R. 11 E. It can be ascribed an average value of +130γ on which maxima and minima are superposed. The second negative section lies adjacent to the east where its terminal is located at about 625 m (0.39 miles) east of the 96°-W meridian. The average value from which maxima and minima deviate within this negative portion may be fixed at -65γ. Eastward a single maximum represents the second positive anomaly which decreases in magnitude beyond the range of the profile proper.

The highest positive peak attains +302 γ, and the smallest value is -145 γ right at the beginning of the curve; the difference between the average levels of the central positive section and the negative portion juxtaposed on the east equals 195 γ.

From the minimum value of -145 γ the anomaly increases steadily to the first maximum slightly west of the boundary of Ranges 9 E. and 10 E., T. 6 S. The average field gradient is small (about 1.2 γ/100 m) and remains constant to the central portion of R. 9 E. (just east of Blaine), T. 6 S. There, the gradient increases (to 2.8 γ/100 m) and is reversed on the crest of the maximum.

This gentle rise over a comparatively large distance constitutes the greatest portion of the profile with a uniform gradient. To the east, variations occur more frequently; they are larger in magnitude and less regular giving the curve a jagged appearance.

The central positive portion displays three principal maxima with intervening minima superposed on an average level of some +130 γ. The western peak reaches a value of +179 γ. It is nearly symmetrical in shape and resembles a bell due to indentations of its flanks, which also gives rise to a fairly narrow crest. Gradients are moderate, +3 γ/100 m on the west slope and -5.6 γ/100 m on the east side of the peak.

From this magnetic high the curve descends eastward to a minimum of +105 γ the western slope of which is rather smooth with a small gradient. To the east minor irregular features follow beyond which the gradient steepens rapidly to form the west flank of the second principal maximum. This peak exhibits a sharp crest at +208 γ above the zero line and flanks that differ in aspect, being uniformly steep on the east and a little gentler on the west. The gradient, which is variable to the west averages +6.5 γ/100 m; to the east it is constant and attains as much as -20 γ/100 m.

A deep symmetric trench, only +73 γ in magnitude, separates this peak and the most conspicuous magnetic high east of it. The abrupt and almost steady rise of the curve from the deep of the trench to the absolute maximum of +302 γ produces a steep average gradient of +22 γ/100 m. To the east of the sharp crest, two step-like flexures interrupt the rapid drop of values; here the gradient varies from -24 γ/100 m between the first and second kink to almost zero at the lower step. The different gradients on both flanks are responsible for the asymmetric shape of the maximum.

The marked decrease of values east of the principal high constitutes the transition zone to the second negative portion of the profile. It reaches -53 γ in the narrow trough-like minimum to the west bounded by steep flanks with gradients of -8 γ/100 m and +15 γ/100 m. A broad, hump-like maximum with values ranging from -17 γ to -24 γ locally inverts the negative trend which is then resumed to form the deepest minimum within this portion of the anomaly. The lowest value is -113 γ, 48 γ below the average level of -65 γ, and is reached in a broad depression with smooth flanks of moderate steepness.

The gradients in this section of the anomaly are much like those on its western limb; they are more variable, however, giving rise to irregular undulations of small magnitude.

Adjacent to the east a second magnetic high within the negative section reaches a maximum of -20 γ; it is subsymmetrical in shape and resembles a broad mound with smooth indented flanks. Gradients are of the order of $\pm$ 2.7 γ/100 m. The adjoining minimum of -71 γ is bounded to the east by the last pronounced rise leading to the single peak that represents the second positive portion of the anomaly.

The gradient is constant along the slope with a magnitude of +20 γ/100 m. It is inverted at the crest of the high, 61 γ above the zero line, remains nearly constant on the east flank and approaches zero beyond the range of the profile.

Discussion

The magnetic anomaly measured along the profile ranges from -145 γ to +302 γ (a difference of some 450 γ), but the average levels of its positive (+130 γ) and negative (-65 γ) portions differ by only 195 γ (Plate III). Anomalies of this magnitude may be expected to originate from three causes, (1) sedimentary rocks, (2) topographic relief of igneous and metamorphic basement rocks, and (3) lithologic variations within the crystalline basement complex (Heiland, 1940).

In the northern magnetic hemisphere the interpretation of magnetic data is based on the assumption that increasing concentrations of magnetized matter, owing to variations in rock and mineral compositions, enhance the magnetic field intensity giving rise to positive anomalies (Heiland, 1949).

Sedimentary Rocks. In comparing the magnetic-anomaly curve with the geologic cross section it will be noticed that thickness and structural attitude of the sedimentary beds disagree markedly with shape and level of the curve (Plate III).

Starting on the west the sediments thin eastward to the crest of the Nemaha Anticline. If the body of sedimentary rocks, due to its content of magnetized minerals, were responsible for a positive anomaly the curve would show decreasing values from west to east. A pronounced positive anomaly would be expected over the Brownville Syncline just east of the fault scarp since here the sediments attain a thickness twice as great as on the western limb of the anticline. Yet a magnetic low is observed, $-65\ \gamma$ on the average with some superposed minor peaks, which are so irregular in shape and magnitude, however, as to preclude any reasonable correlation.

There is but mild deformation of the sedimentary sequence, except for the strong upward drag of the strata near the fault. Notwithstanding, no reflection of this structural pattern can be detected in the magnetic data.

Due to the importance of the subject considerable information is available in the geophysical literature regarding the magnetic properties of rocks.

According to Haalck (1934) it is often impossible to attribute the magnetic susceptibilities of igneous and metamorphic rocks to their percentage of magnetizable minerals, although, in general, this correlation may be valid (Heiland, 1940). The magnetization of sedimentary rocks, however, is directly related to their content of magnetic minerals, predominantly magnetite (Nettleton, 1940). Usually only small quantities of magnetite are present in sediments, and, accordingly, sedimentary rocks have low susceptibilities. Exact values are given by Heiland (1940, p. 312-314), Rössiger (1952, p. 345), and Dobrin (1960, p. 269, 270), from which a susceptibility of 40×10^{-6} may be taken as an average for sediments in accordance with Haalck's (1934) statements.

Metamorphic and igneous rocks range greatly in their magnetic properties but as a rule their susceptibilities lie far above those of the sediments. If an average magnetite content of 0.9 per cent is assumed for granite its susceptibility is $2{,}700 \times 10^{-6}$ (Nettleton, 1940), and Rössiger (1952) reported a mean value of about $1{,}000 \times 10^{-6}$ for magnetite-bearing granite.

Inasmuch as the magnetic susceptibility is only related to the induced magnetization the magnetic properties of rocks are not yet fully determined. The contribution of the second factor, the remanent magnetization is rarely known, however. Especially in effusive igneous rocks it may exceed the induced magnetization considerably (Kertz, 1969). In most cases induced and remanent magnetism are assumed to be identical in sign and direction (Heiland, 1940).

Despite their generally small susceptibilities sedimentary rocks may contain sufficient magnetized minerals as to have appreciable disturbing influences on the magnetic field, especially if they are close to the surface. Jenny (1941) reported that thick sedimentary sequences are capable of producing large positive anomalies, but more frequently the contribution of sedimentary rocks to magnetic anomalies is considered totally negligible (Haalck, 1934; Heiland, 1940; Nettleton, 1940; Vacquier et al., 1951; Dobrin, 1960).

Very little is known regarding the magnetic properties of rocks in Kansas. In their discussion of Jensen's (1949) profile Merriam and Hambleton (1956) stated that the susceptibility of pre-Pennsylvanian and Permo-Pennsylvanian rocks is probably low; the same authors reported an average quantity of magnetite of 0.5 percent for the Precambrian granites. This percentage results in a magnetic susceptibility of $1{,}500 \times 10^{-6}$ computed by means of the formula given in Nettleton (1940, p. 201). Cole et al. (1964) reported very low susceptibilities of 15×10^{-6}, 12×10^{-6} to 16×10^{-6}, and 15×10^{-6}, respectively, for various Precambrian rocks including granite, schist, and quartzite. These values are among the lowest published in the geophysical literature and should indicate that magnetized minerals are virtually lacking. The wells from which these data were obtained are located in south-central and west-central Kansas.

A difference in magnetic susceptibility of 150×10^{-6} is required for two rock bodies in juxtaposition to produce a detectable magnetic anomaly (Jakosky, 1940). With an average value of 40×10^{-6} for the Paleozoic rocks and that of $1{,}500 \times 10^{-6}$ for granite a susceptibility contrast of $1{,}460 \times 10^{-6}$ results, well in excess of the required minimum. Distinct positive anomalies should be expected, therefore, where these rocks lie adjacent to each other in steep contact.

The assumption that sedimentary rocks are without influence on the magnetic field appears to be contradictory to Merriam and Hambleton's (1956) conclusions. They suggested that the general thinning of the sedimentary sequence in Kansas from west to east gives rise to a positive field gradient directed eastward. Thus, by suppressing the magnetic effect of the Precambrian rocks the sediments would have a greater influence on the magnetic field than the underlying crystalline basement.

A look at the total magnetic intensity chart reveals that the eastward field gradient is due to the distribution of the normal magnetic intensity. Throughout the state of Kansas the isodynamic lines trend roughly northwest - southeast with higher intensities toward magnetic north; as one progresses from west to east on the fortieth parallel, above which the aeromagnetic profile was measured, successively greater values are recorded. The gradient thus measured steepens with an increase of the acute angle and approaches zero as the isodynamics parallel the profile. This is well illustrated by Jensen's (1949) data: the steepest positive gradient occurred in eastern Colorado and western Kansas, it approached zero in western Illinois, and became slightly negative at the borderline of Illinois and Indiana. It is realized, of course, that due to secular variation the magnetic pattern of today, on which these considerations are based, is different in detail from the field distribution in 1948 when the profile was flown. However, Burmeister and Bartels' (1952; p. 412, 413) maps show that the basic trend of the isodynamic lines has not changed since 1945.

As an inherent part of the normal field the gradient is attributable to large-scale regional anomalies or the magnetic dipole field. Its origin, therefore, lies deep within the earth's body well below the thin sedimentary cover.

Consequently, it is assumed that the sedimentary rocks are virtually nonmagnetic and do not contribute to magnetic anomalies in the area of investigation. This assumption appears to be justified by the fact that (1) the average magnetite content in sedimentary rocks is low and (2) an appreciable amount of ferromagnetic minerals has been reported for the Precambrian granites.

Yet magnetized sediments, close to or at the surface did interfere with the measurements. At places glacial till was found to rest on Paleozoic rocks. Its disturbing effect could be reduced in most cases, but in two instances it was not possible to eliminate the influence. Thus the small fluctuations in the central part of R. 12 E. east of the adjacent low are likely to be due to such interferences and the easternmost positive maximum is certainly attributable to glacial drift. Its existence was strikingly revealed by large pink quartzite erratics in an area east of the 96°-W meridian.

Basement Topography. Compared with the sedimentary sequence basement topography appears to be more closely related to the magnetic anomaly (Plate III).

The very gentle rise of the Precambrian rocks, exaggerated in the geologic cross section, corresponds to the small positive magnetic gradient of 1.2 γ/100 m which is constant over the considerable distance of 17.5 km (11 miles). When approached from the west, the crest of the Nemaha Anticline results naturally from a gradual reversal of dip rather than abrupt elevation; its counterpart is the average positive level of about 130 γ originating from a gradual flattening of the mean gradient. The rapid descent east of the crest forms the transition zone to the basement floor deep below the adjacent high; correspondingly, the average magnetic level drops eastward to form the negative portion of the anomaly.

In detail, however, several features of the curve are inconsistent with this simple configuration of the subsurface. Right over the fault there is no drop in magnetic values that would correspond in magnitude to the displacement shown. About 8.75 km (5.5 miles) west of the fault, however, a sharp decrease in magnetic intensity is observed.

Corresponding to the asymmetry of the anticline its center of mass is shifted westward relative to the crest. This might account for a westward translocation of the magnetic high, as Jenny (1932) suggested, and he expected the shift of the magnetic axis to be a few miles in magnitude.

It is not believed, however, that such marked magnetic disturbances as originate from faults would be appreciably influenced in their location by this mechanism because depth of burial and magnetization contrast should outweigh all other factors.

As to the principal anomaly absolute confidence is placed in its location. It is part of that portion of the traverse which was measured twice and allowed excellent reproducibility to be established.

However, only very limited control is available regarding the position of the fault. The recently issued Herndon map of May 13, 1971 shows that only two wells have been drilled in T. 7 S., R. 11 E. The westernmost well, located 80 m (260 feet) east of the borderline between R. 10 E. and R. 11 E. in the SW 1/4, Section 19, R. 10 E., is the only one to provide information regarding the depths of subsurface rocks.

On the basis of geological evidence derived from a single well the exact location of the major fault is not possible. The magnetic profile, however, strongly suggests the need for a relocation of the fault to the west by as much as 6.25 km (3.9 miles) with respect to its former site. This is indicated by the dashed line at the crest of the Nemaha Anticline in Plate III. The character of the fault is idealized and certainly does not represent all the minor features associated with it.

Not all three major peaks in the central section of the profile are similar in nature. The westernmost maximum is of small magnitude, yet of considerable width with gradients that are almost indistinguishable from those of the gentle rise on the west. These features and certain information pertaining to lithologic variations in the basement complex indicate that its origin probably is not topographic relief.

The two remaining peaks, in contrast, have much in common. They display narrow crests, steep flanks, and rise abruptly from the average level. Gradients are also similar, $-20\ \gamma/100$ m on the eastern flank of the smaller peak and up to $-24\ \gamma/100$ m on the eastern slope of the principal maximum. These characteristics suggest a common cause (Dobrin, 1960).

Grant and West (1965) analyzed magnetic anomalies quantitatively and used the step model as an approximation of normal faults. They made certain assumptions: the total field anomaly vector $\Delta\vec{F}$ points in the direction of the magnetic field $\vec{F}$; the geologic body causing the anomaly is uniformly magnetized by induction, has negligible permanent magnetization and is two-dimensional; its variable parameters are inclination and strike declination.

The authors presented several anomaly curves for profiles measured across steps of variable directions of magnetization but with a constant magnetic inclination of sixty degrees. The principal highs and the adjacent lows of the magnetic curve are strikingly similar to the profile for a model magnetized approximately parallel to the fault plane. Almost identical geometric relationships for the step and the Nemaha Anticline account for this similarity. In the area of investigation the inclination is roughly sixty-six degrees (taken from Burmeister and Bartels' (1952, p. 413, 414) chart and corrected for secular variation), the strike of the Nemaha Anticline and the fault is nearly parallel to the magnetic declination (deviation of ten degrees to the east) and, consequently, the induced magnetization vector approximately lies in the fault plane.

Grant and West (1965) stated that it is very difficult to estimate this type of anomaly quantitatively because of frequently occurring disturbances that interfere with the magnetic effect of the fault proper. Yet they gave a formula for a simpler and less accurate model, a thin horizontal step buried at a certain depth, which enabled rough depth estimates to be made. The formula is only valid if the depth of burial is much greater than the thickness of the step. Because this is not the case for the major fault on the east flank of the Nemaha Anticline no estimation of its depth was made. For the minor fault the formula was assumed to be applicable.

The formula is

$$L = \frac{2h}{\cos 2\beta},$$

where L : horizontal distance between the points of maximum and minimum value of ΔF

h : depth of burial

β : defined by $\tan \beta = \frac{\tan i}{\sin \lambda}$ with

i : magnetic inclination

λ : strike declination.

For the angle i 66° were assumed, and $\lambda = 10^{\circ}$ was obtained from the N 20° E strike of the Nemaha Anticline and a magnetic declination of 10° E.

The determination of L and the zero line of the anomaly constitutes the greatest problem since in most cases disturbing effects distort the shape of the anomaly curve. With respect to the profile across the Nemaha Anticline the fault adjacent to the east was known to be the largest disturbing factor.

Two different estimates were made; in both cases the zero line was assumed to be +137 γ. Disturbing effects were not considered for the first depth estimation, and L was simply measured from the maximum at +208 γ to the adjacent trough-like minimum of +73 γ. A depth of h = -741 m was obtained with L being 1,500 m. This depth is far in excess of the value of 470 m shown in the geologic cross section at the location of the fault.—For the second estimate the ideal curve shown by Grant and West (1965) served as a criterion in eliminating the magnetic disturbing influence from the fault to the east. This curve is almost antisymmetric with a slightly greater negative deflection from the zero line. Inspection of its characteristics shows that the juxtaposition of two curves representing the compound effects of adjacent normal faults will raise the level of the intervening minimum. The geometric proportions of positive and negative deviations from the zero line as exhibited by the ideal curve governed the estimation of an ideal minimum at +50γ by producing the eastern slope of the anomaly curve downward with a constant gradient. The distance L then measured was 1,000 m, which finally resulted in h = -494 m very close to the depth of the cross section.

It was realized that the estimates could only give an idea of the range of depth to be expected without claiming high accuracy. Only the major of all disturbing factors could be judged in its effect and eliminated; furthermore, the inclination of 66^{o} was certainly in error, and the model used is only a crude approximation. Yet the comparatively good agreement between the range of depth obtained and the depth of burial taken from the structural contour map was considered to confirm the initial assumption of a second normal fault in the subsurface.

Thus, the two major peaks of the profile are interpreted as being indicative of two normal faults, both upthrown to the west. The eastern fault corresponds to the known scarp on the east limb of the Nemaha Anticline but shifted westward relative to its site in the published map. For the fault to the west, which has a smaller throw than its eastern counterpart, a location about 2.75 km (1.7 miles) west of the boundary of R. 10 E. and R. 11 E., T. 7 S., is suggested and indicated in the geologic cross section by a short dashed line (Plate III). No attempt was made to show relative displacement along this fault. It is presumed that the faulting occurred in pre-Desmoinesian time.--South of the profile in T. 8 S., R. 10 E., a normal fault is shown in the structural map west of the Nemaha Anticline. It is in approximate alignment with the suggested fault, but the wells drilled in the southern part of T. 7 S., R. 10 E., give no indication as to the continuation of either fault. Recently (November 1970), a well has been drilled close to the fault trace in Section 14, T. 7 S., R. 10 E. but information has not been released.

The flexures on the east slope of the principal peak, the narrow minimum, and, possibly, the first maximum in the eastern negative portion of the anomaly may be related to secondary magnetic effects of the main fault. Usually, a fracture zone is associated with a major fault, and small faults, fractures, and other secondary features are all likely to have disturbing magnetic effects. The geometric relations involved are too complex, however, to allow more than a qualitative approach.

The rather high magnetic level over the Brownville Syncline constitutes another inconsistency in relation to a purely topographic cause of the magnetic anomaly. Here, magnetic data would be expected to lie well below those of the western part because of the deeply depressed basement floor, but exactly the opposite is observed: the negative level of -65 γ over the Brownville Syncline is appreciably higher than the lowest value (-145 γ) to the west.

Basement Lithology. Irrespective of the need for additional causes of magnetic anomalies there are indications of lithologic variations in the Precambrian basement underlying the area of investigation.

In a block diagram of Precambrian and younger rocks of Kansas, Farquhar (1957) showed a rock distribution involving granite west of the Nemaha Anticline, metasedimentary rocks (schist and non-granitic gneiss) on its crest, and granite in the Brownville Syncline. The contacts of these rock types are steep resulting in considerable thicknesses; west of Westmoreland, for example, the metasedimentary rocks are more than 875 m (2,500 feet) thick according to Farquhar's diagram.

In another paper, Merriam et al. (1961) presented a different distribution of Precambrian rocks. In the extreme western portion of northern Pottawatomie County mainly schist and quartzite underlie the Paleozoic sequence whereas granite adjoins these rocks to the east forming the rest of the Precambrian surface. However, as the authors stated, there is lack of control for large areas of Kansas including the Forest City Basin east of the Nemaha Anticline; there, the presence of granite is merely an assumption. Two small outliers of quartzite and schist are shown on their map to be located slightly south of the traverse line, but due to the lack of a scale their exact positions relative to the length of the profile cannot be determined. If it is assumed that these outliers extend northward across the profile the western remnant of metasedimentary rocks would be roughly located in the eastern part of R. 9 E., about halfway between Blaine and the borderline of R. 9 E. and R. 10 E., and its eastern counterpart would be found slightly west of the boundary between Pottawatomie and Jackson Counties. As to the thickness of these rocks Merriam et al. (1961) stated that they appear to be underlain by granite with the deepest penetration into metasedimentary rocks being almost 560 m (1,600 feet).

Concerning the mineralogical composition Farquhar (1957) reported mostly quartz and mica for quartzite but dark minerals (among them magnetite) give the rocks a slightly speckled appearance. Examples containing conspicuous magnetite crystals occur in central Kansas. The schist consists principally of quartz with smaller amounts of feldspar, mica, and magnetite. No quantitative data are available.

According to the tables given by Heiland (1940, p. 312) and Rössiger (1952, p. 345) the susceptibility of quartzite is low, only 4×10^{-6}, but iron quartzite may show values of 550×10^{-6}; figures for schist range from 5×10^{-6} to 115×10^{-6}. It is believed that great variations in susceptibilities are possible depending on the content of magnetic minerals; owing to their very high magnetization already small amounts of ferromagnetic minerals are sufficient to cause the susceptibility values observed for rocks, as pointed out by Jakosky (1940). As long as definitive data are missing all conclusions regarding the magnetic effects of these rocks are of necessity conjectural.

The anomaly suggests that there are magnetic influences other than those arising from basement topography. Since changes in lithology have been reported for the Precambrian rocks, they require to be considered as possible sources.

According to Farquhar (1957) a well drilled in Section 33, T. 6 S., R. 9 E., reached quartzite and schist but their relative amounts could not be determined. It is reasonable to assign the smooth maxima and minima east of Blaine (Plate III) to the disturbing magnetic field of these rocks because the profile passed through the northeast corner of that section (just southwest of Blaine) and through the northern part of Section 34, T. 6 S., R. 9 E. The map of Merriam et al. (1961) shows an east-west trend of this metasedimentary outlier so that its effect on the magnetic field would be indicated by the magnetic data to the east of Section 33, which is in accord with the results obtained.

It is thought that the magnetic maxima and minima could result from variable proportions of quartzite and schist if a positive effect is attributed to the schist (magnetic susceptibility higher than that of granite due to magnetite) and a negative magnetic contribution is ascribed to the quartzite (magnetic susceptibility lower than that of granite).

Order of magnitude and shape of the anomalies suggest a relatively thin cover of these rocks rather than a separate body with steep contacts extending indefinitely downward (Vacquier et al. 1951). This corresponds to the statements made by Merriam et al. (1961) regarding the thickness of metasedimentary rocks.

Magnetic effects related to lithologic variations in the basement are believed to be also indicated by the second negative section of the anomaly curve. Rocks with a magnetization greater than that of granite could account for the comparatively high average level of $-65\ \gamma$, which should be much lower if basement topography were the only mechanism to account for magnetic anomalies. A moderately thin slab is thought to cover the granitic rocks of indefinite thickness. Lithologic variations within the sheet might explain the small and irregular deviations from the average level.

This interpretation is contrary to the rock distribution shown by Farquhar (1957) and by Merriam et al. (1961) who are in favor of a granitic basement floor in the Brownville Syncline although this has not yet been proved (Merriam et al., 1961). The latter authors also suggest a basement cover of metasedimentary rocks for the extreme western portion of the area crossed by the profile. However, the contact of these rocks with the granite could not be spotted by magnetic means. This might suggest an eastward wedging-out of the metamorphic rocks the gradually increasing thickness of which would enhance the negative magnetic effect arising from the sloping granite surface, provided that a smaller magnetic susceptibility is attributable to the metasediments. Following this line of thought a granitic basement floor could then be assumed for the Brownville Syncline with the mild anomalies possibly due to northward extensions of the metasedimentary outlier located slightly south of the profile in that area. Because of lack of control, as shown in the Herndon map, no definitive decision is as yet possible.

It should be emphasized that most of these considerations are speculative. As long as the distribution of Precambrian rock types in the area of investigation is not better known, and, above all, no information pertaining to magnetic properties of these rocks is available any conclusion will be a matter of surmise.

EXPLANATION OF PLATE III

Relation of magnetic anomaly to subsurface geology. The dashed lines indicate the new location of the major fault, and the proposed minor fault to the west.

The geologic cross section has been compiled from the following references:

Cole (1962)

Merriam (1960)

Merriam and Kelly (1960)

Merriam and Smith (1961)

Merriam et al. (1958)

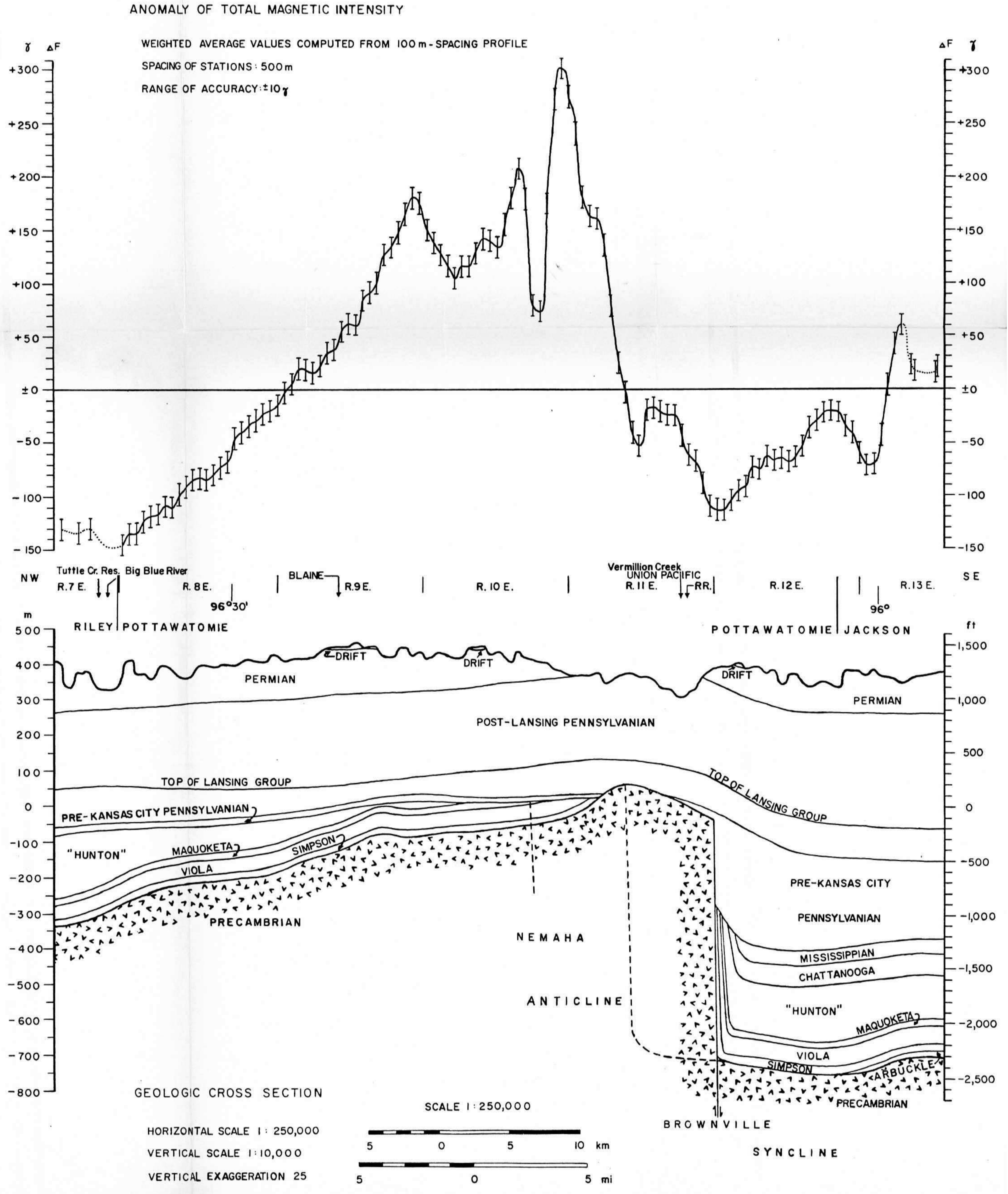
Lee (1943, 1956)

Zeller (1968)

Geologic Map of Kansas (1964 edition)

Herndon Map S-2F.

PLATE III


ANOMALY OF TOTAL MAGNETIC INTENSITY
WEIGHTED AVERAGE VALUES COMPUTED FROM 100 m-SPACING PROFILE
SPACING OF STATIONS: 500 m
RANGE OF ACCURACY: ±10 γ
γ ΔF
+300
+250
+200
+150
+100
+50
±0
-50
-100
-150
NW
SE
Tuttle Cr. Res.
Big Blue River
R.7 E.
R. 8 E.
96°30'
BLAINE
R.9 E.
R. 10 E.
Vermillion Creek
UNION PACIFIC
R. 11 E.
RR.
R. 12 E.
R. 13 E.
96°
RILEY
POTTAWATOMIE
POTTAWATOMIE
JACKSON
m
ft
500
400
300
200
100
0
-100
-200
-300
-400
-500
-600
-700
-800
1,500
1,000
500
0
-500
-1,000
-1,500
-2,000
-2,500
DRIFT
DRIFT
DRIFT
PERMIAN
PERMIAN
POST-LANSING PENNSYLVANIAN
TOP OF LANSING GROUP
TOP OF LANSING GROUP
PRE-KANSAS CITY PENNSYLVANIAN
"HUNTON"
MAQUOKETA
SIMPSON
VIOLA
PRECAMBRIAN
NEMAHA
ANTICLINE
PRE-KANSAS CITY
PENNSYLVANIAN
MISSISSIPPIAN
CHATTANOOGA
"HUNTON"
MAQUOKETA
VIOLA
SIMPSON
ARBUCKLE
PRECAMBRIAN
BROWNVILLE
SYNCLINE
GEOLOGIC CROSS SECTION
SCALE 1:250,000
HORIZONTAL SCALE 1:250,000
VERTICAL SCALE 1:10,000
VERTICAL EXAGGERATION 25
5 0 5 10 km
5 0 5 mi

However, it is thought plainly indicated by the magnetic data that lithologic variations in the crystalline basement do have disturbing influences on the earth's magnetic field.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This magnetic investigation based on a 100-m (110-yard) traverse leg has shown that a spacing of 500 m (0.32 miles) is sufficiently close to furnish detailed geophysical information for a meaningful interpretation.

The magnetic anomaly measured across the Nemaha Anticline is determined by several interacting factors. Magnetic interference from surface-near glacial sediments accounts for a positive anomaly in one instance. However, disturbing effects arising from the Paleozoic sedimentary sequence are considered negligible. The two remaining factors of major influence are (1) structural attitude of the Precambrian crystalline rocks and (2) lithologic variations within the basement complex.

The broad characteristics of the anomaly curve reflect the configuration of the Precambrian basement. This conformity between subsurface structure and magnetic anomaly is virtually undisturbed for the northwestern portion of the profile, about 20 km (12.5 miles) in length.

The two highest peaks of the curve with the intervening minimum are interpreted as the combined magnetic effects of two normal faults in the Precambrian basement. Both faults are upthrown on the west but differ in the amount of displacement. The eastern dislocation is the known fault scarp on the east flank of the Nemaha Anticline. The magnetic anomaly indicates this fault at a distance of about 4 km (2.5 miles) east of the borderline between R. 10 E. and R. 11 E., T. 7 S., approximately 6.25 km (3.9 miles) west of its original location in T. 7 S., R. 12 E., depicted on the available structural contour map. The second fault is proposed in T. 7 S., R. 10 E., approximately 2.75 km (1.7 miles) west of the boundary between R. 10 E. and R. 11 E. Its character as a normal fault and the smaller throw compared to that of its eastern counterpart are confirmed by comparatively good agreement between quantitative depth estimates and subsurface elevations obtained from the structural map.

Anomalies of smaller magnitude and different characteristics superposed on the broad features related to basement topography indicate lithologic variations in the subsurface. Close to the borderlines of T. 6 S. and T. 7 S., R. 9 E. and R. 10 E., minor magnetic highs and lows are attributed to the presence of a known outlier of Precambrian metasedimentary rocks consisting mainly of quartzite and schist.

The magnetic effect related to the Brownville Syncline is probably reduced by the influence of metamorphic rocks with a magnetization higher than that of granite. A different rock association in agreement with current geologic opinion consists of granite in the Brownville Syncline and metamorphic rocks on the extreme western limb of the Nemaha Anticline. In order to produce the observed magnetic anomaly the metasediments are visualized to be wedge-like in shape, thinning to the east and with lower susceptibility compared to that of granite. The scarce information available on magnetic properties of Precambrian rocks precludes any definitive decision, however.

The character of the anomalies associated with lithologic changes suggests tabular plates of comparatively small thicknesses rather than metamorphic bodies bounded by steep contacts of indefinite extent.

Suggestions for Further Investigations

The conspicuous anomalies of the magnetic profile originating from faults in the crystalline basement appear to be the most challenging objects for further magnetic investigations.

The proposed location of the fault on the eastern limb of the Nemaha Anticline constitutes a prominent deviation from its trend in adjacent areas. It should be of considerable geologic interest to investigate whether this portion is separated from the remainder of the fault or--if this proves not to be the case--to examine its spatial relation to adjoining parts.

The strike direction of the smaller fault to the west is not yet determined nor is any information available on the type of normal fault (i.e., rotational or non-rotational) or its relation to the major fault on the east. The tracing of its strike in neighboring areas should contribute to a better understanding of this new structural feature.

Several short magnetic profiles measured in an approximate east-west direction should determine the extent of the faults and their strikes. One profile or more following the established trend would be of value in the investigation of possible transverse disturbances.

A detailed areal survey based on this reconnaissance work will furnish the most comprehensive magnetic information and render a meaningful quantitative analysis possible. For these magnetic investigations a spacing not larger than 500 m (0.32 miles) is recommended.

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REFERENCES CITED

Agocs, W. B., 1959, Comparison of basement depths from aeromagnetics and wells along the northern border of Kansas: Kansas Geol. Survey Bull., v. 137, p. 143-152.

_________ 1959a, Airborne magnetometer profiles, Morris and Wabaunsee Counties, Kansas: Kansas Geol. Survey Bull., v. 137, p. 175-180.

Alexanian, M. C., 1931, Practical rules for the use of the magnetometer in geophysical prospecting: U.S. Bur. Mines Inf. Circ. 6527, 19 p.

Anderson, K. H., and Wells, J. S., 1968, Forest City Basin of Missouri, Kansas, Nebraska, and Iowa: Am. Assoc. Petroleum Geologists Bull., v. 52, p. 264-281.

Angenheister, G., 1959, Gesteinsmagnetismus: Unpub. lab. man., 29 p., Inst. Angew. Geophysik, Univ. München.

Angenheister, G., and Helbig, K., 1962, Allgemeines über Störfelder: Unpub. lab. man., 12 p., Inst. Angew. Geophysik, Univ. München.

_________ 1965, Elektronische Lokalvariometer (Saturations-Kern-Magnetometer, Kernpräzessions-Magnetometer): Unpub. lab. man., 9 p., Inst. Angew. Geophysik, Univ. München.

Bartels, J., 1952, Erdmagnetische Variationen, in Landolt-Börnstein, Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik: Berlin, Springer-Verlag, v. III, Astronomie und Geophysik, p. 728-767.

Baysinger, B. L., 1963, A magnetic investigation of the Nemaha Anticline in Wabaunsee, Geary, and Riley Counties, Kansas: Unpub. Master's thesis, 46 p., Kansas State Univ., Manhattan, Kansas.

Burmeister, F., and Bartels, J., 1952, Magnetismus des Erdkörpers und erdmagnetische Säkular-Variation, in Landolt-Börnstein, Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik: Berlin, Springer-Verlag, v. III, Astronomie und Geophysik, p. 396-425.

Chapman, S., and Bartels, J., 1940, Geomagnetism: London, Oxford Univ. Press, 2 v., 1049 p.

Cole, V. B., Merriam, D. F., and Hambleton, W. W., 1964, Activities of the Kansas Basement Rocks Committee in 1963 and additional Precambrian wells: Kansas Geol. Survey Bull., v. 170, pt. 4, 11 p.

Dobrin, M. B., 1960, Introduction to geophysical prospecting: New York, McGraw-Hill Book Co., Inc., 446 p.

Dowell, A. R., 1964, A magnetic investigation of northern Riley County, Kansas: Unpub. Master's thesis, 84 p., Kansas State Univ., Manhattan, Kansas.

Farquhar, O. C., 1957, The Precambrian rocks of Kansas: Kansas Geol. Survey Bull., v. 127, p. 49-122.

Fath, A. E., 1921, The origin of the faults, anticlines, and buried "granite ridge" of the northern part of the Mid-Continent oil and gas field: U.S. Geol. Survey Prof. Paper 128, p. 75-84.

Fleming, J. A., 1949, The earth's magnetism and magnetic surveys, in Fleming, J. A., ed., Terrestrial magnetism and electricity: New York, Dover Pubs., p. 1-58.

Frye, J. C., and Leonard, A. B., 1952, Pleistocene geology of Kansas: Kansas Geol. Survey Bull., v. 99, 230 p.

__________ 1959, Flint Hills physiography, in Kansas Geol. Soc. Guidebook 24th Field Conf., south-central Kansas, 1959: p. 79-85.

Frye, J. C., and Schoewe, W. H., 1953, The basis for physiographic subdivision of Kansas: Kansas Acad. Sci. Trans., v. 56, p. 246-252.

Gasaway, M. A., 1959, Surface expression of the Nemaha Anticline in southeastern Riley County and northwestern Wabaunsee County, Kansas: Unpub. Master's thesis, 74 p., Kansas State Univ., Manhattan, Kansas.

Grant, F. S., and West, G. F., 1965, Interpretation theory in applied geophysics: New York, McGraw-Hill Book Co., Inc., 583 p.

Haalck, H., 1934, Lehrbuch der angewandten Geophysik: Berlin, Verlag Gebrüder Borntraeger.

Hahn, A., 1961, Geomagnetik, in Bentz, A., ed., Lehrbuch der angewandten Geologie: Stuttgart, Ferdinand Enke Verlag, v. I, p. 485-565.

Hambleton, W. W., and Merriam, D. F., 1957, Review of geophysical activity in Kansas through 1956: Kansas Geol. Survey Bull., v. 127, p. 1-24.

Heiland, C. A., 1940, Geophysical exploration: New York, Prentice-Hall, Inc., 1013 p.

__________ 1949, Magnetic prospecting, in Fleming, J. A., ed., Terrestrial magnetism and electricity: New York, Dover Pubs., p. 110-148.

Jakosky, J. J., 1940, Exploration geophysics: Los Angeles, Calif., Times-Mirror Press, 786 p.

Jenny, W. P., 1932, Magnetic vector study of regional and local geologic structure in principal oil states: Am. Assoc. Petroleum Geologists Bull., v. 16, p. 1177-1203.

________ 1940, Geological problems in the interpretation of the earth's major regional and local anomalies [abs.]: Oil and Gas Jour., v. 38, no. 48, p. 58.

________ 1941, Geological interpretation of regional magnetic anomalies in central and southern United States: Oil Weekly, v. 103, no. 3, p. 17-22.

Jensen, H., 1949, Airborne magnetic profile above 40th parallel, eastern Colorado to western Indiana: Geophysics, v. 14, p. 57.

Jewett, J. M., 1951, Geologic structures in Kansas: Kansas Geol. Survey Bull., v. 90, p. 105-172.

Jewett, J. M., and Merriam, D. F., 1959, Geologic framework of Kansas--A review for geophysicists: Kansas Geol. Survey Bull., v. 137, p. 9-52.

Kertz, W., 1969, Einführung in die Geophysik: Mannheim, Bibliographisches Institut, v. I, Erdkörper, 232 p.

Koons, D. L., 1955, Faulting as a possible origin for the formation of the Nemaha Anticline: Unpub. Master's thesis, 33 p., Kansas State Univ., Manhattan, Kansas.

Lee, W., 1943, The stratigraphy and structural development of the Forest City Basin in Kansas: Kansas Geol. Survey Bull., v. 51, 140 p.

________ 1956, Stratigraphy and structural development of the Salina Basin area: Kansas Geol. Survey Bull., v. 121, 167 p.

McClellan, H. W., 1930, Subsurface distribution of pre-Mississippian rocks of Kansas and Oklahoma: Am. Assoc. Petroleum Geologists Bull., v. 14, p. 1535-1556.

McNish, A. G., 1949, On causes of the earth's magnetism and its changes, in Fleming, J. A., ed., Terrestrial magnetism and electricity: New York, Dover Pubs., p. 308-384.

Merriam, D. F., Cole, V. B., and Hambleton, W. W., 1961, Distribution of Precambrian basement rock types in Kansas: Am. Assoc. Petroleum Geologists Bull., v. 45, p. 2018-2024.

Merriam, D. F., and Hambleton, W. W., 1956, Relation of an airborne magnetic profile to the geology along the Kansas-Nebraska border: Kansas Geol. Survey Bull., v. 119, p. 251-266.

_________ 1959, Relation of magnetic and aeromagnetic profiles to geology in Kansas: Kansas Geol. Survey Bull., v. 137, p. 153-173.

_________ 1959a, Exploration geophysics in Kansas: Kansas Geol. Survey Bull., v. 137, p. 53-62.

Moss, R. G., 1936, Buried Precambrian surface in the United States: Geol. Soc. America Bull., v. 47, p. 935-966.

Nelson, J. H., Hurwitz, L., and Knapp, D. G., 1962, Magnetism of the earth, U.S. Coast and Geod. Survey Pub. 40-1: Washington, D.C., U.S. Govt. Printing Office, 79 p.

Nelson, P. D., 1952, The reflection of the basement complex in the surface structures of the Marshall-Riley County area of Kansas: Unpub. Master's thesis, 73 p., Kansas State Univ., Manhattan, Kansas.

Nettleton, L. L., 1940, Geophysical prospecting for oil:New York, McGraw-Hill Book Co., Inc., 444 p.

_________ 1943, Transcontinental gravitational and magnetic profile of North America and its relation to geologic structure [rev.]: Geophysics, v. 8, p. 419-421.

Powers, S., 1922, Reflected buried hills and their importance in petroleum geology: Econ. Geology, v. 17, p. 233-259.

Ratcliff, G. A., 1957, Surface structure on the east flank of the Nemaha Anticline in northeast Pottawatomie County, Kansas: Unpub. Master's thesis, 33 p., Kansas State Univ., Manhattan, Kansas.

Rieb, S. L., 1954, Structural geology of the Nemaha Ridge in Kansas: Unpub. Master's thesis, 36 p., Kansas State Univ., Manhattan, Kansas.

Rössiger, M., 1952, Magnetische Eigenschaften von Mineralen, Erzen und Gesteinen, in Landolt-Börnstein, Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik: Berlin, Springer-Verlag, v. III, Astronomie und Geophysik, p. 331-348.

Runcorn, S. K., 1956, The magnetism of the earth's body, in Flügge, S., ed., Handbuch der Physik: Berlin, Springer-Verlag, v. XLVII, Geophysik I, p. 498-533.

_________ 1956a, Magnetization of rocks, in Flügge, S., ed., Handbuch der Physik: Berlin, Springer-Verlag., v. XLVII, Geophysik I, p. 470-497.

Thomas, C. R., 1927, Flank production of the Nemaha mountains (granite ridge), Kansas: Am. Assoc. Petroleum Geologists Bull., v. 11, p. 919-931.

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

Waters, G. S., and Francis, P. D., 1958, A nuclear magnetometer: Jour. Sci. Instr., v. 35, p. 88-93.

Whitham, K., 1960, Measurement of the geomagnetic elements, in Runcorn, S. K., ed., Methods and techniques in geophysics: New York, Interscience Publishers, Inc., v. I, p. 104-167.

Woollard, G. P., 1943, Transcontinental gravitational and magnetic profile of North America and its relation to geologic structure: Geol. Soc. America Bull., v. 54, p. 747-790.

Zeller, D. E., ed., 1968, The stratigraphic succession in Kansas: Kansas Geol. Survey Bull., v. 189, 81 p.

Maps Used for the Interpretation

Cole, V. B., 1962, Configuration of top of Precambrian basement rocks in Kansas: Kansas Geol. Survey, Oil and Gas Inv. No. 26, Map, scale 1:633,600.

Herndon Map Service, 1971, Geologic maps: Oklahoma City, Oklahoma, map S-2F, scale 1:63,360.

Kansas Geol. Survey, 1964, Geologic map of Kansas, prepared by the staff of the State Geological Survey of Kansas under the supervision of J. M. Jewett: Lawrence, Kansas, Kansas Univ. Pubs., scale 1:500,000.

Merriam, D. F., 1960, Preliminary regional structural contour map on top of Mississippian rocks in Kansas: Kansas Geol. Survey, Oil and Gas Inv. No. 22, Map, scale 1:615,226.

Merriam, D. F., and Kelly, T. E., 1960, Preliminary regional structural contour map on top of "Hunton" (Silurian-Devonian) rocks in Kansas: Kansas Geol. Survey, Oil and Gas Inv. No. 23, Map, scale 1:633,600.

Merriam, D. F., and Smith, P., 1961, Preliminary regional structural contour map on top of Arbuckle rocks (Cambrian-Ordovician) in Kansas: Kansas Geol. Survey, Oil and Gas Inv. No. 25, Map, scale 1:603,187.

Merriam, D. F., Winchell, R. L., and Atkinson, W. R., 1958, Preliminary regional structural contour map on top of the Lansing Group (Pennsylvanian) in Kansas: Kansas Geol. Survey, Oil and Gas Inv. No. 19, Map, scale 1:603,187.

U.S. Dept. of Commerce, Coast and Geod. Survey, compiler, 1965, Total intensity chart of the United States, 1965.0: Washington, D.C., U.S. Dept. of Commerce, chart 3077f, scale 1:5,000,000.

A MAGNETIC PROFILE ACROSS THE NEMAHA ANTICLINE IN POTTAWATOMIE AND WESTERN JACKSON COUNTIES, KANSAS

by

MICHAEL KÖNIG

Vordiplom, Ludwig-Maximilians-Universität München, 1970

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ABSTRACT

A review of the pertinent geophysical literature revealed that considerable uncertainty exists regarding the correlation of magnetic anomalies with the configuration of the Precambrian basement. In view of this uncertainty a detailed magnetic investigation was conducted to (1) prove or refute the conformity between basement topography and magnetic anomalies, (2) delineate a possible subsurface fault on the eastern flank of the Nemaha Anticline, and (3) determine the optimum spacing for future magnetic investigations in the area.

A traverse leg of 100 m (110 yards) was chosen for the magnetic profile. From the northwestern corner of Pottawatomie County the profile was measured in a S 70^{o} E direction (at right angles to the strike of the Nemaha Anticline) into western Jackson County. Readings were taken at 551 stations covering a distance of 55 km (34 miles) and at 13 base stations distributed along the profile. The Varian Model M-49A Portable Magnetometer was used for this investigation.

The broad geologic characteristics including the structural history of the area traversed are briefly summarized, and a concise résumé of the principal features of the geomagnetic field, its secular and transient variations, and the magnetic properties of rocks is presented.

Regarding the procedure of measurement in the field, of which a brief account is given, the nuclear precession magnetometer and its principle of operation are explained.

The reduction of magnetic field data is discussed, and the readings were corrected for diurnal and normal variations.

A total magnetic intensity curve based on the data corrected for diurnal variations was constructed at a scale of 1:50,000. Variable spacings and their effects on magnetic data were examined, from which the most suitable distance for future investigations was determined to be 500 m (0.32 miles).

By use of an adequate formula a weighted profile based on a 500-m (550-yard) spacing was computed. The data, corrected for diurnal and normal variations, were plotted at a scale of 1:250,000 and compared with the geologic cross section compiled from various sources.

The magnetic anomaly across the Nemaha Anticline ranges from -145 γ to +302 γ, but the average levels of the principal positive and negative portions are -65 γ and +130 γ.

The anomaly reflects the interaction of several factors. Magnetic effects associated with the Paleozoic sedimentary sequence resting upon Precambrian rocks are considered negligible.

The broad characteristics of the anomaly are attributed to the configuration of the crystalline basement. The two principal positive anomalies arise from two faults in the Precambrian complex. The dislocation giving rise to the greatest magnetic anomaly is recognized as the known normal fault on the east flank of the Nemaha Anticline. The magnetic data indicate, however, that it is located 6.25 km (3.9 miles) west of its heretofore assumed site in T. 7 S., R. 12 E.--The fault to the west, hitherto unrecognized, is proposed in T. 7 S., R. 10 E., and is interpreted as an eastward-dipping normal fault with a throw smaller than that of its eastern counterpart. Quantitative depth estimates showing comparatively good agreement with known subsurface elevations confirm this interpretation.

Minor magnetic anomalies superposed on the broad features related to basement topography are believed to indicate lithologic variations of the Precambrian rocks. One known outlier of metasediments is indicated by the magnetic data. Different rock distributions producing the observed magnetic effects are considered possible. However, owing to lack of information on magnetic properties of Precambrian rocks in the area of investigation no definite conclusion could be drawn.

Suggestions are made for further magnetic investigations of the two subsurface faults in adjoining areas.