MAGNETIC INVESTIGATION IN THE VICINITY OF DERBY, ADAMS COUNTY, COLORADO, U.S.A.

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RESUMEN

Durante el verano y otoño de 1967, se realizaron levantamientos magnéticos de intensidad vertical en dos áreas adyacentes al pozo Rocky Mountain Arsenal Núm. 1, localizado al NE de la ciudad de Denver, Condado de Adams, en el Estado de Colorado. Se dio a estos levantamientos el nombre de Area Manila y Area Eastlake, las cuales están cubiertas con aluvión; la edad de las rocas subyacentes varía del Precámbrico al Cenozoico y se piensa que el basamento cubierto por dichas rocas está constituido por rocas metamórficas completamente plegadas y falladas. La profundidad de las rocas basales, inferida por la columna estatigráfica del Pozo Arsenal No. 1 fue tomada como base para la evaluación cuantitativa de las anomalías magnéticas en ambas áreas cuya interpretación se dificultó por la falta de información de subsuelo y por la variación de propiedades magnéticas de las rocas basales.

No existe evidencia de grandes desplazamientos debidos a fallas verticales en las dos áreas, luego la única posibilidad de fallas en el área de Eastlake que pudiesen producir temblores son las de resbalamiento a rumbo de inclinación acompañadas por pequeños desplazamientos verticales. La amplitud de las anomalías tanto observadas como calculadas en este estudio es concordante para una profundidad del basamento del orden de 3,510 a 3,960 m. La interpretación obtenida en el Area Manila pudiera ser objetada, pero la tendencia de las anomalías magnéticas terrestres encontradas concuerda con las del levantamiento aeromagnético.

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El cambio de gradiente magnético en el área de Eastlake probablemente se debe a un contraste de susceptibilidad magnética de 1,350 x 10^{-6} cgs entre un bloque de 6,436 m de roca alterada por esfuerzos tectónicos y un gneiss anfibolítico. Este contacto podría representar la extensión oriental de las formaciones con rumbo este-oeste que afloran en las montañas Front Range hacia el oeste. Las causas de las anomalías magnéticas en la Cuenca de Denver son variadas, por lo que no es posible extrapolar los resultados obtenidos a otras áreas dentro de la misma cuenca.

ABSTRACT

During the summer and fall of 1967, vertical magnetic intensity surveys were conducted in two areas adjacent to the Rocky Mountain Arsenal well No. 1, northeast of Denver, Adams County, Colorado. The surveys are described as the Manila and the Eastlake areas, both of which are covered with alluvium material; the age of the underlying rocks ranges from Precambrian to Cenozoic; the buried basement metamorphic rocks are assumed to be complexly folded and faulted. The depth of the basement rocks, based on the stratigraphic logs of Arsenal well No. 1, was used as a basis for quantitative calculations of the magnetic anomalies in the areas, but the interpretation of magnetic data was difficult because of lack of sufficient drill-hole information and of variation of basement rock magnetic properties.

There is no magnetic evidence of major vertical fault displacements in the two areas; hence, the only faults in the Eastlake are that could possibly cause tremors are the horizontal slide-strike faults accompanied by minor vertical displacements. Amplitudes of computed and observed anomalies in both areas are in agreement at a basement depth of 11,500 to 13,000 feet. The interpretation so arrived at in the Manila area could be objectionable, but the vertical ground-magnetic patterns are in accordance to the general aeromagnetic patterns.

The steep magnetic gradient at the Eastlake area is probably due to a magnetic susceptibility contrast of about 1,350 x 10^{-6} cgs unit between a 4-mile block of sheared rock and amphiobolitic gneisses. This rock interface may be the eastern extension of the east-west striking formations which crop out on the Front Range to the west. The causes of magnetic anomalies in the Denver basin are varied, therefore extension of the results to other areas in the same basin is not possible.

INTRODUCTION

This magnetic survey is an effort to obtain information about the structural attitude of the basement complex rocks in the vicinity of Derby, Adams County, Colorado. The work represents a minor contribution to the Geophysical and Geological Investigation Project relating to earthquakes in the Denver area, Colorado. This project has been conducted by the Geophysics and Geology Departments of the Colorado School of Mines, in cooperation with the U.S. Geological Survey, from 1966 to 1968.

The study of earthquakes in the vicinity of the Rocky Mountain Arsenal well No. 1 is based upon the premise that faults in the basement are responsible for the earthquakes. According to Haun (1967), the sedimentary structural fabric of the Denver basin shows a northeasterly orientation of the folds. Also, major faults follow a northwesterly trend, and the strike of the metamorphic basement rocks flanking the west central part of the Denver basin is east-west; the development of minor folds was possibly controlled by the pre-Laramide structural fabric on the basement complex.

Another important fact is the trend of aeromagnetic anomalies in the surrounding area of the disposal well. Here, the aeromagnetic map of the Denver area (Petty and others, 1966) shows a strong east-west series of magnetic lows separated 4 to 5 miles; these lows cover a 40-mile long and 1-to-5-mile-wide east-west area, from north of Golden, Colorado, to the Manila quadrangle (Plate 1), having a magnetic amplitude of 60 to 100 gammas on the average. This characteristic might be correlated with the attitude of exposed Precambrian rocks on the Front Range to the west.

The Colorado School of Mines has recorded the Denver earthquakes by means of extensive seismic instrumentation. Since December 1961, with the strain-meter data, it has been possible to infer the orientation of Precambrian faulting systems in the seismically active area in the vicinity of Derby, Adams County, Colorado (Major and Wideman, 1967). The main purpose of the study was to collect and interpret additional data that could contribute to the knowledge of the basement complex in the seismically active area, in special the recognition of any structural pattern in the basement rocks from ground-magnetic anomalies.

Previous analysis of ground-magnetic anomalies in the Denver basin have been outlined briefly in the Kassler area, south of Denver, Colorado (Adamson, 1956). In this study, the magnitude, shape, and other characteristics of vertical magnetic intensity anomalies caused by magnetic basement rocks with constant susceptibility were interpreted. Furthermore, several geophysical (Stewart, 1953; Hamzawi, 1966) and geological (Fogarty, 1952; Reichert, 1953) studies for oil in the Denver basin included seismic, gravity, and surface and subsurface stratigraphic investigations, but they paid little attention to the possible structure of the basement complex rocks.

In 1966 detailed geologic description of the buried Precambrian rocks (Edwards, 1966) and Recent deposits (DeVoto, 1967) appeared in the literature. In the same year, the strain-meter records associated with earthquakes were applied (Major and Wideman, 1967). On this basis Plate 1 shows the interpreted orientation of the faults in some portion of the Eastlake area, which is considered a part of the seismically active zone (Romig[1]).

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[1] *Personal Communication, March 21, 1968.*

In spite of exhaustive research, there are no definite indications at the present time that support the assumed structure of the basement rocks in the active zone, as shown by studies of the unexposed (Edwards, 1966) and exposed basement rocks (Lickus and Leroy, 1967; Sheridan and others, 1967). These studies constitute an attempt to decipher the structural and stratigraphic problems of the basement complex, but to this time, however, it has not been possible to disclose detailed structural patterns accurately. Consequently, neither geological nor geophysical investigations have indicated the attitude of the presumed faults in the buried basement of the Denver basin.

GEOLOGICAL SETTING

The vertical magnetic survey involved two areas in Adams County north and east of Denver; both are described as the Eastlake and the Manila areas. The first one encloses about 54 squares miles southwest of Brighton, Colorado, while the second comprises 57 square miles northwest of the Manila railroad station; these two areas are about 15 miles apart. The Eastlake area is accessible by the Interstate Highways 25 and 85, which run along its east and west boundaries; the Manila area is accessible by the Interstate Highway 40 that passes near its south limit.

Elevation above sea level at Eastlake ranges from 5,000 feet close to the town of Brighton, in the northern part of the area, to 5,230 feet in the north-central part; the topographic variations of the Manila area are similar in magnitude; they range from 5,300 feet in the northern part to 5,500 feet in the southern. Both areas are drained by the South Platte River and its tributaries, Lower Clear Creek at Eastlake, and Elder Creek at Manila, with various well-developed valleys in both areas.

The sediments overlying the basement complex in the central part of the Denver basin range in age from Paleozoic to Pleistocene (Lindvall, 1966). In addition, DeVoto (1967) identified, in the vicinity of the Rocky Mountain Arsenal, a series of stream erosion cycles which include several phases of alluvial and soil deposition during the Quaternary. Lindvall (1966), on the basis of petrographic reports by Sheridan and others (1966), described 11,900 feet of Cenozoic, Mesozoic, and Paleozoic sediments penetrated by the Arsenal well No. 1 (Plate 1).

These rocks are mainly unconsolidated sands, clays, shales, sandstones, and marlstones; these sediments are believed to be monoclinal and to follow the regional southwesterly slope of the basement complex (Fogarty, 1952; Stewart, 1953). Furthermore, the closest faults with some significant displacement in those sediments are reported in an area 15 miles from Eastlake (Lindvall, 1966). The basement complex penetrated by Arsenal well No. 1 from 11,950 to 12,045 feet is a mica-schist to a granite gneiss (Scopell, 1964), and according to Sheridan and others (1966), the rocks 15 feet above are also of Precambrian age and complex in nature (11,935-11,950 feet).

There is no reason to believe that the above Paleozoic and Mesozoic sediments contain ferromagnetic minerals in sufficient quantity to produce detectable magnetic anomalies. Thus, the only geological features as sources of magnetic anomalies are those contained in the basement complex rocks. The only basement sample in the Derby area is from Arsenal well No. 1, although several authors (Lovering and Goddard, 1950; Boos and Boos, 1957; Edwards, 1966; Lickus and Leroy, 1967) have established stratigraphic and structural patterns of the basement in Colorado along the Front Range west of Golden, Colorado, (Fig. 1-a).

Edwards (1966) made use of Precambrian samples from wells and from the Front Range to establish his interpretation about the complex basement. In his petrographic and petrologic investigation ten lithologic terranes in the State of Colorado were defined. The Eastlake and Manila areas lie in the Weld-Delta metasedimentary terrane consisting of gneissosse to schistose metasedimentaries, where Edwards (1966) pointed out that some of the samples show a severe strained, fractured, and granulated quartzite or gneiss.

Lickus and Leroy (1967) mapped in detail a 20-mile long and 2-mile wide section of the Front Range between Ralston Creek and Turkey Creek, which constitutes the eastern part of the Front Range near Golden, Colorado, about 20 miles west of Arsenal well No. 1 (Fig. 1-b). Besides Sheridan and others (1967), in their study of the Ralston Buttes Quadrangle, Jefferson County, Colorado, described in some detail the metamorphic rocks which crop out to the west of Golden, Colorado. Leroy's and Sheridan's studies are in good agreement, and differ only in nomenclature (Table I).

Geological maps and cross sections of the exposed Precambrian rocks (Leroy, 1968) reveal a schistic rock between Ralston Creek and Clear Creek about 3.5 miles wide. This band of schists strikes approximately east-west and dips 70 to 85 degrees to the south, which belong to the Belcher Hill, Crawford Gulch, and Junction Formations. By far the major portion of Leroy's section (Lickus and Leroy, 1967) is a series of gneissic rocks containing a bulk of schists, which is a significant fact in regard to the magnetic properties of rocks.

The more amphibolitic gneissic rocks are perhaps more important as causes of magnetic anomalies (Table I), and are widespread in the Ralston Buttes, Golden Gate Canyon, and Cressman's Gulch Formations as described by Leroy. The amphibolite gneisses are also associated with intercalated calcite-epidote-garnet tactites in the Cressman's Gulch Formation. A third type of rock is represented by biotitic gneiss to gneissic granite constituting the Cedar Gulch, Clear Creek Canyon, and Golden Gate Canyon Formations.

Sheridan and others (1967) identified the same type of rocks, but they included Leroy's Ralston Buttes Formation in microcline gneiss and undivided hornblende gneiss units. These two subdivisions include a complex gneiss interlayered with amphibolite, hornblende gneiss, layered calcsilicate gneiss, biotite-quartz-plagioclase gneiss, and quartz gneiss. The schistose rocks of Leroys formations were grouped by Sheridan and others in a mica-schits unit.

In Sheridan's modes (volume percent) of rocks, the amphibolite gneiss shows 0.6 to percent of magnetite-ilmenite content (Table I). In contrast, the mica-schist unit contains only 0.6 to 3.0 percent of magnetite-ilmenite, having a high percentage of magnetic minerals in some samples located in the boundaries of the unit.

A summary of the exposed Precambrian basement rocks in the eastern part of the Ralston Buttes quadrangle is described from north to south (Fig. 1-a). The exposure (Fig. 1-b) lies between longitudes 105° 15' and 105° 18' W and between latitudes 39°27'30" and 39°52'30" N (Lickus and Leroy, 1967). The remainder of the Precambrian rocks from the town of Golden southward are difficult to separate into definite formations (Lickus and Leroy, 1967), and do not appear in the generalized sections. The contacts and lithology are transitional, and the formations in this portion of the section include Clear Creek Canyon, Mount Vernon, Idledale, Turkey Creek, and Mount Morrison. They consist of hornblende-biotite gneiss in the Clear Creek Canyon Formation to a more defined igneous rock like quartz monzonite gneiss in the Mount Morrison Formation; the estimated total thickness of these five formations ranges from 16,000 to 20,000 feet (Table I includes the modes of Sheridan's units and formations defined by Leroy).

All the above formations (from Ralston Buttes to Mount Morrison) are folded, faulted, and locally highly altered Precambrian rocks as a result of strong dynamothermal metamorphism and repeated periods of tectonic and igneous action. The major fault zones in the Ralston Buttes quadrangle are Junction Ranch, Hurricane Hill, Guy Hill, Rogers, and Livingston (Lovering and Goddard, 1950), where faults and fracture zones trend predominantly northwest. Some of them extend from Precambrian into sediments (Lovering and Goddard, 1950) of Paleozoic and Mesozoic age, while most of the faults are brecciated (breccia-reef fault) along their extent (Sheridan and others, 1967).

The displacement of contacts is not clear in the breccia zones and zones of iron-stained fractured rock, and the width of breccia zones varies from a few feet to 2,000 feet while the shear zones range from 4,700 to 8,200 feet near the contact of quartz-feldspar cataclastic gneiss (Sheridan and others, 1967). The shear zone is considered a master one extending diagonally across much of the State of Colorado and along the mineral belt (Tweto and Sims, 1963).

The folding following a northeast-southwest trend, is a product of several periods of plastic deformation (Sheridan and others, 1967). Faulting and tilting in the basement rocks led to the development of a maturely dissected landscape of ridges and deformed knobs after sedimentation. A portion of the foothills at the Precambrian Front Range is characterized by sedimentary formations that lap against or bury ridges of the deformed basement (Lovering and Goddard, 1950) and it is believed that some evidence of the batholithic action is present far from the exposed Front Range, because according to Edwards (1966) there are at least five periods of large-scale igneous activity.

MAGNETIC INVESTIGATION

The field magnetic survey was conducted during 1967, by means of a Sharpe model MF-IT fluxgate magnetometer; the reading accuracy of this instrument is ± 2 gammas per scale division with the most sensitive scale. However, the meter was read with a lesser sensitivity scale with the aid of a rudimentary tripod; this procedure gave an accuracy of ± 5 gammas for stations in the Eastlake area. Since anomalies of low intensity were expected, diurnal, geographical and local effect variations were carefully controlled; it is believed that sufficient magnetic data were accumulated to permit construction and interpretation of a magnetic contour map in the Manila area, and profiles in the Eastlake area.

A total of 518 stations were occupied in the Manila area; some of them were distributed on 1-mile grid over 56.8 square miles; another set of 16 stations was established at a 0.2-mile interval along the boundaries at each 1-mile-square section. At Eastlake the number of occupied stations was 2,590. The detailed north-south profiles were separated 500 feet approximately; there were 2,264 occupied stations at variable intervals (25 to 100 feet), whereas on the profiles along the roads there were only 336 occupied stations at a fixed interval of 0.2 mile (Plate 1). The magnetic survey in each area was referred to an arbitrary independent relative magnetic level. The corresponding intensity, inclination, and declination of the total Earth's magnetic field for both areas are 55,550 gammas, 67° 30' and 14°W, respectively (United States Coast and Geodetic Survey, Deel and Howe, 1945).

Vertical magnetic intensity anomalies were calculated using various programs for the CDC 8090 electronic digital computer. The programs compute the vertical magnetic field due to an infinitely long body with cross section in the form of an nth-sided polygon and having a magnetization $\overline{M}$. The vertical component of magnetic field intensity due to the polygon is calculated with the general formula:

$$H_z = \overline{M} \cdot \overline{N} \sum_{k=1}^{n} \left\{ \sin \delta_k \sin \alpha \ln \frac{r_k^2}{r_{k+1}^2} - 2 \cos \delta_k \left(\phi_k - \phi_{k+1} \right) \right\} \qquad (1)$$

It was found convenient to choose a fixed value of M for all the computations and then to adjust the amplitude of the calculated anomalies to the amplitude of the observed ones.

The assumption of infinitely long blocks is reasonable for the interpretation of vertical magnetic anomalies in the surveyed areas. For example, the negative anomaly A in the Manila area (Plate 2) extends for some 40 miles (Plate 1); this aeromagnetic anomaly has a longitudinal trend in an east-westerly direction. However, the assumption of infinitely long blocks is limited to anomaly B (Plate 2) and some of the anomalies at Eastlake (Figs. 2 and 3); they do not confirm an extensive longitudinal trend, and it is possible that the third dimension of the bodies producing these anomalies cannot be considered as infinitely long.

If this is the case, the detail of the computed anomalies will be altered but their general shape will remain the same. For purposes of interpretation, the superjacent sedimentary rocks in the Denver basin were considered nonmagnetic; the susceptibility of rocks in the basement is caused by varied content of accessory magnetite disseminated throughout large volumes of metamorphic rocks. Examination of the modes of rocks (Table I) showed that other magnetic minerals such as ilmenite and opaque minerals (hematite-magnetite-ilmenite, and pyrrhotite series) may also contribute to the magnetic properties of rocks, because magnetite properties are mainly a function of minerals of the $FeO-Fe_2O_3-TiO_2$ system and thus are a function of the chemical composition of rocks (Nagata, 1961).

For simplication of the calculations, especially at the start, the top of interpreted bodies was assumed to be at 12,000 feet below the surface and at extensions to great depth. Both assumptions tended to make the calculated susceptibility too low; hence the width of the body was assumed equal to the distance between inflection points (Gay, 1963). The calculated values might be low, but the errors were assumed not excessive provided that the length of the body is larger than the depth of it below the magnetometer.

Susceptibility measurements of basement rocks from Front Range (Adamson, 1956; Bath,[2] 1968) range in values from 0.0010 to 0.0035 cgs unit. Using Gay's methods, the susceptibilities vary from 0.00095 to 0.0027 cgs unit; then micaceous schists were assumed with a low uniform magnetite content and a susceptibility of less than $1,350 \times 10^{-6}$ cgs while amphibolitic gneisses were assumed with a higher and more varied magnetite content than schits with susceptibilities from $2,700 \times 10^{-6}$ to $3,300 \times 10^{-6}$ cgs. Moreover, a rough estimation of the magnetic susceptibility of some samples collected by Leroy from the basement rocks shows that the amphibolite gneisses of the Ralston Buttes and Cedar Gulch Formations are much more magnetic than the schistose rocks; these results are in agreement with Sheridan's modes (Table I).

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[2] *Personal communication. January 26, 1968.*

Magnetic anomalies produced by geologic features whose lengths are at least three times as great as their width were considered for calculations. Faults, small relief anticlines or synclines, and dikes were the most common geologic features which could match in the configuration of the basement rocks. Major (1967) believes that faults and related fractures produce the tremors in the Derby area; thus recognition of these faults is the problem in question.

Fault zones containing altered magnetic minerals might be detected from a series of closed lows on contour maps, from inflection points, or from lows in magnetic profiles. Hence, the interpretation of data could be facilitated by comparison with characteristic profiles across faulting models. The major fault zones (breccia zones) contain leached, silicified, or oxidized rocks of negligible magnetic susceptibility where the magnetic minerals have altered to nonmagnetic assemblages.

Assuming a similar picture in the buried basement, the magnetic profiles over the Eastlake fault zone (Plate 1 and Figs. 2 and 3) should show the magnetic effect of sheared rock. By inference, a zone of crushed rock along a normal fault plane results in a combination of effects and a greater amplitude in the vertical intensity anomaly is expected. However, better agreement of the detected magnetic anomalies has been obtained by assuming a dike-like mass of rock dipping to the south, or a nearly vertical contact between two different rocks, as shown on the interpreted profiles (Figs. 2 and 3).

A magnetic anomaly caused by topographic relief on a magnetically homogeneous rock is designated as a topographic anomaly. It is supposed in this investigation that the upper surface of the anomaly-producing rock mass coincides with the surface of the Precambrian basement and that is almost flattopped. For topographical relief of several hundred feet at the actual extent of depth in the basement (12,000 feet), the effect would contribute little, if at all, to the magnetic anomaly.

Considering the small topographic relief for the ground surface and for the basement, the writer will not argue that some anomalies are caused by this effect. Hence, in all the calculations the field points are considered at a constant elevation.

Since the inclination I of the induced magnetic field in the studied areas is relatively high, the shape of vertical magnetic anomalies is not greatly affected by the strike of the body; thus the dike-like anomalies are all similar in shape and magnitude to the vertical magnetic profiles for eastwest magnetic strike bodies, and in Equation(1) the angle-term dominates over the log-term in high latitudes. This consideration suggests that in the first trial of matching anomalies, the log-term can be ignored. The errors introduced by omitting the topographic anomaly correction and the effect of the angle between the strike of the body and the magnetic north are practically negligible in the case of the Manila and Eastlake areas.

In the surveyed areas, a strong magnetic contrast would have been represented between the schistose-zone rocks and the more ferromagnetic rocks like amphibolite gneisses that surround them. One possible cause of anomalies would be faulting in the Precambrian basement or zones of sheared rocks. Inspection of the magnetic profiles (Figs. 2 and 3), show that there is no significant indication of faults which could be identified by a steplike or sharp jump of considerable vertical magnetic amplitude; the theoretical anomalies based on the plausible geological fault-zones in Precambrian rocks (Figs. 2 and 3) do not resemble the observed profiles and the steep gradients in the vertical intensity profiles may represent the boundaries among the various sorts of small structures or rocks that constitute the basement.

Manila Area

The vertical magnetic intensity map of the Manila area (Plate 2) shows an apparent series of low and high featureless zones separated by a well-defined band of sharp gradients. However, the map has three conspicuous characteristics: 1) a magnetic east-west low A in the north-central portion of the map (secs. 27 to 30, T. 2 S., R. 64 W.), centering just on the farthest portion of the strong east-west aeromagnetic low (Plate 1); 2) a series of a cross-cut high-trend southeast-northwest-northeast B (secs. 5, 6 and 8, T. 3 S., R. 64 W.); C (sec. 36, T. 2 S., R. 65 W.), and D (secs. 18 and 19, T. 2 S., R. 64 W.), in the central and northwestern part of the quadrangle; and 3) two lows oriented northwest E (sec 7, T. 3 S., R 64 W.) and almost north-south F (secs. 3, 4, 9 and 10, T. 3 S., R 64 W.) partially bounding the latter cros-cut high-trend. These anomaly trends are about 6.5, 7, and 8 square miles in area.

In the northwestern portion of the map, the B, C and D highs extend northwestward and southwestward until they join and culminate to form the broad anomaly southwest of the remarkable east-west A low. The magnetic intensity map (Plate 2) can be divided into two parts of different character: a magnetically flat area best developed east and south of the low F in the middle-east and southeast part of the quadrangle; and a magnetically complex area best developed in A, B, C, D, and E zone-anomalies in the west-central to northern part of the area. Comparison of magnetic trends between the aeromagnetic (Plate 1) and the ground magnetic (Plate 2) maps show that the magnetically described flat area does not correspond with the low in the aeromagnetic map.

Also the vertical intensity anomalies can be related to three different groups with respect to their intensity: a) high-amplitude anomalies whose intensities exceed the average map intensity (500 gammas) by as much as 120 gammas, such as those in B, C, and D; b) anomalies whose amplitudes are less than 550 gammas but greater than 500 gammas, such as the sharp gradients between A and B, C and D; and c) anomalies whose amplitudes are less than 500 gammas, such as those in A, south of E, and the southeasternmost part of the quadrangle (secs. 22 to 27, T. 3 S., R. 64 W.). The preceding description of the metamorphic rocks in the Colorado basement would suggest early Precambrian bodies of basic or acid rocks of gentle relief as possible sources of the vertical magnetic anomalies. It is important to point out that the northwest B, C, and D high trend and its associated E low have an orientation similar to that of the faulting systems in the Front Range to the west; this magnetic pattern may follow the preexisting planes of weakness in the Precambrian host rocks (Tweto and Sims, 1963; Haun, 1967).

A tentative comparison of the groups of anomalies with the basement complex rocks shows that the high-amplitude anomalies might be correlated with geological features of the high-magnetic gneisses. The geological causes of the intermediate-amplitude anomalies are varied; these causes may be the result of several isolated or combined geological facts in the basement rocks such as intrusive dike-like bodies, contacts between different metamorphic rocks, and facies change in a determined rock unit. The isolated low anomaly A may be due to schistose rock with low content of ferromagnetic minerals as accessories, or due to some fractured and sheared zones of negligible magnetic susceptibility.

In trying to relate the vertical magnetic anomalies to the structural geology of the basement, it is necessary to know the subsurface geology below the sedimentary rocks in the area. The knowledge of the basement characteristics in the Manila area is limited since no reliable information on the thickness of the sedimentary section is available. Haun (1967) states that the dominant structural trend north of Arsenal well No. 1 is northeasterly, and extends at least 60 miles in an area east-west. Also, he concludes that the area of north-east-trending structures may terminate abruptly in the vicinity of the Arsenal well, and structures southeast of the well may have a different trend.

On this basis, a direct correlation between the geological picture and the magnetic anomalies of profiles A-A', B-B', and C-C' (Plate 2, Fig 2-a) is not evident due to the magnitude of the sharp anomalies. In addition, several geologists (Fogarty, 1952; Edwards, 1966) report that the sedimentary rocks in the Manila area appear to be free from structural deformation. In summary, there are no available geological evidences which may be of value for a simple correlation of the vertical magnetic anomalies.

Figure 2-a shows that the east-west low magnetic trend in the north part of the profiles (Plate 2, secs. 19 to 25, T. 2 S., R. 64 W.) is consistent along the area; however, the width of the rock-body producing anomaly map may be variable along the E-W strike of the body. On the other hand the northwest high B (Plate 2, secs. 5 to 8, T. 3 S.) is too sharp and narrow to be related to geological characteristics in the basement. On the basis of induced magnetism theory, profiles A-A' and C-C' would show a big discrepancy between the observed and calculated magnetic anomalies; thus the explanation of the vertical magnetic anomalies implies additional magnetic characteristics such as the remanent magnetism theory (Nagata, 1961).

Edwards (1966) points out that the Precambrian basement rocks in the Denver basin have been affected by subsequent igneous activity; hence, the anomalies in the Manila area could be explained in terms of remanent magnetism associated with those different periods of igneous activity. Geologically, the explanation has significance and may be correlated because the structural patterns of faults, following a northwest trend, suggest that the weak-rock zones may be in the same direction (Sims and Tweto, 1963). Therefore, there are geological factors which might have produced conspicuous changes in the north-south gradients of the vertical magnetic anomalies at the Manila area.

Profile B-B' (Fig. 2-a) was selected to show the vertical magnetic anomalies when induced and remanent magnetism were considered in the interpretation. The theoretical curves for two dike-like bodies M and N with reverse magnetization were evaluated; when the individual anomalies produced by L, M, N, and O are added, the result gives the points ilustrated in the profile. The calculated curve (Fgi. 2-a) has not been adjusted to agree with that of the observed anomaly; that is, it still shows some discrepancy that could be due to the combination of several facts such as knobs from the basement, or local concentrations of magnetic minerals in the basement complex and within the post-Precambrian sediments.

However, the 60-to 70-gamma anomalies deviated from the calculated curve show erratic patterns from one profile to another that indicates local magnetic causes. The writer believes that for the purposes of this investigation, a better matching of local effects would have to be based on unknown and detailed geological characteristics which could logically lead to a controversial interpretation. The negative magnetic anomalies on either side of Y (Fig. 2-a) may be the results of several plugs in the basement produced by some deeper intrusions.

Also, a considerable contribution to the low Z comes from body O, a dike-like body with low magnetic susceptibility; however, the assumed reverse magnetization for bodies M an d N in this case may be due to a chemical mechanism. The metamorphic rocks in the basement are reported to be of different mineralogical composition (Sheridan and others, 1966 and 1967) and are affected by post-Precambrian intrusions (Edwards, 1966). These geological considerations, possibly involved in the Manila area, are responsible for the magnetic anomalies, and the apparent relationship might not be real, but with the geological information available there is no way to discern other probable causes.

Eastlake Area

The vertical magnetic profiles over roads in the area (Figs. 2 and 3) present steeper magnetic gradients than those at Manila. The vertical magnetic intensity decreases about 300 gammas from the Base Line (Plate 1) at the north to the vicinity of the Quimby railroad station in the south. The rate of decrease is about 35 gammas per mile. Also, the profiles show some magnetic noise, probably produced by ferromagnetic minerals in the outcropping sediments; or perhaps produced by local disturbances due to cultural activities. The detailed profiles (Plate 1 and Figs. 2 and 3) north of the Quimby railroad station show some magnetic gradients, but they are not so strong as the one in the northern part of the area. This gradient coincides with the regional one, which seems to disappear in the neighborhood of this detailed zone. The small anomalies in these profiles show inconsistent patterns along the different lines of surveying.

The gradient of this area is in agreement with the one on the aeromagnetic map (Plate 1). The minimum of the total intensity anomaly is virtually offset south of the vertical anomaly, although the offset would not be discernable from a nearby source.

By observing the profiles (Figs. 2 and 3) it is noticeable that the trends of the small anomalies cross-cut the area for the most part, thereby suggesting a lack of relationship between the magnetic anomalies and some structural control. In this area, the basement rocks probably have not been so severely deformed as in the Front Range. However, the slight flatness in the profiles toward the south seems to be consistent, but the area of agreement is too small to justify the statement that the magnetic feature reflects the basement structure.

According to geological data, the gradient in this area could be related to a change in magnetite content of the Precambrian rocks. Furthermore, the zones of higher magnetic intensity may be considered to be underlain by rocks of a higher ferromagnetic content than the featureless zones of low intensity. If this is the case, the schistose rocks in the Front Range lie 3 or 4 miles off to the north. Thus, a better approach is to establish some relationship with sheared rocks north of Leroy's Ralston Buttes Formation. This assumption matches quite well, since the steep gradient must be produced by a sharp contrast in magnetic susceptibility.

The interpretation of the magnetic profiles of Eastlake in Figures 2 and 3 has been attempted on the basis of the available subsurface information. The presence of the steep gradient in sections A-A', B-B', C-C', D-D', E-E' and F-F' (Plate 1) indicates that is must be produced by a contact within rocks of high and low susceptibility. However, it is not possible to determine whether such a contact is between amphibolite gneisses and schistose rocks or sheared rocks. Therefore, an interface between an intrusive plug and the sedimentary rocks is not to be expected, at least in the northern part of the Eastlake area.

The best fitting for these anomalies is obtained through the consideration of a broad section of metamorphic rocks striking east-west. It is assumed that these rocks constitute, magnetically, two metamorphic units: A (2,700 x 10^{-6} cgs) and B (1,350 x 10^{-6} cgs), whose dip is 70 to 85 degrees to the south; these dips conform to the attitude of the Precambrian rocks on the Front Range (Lickus and Leroy, 1967). Magnetically, the amplitude of the anomalies is considerably reduced when the body-rock dips to the north. A third unit rock C may correspond to the eratic anomalies toward the south in the area. This assumption in terms of the generalized statrigraphic section (Fig 1-a) suggests that at least three distinct rock units might produce the magnetic anomalies at Eastlake. If such is the case, there exists a lateral change in facies in the rock of the lower susceptibility which produces the inconsistent anomalies in the south part of the profiles (Figs. 2 and 3). It appears that the change in facies may be present, but the contact has not been delineated from magnetic data. A distinct lithology equivalent to the geological profile between rock types B and C has not been defined with confidence; hence, magnetic type C cannot be explained satisfactorily.

Another possible assumption in the interpretation is that rock type C (K =1,800 x 10^{-6} cgs) may be related to a rock-body of a slightly higher susceptibility. On this basis, a plug-stock in the basement can produce a distribution of granite-gneisses interlayered in rocks of low susceptibility. Edwards (1966) reports that the Laramide and Tertiary batholithic intrusions are present in the buried basement. Clark (1942) mentions that some of the Upper Createaceous formations crop out between the Eastlake area and the Manila area. This fact is explained by considering a dome structure superimposed on a buried knob in the basement. In addition, the Bouguer anomaly of the Derby area (Hamzawi, 1966) shows the possibility that there is an uplift in the basement in the vicinity of Derby. However, no reliable information on the structure of the post-Precambrian intrusions in the areas surrounding Arsenal well No. 1 is available from the gravity map. On this basis, the effect of the supposed domal structure would be and evident magnetic disturbance resulting from a change of magnetic properties in the rocks. This explanation conforms to the gravity data of the Derby area, but it does not assure the presence of an uplift. Therefore, the apparent relationship between magnetic and gravity data remains unexplained. A definite geologic correlation of the magnetic data is not possible until more information about the subsurface geology is available.

Schematic geologic profiles of the basement at the Eastlake area (Figs. 2 and 3) show the different bodies that were used in the calculations of magnetic anomalies. The major contribution to the anomalies comes from the sharp contact between bodies A ($K = 2{,}700 \times 10^{-6}$ cgs) and B ($K = 1{,}350 \times 10^{-6}$ cgs); the maximum contribution resulting from the interface B and C ($K = 1{,}800 \times 10^{-6}$ cgs) in the south is about 20 gammas, which is small compared with an amplitude of 260 gammas produced by the first contact in the north. The magnetic anomalies along the different profiles indicate that the assumed rock-bodies are consistently present in the area. This fact suggests a correlation with the stratigraphic generalized sections in the Front Range (Fig. 1-a) toward the north and the sheared rocks of Sheridan and others (1967) referred to in this article. The magnetic gradient of profiles A-A' to F-F' (Figs. 2 and 3) corresponds with the one in the detailed short profiles (Plate 1) because there is a similar gradient between X and Y of Figure 2-b and along the foretold profiles.

SUMMARY AND CONCLUSIONS

In the analysis of the results, several remarks should be made. First, uncertainty factors play an important role in the interpretation of magnetic anomalies. These factors depend on the limited subsurface geological information and sampling from the buried basement. These features should be kept in mind when the observed and the computed anomalies are compared. Hence, the following statements should be taken into consideration.

1. Inhomogeneities in the susceptibility of the metamorphic rocks may considerably reduce the reliability of the quantitative results. Moreover, there is remanent magnetism within the buried basement rocks; however, there is no way of assessing the implications.
2. A good matching of the observed anomalies might also have been obtained by varying the shape of the boundaries and the directions of magnetization.
3. No attempt was made to interpret the small-amplitude anomalies in the magnetic profiles of the Eastlake and Manila areas. For the purpose of this study, they were considered to be geologic noise and small in areal extension for a deeper analysis.
4. From geological information, it was reasonable to postulate that the magnetic properties used for the computations in the studies

areas matched with an altered broad banding of metamorphic rocks. This banding includes the sheared, schistose, and gneissic rocks. However, the magnetic data do not distinguish between the sheared and schistose rocks.

5. If the cause of the magnetic variations in the Eastlake area is the susceptibility contrast between fracture zones and amphibolite gneisses, there should be a corresponding gravity variation. The density contrast between the material of broad sheared rock zones and the gneissic rocks may have been detected by the gravity survey (Hamzawi, 1966).

6. It is important to make clear whether the fracture zones in the seismically active area (Plate 1) reach the top of the basement or come from within the basement.

According to the seismic data, the vertical distribution of the earthquake foci ranges from about 4 to 8 Km (Romig[1], 1968). These figures suggest that the epicenter zone and the faulting movements should be associated with an active intrabasement zone. In such a case, the magnetic anomalies produced by a sharp contact between large masses of sheared rock and highly magnetic metamorphic rocks should be similar in amplitude and greater in areal extent than the ones detected at the Eastlake area.

7. It is recommended that, if geophysical exploration work is going to continue in this highly interesting area, more conclusive results may be obtained from seismology, or from the use of more refined and deeper magnetic techniques along the exposed Precambrian rocks on the Front Range and in the seismically active area. From these data other geological and geophysical intended work can proceed with some confidence. It would be useful to establish first the characteristics of a sheared zone in the seismically active area, since the relationship between vertical magnetic anomalies and structural geology at the Eastlake area have not been made clear.

On the basis of the vertical magnetic intensity data and the geological and geophysical information in the studies areas, the author presents the following conclusions:

1. One of the most significant conclusions to come from the magnetic data is that the amplitude of the computed anomalies are, in general, close to the observed ones. The matching was obtained for a basement depth of 11,500 to 13,000 feet in both areas.

2 The interpretation at the Manila area may arouse objections,

but it may also be improved according to the available geological and magnetic information.

3. It is evident that the east-west aeromagnetic trend in the north part of the Eastlake area (Plate 1) conforms to the steep ground-magnetic gradient of 35 gammas per mile between the Base Line and 5 to 6 miles southward (Figs. 2 and 3). From these points to the south, there exists certain flatness in the vertical magnetic profiles (Figs. 2a and 3a), that also coincides with the one in the aeromagnetic map. This aeromagnetic trend seems to be distorted along the outlined seismically active area and has not been related to before.

4. Vertical or dipping faults in the seismically active area would have to have a displacement of more than 5,000 feet depth to account for an anomaly of a about 100 gammas. Geologically, this assumption is unreasonable. Hence, the mentioned steep gradient is not due to a major displacement vertical fault. Therefore the only possibility of a faulting system is the horizontal slide-strike type accompanied by minor vertical displacements. This type of faulting with small horizontal displacement in a given rock type unit cannot be detected by magnetic surveys.

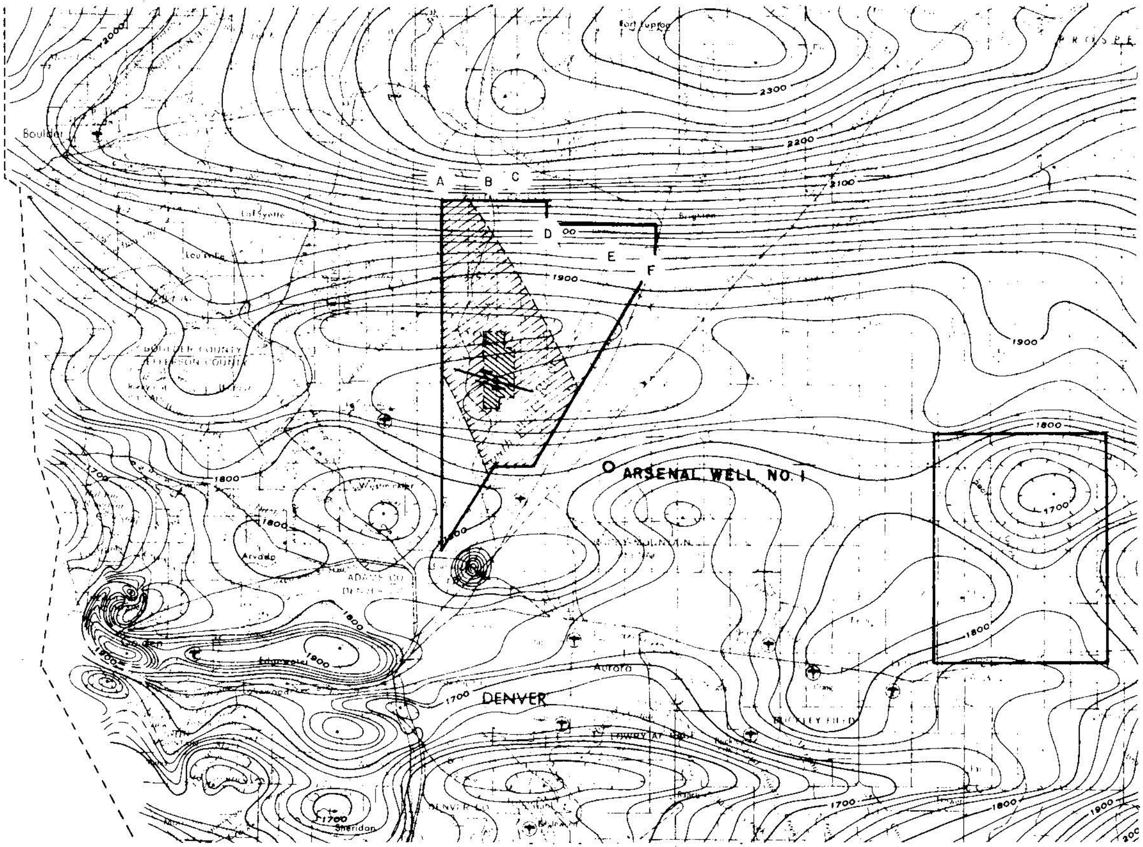
5. The above gradient probably is due to a 4-mile-wide section of metamorphic rocks striking east-west and dipping about 80 degrees to the south. The susceptibility contrast between this bulk of metamorphic rocks and the host rock is about 1,350 x 10^{-6} cgs. unit.

6. The rock-producing anomaly at the Eastlake area is believed to represent the eastern extension of the sheared zone north of the Ralston Buttes Formation of Leroy. This fact seems to be in agreement with the extension of Leroy's formations eastward into the Denver basin.

7. According to the ground magnetic data, the width of the low east-west aeromagnetic trend (Plate 1) seems to decrease toward the east at the Manila area (secs. 19 to 25, T. 2 S., R. 64 W., Plate 2). This diminishing in areal magnetic extent probably indicates that the rocks of low magnetic susceptibility (i.e. schistose rocks) also decrease in width from west to east.

8. The causes of magnetic anomalies in the Denver basin are varied. Therefore, the extension of the results obtained in this study to other areas within the Denver basin is not possible. Independent analyses should be done in each particular area, considering the available geological information.

PLATE 1



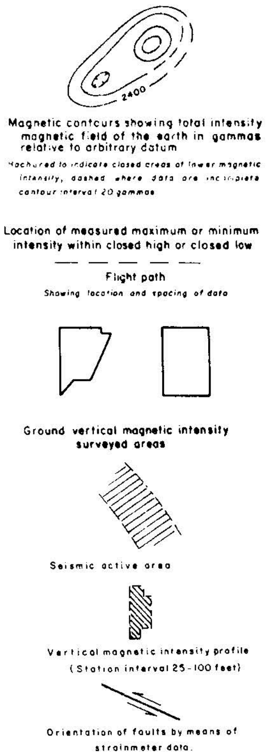
PORTION OF THE AEROMAGNETIC MAP OF THE DENVER AREA, COLORADO

(AFTER A. J. PETTY, J. I. VARGO, and F. C. SMITH, 1966)

L. Del Castillo 1968

Scale

EXPLANATION



Magnetic contours showing total intensity magnetic field of the earth in gammas relative to arbitrary datum

Hachured to indicate closed areas of lower magnetic intensity, dashed where data are incomplete contour interval 20 gammas

Location of measured maximum or minimum intensity within closed high or closed low

Flight path

Showing location and spacing of data

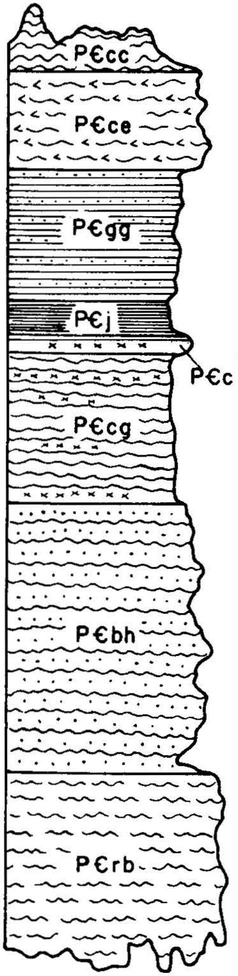
Ground vertical magnetic intensity surveyed areas

Seismic active area

Vertical magnetic intensity profile

(Station interval 25-100 feet)

Orientation of faults by means of strainmeter data.



UNIT NAME	ROCK TYPE	THICKNESS
CLEAR CREEK CANYON	GRANITIC GNEISS	?
CEDAR GULCH	GNEISSIC GRANITE	4000'
GOLDEN GATE CANYON	AMPHIBOLITE GNEISS	4500'
JUNCTION	MUSCOVITE-SILLIMANITE SCHIST	1100'
CRESSMAN'S GULCH	TACTITE	400'
CRAWFORD GULCH	MICACEOUS SCHIST	5000'
BELCHER HILL	MICACEOUS SCHIST QUARTZITE	10,000' to 12,000'
RALSTON BUTTES	AMPHIBOLITE GNEISS & TACTITE	± 7000'

Figure 1-a. Generalized stratigraphic section of Precambrian basement rocks in the Front Range, northwest of the city of Golden, Colorado

(After L. W. Leroy, 1967)

Figure 1b Generalized geologic diagram of the buried Precambrian in the studied areas (from Edwards, 1966).

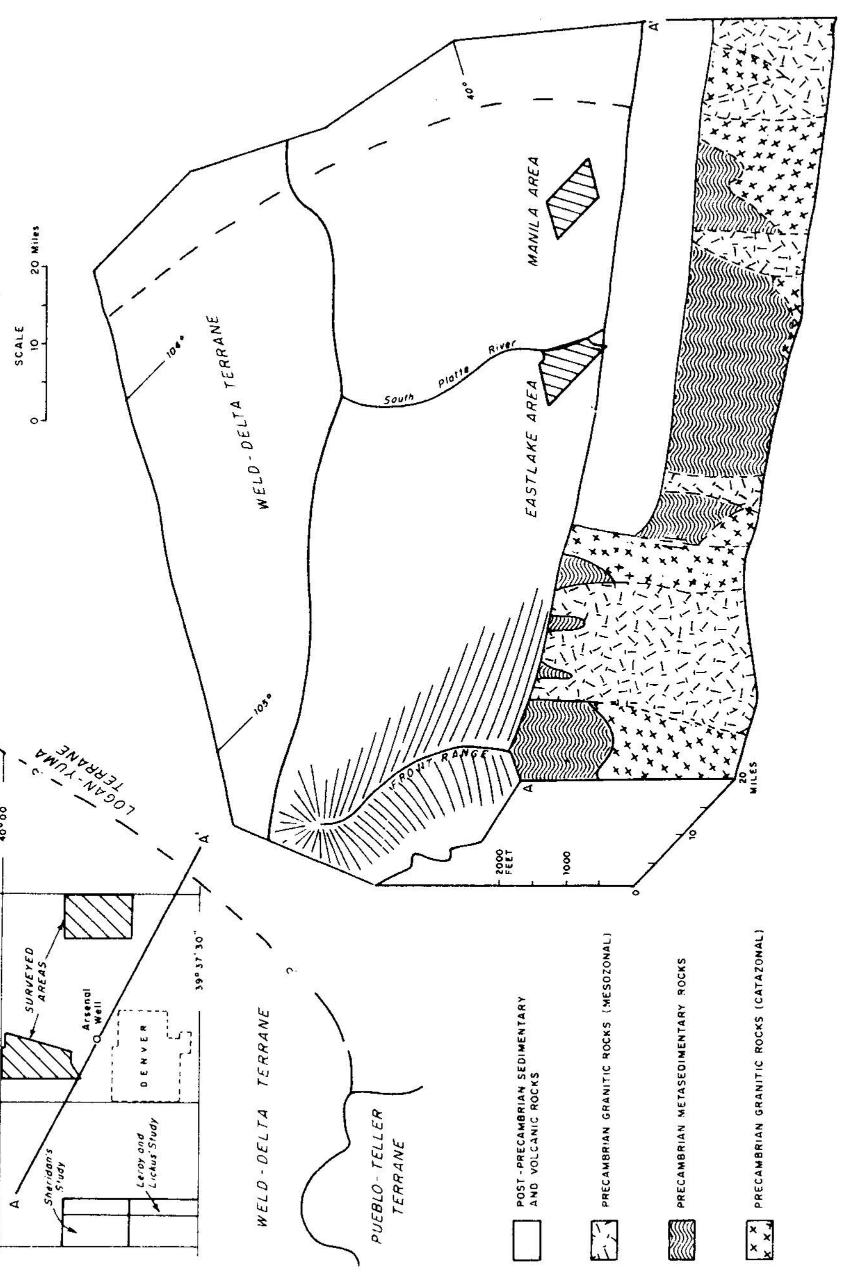
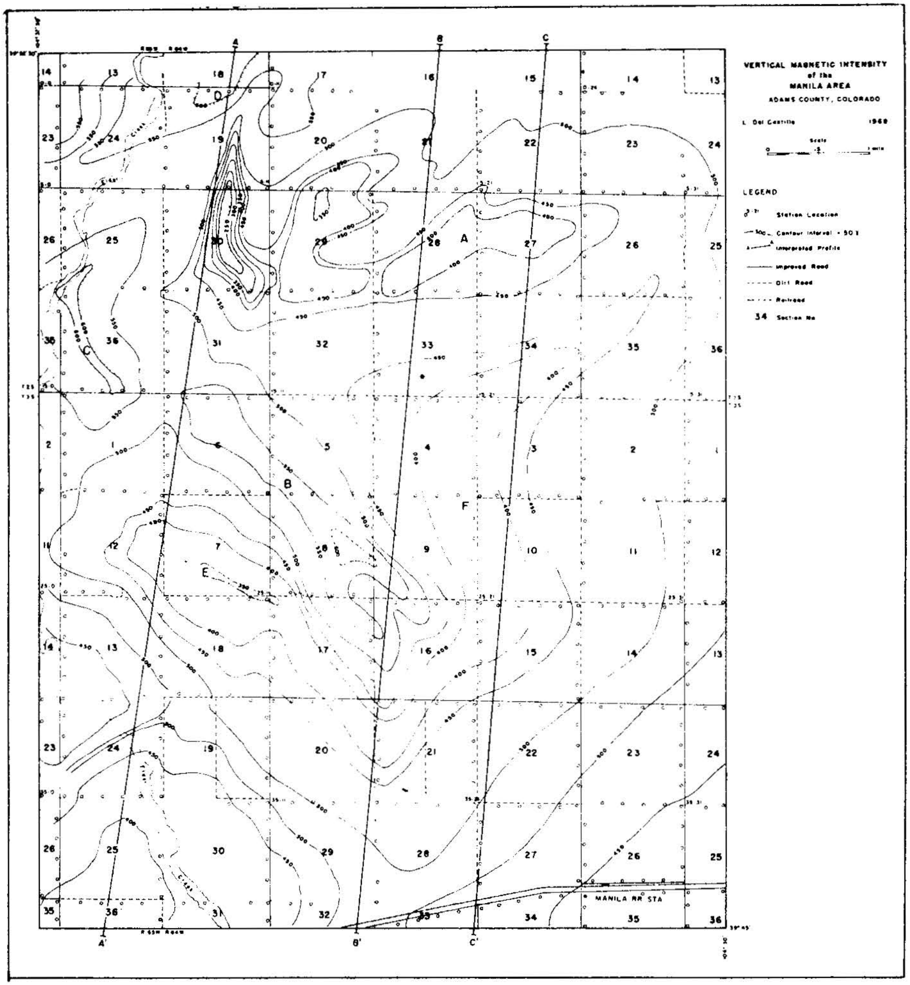


Plate 2


VERTICAL MAGNETIC INTENSITY
of the
MANILA AREA
ADAMS COUNTY, COLORADO
L. Del Castillo
1969
Scale
0
1 mile
LEGEND
Station Location
Contour Interval = 50 γ
Interpreted Profile
Improved Road
Dirt Road
Railroad
34 Section No
A
B
C
A'
B'
C'
A
B
C
D
E
F
MANILA RR STA
Creek
R 65 W
R 64 W
T 2 S
T 3 S
300
350
400
450
500
550
600

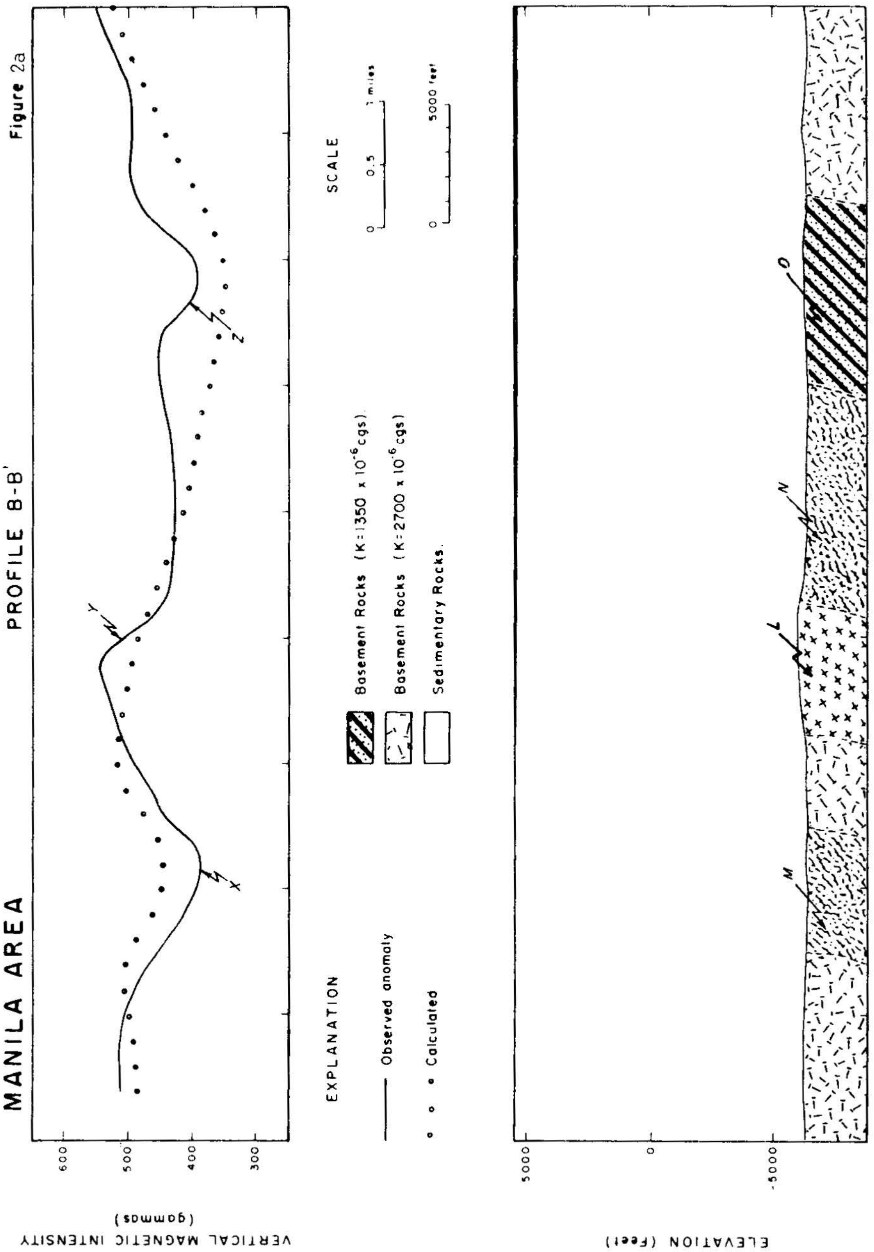


Figure 2a
MANILA AREA
PROFILE B-B'
VERTICAL MAGNETIC INTENSITY (gammas)
600
500
400
300
X
Y
Z
EXPLANATION
Observed anomaly
Calculated
SCALE
0
0.5
1 miles
0
5000 feet
Basement Rocks (K=1350 x 10⁻⁶ cgs)
Basement Rocks (K=2700 x 10⁻⁶ cgs)
Sedimentary Rocks.
ELEVATION (feet)
5000
0
-5000
M
L
N
O

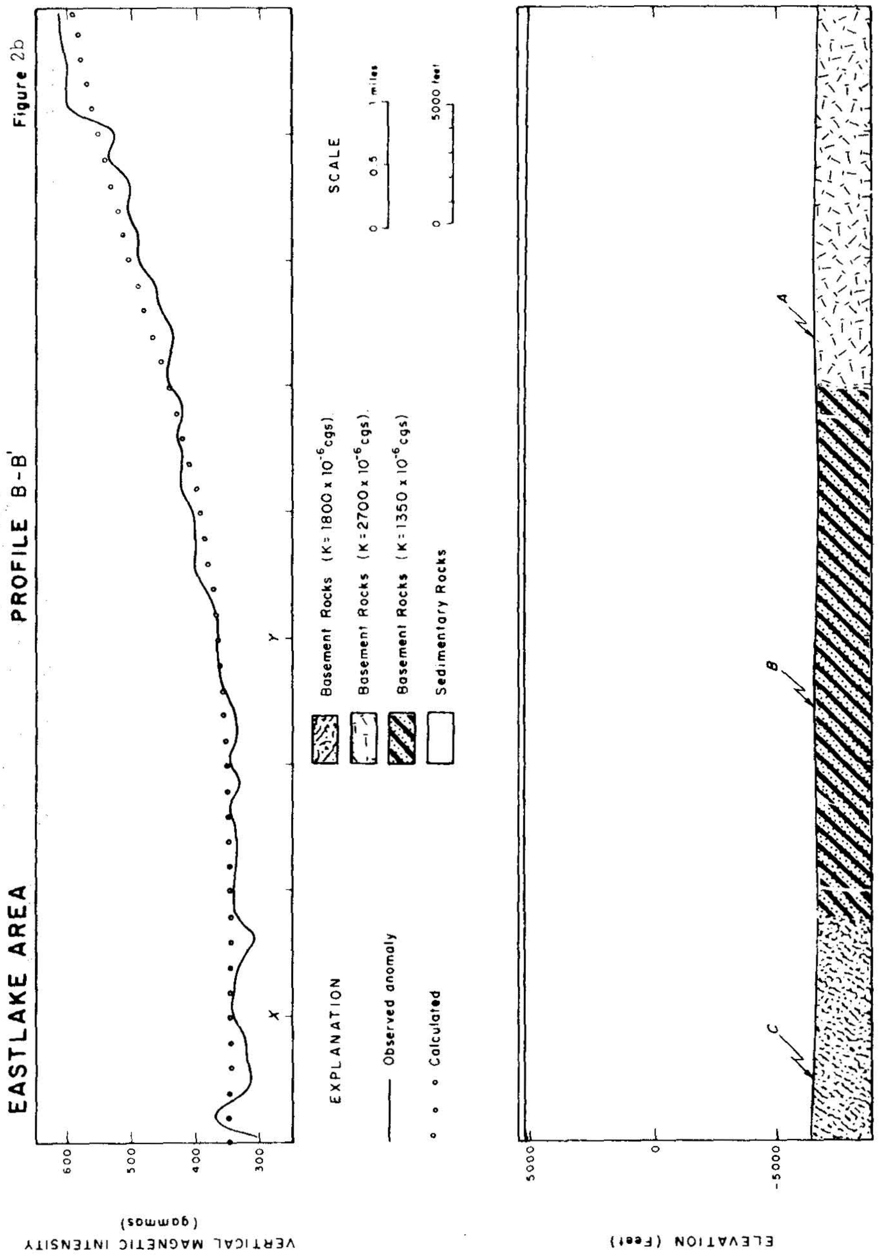

EASTLAKE AREA
PROFILE B-B'
600
500
400
300
VERTICAL MAGNETIC INTENSITY (gammas)
X
Y
EXPLANATION
Observed anomaly
Calculated
Basement Rocks (K= 1800 x 10⁻⁶cgs)
Basement Rocks (K= 2700 x 10⁻⁶cgs)
Basement Rocks (K= 1350 x 10⁻⁶cgs)
Sedimentary Rocks
SCALE
0
0.5
1 miles
0
5000 feet
A
B
C
5000
0
-5000
ELEVATION (Feet)

Figure 2b

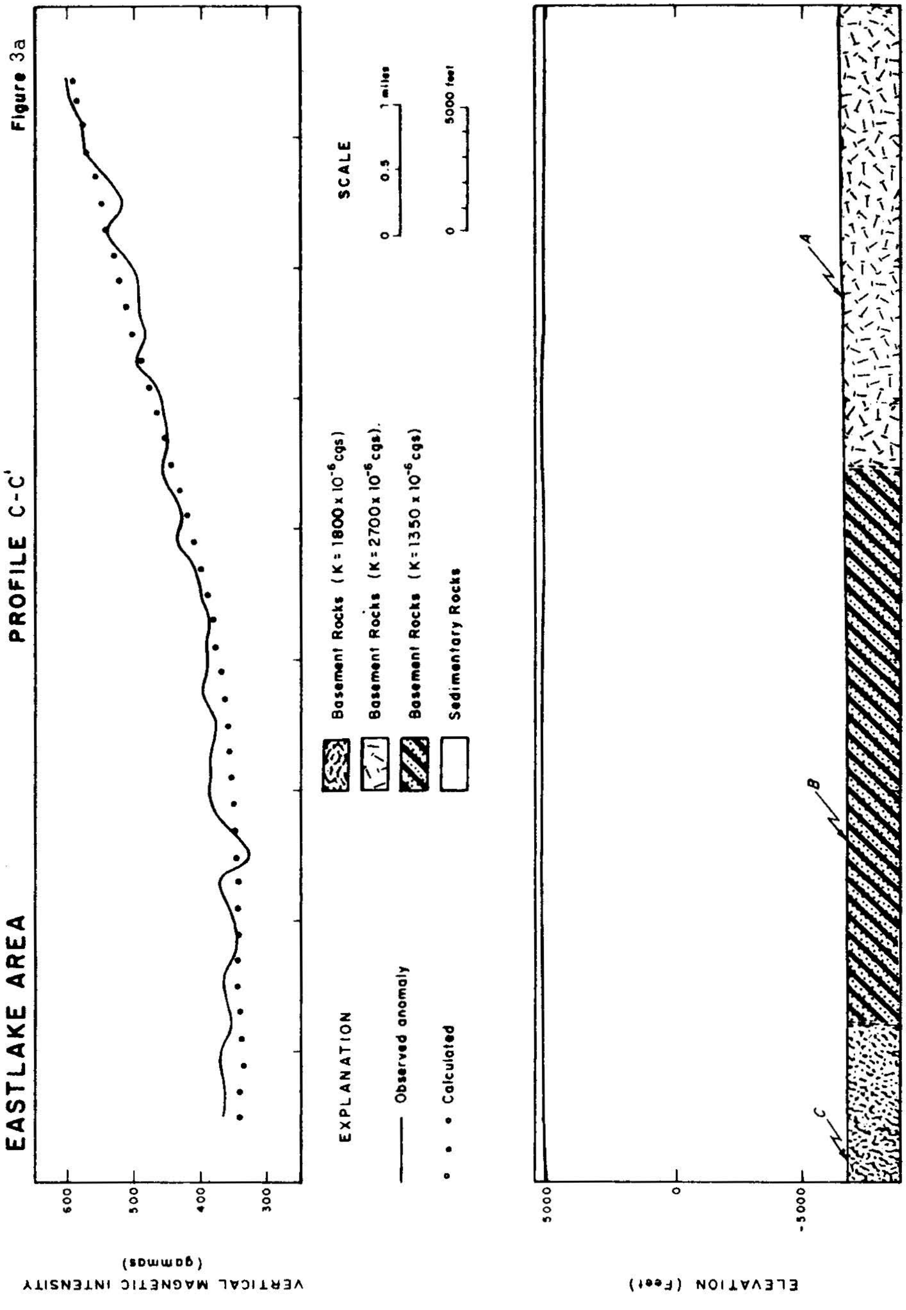


Figure 3a

EASTLAKE AREA PROFILE C-C'

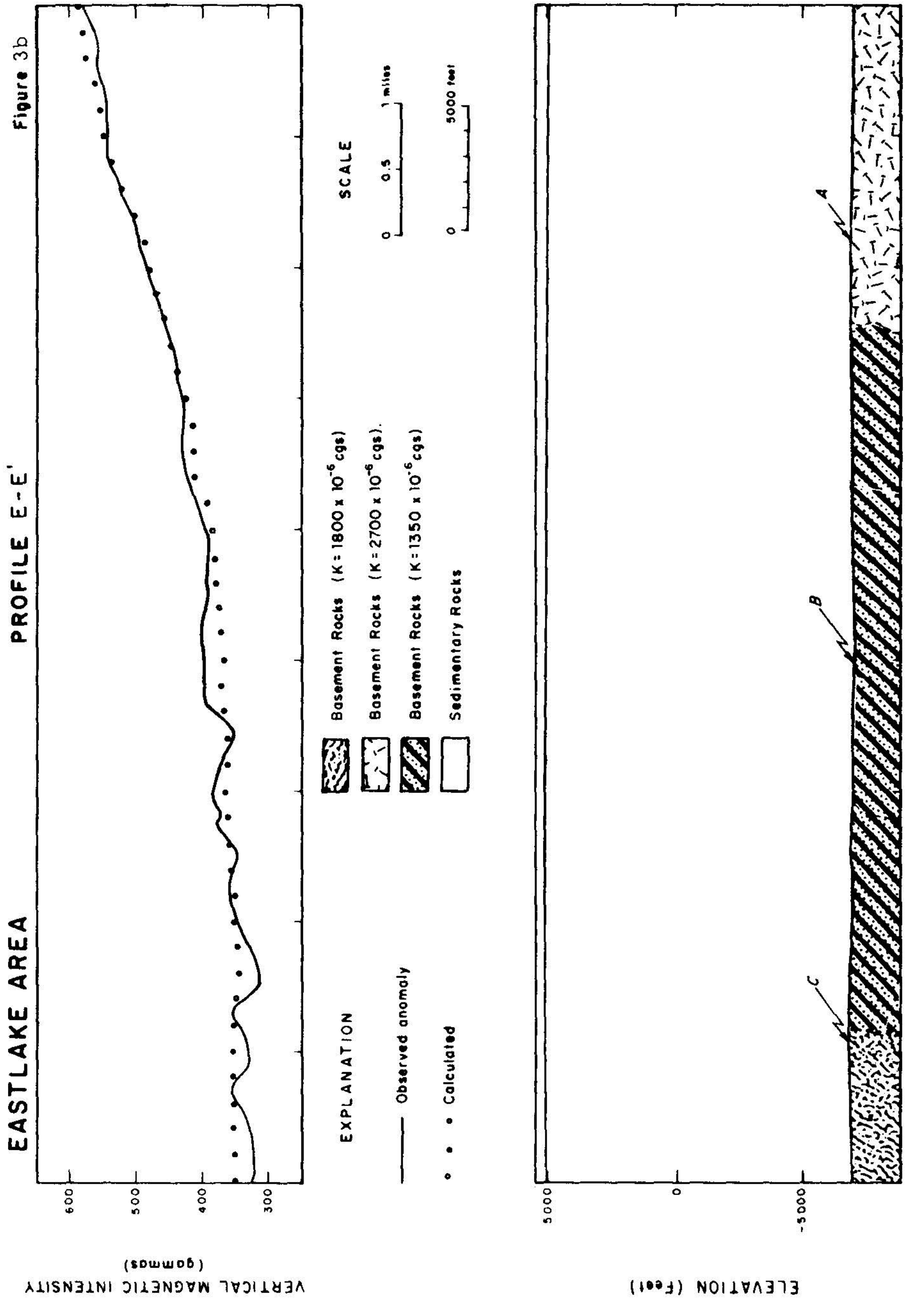


Figure 3b

EASTLAKE AREA PROFILE E-E'

TABLE I

TENTATIVE CORRELATION BETWEEN PRECAMBRIAN UNITS MAPPED BY LEROY AND SHERIDAN, MAXWELL, AND ALBEE IN THE RALSTON BUTTES QUADRANGLE AND ITS VICINITY, COLORADO

(Data from Leroy, 1967; Sheridan and others, 1967)

Leroy's Formation	Description	Sheridan's Unit
Cedar Gulch Formation (PЄce)	Medium-grained biotite granite gneiss to gneissic granite. Coarse-grained discordant and concordant pegmatites occur throughout and range up to 30 feet thick. Free quartz injections occur frequently in the more granitic phases.	Microcline-quartz-plagioclase biotite unit (Microcline gneiss unit) (gm) (gmab)
Golden Gate Canyon Formation (PЄgg)	Well banded nonptygmatically folded amphibolite gneiss. Quartzite lenses are present at various stratigraphic positions.	Hornblende gneiss unit (hab) (habm)
Junction Formation (PЄj)	Banded muscovite-sillimanite gneissic schist containing numerous thin quartz and granite stringers and lenses. Occasional 6- to 8-inch beds of fine-grained, dark gray quartzite occur.	Hornblende gneiss unit (hcq-hcs)
Cressman's Gulch Formation (PЄc)	Amphibolitic gneisses and intercalated calcite-epidote-garnet tactites. Quartz stringers and pods occur sparingly throughout.	Hornblende gneiss unit (hc)
Crawford Gulch Formation (PЄcg)	Facies A: thinly laminated, microgranulated, fine-textured, medium gray micaceous schist. Facies B: micaceous, medium-textured schist. Facies C: highly muscovitic-sillimanitic schist and gneissic schist. It shows thin beds of fine-grained quartzite and numerous quartz and granitic pegmatite lenses and pods.	Mica schist unit (S, Sc)
Belcher Hill Formation (PЄbh)	Schist facies: dark gray, highly crenulated micaceous, coarse-textured schist impregnated with numerous quartz and granite pegmatite lenses. Quartzite facies: dark bluish-gray, fine to medium-grained, thinly laminated to massive quartzite. It exhibits shear folds and pegmatite injections.	
Ralston Buttes Formation (PЄrb)	Amphibolite, thin-banded gneiss containing sporadic intercalations of epidote-garnet calcite tactites (skarns). Thin quartz and granitic stringers occur throughout. Dense, dark gray, fine textured quartzites up to five feet thick occur in restricted number. Concordant and discordant coarse-textured granite pegmatites are frequent.	Microcline-quartz-plagioclase-biotite gneiss complexly interlayered with other rocks. (gmh-hgm) Hornblende gneiss unit (h). Quartzite unit (q)

a. Number of samples analyzed in the unit
b. Number of samples with trace amounts
c. Number of samples with 0.5 or + percent content
d. Number of samples with less than trace amounts
e. Percentage includes undetermined amounts of pyrite and other sulphide minerals
f. Percentage includes some sulphide minerals and limonite

Description	Modes (volume percent)									
icrocline gneiss, light-orange pink, pink- sh-gray and dark gray, conspicuously oliated, fine- to medium-grained, granitic ppearing. ray to black layers and lenses of amphi- olite and biotite-quartz-plagioclase gneiss.	a	A 11			B 11			C 0		
	11	b	c	d	b	c	d	b	c	d
		4	3	4	3	0	8	-	-	-
	Av	2.2, 1.1, 2.2								
	Bv									
nterlayered hornblende gneiss, amphibolite nd biotite quartz-plagioclase gneiss; gray o black, mostly fine-grained equigranular. nin discontinuous layer of medium-grained mphibolite, spotted texture.	a	A 19			B 12			C 0		
	19	b	c	d	b	c	d	b	c	d
		2	12	5	4	0	8	-	-	-
	Av	1.4, 2.3, 0.5, 1.9, 1.5, 3, 1.9, 2.4^f, 2.7, 1.2, 0.7, 0.9								
uartz-gneiss lenses ica schist	NO ANALYSES									
aricolored well-layered calc-silicate gneiss; t contains minor layers of amphibolite, horn- lende gneiss, and biotite-quartz-plagioclase neiss.	a	A 5			B 5			C 0		
	5	b	c	d	b	c	d	b	c	d
		3	1	1	0	1	4	-	-	-
	Av	2.3								
	Bv	5								
lver-gray to dark-gray, well foliated, fine- medium-grained mica schist; porphyroblasti rieties contain sillimanite, andalusite, or rnet; feldspathic varieties are gradational gneiss. It contains numerous small lenses calc-silicate rock. Sometimes it shows cal conglomeratic schist lenses.	a	A 24			B 20			C 4		
	24	b	c	d	b	c	d	b	c	d
		9	9	6	5	1	14	2	0	2
	Av	3^e, 3^e, 1.0, 1.1, 0.8, 1.1, 1.0, 0.6, 1.2								
	Bv	1.0								
	Cv	-								
rocline gneiss complexly interlayered with hibolite, hornblende gneiss, layered calc- icate gneiss, biotite-quartz-plagioclase iss, and locally quartz gneiss. nblende gneiss unit undivided hornblende iss. Quartzite, gray to white, less common- black or pale red, predominantly fine- ined, foliated; it contains numerous thin glomeratic layers and lenses.	a	A 4			B 0			C 13		
	17	b	c	d	b	c	d	b	c	d
		1	2	1	-	-	-	1	11	1
	Av	1.7, 0.6								
	Cv	3, 1.2, 2.9, 1.1, 4, 4, 0.5, 0.6, 1.7, 6, 0.7								

A, B, and C accompanied by a number indicate number of analyzed samples for magnetite-ilmenite, hematite, and opaque minerals, respectively.

Av. Bv and Cv indicate the corresponding volume percent of c values. Values of 3 percent or more are reported to the nearest percent. Values from 0.5 to 2.9 percent are reported to the nearest tenth of a percent.

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