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A Magnetic Survey in the Rio Grande Depression

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MAGNETIC SURVEY IN THE RIO GRANDE DEPRESSION - M'GONIGLE

A MAGNETIC SURVEY IN THE

RIO GRANDE DEPRESSION

By

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ABSTRACT

A vertical magnetic survey of a part of the Albuquerque basin was made in the fall and winter of 1959 to test the feasibility of detecting major faults in the Precambrian basement rocks.

A series of 29 traverses was run normal to the suspected north-trending basement faults. Readings were made with a vertical magnetometer at stations spaced from 0.3 to 0.5 miles apart along traverse lines. The lines of traverse were two to eight miles in length and spaced about two miles apart.

Thirteen anomalies coincided fairly well with the Ojuelos fault, and three with the San Francisco fault. This led the writer to interpret other anomalies as reflections of faulting. The possibility is present that basalt intrusions, tilted and folded magnetic beds, and buried ridges of susceptible materials may exert an influence upon the vertical magnetic intensity; however, the interpretation based upon faulting is simpler. Furthermore, only one intrusion is known in the area surveyed, and the Albuquerque basin seems to be a graben, with any folding of formations probably minor. Great relief in the Precambrian basement is unlikely, and buried topography in the sedimentary sequence can only be conjectured. In all, nine north-trending fault zones are indicated by the magnetic survey.

The expected decrease in gamma values toward the center of the Albuquerque basin was not observed in about one-third

ABSTRACT

A vertical magnetic survey [illegible] Albuquer-que basin was made [illegible] to test the feasibility of tracing [illegible] basement rocks.

A series of [illegible] north-trending [illegible] with a vertical magnetometer [illegible] 0.5 miles apart along [illegible] were two to eight miles in length [illegible] apart.

[illegible] Ojuelos fault, [illegible] This led the [illegible] tions of [illegible] intrusions, [illegible] ridges of [illegible] the vertical magnetic [illegible] tion based upon [illegible] intrusion is shown [illegible] que basin [illegible] tions probably [illegible] basement is [illegible] sequence can only [illegible] fault zones and intrusives [illegible] magnetic survey.

The [illegible] of the Albuquerque basin [illegible]

of the anomalies. This indicates that the vertical magnetic intensity is not influenced solely by the Precambrian rocks, but also by susceptible sedimentary formations, as the depth to the Precambrian basement increases toward the center of the basin.

Susceptible formations could be found along the downthrown side of faults, and would probably be a result of concentration of magnetite grains at the foot of former fault scarps. In this case, a magnetic anomaly would indicate the magnetite concentration, thereby showing the location of the fault.

INTRODUCTION

Location and Accessibility

The area of study lies in parts of Bernalillo, Valencia, and Sandoval Counties, New Mexico. The principal study was confined to the pediment extending from U. S. Highway 85 to points near the base of the Sandia, Manzanita, and Manzano Mountains. The area lies generally between 106°37'30" and 106°18' W. longitude, and 35°30' and 34°37'30" N. latitude.

Most of the area is readily accessible by U. S. Highway 85 and numerous private and secondary roads, although numerous fence lines impede rapid transit to a great extent. A small portion of the area was unavailable for study because of military restrictions.

Purpose and Scope

The purpose of the study was to detect and delineate major faults in the basement rocks by means of magnetic traverses. The study was confined to the eastern margin of the depression, for reasons of time limitations.

A survey of a known basement fault might produce a background of reference in the form of anomaly curves which, it was believed, would aid interpretation of other anomaly curves plotted from data gathered in areas where no surface expression, and hence, no definite knowledge of basement faults is known.

[illegible]

Location and [illegible]

The area of study lies in parts of [illegible], Valencia, and Bernalillo Counties, New Mexico. The prin- cipal [illegible] U. S. Highway 85 [illegible] Manzanita, and Manzano Mountains. The area lies gen- erally between 106°37'30" and [illegible] W. longitude, and 35°30' and 34°37'30" N. latitude.

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A survey of a [illegible] background of the [illegible] which, it was believed, [illegible] other [illegible] where no surface evidence [illegible] ledge of [illegible].

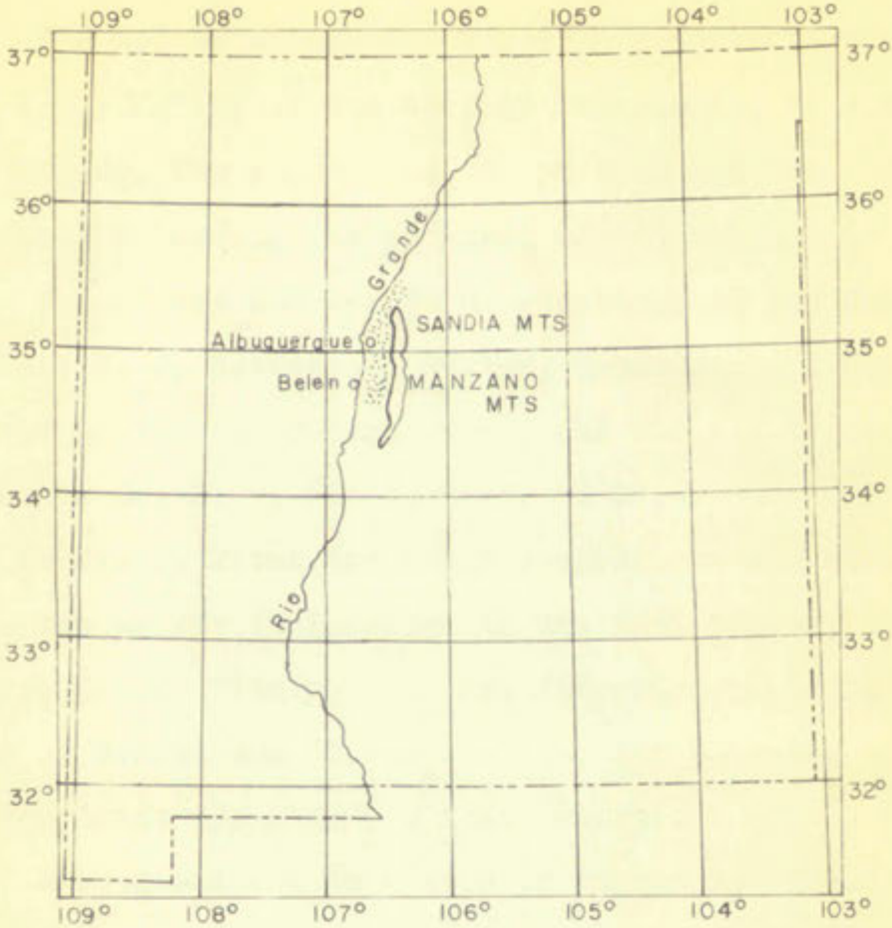

Figure 1. Index map. Area of study stippled.

Therefore, a known fault was chosen, and a magnetic study of it and other parts of the Rio Grande depression were compared.

Acknowledgments

The writer wishes to express his appreciation to Dr. V. C. Kelley of the Geology Department, University of New Mexico, for suggesting the problem and for his helpful criticisims during the progress of the work.

Thanks are due Mr. H. R. Joesting, of the Geophysics Branch, U. S. Geological Survey, Washington, D.C., for providing the instruments used, and for his helpful information; to Dr. J. P. Fitzsimmons, to Dr. A. Rosenzweig, and to Mr. F. Titus for their suggestions and aid.

The writer is indebted to Mr. Paul Torres, Mr. E. A. Berry, Mr. T. Witherspoon, Mr. John Simms, and to the governors of Sandia and Isleta Pueblos, for allowing him access to the lands committed to their charge.

Deep gratitude is expressed to the New Mexico Geological Society for their financial aid.

Previous Work

No previous magnetic surveys of the area are known to the writer.

A number of surface studies have been made of the geology, and numerous writers have commented upon the structure of the Rio Grande Valley adjacent to the Sandia, Manzanita, and Manzano Mountains.

Darton (1915, p. 85) commented upon the nature of the Sandia Mountains, designating them as "an upward arch of

the strata, effected mostly by bending, but doubtless with minor local breaks." Stearns (1953, p. 459-507) described and mapped several faults at the north end of the Sandia Mountains. Reiche (1949, p. 1183-1212) has described and mapped in some detail the attitudes of faults in the area immediately west of the Manzanita and North Manzano Mountains. Stark (1956, p.23-26) made a study of the South Manzano Mountains. Ellis (1922) studied the geology of the Sandia Mountains, but did not show any of the faults to the west of the main mountain mass. Bryan (1938, p. 195-225) described the bordering faults of the Albuquerque basin, and showed known and conjectured bordering faults of the basin on a map contained in his report. Kelley (1954) has compiled a map of a portion of the upper Rio Grande area, and has also described the tectonics of the Rio Grande depression (Kelley, 1952, p. 92-105). Read, et al., (1944) and Darton (1928) have drawn geologic maps which include this area of study.

AREAL GEOLOGY

Regional Geologic Setting

The faults which were investigated are a part of the structure of the eastern side of the Rio Grande depression, and the portion of the depression studied is known as the Albuquerque basin or as the Albuquerque-Belen basin. The basin is a trough or graben, bounded on the

east and on the west by faults or fault systems. The entire Rio Grande depression, which extends from the San Luis Valley in Colorado to El Paso, Texas, is made up of similar troughs or grabens arranged en echelon, and is a part of the Rocky Mountain belt. In the Albuquerque area the trough is about 50 miles in width (Kelley, 1952, p. 93). This part of the Rocky Mountains is in the Basin and Range Province, but Kelley (1952, p. 102) believes the features of the Rio Grande depression to be unique enough to be called the Rio Grande rift belt of the Rocky Mountains structural province, rather than being designated as merely of the Basin and Range type.

There is some speculation on the nature of the fault blocks which border the depression; as mentioned above, Darton considered them to be faulted anticlines, but some workers think the folding to be secondary to the faulting of the blocks.

The Albuquerque basin is nearly 90 miles in length, and is bounded on the west by the Lucero and Ladrone uplifts, on the north by the Santa Domingo basin, on the east by the Sandia, Manzanita, Manzano, and Los Pinos line of mountains, and on the south by the entrance of the Rio Salado into the valley of the Rio Grande.

General Lithology of the Area

The eastern mountain mass is predominantly of Precambrian rocks capped by a late Paleozoic sedimentary sequence. The Precambrian rocks are composed of granite,

schist, slate, quartzite, metavolcanic tuff, rhyolite, and of basic and intermediate dikes. The Paleozoic rocks are principally limestone.

Near the base of the mountains there are patches of late Paleozoic rocks, but most of the surface beds of the Albuquerque basin are Pliocene and Quaternary, the Pliocene beds belonging to the Santa Fe formation. There is in all probability a considerable variation in the thickness of beds beneath the Santa Fe formation from one part of the basin to another; at one location it might overlie considerable thicknesses of late Paleozoic, Cenozoic, and middle Tertiary beds, whereas in another location it might lie directly on the Precambrian basement. (Reiche, 1949, p. 120; Kelley, 1952, p. 97.)

The Quaternary sediments consist of sand, silt, and poorly consolidated pediment gravel. These Quaternary materials conceal most of the structure that exists directly to the west of the mountain ranges, at the border of the Rio Grande depression.

In the portion of the Albuquerque basin studied, there are few intrusive masses of basaltic material visible at the surface, whereas elsewhere in the basin, they are much more prevalent. (See Figure 9.)

South of U. S. Highway 60 there is an intrusive mass of basalt, known as Black Butte; to the northeast of the town of Tome, New Mexico, there is another intrusive mass known as El Cerro; and in the Tome grant, at approximately

schist, slate, quartzite, [illegible] with [illegible] of basic and intermediate [illegible]. The [illegible] are principally limestone.

[illegible] are beds [illegible] late Paleozoic [illegible] of the Albuquerque Basin [illegible] wells belonging to the [illegible] probability a considerable [illegible] beds beneath the [illegible] basin to [illegible] considerable thicknesses [illegible] middle Tertiary [illegible] lie directly on the Precambrian basement [illegible] p. 120; Kelley, 1952, p. [illegible]).

The Quaternary [illegible] poorly consolidated sediments [illegible] materials [illegible] directly to the [illegible] of the Rio Grande depression.

In the portion of [illegible] are few [illegible] the surface, whereas [illegible] more prevalent. [illegible]

South of U. S. Highway [illegible] of basalt, known as [illegible] town of [illegible] known as El [illegible]

106°32'30" W. longitude, and 34°37'38" N. latitude there is a small amount of basaltic material mapped by Read, et al., (1944) as an intrusive body.

There have been numerous wells drilled in the Albuquerque basin both for water and for oil. The logs for the water wells were not available to the writer, but Mr. Frank Titus of the U. S. Geological Survey has found that none of the wells penetrated basalt. (oral communication, 1960.) Most of these water wells were drilled to shallow depths of a few hundred feet. Two well logs have been published, and an examination of the data shows that neither well penetrated basalt. One of these is the Grober No. 1 Fuque well, in S. 19, T. 5 N., R. 3 E., drilled to a total depth of 6300 feet. (Reiche, 1949, p. 1204). The other is the North Albuquerque Acres Well No. 2, also known as the Norins Well, in S. 19, T. 11 N., R. 4 E., drilled to a total depth of 5024 feet. (Stearns, 1953, p. 505).

The negative evidence afforded by the well data allows no definite conclusion to be reached as to the presence or absence of basalt flows at depth in the Albuquerque basin; however, it seems likely that the amount of basaltic material at depth is not very great in the portion of the basin studied.

The magnetic properties of the principal lithologic materials are of particular interest in the interpretation of this magnetic survey.

166°32'30" E. [illegible] is a small amount of [illegible] et al., (1961) [illegible]

There have been [illegible] quorque basin [illegible] the water [illegible] Mr. Frank Tilton [illegible] that none of the [illegible] tion, 1960.) [illegible] shallow depths [illegible] been published, [illegible] neither well [illegible]. [illegible] No. 1 Pogue well, [illegible] total depth of [illegible] feet, [illegible] other in the [illegible] as the Harris well, [illegible] a total depth of [illegible] feet [illegible].

The [illegible] no definite conclusion [illegible] absence of [illegible] however, it [illegible] material at [illegible] basin studies.

The [illegible] material [illegible] of this material [illegible].

Table 1.

Susceptibilities of Rocks and Minerals

(Taken from Jakosky, 1940, p. 164)

Material	Field strength in gauss	Susceptibility, k in C.G.S. units
Magnetite crystals	2	6.3 to 24.0
Magnetite	1	0.04 to 2.0
Ilmenite	1	0.03 to 0.14
Hematite	51.3	0.00004 to 0.0001
Pyrrhotite	0.6	0.007 to 0.028
Basalt	10	0.00068 to 0.0063
Diabase	1	0.000078
Granite	60	0.0027
Shale	?	0.00004 to 0.00005
Clay	94-375	0.00002
Sandstone	1-180	0.000017
Limestone	200-515	0.000004
Anhydrite and Gypsum	0.5	-0.0000011 to -0.00001

Magnetic susceptibility may be defined as a measure of the degree to which a substance is attracted to a ma magnet. A more detailed discussion of the term will be presented under the heading "Basic Concepts and Definitions," p. 15.

Table 1 lists values of the magnetic susceptibilities of rocks and minerals, and was compiled by J. Jakosky from various sources. (Jakosky, 1940, p. 164) The magnetic field in which the susceptibilities were measured varied in strength from a minimum of 0.5 gauss to a maximum of 515 gauss. Despite this variance, some idea of the relative susceptibilies of the different materials may be gained from the table.

This table allows some calculation to be made of the size of the vertical magnetic anomaly which can be expected under certain structural conditions. For example, above a vertical fault along which there is granite on the upthrown side and gravel on the downthrown side, there should be an anomaly on the order of several hundred gammas. This depends, of course, upon the amount of vertical displacement along the fault, and on the absolute susceptibilities of the lithologic materials involved.

From the table it can be seen that, of the known lithologic materials present in the Albuquerque basin, basaltic rocks should have the highest magnetic susceptibilities. The Precambrian granite would probably have the next lower susceptibility, while the sedimentary

[illegible]

of the magnetic [illegible] strongest [illegible]

magnet. A [illegible] of [illegible]

presented under the heading [illegible] and [illegible]

tions," p. [illegible].

Table 1 lists [illegible] of [illegible]

of rocks and [illegible], [illegible]

from various [illegible] [illegible]

field in which [illegible] magnetic [illegible]

in strength from [illegible]

515 gauss. [illegible]

tive susceptibility [illegible]

gained from the [illegible].

This table [illegible] the [illegible]

size of the [illegible] magnetic [illegible]

under surface [illegible]

vertical [illegible] the magnet [illegible]

side and [illegible] the [illegible]

[illegible] of the [illegible]

deposits, or [illegible]

mal [illegible] the [illegible]

of the lithologic [illegible]

From the [illegible]

lithologic [illegible]

possible [illegible]

distinct. The [illegible]

the most [illegible]

materials should have the lowest susceptibility. In general, erosion of granitic rocks which contain magnetite will result in a reduction of the size of the individual magnetite particles, and a dispersion of them throughout the sediments, with the result that the detritus from the granitic rocks will not have nearly as great a magnetic susceptibility as did the rocks themselves. This is the general case, however, and, since magnetite is a rather heavy mineral, local concentration of magnetite grains by stream action may occur, with the result that the sediments will have a greatly increased susceptibility along the concentration. Sediments with concentrations of basalt fragments might also have a high magnetic susceptibility. Both magnetite and basalt may be locally concentrated in the sediments of the Albuquerque basin, but their disposition would be quite erratic and unpredictable.

No tests of magnetic susceptibility of the lithologic materials found in the Albuquerque basin are known to the writer.

Structural History of the Albuquerque Basin Area

Movements on the bounding faults of the Albuquerque basin have not been continuous, and the present surface expression of these faults may or may not reflect the original fault positions in the Precambrian basement rocks.

Bryan (1936, p. 204), Reiche (1949, p. 1210), and Kelley (1952, p. 101) dated the incipient development of the Rio Grande structural belt as late Miocene, the event

being accompanied by a great outburst of volcanism. Earlier deformations, in Laramide time and in the middle Tertiary, probably developed basins of sedimentation which were, however, rather wider and not of the same type as the rifts or troughs which began to develop at this time.

Further movements evidently took place in the late Pliocene (Reiche, 1949, p. 1211; Stearns, 1953, p. 504), when the great blocks of the Sandia, Manzanita, and Manzano Mountains assumed their present elevations and extent, and the modern Rio Grande depression was outlined.

Bryan (1936, p. 205) considered the main body of the sedimentary deposits of the Rio Grande depression to be of the same general age and to belong to the Santa Fe formation. However, Reiche (1949, p. 1210), in his discussion of the Albuquerque basin, mentioned a filling of the depression by more than 4000 feet of Miocene-Pliocene continental sediment, which in turn was buried by the Santa Fe formation.

The faults bounding the Albuquerque basin, where exposed, are steep (greater than 50°) to vertical and generally dip toward the basin, but whether they are mainly high-angle thrusts, ramps, or high-angle gravity faults is not known. (Kelley, 1952, p. 103.)

Several faults mapped or inferred by earlier workers were encountered in the course of the magnetic investigation; their structural history is summarized below.

being accompanied by [illegible] volcanic [illegible].
Earlier [illegible], in the [illegible] Tertiary, probably [illegible] Santa Fe [illegible]
which were, however, [illegible] not of the same kind
as the [illegible] of [illegible]
time.

Further movements [illegible] the [illegible] Pliocene (Bryan, 1938, p. [illegible] when the great [illegible], the [illegible] Mountains [illegible] their present [illegible], and the trough [illegible] the Rio Grande [illegible].

Bryan (1938, p. [illegible]) [illegible] sedimentary deposits of the [illegible] the same general age [illegible] tion. However, [illegible] (1939, p. [illegible]), [illegible] of the Albuquerque basin, [illegible] of the [illegible] by more than 2000 feet of [illegible] tinental sediment, [illegible] Santa Fe formation.

The [illegible] exposures, [illegible] generally [illegible] mainly [illegible] fauna [illegible].

Several [illegible] were encountered [illegible] tion; [illegible].

The Ojuelos fault (Reiche, 1949, pl. 5), which is also known as the Hubble Spring fault (Kelley, 1954) was considered by Reiche to be a fault that has been active in Recent time. This fault is probably very near to the original position of the eastern bordering faults of the Rio Grande depression, and was active in the Pliocene deformation. (Reiche, 1949, p. 1203).

The Sandia, Manzano, and Coyote faults are bounding faults on the main mountain masses, and are probably related to the late Pliocene uplifts (Reiche, 1949, p. 1210).

The Bernalillo and San Francisco faults as mapped by Stearns (1953, pl. 1) are of post Santa Fe age in part, although he mentions that the younger basin of Santa Fe deposition was probably bounded on the east by strong faults as far north as the Galisteo-Tonque area, and presumably the earlier faults were near or on the planes of the Bernalillo and San Francisco faults.

In any event, Stearns (1953, p. 482) suggested that the Bernalillo fault is the northernmost member of the fault system at the base of the Sandia Mountains, and that the probable relative uplift in the Placitas area dates from pre-Abiquiu (late Oligocene-early Miocene) time.

Movements along the general northerly direction of the post-Santa Fe, San Francisco fault were postulated by Stearns (1953, p. 484) for the Las Huertas fault, which he believed continued past its intersection with the

The Santa Fe fault [illegible] also known as the [illegible] fault [illegible], have considered by [illegible] to be a fault [illegible] in Recent time. This fault is [illegible] the [illegible] position of the [illegible] Santa Fe [illegible] Rio Grande depression, and [illegible] in the [illegible] tion. (Bachman, [illegible]).

The Santa, [illegible], and [illegible] faults on the high [illegible] are related to the same [illegible] ([illegible], p. 1210).

The Bernalillo and San Felipe faults [illegible] of Stearns (1953, p. [illegible]), although he [illegible] deposition was probably [illegible] faults at the [illegible] -- [illegible] Probably the earlier faults [illegible] the Bernalillo and San Felipe escarpments.

In any event, Kelley (1952, p. [illegible]) [illegible] the Bernalillo [illegible] fault system on the [illegible], the probable [illegible] from [illegible].

Movement along the [illegible] the post-Santa Fe, [illegible] by Stearns (1953, p. [illegible]) [illegible] which [illegible]

San Francisco fault system. The time of these movements he believed, is pre-Santa Fe, probably pre-Abiquiu (?).

THEORY OF MAGNETIC SURVEYING

Basic Concepts and Definitions

In order to orient the theory of magnetic surveying, the basic concepts and definitions are reviewed. The information given here follows Dobrin (1952, p. 103-107), and the reader is referred to those pages for a more complete discussion of this material.

Magnetic Poles

Points near the ends of a magnet, at which the "lines of force" of the magnetic field concentrate, and toward which they are directed, are known as the poles of the magnet, or as the magnetic poles.

Magnetic Force

If two poles of strength P and P_o are separated by a given distance r, the force F between them is:

$$F = \frac{1}{x} \cdot \frac{P \cdot P_o}{r^2}$$

where x depends upon the magnetic properties of the medium in which the poles are situated, and on the fact that this medium occupies all the intervening space.

A unit pole is defined as one producing a force of one dyne at a distance of one centimeter from a similar pole. In this case, F = one dyne when x = 1, as it will for all practical purposes when the medium is air.

San Francisco [illegible] he believed, is [illegible].

[illegible]

[illegible]

In order to [illegible] the [illegible] the basic concepts and definitions [illegible]. [illegible] information given [illegible] and the reader is [illegible] plete discussion of this subject.

Magnetic Pole

Points near the ends of a magnet, where [illegible] of force [illegible] which they [illegible] magnet, or as the magnetic poles.

Magnetic Force

If two poles of strength [illegible] are [illegible] a given distance [illegible], the force [illegible]

$$F = \frac{m_1 m_2}{\mu r^2}$$

where [illegible] the magnetic [illegible] of the medium in which the poles [illegible] that this [illegible].

A unit pole is defined [illegible] one dyne [illegible] pole. In [illegible] for all [illegible].

Magnetic Field Strength

The magnetic field strength is defined as the force per unit of pole strength which would be exerted when a small pole of strength P_0 is placed at that point. Another way of expressing the magnetic field strength is by the density of the lines of force in the field. If H = one line of force per square centimeter, then H = one dyne per unit pole, or H = one oerstead.

Magnetic Moment

Since all magnets are composed of two poles of equal strength and opposite sign, the pole strength of the magnet is not referred to, but rather the magnetic moment of the dipole. The direction of the moment is toward the north-seeking pole of the magnet.

Polarization

The magnetism induced in a substance that is placed in a magnetic field is called polarization; it is proportional to the strength of, and is in the same direction as the applied field.

The induced pole strength per unit area along an area normal to the inducing field is called the intensity of magnetism (I). Here I equals the magnetic moment per unit volume of the substance that is placed in the magnetic field.

Magnetic Susceptibility

Magnetic susceptibility is a coefficient equal to the ratio of the magnetization to the magnetizing force; the symbol used to designate it is k. It is used in the equation

$I = kH\cos\theta$ where:

I = the intensity of magnetism

H = the external magnetic field

θ = the angle between the normal and the surface of the magnetic substance. (If $\theta = 0$, then $\cos\theta = 1$.)

k = susceptibility

Materials with a positive susceptibility are called paramagnetic; those with a negative susceptibility are called diamagnetic.

Some rock materials as they are found in the crust have a direction of moment that is different from that which would result from the present field of the earth; this direction is considered to be the resultant between the present polarizing field of the earth and the residual magnetism in the rock materials. This residual magnetism may have been formed by a field which had a different orientation than the present field of the earth. In igneous rocks, the residual magnetism is produced when the molten material cools below the Curie point.

Terrestrial Magnetism

The entire globe of the earth has a magnetic field, which is concentrated in such a manner that the earth

Magnetic Susceptibility

Magnetic susceptibility [illegible] is equal to the ratio of the magnetization to the [illegible] field. The symbol used to designate it is k. It is used in the equation

$I = kH$ [illegible]

I = the intensity of magnetization

H = the external magnetic field

θ = the angle between the normal and the direction of the magnetic intensity. (If θ = [illegible], then cos θ = 1.0 [illegible])

k = susceptibility

Materials with a positive susceptibility are called paramagnetic; those with a negative susceptibility [illegible] are called diamagnetic.

Some rock materials, as they were formed [illegible] have a direction of magnetization [illegible] which would result from the present [illegible] of the earth; this direction is [illegible] the [illegible] between the present [illegible] and the permanent magnetization in the [illegible] may have been [illegible] orientation when the [illegible] igneous rocks, [illegible] molten material [illegible]

[illegible]

The entire group of [illegible] which is [illegible]

behaves as a large dipole. Were the earth homogeneous in its material distribution, the magnetic lines of force between these two poles should be of even distribution and strength.

The strength of the earth's field is given as equal to one oerstead; this is the theoretical value, and in many places it is less than this amount. Subdivisions of the oerstead are known as gammas, where one gamma = 10^{-6} oersteads.

At any one place on the globe, and at any one given instant of time, the magnetic field of the earth has a certain direction, which is commonly described by the terms declination and inclination. This is to say that if the true north (or south) pole of the earth is taken as a reference direction, and the surface of the earth is considered to be a plane over a small distance, the magnetic field will, in general, have some direction not coincident with the true north, and will also be inclined to the surface of the earth.

Thus the true north and the magnetic north are not at the same place on the globe; the magnetic north is nearly located at 70° 30' N. latitude and 97° 40' W. longitude, while the magnetic south pole is at 73° 39' S. latitude and 146° 15' E. longitude. The magnetic field will have a maximum inclination at the magnetic poles of 90° and a minimum inclination at the magnetic equator of 0°. At other latitudes, the inclination will be at some angle to the horizontal.

behaves as a large magnet, [illegible]
in its detailed distribution, the magnetic [illegible]
force between [illegible]
tion and strength.

The strength of the earth's field [illegible]
to one oersted, [illegible]
many places [illegible]
the [illegible]
oersteds.

At any one place on the earth, and at any given instant of time, the magnetic field is [illegible] in a certain direction, [illegible] declination and inclination. [illegible] true north (or south) pole [illegible] reference [illegible], and the surface of the earth is considered [illegible] field will, in general, [illegible] with the true north, [illegible] face of the earth.

Thus the [illegible] the [illegible] magnetic pole is [illegible] located at [illegible] while the magnetic [illegible] and 108° [illegible] maximum inclination [illegible] minimum inclination [illegible] latitude, [illegible] horizontal.

For purposes of magnetic surveying, a magnetic line of force can be considered to be a vector, the resultant of a vertical (Z) and two horizontal intensities (X and Y). Each of the components X, Y, and Z are at right angles to one another. Mention is commonly made in the literature of the vertical or horizontal intensities, and the majority of measurements made in geophysical prospecting deal with one or the other of these intensities, and not with the total magnetic field (Figure 2).

Several factors are effective in disturbing the homogeneity of the earth's magnetic field, and a brief treatment of these factors is given below. For a more exhaustive discussion of this topic see Jakosky (1940, p. 61-65), Fleming, (1939, p. 3-58), and Nettleton (1940, p. 164-168).

The observation was made above that if the earth's crust were homogeneous, it would have a uniform magnetic field. However, it is not homogeneous, for it is composed of substances which have different susceptibilities, which have been disturbed by tectonic movements. The result of the inhomogeneity is that the field at the surface of the earth is subject to local variations that cannot be predicted from a consideration of the theoretical magnetic field.

The effective susceptibility of the materials depends upon the amount and upon the distribution of paramagnetic minerals within the rocks and formations (Jakosky, 1940,

For purposes of [illegible] measurements, [illegible] of force can be considered [illegible] of a vertical (Z) and a [illegible] (H). Each of the components [illegible] one another. [illegible] of the vertical or [illegible] ity of measurements [illegible] with one or the other [illegible] the total magnetic [illegible].

Several factors [illegible] homogeneity of the [illegible] treatment of these factors is given [illegible] exhaustive [illegible] p. 61-65), [illegible] (1940, p. 164-[illegible]).

The [illegible] crust were homogeneous, [illegible] field. However, it is not [illegible] of substances with [illegible] have been [illegible] the [illegible] earth is [illegible] field.

The effective [illegible] upon the amount and [illegible] minerals [illegible]

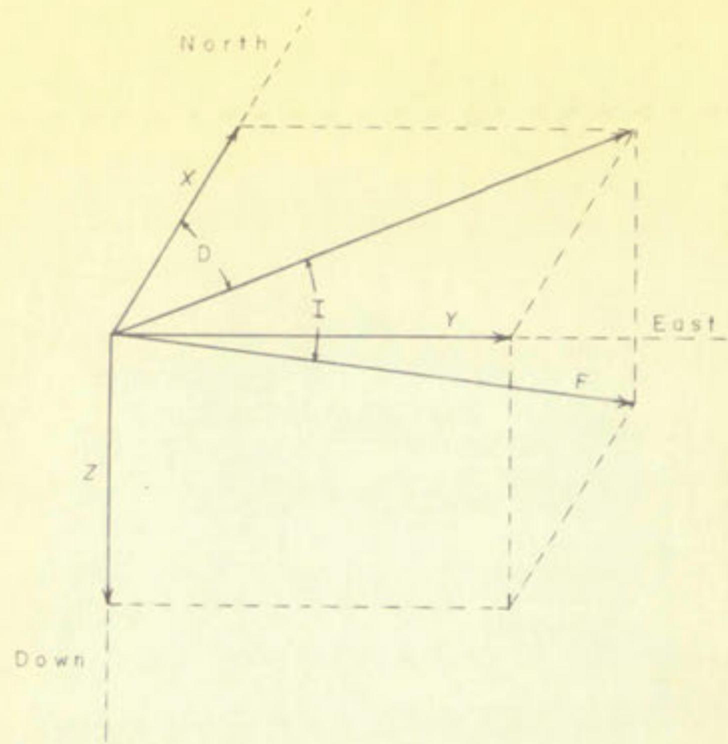

Figure 2. Magnetic field vectors.

F = magnetic line of force.

X,Y,Z = the north, east, and vertical components.

H = the horizontal component.

I = the angle of inclination of F.

H = the angle of declination of H.

p. 62). In the majority of instances, the magnetic mineral present is magnetite.

Faulting, folding, and magmatic intrusions may place materials with different susceptibilities in juxtaposition, thereby creating local variations in the earth's magnetic field.

Another variation which must be taken into account is that of normal variation, or changes in the field corresponding to changes of position with respect to latitude and longitude. At the equator, the field has about one-half of the intensity that it has at the magnetic poles, and, as mentioned above, the inclination at the magnetic equator is zero. Therefore, the increase in inclination and the increase in intensity of the field both greatly enhance the value of the vertical component as we travel from the equator toward the poles. A correction for this change must be made whenever a magnetic survey is made. Again, since true north and magnetic north do not coincide, a correction for movements east or west of the zero magnetic longitude must be made as well, although often this correction is quite small compared to the change of the vertical component with latitude.

The earth's field, at any one location, is slowly changing in declination and inclination, and the change becomes appreciable after a number of years; this change is called secular variation. The cause of this variation

p. 62). In the [illegible] of [illegible], the magnetic [illegible] mineral products or engineering.

Faulting, folding, and also displacement [illegible] place material with differing magnetic [illegible] in juxtaposition, thereby creating local [illegible] in the earth's magnetic field.

Another variation [illegible] to be taken into account is that of actual variation, or changes in the force corresponding to changes of position upon the earth [illegible] latitude and longitude [illegible]. The [illegible] has about one-half of its [illegible] at the magnetic poles, and, as mentioned above, [illegible] the magnetic equator [illegible], the difference in inclination and the difference in intensity of the field both greatly affect the value of the vertical component as we travel from the equator toward the poles. In connection [illegible] the [illegible] magnetic survey [illegible], [illegible] magnetic north of [illegible] east or west [illegible] be [illegible] compared [illegible] latitude.

The earth's [illegible], [illegible], changes [illegible], becomes [illegible] in [illegible].

is not exactly understood, and although it tends to become manifest over a period of time, it usually can be ignored during magnetic surveys, unless they are of a duration covering a number of years.

Diurnal changes in the earth's field are the rule, and are probably the result of the effect of the sun's magnetic field upon that of the earth. The moon also seems to exert a similar, but much smaller, influence. (Fleming, 1939, p. 39.)

Sudden changes in the earth's field sometimes occur; these are collectively termed "magnetic storms," and are of three general types: long-period, short-period, and sudden-commencement disturbances. These disturbances are possibly connected in some way with solar and other cosmic phenomenon. (Fleming, 1939, p. 45 and p. 53.) As these storms are of a fluctuating nature, no correction for their effects upon a magnetic survey is possible, and consequently operations must be suspended for the duration of the "storm."

Magnetic Instruments

There exist several different types of instruments used in studying the earth's magnetic field. Jakosky (1940, p. 65) divides the instruments into two main categories: (a) instruments for determining the absolute values of the magnetic field over extended areas, and (b) instruments for determining the relative values of the magnetic field over small areas.

The first class of instruments is used primarily for studies of the earth's magnetism, whereas the second class comprises the kinds used in mining and oil prospecting. In this class, the earth's field is studied not for its own sake, but to learn something of the disposition of the rocks which locally influence the field. A further division of this second class of instruments is possible, according to their principles of operation: (1) dip needles, (2) deflection instruments, (3) magnetic torsion balances, and (4) magnetic field balances.

A discussion of each of the various types of magnetic instruments is beyond the scope of this paper, and discussion will be limited to the kind used in the survey made by the writer, which was a magnetic field balance, more specifically, a vertical magnetometer.

A very large amount of the geophysical prospecting for oil that has been done with a magnetometer has employed a Schmidt magnetic field balance. Its essential components are a pair of permanent magnets pivoted on a horizontal knife-edge. A horizontal magnetometer measures the horizontal component of the earth's magnetic field; its magnets are arranged vertically. A vertical magnetometer measures the vertical component of the earth's field, and its magnets are arranged horizontally. Both are Schmidt magnetic field balances.

The magnets carry a mirror, and are balanced on a horizontal knife-edge (generally made of quartz) which is

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The magnets carry a mirror, and are mounted on a horizontal knife-edge (generally made of quartz) which

perpendicular to the magnetic axis of the magnetometer. The center of gravity of the moving parts is displaced both horizontally and vertically with respect to the knife-edges. Figure 3, which is taken from Nettleton (1940, p. 171) illustrates the theory of the vertical magnetometer. The following discussion will also be found in Nettleton (1940, p. 171-173).

When the magnetometer is oriented along an east-west magnetic line, there will be no torque impressed on the moving parts by the horizontal component of the magnetic field. The two torques which will affect the moving parts are (1) the gravitational torque, which will tend to rotate them clockwise (Figure 3), and (2) the magnetic torque, which will tend to rotate them counterclockwise. The gravitational torque results from the weight, mg, acting at the center of gravity, c; the magnetic torque results from the reaction of the vertical component of the magnetic field, Z, with the poles of the magnet. At equilibrium these two torques are equal, and

$$2PZL \cdot \cos x = mg(d \cdot \sin x + a \cdot \cos x) \qquad (1)$$

where $2PL = M$, the moment of the magnetic system.

We can divide through equation (1) by the cos x:

$$MZ = mg(d \cdot \tan x + a)$$

$$\tan x = \frac{MZ - mga}{mgd} \qquad (2)$$

A rotation of the moving parts causes a scale deflection of $s - s_o = f \cdot \tan 2x$.

perpendicular to the [illegible] as [illegible].
The center of gravity of the [illegible] and [illegible]
both horizontally and [illegible] [illegible]. The
knife-edges. Figure [illegible], [illegible] (1940, p. [illegible]), illustrates [illegible] of the vertical
magnetometer. The [illegible] [illegible] may be
found in Nettleton (1940, p. [illegible]).

When the magnetometer is oriented in an east-west [illegible], there [illegible] the
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moving parts are (1) the [illegible], which
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poles of the magnet. At [illegible] the [illegible]
are equal, and

[illegible] (4)

where [illegible], the [illegible] [illegible].

We can [illegible] [illegible] (4) [illegible]

[illegible]

[illegible] (5)

A [illegible] of the [illegible]
deflection [illegible]

x is always less than 2°, and for small angles, $\tan 2x \cong 2 \tan x$. Therefore, we can measure the deflection angle x as: $\tan x = \frac{s-s_o}{2f}$. (3)

By equating equations (2) and (3), we get

$$\frac{s-s_o}{2f} = \frac{MZ - mga}{mgd} . \quad (4)$$

At a new location on the earth's surface, where Z is a different value, Z', equation (4) will become

$$\frac{s' - s_o}{2f} = \frac{MZ' - mga}{mgd} . \quad (5)$$

The difference in deflection due to the difference in field strength at the two places may be found by subtracting equations (4) and (5):

$$\frac{s-s'}{2f} = \frac{MZ-MZ'}{mgd} \text{ or } s-s' = (Z-Z') \frac{2fM}{mgd} \quad (6)$$

This simply means that the difference in magnetic intensity between two points is:

$Z-Z' = (s-s') \frac{mgd}{2fM} = K (s-s')$ where K is the scale constant of the instrument. By making K a smaller factor, the sensitivity of the instrument can be changed. Usually m, M, and f are fixed values, and d may be changed by turning a screw in the instrument, which will change the center of gravity with respect to the knife edge.

With this type of instrument, measurements on the order of precision of $\pm$ 2 gammas may be made, if the K value is set to about 10 gammas per scale division.

The vertical magnetometer as constructed for field work is an elaboration upon the sketch shown above.

s is assumed [illegible]

tan 2λ = [illegible], [illegible] angle x [illegible]

By equating [illegible]

[illegible]

As a [illegible] there is a different value, 2λ', equation (?) will be

[illegible] (8)

The difference in [illegible] due to the [illegible] in field strength [illegible] tracting equations (?) [illegible]:

[illegible] (9)

Thus study shows that the difference in magnetic field intensity between two cylinders is

H−H' = [illegible] = A (a−a') [illegible] the scale constant [illegible]. By [illegible] factor, the sensitivity of the instrument can be changed. Usually [illegible], and [illegible] are fixed values, but A may be changed by turning a screw in the instrument, which will change the center of gravity [illegible].

With [illegible] order of [illegible] may be [illegible] value is [illegible].

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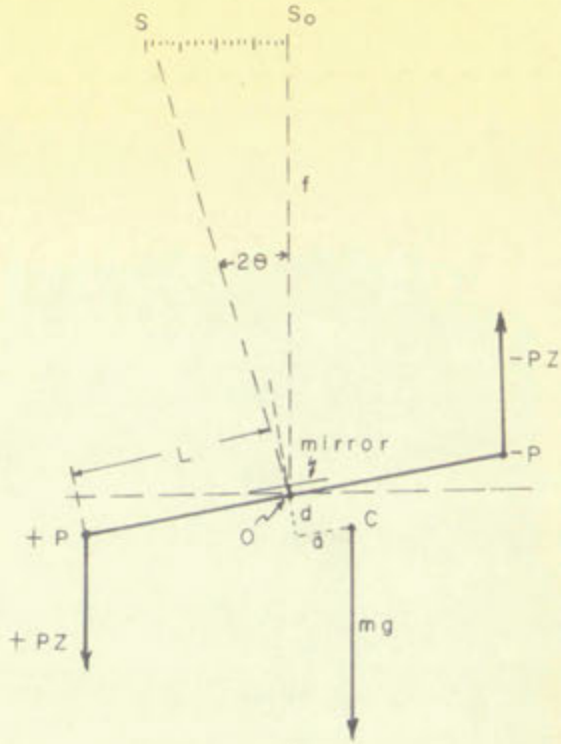

Figure 3. Diagram of vertical magnetometer.
(after Nettleton, 1940, p. 171)

P = pole strength of magnet.

L = length of one-half of magnet.

Z = vertical component of magnetic field.

O = position of knife-edge.

C = center of gravity.

m = mass of moving system.

g = acceleration of gravity.

d,a = displacement components of C from the knife-edge.

(Figure 3), but it remains a simple instrument to use. Figure 4 shows a schematic cross section of a vertical magnetometer, after Nettleton (1940, p. 178).

The magnetometer consists of a metal case containing the magnets, mirror, scale optical system, thermometers to record the temperature of the instrument in degrees centigrade, damping yokes to slow the movement of the magnets, longitude and K value adjusting screws, and a locking device to prevent movement of the magnets and to raise the quartz knife-edges from contact when the instrument is in transport. Insulation is provided to slow the temperature change of the instrument.

The scale value of the instrument is determined before field work is begun. Checks are made from time to time during the course of the work to determine whether or not this value has changed. The best method available for the determination of this value is that which uses a Helmholtz coil, which is a coil of wire that can be placed around the instrument. Varying magnetic fields may be produced by passing a current of known strength through the coils, and the deflection produced by these artificial magnetic fields may then be noted. The current is varied by means of a control box which contains batteries, a rheostat, milliameter, and a reversing switch. A known magnetic field may be produced, and the formula which is used to calculate the strength of this field is:

(Figure 3), and is the [illegible] of a [illegible]. Figure 4 shows a [illegible] Askania [illegible] vertical magnetometer, [illegible] (Askania, [illegible]).

The [illegible] consists of [illegible] the magnets, mirror, [illegible] to record the temperature of the instrument in degrees centigrade, [illegible] to [illegible] the [illegible] of the magnets, [illegible] and [illegible], locking devices to prevent movement of the magnetic system, to raise the [illegible] from [illegible] when the instrument is in transport. [illegible] is [illegible] to allow the temperature change of the instrument.

The scale value [illegible] before field work [illegible] to time during the course of the work to [illegible] whether or not [illegible] value has changed. [illegible] available for the determination of [illegible] which uses a Helmholtz coil, [illegible] can be placed around the [illegible]. [illegible] fields may be produced by [illegible] a [illegible] through the coil, and the [illegible] by these [illegible]. The [illegible] contains [illegible], [illegible], reversing [illegible], and the [illegible] of this [illegible].

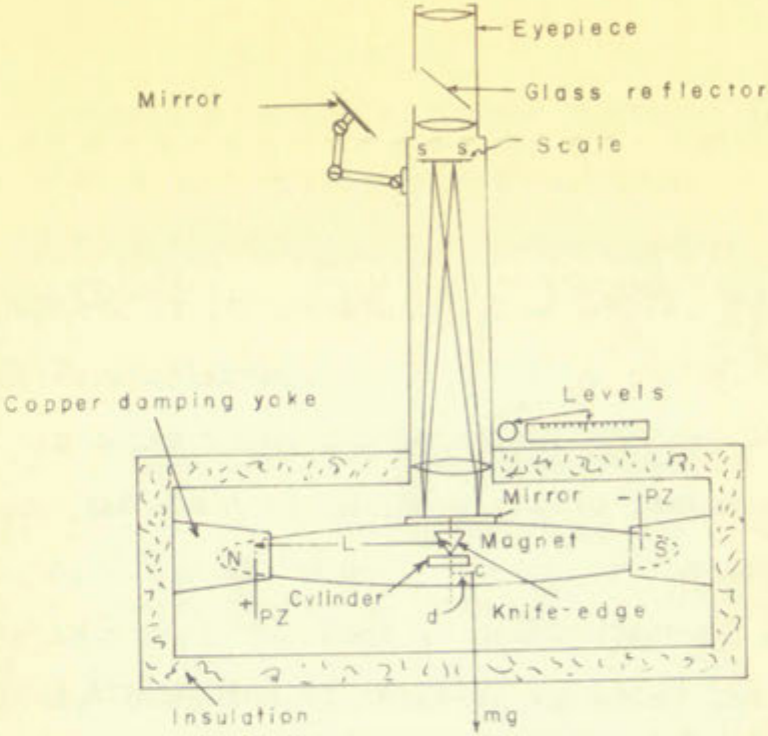

Figure 4. Schematic cross section of the vertical magnetometer. (after Nettleton, 1940, p. 178)

$H = \frac{64\pi ni}{5r}$ where,

H is given in gammas

n is the number of turns in the coil,

i is the current in milliamperes,

r is the coil radius in centimeters.

Generally the constant value $\frac{64\pi n}{5r}$ is supplied by the manufacturer.

The scale value may be calculated by observing the deflections produced in the magnetic fields of known strength, after the zero position, or the position of the scale when no current is passed through the coils, is noted. Once the calibration is made, the internal adjustment provided for the distance d (Figure 4) should not be disturbed.

Many instruments have Helmholtz coils built directly into the instrument case, as did the one used in this particular study.

The effects of temperature changes upon the instrument must also be determined, for not all magnetometers are fully corrected for such changes. This may be done by noting the deflection in scale divisions produced when the instrument is warmed or cooled from some starting or base temperature. This deflection in scale divisions may, of course, be converted into a value given in gammas, once the K value is known. Modern instruments commonly experience a change of no more than 1-2 gammas per degree of change centigrade; older instruments commonly show a much greater deflection.

$H = \frac{2\pi n i}{r}$

H is given in gauss

n is the number of turns in the coil,

i is the current in absolute units,

r is the mean radius in centimeters.

Generally the constant value $\frac{2\pi n}{r}$, is given by the manufacturer.

The constant value may be calculated by measuring the deflections produced in the magnetic field of known strength, after the zero positions of the pointers on the scale when no current is passed through the coils is noted. Once the calibration is made, the horizontal adjustment provided for the distance d (Figure 3) should not be disturbed.

Many instruments have Helmholtz coils built directly into the instrument case, as did the one used in this particular study.

The effects of temperature changes upon the instrument must also be determined, so that the magnetometers are fully corrected for temperature. This may be done by noting the deflection at constant field produced when the instrument is warmed or cooled from some standard or base temperature. This deflection is usually small and may, of course, be converted into a value of gammas per degree once the K value is known. Modern instruments generally experience a change of no more than 1-2 gammas per degree of change centigrade, older instruments commonly show a much greater deflection.

Field Methods

In field procedure, the magnetometer is placed upon a tripod, which has a leveling bubble for establishing an approximately level position of the tripod. As a vertical magnetometer should be set in an east-west direction, so that the inclination of the earth's field will not produce any horizontal torque component on the moving system, a compass is employed to find the magnetic north direction at each station. The magnetometer is then placed upon the tripod in the east-west direction, leveled by means of two leveling bubbles on the instrument case, and by three leveling screws on the tripod; the moving system is then carefully released, and the deflection read and noted in scale divisions. The magnetometer is then locked and rotated 180° on the tripod head, re-leveled, released, and the deflection read and recorded. The average of the scale readings is later used for computation. After the magnetometer is again locked, the temperature and time are recorded.

This constitutes the basic procedure for reading the vertical magnetometer at each station. The amount of time that will be needed to perform the foregoing operations at two successive stations will vary, depending upon the distance between them, the roughness of the terrain, and the climatic conditions. Should a strong or gusty wind be blowing, the operation of leveling the magnetometer will be rendered extremely difficult. The average time between stations was about 20 minutes for the writer.

The readings taken at each station, as recorded in scale divisions, may be converted into gammas by multiplying the value in scale divisions by the K value, as previously determined. The value so obtained is a basic field reading; it must later be corrected for temperature variations, for the diurnal variation, for normal variation (latitude and longitude corrections), and for a tie-in correction with other traverses. A correction can be made for terrain, if the relief is very great, but it is a difficult correction to make, and avoided wherever possible.

Temperature corrections are made by reducing all field data to a common temperature, usually to 20° centigrade. The correction is made by adding or subtracting the number of gammas necessary to raise or to lower the field reading to what it would be at 20°.

Usually during the day there will be a change in the magnetic field, called the diurnal variation. The variation is regular enough that it may be corrected by:

(1) making a continuous recording of the field at some base station, by the use of a continuously-recording instrument or by the use of a standard instrument read by an assistant every 10 or 15 minutes during the day.

Another method, which was employed by the writer was:

(2) making a record of the variation by checking the original reading made at a base station every two

The reading [illegible] , [illegible] in scale divisions, may be [illegible] to [illegible] by multi- plying the value [illegible] previously determined. [illegible] field reading, [illegible] variations, [illegible] tion (latitude and longitude [illegible]), [illegible] tle-in correction [illegible] be made for [illegible] is a difficult [illegible] possible.

Temperature [illegible] field sets to a [illegible] grade. The correction is [illegible] the number of [illegible] field reading to [illegible].

Usually [illegible] magnetic field, called the diurnal [illegible] tion is regular [illegible]

(1) making [illegible] base station, [illegible] instrument [illegible] read by an [illegible] the day.

Another method, which [illegible]

(2) making [illegible] original reading [illegible]

hours or less during the course of the working day.

This latter method is not as accurate as the first method, but it was considered good enough for this particular survey, as the anomalies encountered were of such magnitude, that any slight discrepancies of a few gammas in the diurnal correction would not noticeably affect their significance. The check for diurnal variation serves as a check for the unpredictable magnetic "storms," and so, in any event, the diurnal variation checks should be made.

A local survey for buried structure has its significance in the relative values of the magnetic readings of one station to another; therefore, the normal variations must be taken into account, as they are of a considerable magnitude if the survey covers a few miles of latitude. The corrections for latitude and longitude in various parts of the country may be obtained from maps and charts published by the U. S. Coast and Geodetic Survey. The corrections used by the writer were obtained from the "U. S. magnetic tables and magnetic charts for 1935" by H. H. Howe; the correction amounted to about 14 gammas per mile of latitude, and about 5 gammas per mile of longitude. A later series of charts and tables for 1955 were unavailable to the writer, but probably the field had not changed very greatly in that time.

The value of the correction for latitude and longitude variation lies in its effect of bringing all of the observed

hours or less during the course of the [illegible]

This latter method is [illegible] than the method, but it was considered [illegible] for this particular survey, as the [illegible] of such magnitude, that are [illegible] in the gammas in the diurnal correction could [illegible] affect their significance. [illegible] tion serves as a check [illegible] "storms," and so, in any event, the diurnal variation checks should be made.

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The value of the [illegible] variation [illegible]

field readings to a common datum, so that their significance may be more easily realized from one traverse to another.

To make the correction for latitude and longitude, a station is selected on the survey as the zero station, and the latitude and longitude correction, which was obtained from the charts or tables, is applied to every other station on the survey, by determining the latitude and the longitude (in miles) of every other station with respect to the zero station. For example, if the correction is -10 gammas per mile of latitude to the north, and -3 gammas per mile of longitude to the east, then the total correction for a station that is situated 2.3 miles north and 5.6 miles east of the zero station would be: $(-10)\times(2.3) + (-3)\times(5.6) = (-23) + (-16.8) = -39.8$ gammas.

The correlating of the traverses on a survey is called "tying-in," a procedure made necessary because of the cumulative effect of the earth's magnetic field variations from day to day. It also serves to bring the readings to a common datum. The "tie-in" traverse is run by a survey made more or less at right angles to the other traverses, incorporating one former station per earlier run traverse. This practice clearly shows the relationship of these earlier traverses, one to another; one of these is selected as a base traverse, and all other traverses in the entire survey are corrected to this base.

field readings [illegible], [illegible] differ-

ences may be [illegible] from one [illegible] to another.

To reduce the observations to [illegible], a station is selected on the [illegible] and the latitude and longitude [illegible] are obtained from the [illegible] other station on the [illegible], the latitude and the longitude (in miles) of each other station with respect to the base station. For example, if the [illegible] is -10 gammas per mile of latitude to the north, and -3 gammas per mile of longitude to the east, [illegible] the total correction for a station which is located 2.3 miles north and 5.0 miles east of the base station would be (-10)(2.3) + (-3)(5.0) = (-23) + (-15.0) = -38.0 gammas.

The correlating of the traverses into a network by means of "tying-in," or previous base readings, removes any cumulative effect of the [illegible] from day to day. It also serves to bring the readings to a common datum. The tie-in traverse is run to extend more or less at right angles to the other traverses, [illegible] corrects the [illegible]. This procedure [illegible] the [illegible] earlier traverses, [illegible] as a base traverse, and all other traverses [illegible] survey, are [illegible] adjusted.

When all these various corrections have been made, we have, as a final result, a fairly correct value in gammas of the vertical magnetic component for each station on the magnetic survey.

Interpretation of Magnetic Data

Most of the work of interpretation of magnetic data is of an empirical nature. The interpretation is usually quite qualitative, although commonly a consideration of theoretical anomalies will result in a clearer image of the actual conditions which exist. This is so because an interpretation of a magnetic survey is never unique in itself; it must be strengthened by other data of a geological, geophysical, or subsurface nature before a concrete interpretation of the survey is possible.

An anomaly may signify either relief in the basement surface, or a variation in the susceptibility of the rocks. It is this possible variation in the susceptibility, as well as a lack of knowledge of the direction of a rock's polarization, that makes a quantative analysis of magnetic data so very difficult. (Dobrin, 1952, p. 144) Without knowing the relative proportion of induced and of permanent magnetism, it is very difficult to be sure of the direction of a rock's polarization. However, when there is some control which might allow a fair amount of confidence in the type of structure which probably exists in the magnetic body, coupled with magnetic data on the type of anomalies which exist over similar known structure

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in the same area, interpretation of new magnetic data on the basis of the anomalies found over the known structure would seem to be a fairly safe procedure.

Figure 5 is a reproduction of a figure after Nettleton (1942, p. 299), which is a curve of a vertical magnetic intensity profile over a theoretical fault. In this article Nettleton stated (p. 293) that it is often possible to calculate, from rather generalized forms, geophysical effects which are in agreement with those observed within the precision of the observation. He adds that the effects from certain generalized forms are often close enough to those observed so that they give all the information that can be usefully applied in connection with the interpretation of reconnaissance surveys. The generalized forms are easier to use than the more complex expressions, which must take the direction of polarization into account.

Figure 6 is a reproduction from Soske (1935, p. 70), and represents the variation of horizontal and vertical anomalies above faulted zones involving a uniformly magnetized layer. Soske states (p. 70) that "the diagrams are drawn to scale, and represent anomalies in their respective magnitudes, considering the same materials and magnetization."

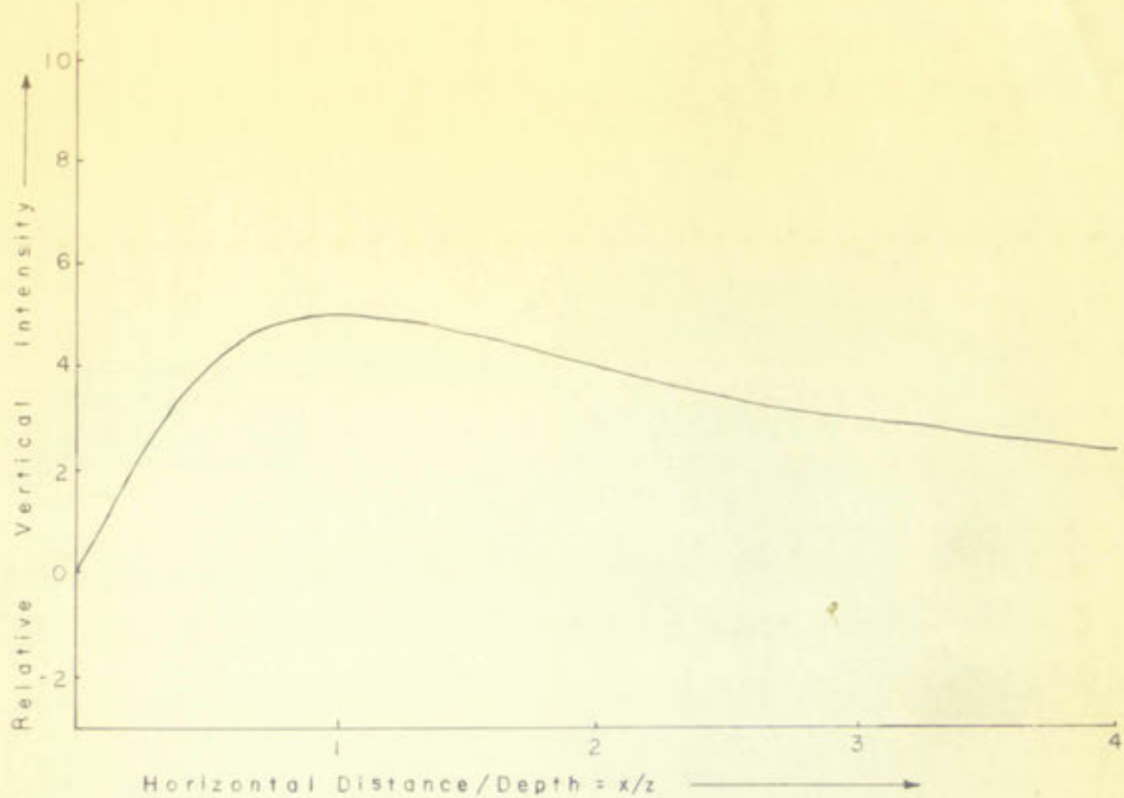

Figure 5. Curve of vertical magnetic intensity over a theoretical fault. (after Nettleton, 1942, p. 299)

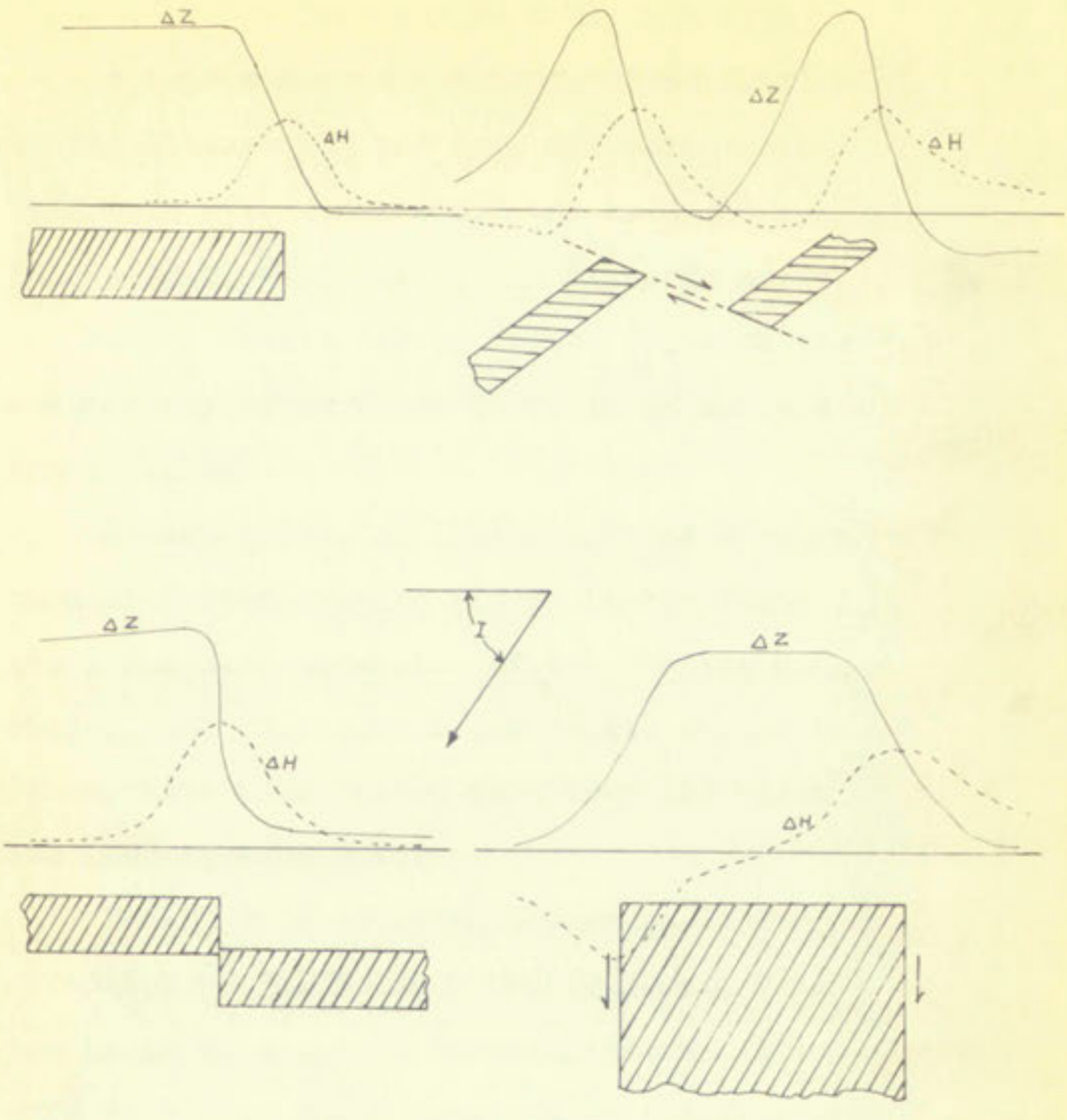

Figure 6. Theoretical anomalies of horizontal and vertical intensity above various magnetic material distribution. (after Soske, 1935, p. 70)

APPLICATION OF MAGNETIC METHODS TO BURIED FAULTS

Previous Work of this Type

A fair number of magnetic investigations are described in the literature, and many of these investigations have been made over areas where the basement rocks are faulted. As a result, a number of the magnetic surveys show that the buried faults can be traced for some distance under sedimentary cover where there is no surface indication of the faulting.

Stearn (1932, p. 189) described a magnetic investigation of buried granite ridges in the Texas Panhandle, which are a westward extension of the Wichita Mountains. These ridges, and an accompanying fault, called the Potter County fault, have been traced more than 100 miles westward from the last igneous outcrop.

In the same article, Stearn (p. 190) relates that an extension of the Beckham County fault, Texas, was made on the basis of magnetic investigations. Original traverses were made over known portions of the fault, and the type of anomalies which resulted were used in the interpretation of similar anomalies found to the west of the known segment of this fault.

Cram (1948, p. 327-333), and Peters (1949, p. 14-15) described buried faults detected by a magnetic survey in the Cumberland Oil Field, Oklahoma.

Lynton (1931, p. 1357) described a case in California where two faults were traced across an alluvial-filled

valley by a magnetic survey. In this case, Cretaceous sedimentary rocks were very magnetic, whereas overlying Eocene sediment was weakly magnetic. Depressions in the magnetic profiles near the assumed fault locations checked with the visible faults in the hills where the rocks were exposed.

Lynton (1931, p. 1361) also described a fault anomaly which was discovered in a survey made over a gabbroic mass in the San Joaquin Valley, California. The gabbroic mass is strongly magnetic, and the fault anomaly is rather small in comparison with that of the main anomaly.

Soske (1935, p. 90) made a magnetic survey of the San Andres fault, California, and on the basis of the magnetic anomalies which were shown on traverse profiles, was able to extend the trace of the fault some 60 miles beyond the point at which it could be definitely seen at the surface.

In each case of the magnetic surveys described above, a number of profiles of the magnetic field were shown, showing anomaly curves over faulted rocks. These profiles aided the writer in evaluating the anomalies found in the survey that he ran.

Application of Magnetic Methods to the Albuquerque Basin

Several traverses were run across a known fault, the Ojuelos, in the early fall of 1959. The Ojuelos fault is believed by Reiche (1949, p. 1210) to be near the original eastern border of the Albuquerque basin, and so it was believed that a magnetic traverse might show an anomaly

near the surface expression of the fault. A substantial anomaly was noted, and so further work was done on the Ojuelos fault, and also in areas where there were no surface expressions of basement faulting, but where earlier workers had postulated the existence of such faults.

The methods used for the field work were rather standard; stations were set up at regular intervals along a traverse, which was run where possible at right angles to the suspected trend of faults. During a field day frequent readings were made at a base station so that the diurnal variation could be corrected, and so that any magnetic storms would be detected. Several "tying-in" traverses were run after the main field work was done, and the corrections for temperature and for the latitude and longitude of each station were made.

When the data for all of the stations had been reduced, their positions were plotted on a base map. The traverses of importance are thus shown on three maps, Figures 7, 8, and 9. Figures 7 and 8 show the position of each station, and also the magnitude and shape of the magnetic vertical intensity profiles. Figure 9 shows the traverses, and the position of the faults inferred from the profiles as compared to the position of the postulated faults of the earlier workers.

Discussion of the Vertical Intensity Magnetic Profiles

The scale of each profile on the maps (Figures 7 and 8) indicates the magnitude of the vertical magnetic intensity

near the surface [illegible]

anomaly was noted, such as [illegible] Olmstead fault, was also in these areas [illegible] face extremes of constant [illegible], but [illegible] unknown and [illegible] the [illegible].

The records [illegible] for the field [illegible] were [illegible]; stations were [illegible] along traverses, which [illegible] the [illegible]. [illegible] readings were made at [illegible] variation [illegible], [illegible] would be [illegible]. [illegible] run [illegible] for temperature and [illegible] station were made.

When the [illegible] all of the [illegible], their positions were plotted [illegible]. The [illegible] of importance [illegible] Figures [illegible], and 9. Figures 7 and 8 show the [illegible], and also the [illegible] of the [illegible] intensity profiles. Figure 9 [illegible] traverses, [illegible] position of the [illegible] compared to the [illegible] of the [illegible] earlier [illegible].

[illegible]

[illegible]

in gammas, and allows a comparison of one profile with another.

Only inferences can be made from examination of the profiles as to the disposition and nature of the lithologic materials at depth. Under the section "General Lithology of the Area," the probable magnetic properties of the lithology in the Albuquerque basin were discussed. The general conclusion is that granitic basement rocks probably exert the more widespread influence upon the vertical magnetic intensity, although the local influence of basaltic rocks, and of magnetic sand and gravel may modify the general picture.

A consideration of the probable structural disposition of the lithologic materials must accompany any study of the magnetic profiles.

Thus, magnetic anomalies may be caused by: (1) a difference in the polarization of a magnetic formation; (2) a difference in the magnetic susceptibility of adjacent materials due to (a) faulting, which might place materials of differing susceptibility next to each other, (b) buried topography, which might result in materials of differing susceptibility being placed in juxtaposition, and for example, granitic ridges covered by gravels, and (c) intrusions and flows of igneous material with a high susceptibility; (3) a variation of the magnetic susceptibility within a formation; (4) folding or tilting of formations, which could vary the depth below the surface of a susceptible formation and the surface of the ground.

In general, [illegible] of one [illegible] another.

Only in [illegible] profiles [illegible] materials at depth. Thus, for example, [illegible] of the area, [illegible] lithology in the [illegible]. [illegible] general conclusion is that [illegible] exert the more important influence [illegible] netic intensity, although the local influence of [illegible] rocks, and of [illegible] general picture.

A consideration of [illegible] of the lithologic [illegible] magnetic profiles.

Thus, magnetic anomalies may [illegible] difference in the [illegible] a difference in the magnetic susceptibility of adjacent materials due to (a) [illegible] of differing susceptibility, [illegible] (b) [illegible] topography, [illegible] susceptibility [illegible] example, [illegible] trusions [illegible] (c) a variation of the magnetic [illegible] within a [illegible] (d) [illegible] which [illegible] tible [illegible].

In the Albuquerque basin, the dominant type of structural deformation seems to have been block faulting; folding of the sediments is probably minor, and subordinate to the faulting. Therefore, the depth to the Precambrian granite should become greater, and its magnetic influence less, as one travels westward from the mountain ranges. A magnetic profile that is made in an east-west direction should reflect the greater depth to the granite by anomalies, with lower readings on the downthrown sides of the granite blocks.

The Ojuelos fault (Figure 9) can be traced on depth-to-water maps constructed by the U. S. Geological Survey, and these maps indicate that this fault is downthrown to the west. (Mr. F. Titus, personal communication, 1960.) Most of the magnetic profiles that were run across the known or projected trace of this fault show an anomaly which could be attributed to vertical displacement of the granite basement and of the sedimentary sequence which lies above the granite. The alignment of the magnetic anomalies agrees fairly well with the trace of the Ojuelos fault as it was mapped from surface and from water well data, and therefore the writer believes that these anomalies do reflect fault displacements. However, only eight profiles of the fifteen which cross the known or projected trace of the Ojuelos fault give any indication that the fault is downthrown to the west. Of the remaining seven, five would seem to suggest that the downthrown side is to the east,

and two show no definite anomaly. There are lower gamma values to the west of anomalies in eight profiles along the Ojuelos fault. This would indicate that the downthrown side of the Ojuelos fault is to the west. These profiles are:

(1) Profile A-V, T. 11 N., R. 5 E., which shows an anomaly about 0.6 miles west of the projected trend of the Ojuelos fault.

(2) Profile A-U, T. 11 N., R. 5 E., which shows an anomaly about 0.5 miles east of the projected fault trend.

(3) Profile A-O, T. 9 N., R. 4 E., which shows an anomaly coincident with the Ojuelos fault.

(4) Profile A-L, T. 8 N., R. 4 E. An anomaly is seen on the western side of the profile. The fault trace as drawn from the magnetic profile is 0.3 miles west of the surface fault trace.

(5) Profile A-F, T. 7 N., R. 3 and 4 E. If this profile is studied in conjunction with profile A-G, T. 7 N., R. 4 E., a gradual decrease in the gamma values to the west will be noted, but no very pronounced anomaly is present here.

(6) Profile A-E, T. 6 N., R. 4 E., displays a gentle peak in the vertical intensity on its western edge, suggesting a decrease in the gamma values farther to the west. The anomaly is displaced 0.8 miles to the west of the extended trace of the fault.

(7) Profile A-D, T. 6 N., R. 4 E., also shows a decrease in the gamma values to the west. The anomaly is displaced 0.9 miles to the west from the surface trace of the Ojuelos fault.

(8) Profile A-C, T. 6 N., R. 4 E., has an anomaly on its western side displaced 0.8 miles to the west of the surface trace of the fault.

The five profiles whose decrease in gamma values to the east of their anomalies would suggest that a downthrown block lay to the east of the Ojuelos fault are:

(1) Profile A-N, T. 8 N., R. 4 E. The anomaly on the western side of this profile coincides with the projected trace of the Ojuelos fault.

(2) Profile A-K, T. 8 N., R. 3 and 4 E. The anomaly is about 0.2 miles east of the fault projection. The higher values of vertical intensity increase steadily to the west of the anomaly.

(3) Profile A-I, T. 7 N., R. 3 and 4 E., which shows an anomaly displaced 0.3 miles to the west of the projected surface trace of the fault.

(4) Profile A-H, T. 7 N., R. 3 and 4 E. This profile has an anomaly which is about 0.7 miles east of the projected fault trace.

(5) Profile A-J, T. 7 N., R. 4 E. The anomaly is some 0.5 miles west of the fault trace.

The two profiles which cross the Ojuelos fault trace but which show no anomaly are:

(1) Profile A-T, T. 10 and 11 N., R. 3 and 4 E. While no discernible anomaly is present, the gamma values do decrease to the west.

(2) Profile A-A', T. 5 N., R. 4 E., exhibits a low value of vertical intensity near the expected fault trace, but shows no definite anomaly.

The San Francisco fault, T. 13 and 14 N., R. 5 E., is presumably downthrown to the west, but the three profiles which were made across the known and the projected fault trace would seem to indicate that the downthrown side was to the east, for the higher values of vertical intensity are to be found on the western side of the anomalies.

Profile B-B' shows an anomaly about 0.5 miles west of the surface trace of the fault. Profile B-C shows an anomaly which coincides with the projected fault trace, the more rapid increase in gamma values being to the west. Profile B-D, which was run diagonally across the projected fault trace from southwest to northeast, also shows an anomaly, displaced about 0.2 miles to the east of the projected trace.

Other anomalies in the Albuquerque basin may be construed as showing evidence of downfaulting, either to the east or to the west. One profile has no anomaly, and three may be indicative of intrusive bodies of basaltic material. Some of the profiles show a decrease in vertical intensity to the west of one or more anomalies in each profile. These profiles are:

(1) Profile A-X, T. 12 N., R. 4 E.

(2) Profile A-W, T. 12 N., R. 4 E.

(3) Profile A-V, T. 11 N., R. 3 and 4 E.

(4) Profile A-U, T. 11 N., R. 3 and 4 E.

(5) Profile A-T, T. 11 and 10 N., R. 3 and 4 E.

(6) Profile A-S, T. 10 N., R. 4 E.

(7) Profile A-R, T. 10 N., R. 4 E.

(8) Profile A-Q, T. 10 N., R. 4 E.

(9) Profile A-P, T. 9 N., R. 4 E.

(10) Profile A-M, T. 8 N., R. 4 E.

(11) Profile A-I, T. 7 N., R. 4 E.

(12) Profile A-D, T. 6 N., R. 4 E.

(13) Profile A-C, T. 6 N., R. 4 E.

The profiles which show a decrease in vertical intensity to the east of one or more anomaly curves are:

(1) Profile A-Y, T. 12 and 13 N., R. 4 and 5 E.

(2) Profile A-O, T. 9 N., R. 4 E.

(3) Profile A-N, T. 8 N., R. 4 E.

(4) Profile A-L, T. 8 N., R. 3, 4, and 5 E.

(5) Profile A-J, T. 7 N., R. 4 E.

(6) Profile A-I, T. 7 N., R. 3 and 4 E.

(7) Profile A-G, T. 7 N., R. 4 E.

There are three profiles, whose anomalies could be attributed to intrusive dikes or stocks of basalt, as well as to faulting. On the western edge of the profile A-Y, in T. 12 and 13 N., R. 4 and 5 E., there is a very pointed anomaly, whose shape could be indicative of a cylindrical

mass of a highly susceptible material. On the other side of the Rio Grande there are numerous basaltic intrusive bodies (Figure 9) so the possibility of one being present at depth under this line of traverse must certainly be considered. On the other hand, this anomaly could be due to a faulted block of a susceptible material, downthrown to the west. However, the shape of the anomaly is not very much like those observed over the trace of the Ojuelos fault, where downfaulting to the west is generally considered to have taken place.

Profile A-A', in T. 5 N., R. 4 E., has an anomaly which could be attributed to an intrusive mass. Profile A-B also in T. 5 N., R. 4 E., has several anomalies which could be a reflection of intrusive bodies. An intrusive mass has been mapped by Read, et al., (1944) near these profiles, as mentioned on page above. The anomalies of profile A-B also could be a reflection of faulted blocks, as their shape is similar to the anomaly drawn over a block-faulted mass, as shown in the lower right corner of Figure 6.

Profile A-Z, in T. 13 N., R. 4 and 5 E., shows a gradual rise in the vertical intensity to the west, but no anomalies.

Topographic effects are seen at the eastern end of several of the profiles. This effect took the form of a decrease in the vertical intensity where a traverse was run near the main front of the mountain mass. Evidently the large amount of granite at elevations above the

magnetometer had an upward attraction upon the moving components of the machine, and this caused the scale in the instrument to show a lower value of vertical intensity. A test of this effect was made by the writer in Tijeras Arroyo east of the Four Hills Ranch. Stations were occupied in the arroyo, and also on the hills of granite which form the south bank of the arroyo. The difference in elevation between stations in the arroyo and those on the bank was about 50 feet, but the vertical readings were around 200 gammas higher for the readings made on the banks. The profiles which show the topographic effects on their eastern ends are:

(1) Profile A-W, T. 12 N., R. 4 E.

(2) Profile A-V, T. 11 N., R. 3 and 4 E.

(3) Profile A-R, T. 10 N., R. 4 E.

(4) Profile A-Q, T. 10 N., R. 4 E.

(5) Profile A-L, T. 8 N., R. 3, 4, and 5 E.

(6) Profile A-D, T. 6 N., R. 4 E.

These profiles either level off or decrease in vertical intensity where the traverse station was located near the mountain front.

If it could be proved that all the magnetic profiles reflect the susceptibility of the granite basement, one could conclude that in the fault zone along the Ojuelos fault there has been fracturing so that some of the fault splinters or blocks moved moved downwards and others upwards, the down-thrown side varying along the fault zone. However, the

magnetometer [illegible]

components of the [illegible]

the instrument to [illegible]

A test of this effect [illegible]

Arroyo side of the [illegible]

in the arroyo, and [illegible]

the south bank of the arroyo. [illegible]

between stations in the arroyo [illegible]

about 50 feet, and the [illegible]

gammas [illegible]

files which [illegible]

ends are:

(1) Profile [illegible]

(2) Profile [illegible]

(3) Profile [illegible]

(4) Profile [illegible]

(5) Profile [illegible]

(6) Profile [illegible]

These [illegible]

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mountain front.

If [illegible]

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conclusion [illegible]

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blocks moved [illegible]

thrown [illegible]

general picture of vertical faulting, with the major downward movements being to the west all along the eastern side of the Albuquerque basin seems to be more compatible with the evidence given by well and water-table data. Thus some other factor besides the susceptibility of granite basement may be influencing the vertical magnetic intensity along the Ojuelos fault, and over the eastern side of the Albuquerque basin in general.

One possible explanation for high magnetic readings over a downthrown fault block is that a magnetic bed, present in the downthrown block, may have been eroded from the upthrown block. Such a bed could be a basalt flow, or a sedimentary formation with a high percentage of basalt fragments or of magnetite grains. In the portion of the Albuquerque basin studied, the possibility of sedimentary beds containing at least local concentrations of magnetite is very great. Magnetite grains can be found at the surface, near the mountain fronts, where it is mixed in with the granite detritus.

Another possible explanation for high readings over downthrown fault blocks could be that there is an accumulation of magnetic material, such as basalt fragments or magnetite grains, in the sediments along the fault line. Discontinuous movements along a fault, followed by deposition of magnetite or basalt fragments along the base of the surface scarp after each movement, could result in a considerable accumulation of magnetic material in the sediments

of the downthrown block. In such a case, magnetic readings might show a higher vertical intensity over the downthrown block.

The writer feels that concentrations of magnetite are more probable than concentrations of basalt in the eastern side of the Albuquerque basin, as there do not seem to be many sources for basalt fragments there. Any concentration of magnetic material, whether in stream channels or at the base of fault scarps, is liable to be quite erratic in distribution and therefore unpredictable. It would seem likely that magnetite grains would be concentrated near the mountain fronts, where the heavy mineral is first separated from the granite. However, it is conceivable that a greater total amount may be found toward the center of the basin, where the sediment thickness is at its greatest.

Where possible, the anomalies were related to one another by fault lines (Figure 9). The possibilities of tilted and folded magnetic beds, of buried topography, and of magnetic intrusions contributing to the anomaly curves must be admitted, but it seemed to the writer that a simpler interpretation based upon faulting fits the information available equally well. The complexity of faulting is difficult to determine from the profiles. In general, the anomalies were connected by smooth, curving fault lines (Figure 9), although the situation is probably more complicated. The faults may be in echelon, or have trends in several directions, and there may be some large east-west

of the [illegible] [illegible]. [illegible] [illegible], [illegible] might show a [illegible] [illegible] over [illegible] [illegible] block.

The writer feels that [illegible] [illegible] [illegible] more probable than [illegible] [illegible] [illegible] side of the [illegible] [illegible], [illegible] [illegible] many sources for [illegible] [illegible]. [illegible] of magnetic material, [illegible] [illegible] [illegible] at the base of [illegible], [illegible] [illegible] in distribution and [illegible]. [illegible] that magnetic [illegible] [illegible] [illegible] fronts; where the [illegible] [illegible] [illegible] granite. [illegible], [illegible] [illegible] amount may be found [illegible] the center of the [illegible], where the sediment thickness is [illegible] greatest.

[illegible] [illegible], the [illegible] were [illegible] [illegible] another by [illegible] (Figure [illegible]). The [illegible] [illegible] and [illegible] magnetic [illegible], [illegible] [illegible] of [illegible] [illegible] [illegible] [illegible] the [illegible] [illegible] must [illegible], [illegible] [illegible] [illegible] interpretation [illegible] [illegible] [illegible] available [illegible]. The [illegible] [illegible] [illegible] [illegible] [illegible] anomalies were [illegible], [illegible] [illegible] (Figure [illegible]). [illegible] [illegible] [illegible] cated. The [illegible] [illegible], [illegible] [illegible] several [illegible] and [illegible] [illegible] [illegible]

trending faults which are not readily recognizable on the profiles, which have east-west trends.

CONCLUSIONS

The magnetic investigation which was conducted along the eastern margin of the Albuquerque basin resulted in a series of vertical intensity magnetic profiles, most of which exhibited some sort of anomaly. These profiles are believed by the writer to reflect faulting which has resulted in vertical displacements of the basement and sedimentary formations of the Albuquerque basin for the following reasons:

(1) The Albuquerque basin is believed to be a graben, with faulting rather than major folding of the formations involved having taken place.

(2) The basement rocks are magnetic, and the sedimentary formations are liable to contain varying amounts of magnetic materials, so that vertical displacements of these formations, if great enough, should allow detection by a magnetic survey.

(3) Intrusions and flows of basaltic material are probably not very numerous in the formations of the eastern side of the Albuquerque basin, and therefore the influence of such material upon the magnetic profiles is probably minimal.

(4) Faults plotted on the basis of magnetic information agree in location rather well with the Ojuelos

fault, which has been plotted on the basis of surface mapping and subsurface water depth data, and with the San Francisco fault, which was plotted from surface mapping.

(5) Many of the anomaly curves in other parts of the area resemble the anomaly curves of the profiles that were made across the Ojuelos and San Francisco faults.

Final confirmation of the faulting picture envisioned by the writer will probably have to come from future geophysical studies, either gravitational or seismic.

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