Geologic Interpretation of an Aeromagnetic Survey of the Iron Springs District, Utah

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GEOPHYSICAL FIELD INVESTIGATIONS

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ABSTRACT

A total-intensity aeromagnetic map is presented as an overprint on a generalized geologic map of the Iron Springs district, southwestern Utah. The isomagnetic contours roughly delineate the three bodies of quartz monzonite porphyry exposed in the district—the Three Peaks, Granite Mountain, and Iron Mountain intrusions. The Three Peaks intrusion extends at shallow depth beneath alluvium to the east and southeast of the area of outcrop. Granite Mountain is an upbulge on a largely concealed intrusive body extending to the north, west, and southwest; additional relief on the concealed surface of this body is inferred from the aeromagnetic data. There is some magnetic evidence for a considerable western extension of the Iron Mountain intrusion.

The zone of "selvaged" joints beneath peripheral rock of the Three Peaks intrusion has a higher effective susceptibility than normal interior rock and produces a local magnetic high superimposed on the general pattern of the anomaly. The amplitude of the high appears to be proportional to the size and abundance of magnetite veins and joint coatings characteristic of this zone. Some contact-replacement ore bodies also produce strong local anomalies; others were not detected by the survey.

INTRODUCTION

The Iron Springs district is in Iron County, southwestern Utah, at the eastern margin of the Great Basin. Cedar City is the nearest sizable community. For many years the important steel industry at Provo and Geneva, 225 miles north of Cedar City, was almost wholly dependent on the open-pit mines of the district as a source of iron ore. As late as 1965 the district still ranked as one of the largest iron-ore producers in the western conterminous United States, although in 1966 production was drastically curtailed.

In 1947 the U.S. Geological Survey made an aeromagnetic survey of the district (Dempsey, 1951) as part of a systematic investigation of the geology and ore deposits. Detailed ground-magnetic surveys were subsequently carried out by the U.S. Bureau of Mines (Cook, 1950), as well as by private parties. A geologic map of the district at a scale of 1:24,000 was prepared by Mackin. Mackin's geologic map in generalized form is presented in this report together with the results of the aeromagnetic survey. Interpretation of the aeromagnetic data was undertaken jointly by the two authors, but responsibility for geophysical conclusions rests on Blank alone.

The paper has benefited from the critical comments of D. M. Lemmon and F. C. Frischknecht, to whom the authors are grateful. Frischknecht independently investigated the magnetic properties of the intrusive rocks, computed theoretical magnetic-response curves, and arrived at a model of the Three Peaks intrusion which agrees closely with the results given here.

GENERAL GEOLOGY

Because of its economic importance, the Iron Springs district has been the subject of numerous geologic investigations. The most pertinent published reports are those of Leith and Harder (1908); Butler, Loughlin, Heikes, and others (1920, p. 568–580); Wells (1938); and Mackin (1947, 1954, 1960). Relevant structural and stratigraphic information is contained in reports of peripheral areas by Thomas and Taylor (1946), Gregory (1950), Cook (1957), and Threet (1963). A comprehensive geologic report on the district by Mackin is currently in preparation. Only a brief outline of the geologic relations is given in this report.

ROCK UNITS

The oldest rocks exposed in the district belong to the Jurassic Carmel Formation of the Colorado Plateau (Gregory, 1950). In Iron Springs the formation is about 250 to 300 feet thick and consists of a thin basal siltstone member overlain by the Homestake Limestone Member (Mackin, 1954), which contains the main replacement ores of the district. Overlying the Homestake is a shale-sandstone sequence 0 to 220 feet thick tentatively correlated with the Jurassic Entrada Sandstone of Gregory (1950). The two Jurassic formations are shown on the geologic map by a single pattern.

A succession up to 4,000 feet thick of clastic beds—predominantly mustard-colored sandstones—rests disconformably upon the Entrada(?) Sandstone. These beds compose the Iron Springs Formation of Late(?) Cretaceous age (Mackin, 1947, 1954).

Conglomerate, siltstone, and lacustrine limestone of the Claron Formation, of probable Eocene age, overlie the Iron Springs Formation disconformably or locally with marked angular unconformity. The basal part of the Claron was deposited in an environment of considerable topographic relief following the Laramide deformation which involved the Iron Springs and older formations. The formation becomes increasingly tuffaceous toward the top, a fact reflecting the onset of volcanic activity in the region. Its maximum thickness is about 1,000 feet.

Volcanic rocks of the Needles Range, Isom, and Quichapa Formations were extruded onto a flattish Claron surface in early(?) and middle Tertiary time. These deposits are composed of welded ash flows (ignimbrites), lava flows, and flow breccias, chiefly of andesitic to quartz-latitic composition. The maximum aggregate thickness is about 1,500 feet. The welded tuffs are parts of vast sheetlike deposits that are distinguishable throughout much of the region. These formations were named by Mackin (1960). The type locality for the Needles Range Formation was designated as the east side of the Needles Range at and south of the Garrison-Milford highway, T. 28 S., R. 11 W., Beaver County, Utah (p. 99). There the formation consists of at least two ignimbrites and has a total thickness of 500 to 1000 feet. Regionally it rests on an erosion surface cut in Paleozoic rocks; locally on older Tertiary deposits filling depressions on that surface. It is overlain by rocks of the Isom Formation.

Type localities for the Isom and Quichapa Formations are in the Iron Springs district. For the Isom, the type locality was designated as the southern slope of an east-west ridge just north of Isom Creek in The Three Peaks quadrangle, sec. 5, T. 35 S., R. 12 W. (Mackin, 1960, p. 98). The Isom consists of three ignimbrite members with a total thickness of about 200 feet. The contact with the underlying Needles Range Formation is exposed at the foot of the ridge; capping the ridge is the basal ignimbrite member of the overlying Quichapa Formation.

The type locality of the Quichapa Formation is Right Quichapa Canyon, northeast quarter of T. 37 S., R. 13 W., in the Harmony Hills southeast of Iron Mountain. Except for a few tens of feet at the base, where rocks of the underlying Isom Formation (and in some places, the Claron Formation) are exposed, the canyon is cut entirely in ignimbrites of the Quichapa. Four ignimbrite members with a total thickness of about 900 feet compose the type section.

The Needles Range and Isom are believed to be Eocene or early Oligocene in age; the Quichapa is Oligocene or early Miocene (Mackin, 1960, p. 98, 103; 1963, p. 76). For convenience and because their distinction serves no purpose here, the Needles Range and Isom Formations are represented on the generalized map as one unit.

Three bodies of quartz monzonite porphyry—the Three Peaks, Granite Mountain, and Iron Mountain intrusions—crop out in the district. The emplacement of these bodies, at or near the end of the Quichapa episode of volcanism, arched up the sedimentary and volcanic roof rocks and produced steep-sided topographic features. All three are roughly alined along a northeast-trending Laramide anticlinal flexure which is locally overthrust; a number of similar intrusions, including those of the Bull Valley district, 40 miles to the southwest, lie along the same structural feature. The intrusions are believed to be laccoliths or bysmaliths floored by the Jurassic and Triassic(?) Navajo Sandstone. This formation, however, has neither been seen in outcrop nor penetrated by drilling. The observed marginal contacts either are concordant with the Carmel Formation or are ruptures in the roof rocks, here called intrusive faults, formed during emplacement. (See Mackin, 1947 and 1954, for a discussion of structural features of intrusive origin.) Along the southeast side of Iron Mountain the contact is a breccia zone on the Laramide thrust.

The quartz monzonite porphyry consists of phenocrysts of intermediate plagioclase feldspar, hornblende, biotite, and augite set in a fine-grained groundmass of orthoclase and quartz. Magnetite is the principal accessory mineral, occurring both as pyrogenic crystals and as blebs produced by deuteric (endomorphic) alteration. The magnetite content is generally between 1 and 3 percent of the rock volume.

Gravity sliding from the roof and from the southern to eastern flanks of the Iron Mountain intrusion formed extensive zones of tectonic breccia composed of finely shattered rock of the Claron, Isom, and Quichapa Formations. The breccias are identified on the geologic map by their predominant material—either Claron or Quichapa.

Volcanic rocks of the Rencher and Page Ranch Formations of Cook (1957), also lumped as a single unit, lie stratigraphically above the Quichapa Formation. They have a maximum thickness of 2,000 feet and are composed predominantly of rhyodacite to quartz latite welded tuff and tuff breccias of middle and late(?) Tertiary age. The basal member of the Rencher Formation in the Swett Hills is a wedge of volcanic debris evidently derived from erosion of the Iron Mountain intrusion and later deformed by emplacement of a now-buried extension of the Granite Mountain intrusion. The Page Ranch Formation, on the other hand, is younger than the Granite Mountain intrusion.

Surficial Quaternary deposits blanket the remainder of the district. In many places a thin veneer of pediment gravels rests on truncated older formations.

ORE DEPOSITS

Two distinct types of iron ore occur in the district: replacement bodies in limestone of the roof rock, and vein or fissure-filling ores in the porphyry. According to Young (1947, p. 6), the replacement ores are composed mainly of hematite in association with magnetite (the magnetite ranging from 10 to 47 percent within each ore body), whereas the vein ores are predominantly magnetite. The principal commercial deposits, nearly all of the replacement type, are indicated diagrammatically on the geologic map.

The iron mineralization has been shown by Mackin (1947, 1954) to represent concentrations of iron released from the intrusive magma by deuteric processes during the final stages of consolidation. Fresh porphyry is limited to the rapidly chilled peripheral shell of each intrusion—a zone 100 to 300 feet thick adjacent to the original upper margins. Elsewhere the rock is deuterically altered, and the primary minerals have been transformed into pseudomorphic aggregates of orthoclase and iron oxides. Iron was concentrated in joints and open fissures produced by late distension of the partially solidified intrusive mass. Magnetite-coated joints and magnetite veins have borders, or "selvages," leached of iron. The zone of selvaged joints forms a resistant layer of irregular thickness between the peripheral shell and crumbly interior. Replacement bodies occur in places where the ore-bearing fluids gained access, through fractures in the peripheral shell, to the capping limestone.

Peripheral shell rock, interior rock with selvaged joints, and normal interior rock are given separate map designations. Normal interior rock is exposed only in the Three Peaks intrusion; peripheral shell and selvaged interior rock are not separated on Iron Mountain.

MAGNETIC PROPERTIES OF THE ROCKS

The response of the airborne magnetometer depends upon the intensity of magnetization of the rocks and the distance between the rocks and the detector. The intensity is the resultant of both induced and permanent components of polarization.

To evaluate the effect of induced polarization, a description of the inducing field and an estimate of rock susceptibility are required. The following parameters for the earth's normal field in the Iron Springs district are taken from the charts of Vestine and others (1947):

Total intensity=54,100 gammas
Declination=16.5° (east)
Inclination=64.3°

No direct measurements of magnetic properties of the Iron Springs rocks were made. However, other workers—for example, Slichter (1929), Werner (1945), and Mooney and Bleifuss (1953)—have shown empirically that the susceptibility of rocks containing up to several percent magnetite is approximately linearly proportional to magnetite content. Satisfactory results in the interpretation of ground-magnetometer surveys for iron deposits in the Iron Springs district are obtained if the magnetite component of the ore is assumed to have a susceptibility of 0.25 cgs (centimeter-gram-second) unit (Cook, 1950). The susceptibility of magnetite in the ore is not necessarily the same as that in the porphyry, but if the value 0.25 cgs unit applies, the susceptibility of quartz monzonite porphyry containing 1 to 3 percent magnetite should range from 2.5 to 7.5×10^{-3} cgs unit. Cook measured the susceptibility of 116 specimens of porphyry on the western margin of the Three Peaks intrusion and concluded that specimens from the border zone (peripheral shell) have a higher susceptibility than "normal" porphyry, but data were not listed. The actual susceptibility range of the porphyry is no doubt greater than the range given above because of atypical values of magnetite content and departures from the susceptibility assumed for pure magnetite. (For a list of measured susceptibilities of magnetite from various sources, see, for example, Birch and others, 1942, p. 295.) Volcanic rocks of the district probably have susceptibilities comparable to or less than those of the porphyry; susceptibilities of the sedimentary rocks are assumed to be negligible.

A study of permanent polarization, or natural remanent magnetization (NRM), of the Granite Mountain and Three Peaks intrusions has been made by R. L. DuBois of the University of Arizona. He (oral commun., 1964) reported that the NRM for these bodies ranges from 158 to 5000×10^{-6} cgs unit, with azimuth averaging 6° W. of true north and inclination 40° to 50° N. Thus the orientation of the resultant total magnetization vector for the Iron Springs bodies is probably not greatly different from the orientation of the earth's present field in the region, but the magnitude of the vector may be significantly larger than that of the induced component alone.

To rapidly obtain an approximate value for the average effective susceptibility of the porphyry (that is, a proportionality factor relating the total intensity of magnetization to the ambient field intensity), magnetic north-south traverses were made with an Arvela vertical magnetometer across two topographic features in the Three Peaks area. Magnetic and topographic profiles are given in figure 1.

Traverse *A—A′* was made across the Irene monocline, a structural feature whose topographic expression is a ridge composed of interior porphyry of the selvaged zone. The magnetic profile is erratic, but the smoothed curve shows an amplitude increase of 600 to 900 gammas associated with the ridge. A graphical two-dimensional analysis of the topographic effect was made with a Pirson polar chart (Pirson, 1940) on the assumptions that the selvaged-zone rock responsible for the topography is uniformly magnetized in the direction of the earth's field and rests on a subhorizontal surface of normal interior rock. Effective susceptibilities of 5 and 7.5×10^{-3} cgs unit, corresponding to the lower and upper limits of the observed amplitude, were obtained. These values span the upper half of the range of susceptibilities computed on the basis of magnetite content.

Traverse *B—B′* was made over Big Peak, a hill having a total relief similar to the Irene monocline ridge (about 300 feet) but composed almost entirely of normal interior porphyry. The thin capping of peripheral shell rock on the summit makes a negligible contribution to the average anomaly; the zone of selvaged joints is absent. This anomaly is obviously difficult to evaluate, but the topographic effect appears to be about 200 to 400 gammas. On the basis of a comparison with traverse *A—A′*, the effective susceptibility of normal interior porphyry is probably lower than that of selvaged zone porphyry by a factor of 2 or 3, and it lies in the lower half of the range of susceptibilities calculated on the basis of magnetite content.

Both profiles demonstrate the highly irregular magnetization of the porphyry from outcrop to outcrop. The difference in average effective susceptibilities of the selvaged zone and normal interior rock is in part attributed to differences in magnetite content, but permanent polarization probably plays a more important role. The average magnetite content of the zone of selvaged joints, including magnetic veins, is probably close to that of fresh peripheral shell rock and is only slightly higher than that of normal interior rock because deuteric alteration chiefly affected the hydroxyl-bearing mafic minerals rather than magnetite. However, the effect of a slight increase in magnetite content could be greatly magnified by permanent polarization. The NRM of shell rock is locally strong enough to have a conspicuous effect on a hand-held Brunton compass; much of the vein magnetite is lodestone.

The ratio of the magnitudes of permanent to induced polarization (Q ratio) is very high in some volcanic rocks of the Iron Springs district. This is illustrated by the basal vitrophyre of the Bauers Tuff Member (Mackin, 1960) of the Quichapa Formation, a highly welded ash-flow deposit (ignimbrite). Although this vitrophyre is only 5 to 10 feet thick, edges of the sheet produce a strong response in the airborne magnetometer. Fortunately, the volcanic rocks are everywhere separated from the porphyry by weakly magnetic sedimentary rocks so that their anomalies are easily distinguished from those of the intrusive bodies.

THE AEROMAGNETIC SURVEY

The aeromagnetic survey was made under the direction of W. J. Dempsey of the U.S. Geological Survey. The detector was a total-intensity flux-gate magnetometer model AN/ASQ 3A towed by a twin-engine AT–11 Beechcraft at an elevation of 1,000 feet above the terrain. Similar equipment and procedures have been described by Balsley (1952) and others. Where the topography is rugged, as over exposed parts of the intrusive bodies, terrain clearance along an individual traverse may have differed as much as several hundred feet from the prescribed value. Profiles were flown in an east-west direction and spaced approximately a quarter of a mile apart; control lines were flown at right angles to the main family of traverses to correct for instrument drift so that all profiles could be reduced to a common (arbitrary) datum. The instantaneous position of the aircraft during each flight traverse was ascertained by referring fiducial marks on the recorder output chart to corresponding marks on continuous strip photographs.

INTERPRETATION OF THE AEROMAGNETIC MAP

Each of the three areas of porphyry exposed in the Iron Springs district—Three Peaks, Granite Mountain, and Iron Mountain—is encompassed by a complex magnetic high (see map). The extent of the general anomalies is a rough indication of the lateral extent of concealed porphyry. Thus the Three Peaks and Granite Mountain intrusions represent larger buried bodies that are probably continuous at depth; the Iron Mountain intrusion appears to be a discrete body whose southern and western extremities are concealed. However, deeply buried intrusive rock may not everywhere have a distinct magnetic expression, particularly if its polarization is less than that of surface samples. Cook and Hardman (1966) concluded on the basis of a gravity survey of the region that intrusive rock underlies a

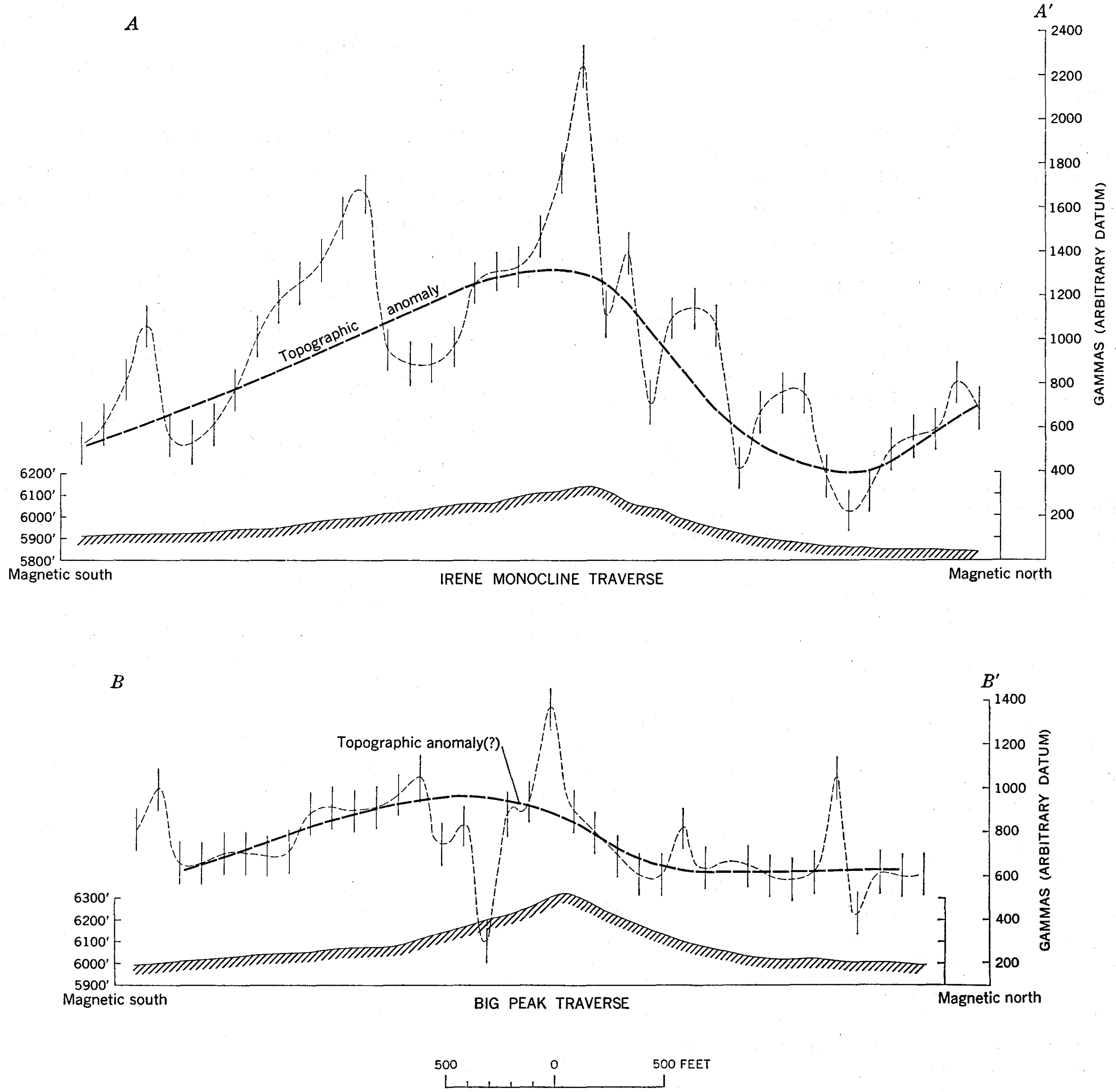

FIGURE 1.—Vertical intensity ground magnetometer profiles across ridges of Three Peaks porphyry. Traverses by H. R. Blank, Jr., assisted by G. W. Green, 1964.

greater area than is inferred from the aeromagnetic data and that all three mapped intrusions have a subsurface continuity.

Anomalies with short spatial wavelengths, here called local anomalies, are superimposed on the broader anomalies associated with each intrusion. They bear no consistent relation either to topographic relief or to the mapped intrusive margins. The relation of known ore deposits to these anomalies is also erratic, although most deposits are associated in a general way with positive magnetic features. The principal source of the local anomalies appears to be the magnetic inhomogeneities discussed previously.

Other groups of local anomalies characterize the areas of outcrop of volcanic rocks northwest of the Three Peaks intrusion and east of the Granite Mountain and Iron Mountain intrusions. The traverse spacing of the aeromagnetic survey is too wide to permit detailed interpretation of these anomalies. They reflect magnetic inhomogeneities in the volcanic rocks and the edges of individual thin sheets, and their true configuration is poorly known.

Even a well-delineated anomaly cannot, of course, be interpreted uniquely. The following discussion of the aeromagnetic map presents interpretations which are believed to be geologically reasonable.

THREE PEAKS AREA

OUTLINE OF THE INTRUSION

The northern part of the Three Peaks intrusion is largely obscured by pediment gravels. However, it is clear that the northern half of the western boundary of the body is an intrusive fault, the Northwest fault, which places porphyry against Cretaceous and Jurassic rocks; the fault passes southward into a monoclinal flexure. Porphyry is generally concordant against the Homestake Limestone Member of the Carmel Formation along the entire southwestern and southern margins in a series of monoclines and monoclinal flexures. No marginal contacts are exposed on the east, but there the outcrops of intrusive rock terminate along a line believed to represent the trace of a fault, called the East fault, which postdates the intrusion (pl. 1). Geologic evidence favoring the existence of the fault includes the following: (1) The line is parallel to the main set of north-trending faults that postdate the intrusion and are associated with the Cedar City graben (Thomas and Taylor, 1946, pl. 3), and (2) pediment gravels east of the line are derived from both Colorado Plateau and Three Peaks sources whereas those west of the line are derived from the Three Peaks area only. These provenances suggest that the western extent of Cedar City graben fill that is older than the pediment was limited here by some topographic obstruction, such as a fault scarp or faultline scarp. The discontinuous joint pattern of the intrusive body at the line also supports the hypothesis of faulting after intrusion rather than faulting at the time of intrusion.

The aeromagnetic data may be used to investigate the configuration of the concealed parts of the intrusive body. The northern edge of the intrusion coincides approximately with the northern boundary of the survey, but the subsurface eastern margin is apparently about a mile east of the East fault, in a region of steep magnetic gradient. The problem of the eastern extension will be considered later. Concealed intrusive rock also extends to the south of the exposed southern contact, as was predicted from the dip of the concordant contact in this vicinity (about 45° S.). Similarly the southwest nose (Mackin, 1947, fig. 2), a smaller feature reflected in surface dips of the sedimentary rocks, is shown by the isomagnetic contours (pl. 1). The nose produces an anomaly extending due west from the 2,063-gamma anomaly at the southwestern margin of the intrusion.

THICKNESS OF THE INTRUSIVE BODY

Various attempts to determine the depth extent of an intrusive body from aeromagnetic data have been reported; for examples, see Zietz (1960) and Allingham and Zietz (1962). The magnetic method, even when used in conjunction with other methods, is subject to severe limitations. The amplitude of an anomaly is relatively insensitive to depth extent of a thick causative body. Also, it is difficult to isolate near-surface effects from the general anomaly, and any calculation based on the assumption of uniform intensity of magnetization throughout the body must be treated with caution. Nevertheless, it is instructive to compare the observed Three Peaks anomaly with the theoretical magnetic field produced by geologically plausible models.

The gross pattern of the Three Peaks anomaly corresponds to that of a thick tabular body magnetized in a direction approximately parallel to the earth's present field. A rather sharp magnetic minimum (only partly delineated by this survey) is present at the northern edge; minimums on the sides are produced by a combination of lateral flaring of the southern half of the body and locally steep margins. The position and amplitude of the minimums provide a preliminary indication of the depth extent of the intrusive body.

Consider, for example, the 1,185-gamma minimum associated with the western edge of the Three Peaks positive anomaly. This minimum is about 1,200 to 2,500 feet west of the intrusion in an area where the intrusive contact is known to be nearly vertical. A precise flight elevation cannot be given, but it may be assumed to be between 500 and 1,000 feet above the upper surface of the intrusion at the western edge. Therefore the minimum is 2.4 to 5.0 times the flight elevation from the western edge for the lower limit and 1.2 to 2.5 times the flight elevation for the upper limit. For a given flight elevation, the westward displacement of the minimum is a function of the thickness of the body. Examination of the edge effect of an ideal vertical-sided two-dimensional body (fig. 2) shows that the thickness of the intrusive body in this vicinity does not exceed about 1 mile, and probably is considerably less. This conclusion is independent of the susceptibility assumed for the body. Departures from the ideal case, such as end effects and outward-sloping sides, tend to displace the minimum farther west, so that the thickness estimates are maximum values.

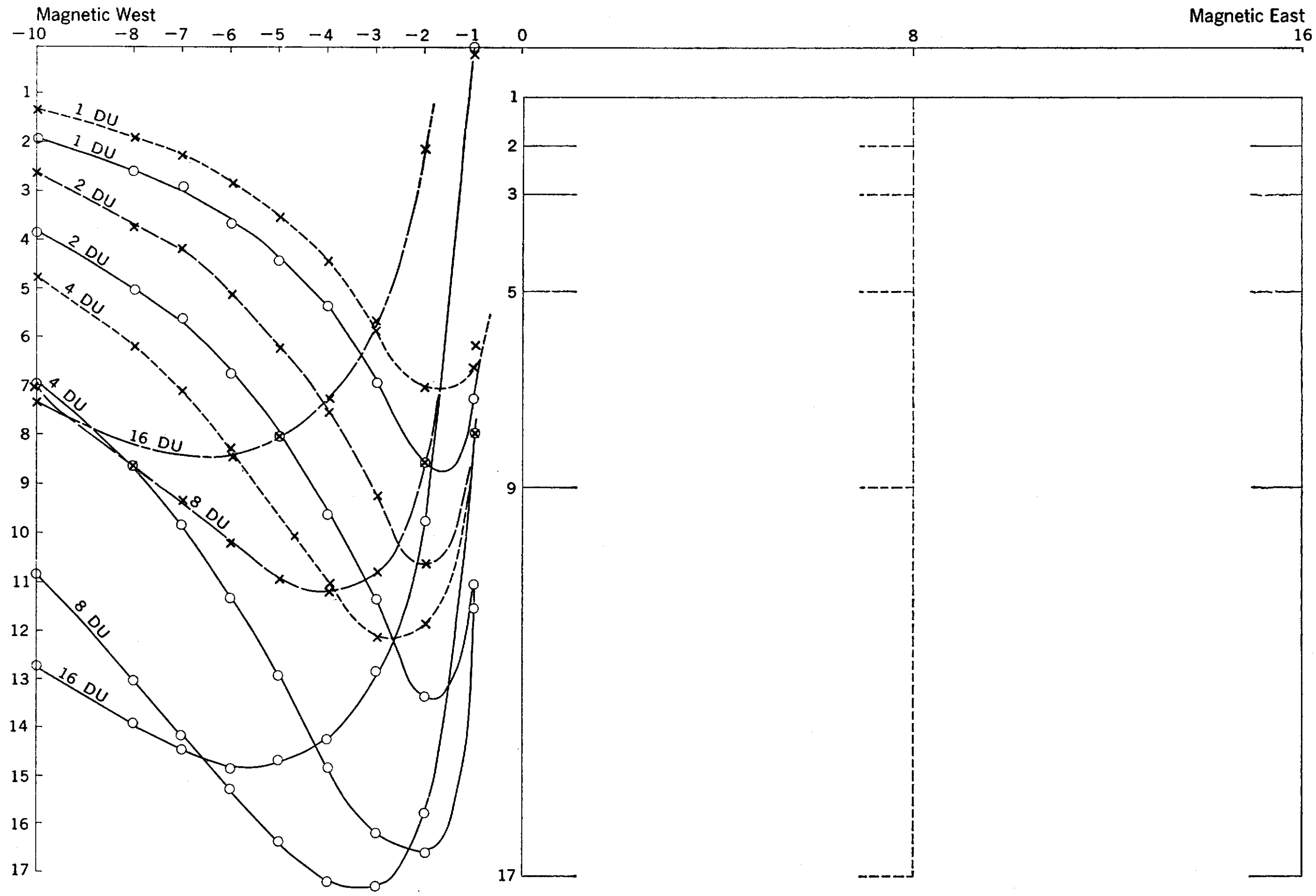

FIGURE 2.—Edge effect of two-dimensional slabs. Position of west minimum is shown for magnetic east-west traverse 1 depth-unit (DU) above slabs of different thickness. Vertical and horizontal scale for models are in depth-units; scale for response curves is in percentage of total half space subtended by lower surface of model minus percentage of total half space subtended by upper surface. Dashed curves and crosses refer to models 8 depth-units wide; solid lines and circles refer to models 16 depth-units wide. Minimum is displaced westward by increasing thickness of slab.

A cross section passing through the intrusive body and intersecting the two lateral minimums approximately along a magnetic meridian was selected for two-dimensional analysis (section *C–C′*, pl. 1). The intrusive body was represented by hypothetical models of several thicknesses, and the magnetic response was computed over a range of susceptibilities. Calculations were made with a Burroughs 220 Datatron computer using a program, based on the theoretical response due to bodies of trapezoidal cross section, which was written and compiled by Gerald Evenden of the Geological Survey. A simulated flight elevation of 6,600 feet above sea level was used; this corresponds to a terrain clearance of about 1,000 feet at the ends of the profile but somewhat less over the intrusive body, as was suggested by examination of the horizontal extent of the steepest aeromagnetic gradients. The response curves were taken directly from the output of an X–Y plotter.

The models and theoretical curves for a susceptibility of 4×10^{-3} cgs units are shown in figure 3. For comparison, the observed aeromagnetic profile (as obtained from the contour map) is reproduced in the same figure, with 1,400 gammas as the zero datum. The best overall match to the observed curve is probably produced by the model about 4,000 feet in thickness. Observed field intensities over the exposed part of the intrusive body no doubt reflect near-surface magnetic inhomogeneities as well as a contribution from the Irene monocline just north of the traverse, and will not be matched by the theoretical response of any simple two-dimensional model of uniform susceptibility. A model having no vertical step on the East fault, but only a change of slope of the porphyry surface, produces an improved fit in this area. This model, however, seems to contradict the independent geological and geophysical evidence presented in the next section (p. B8–B10). Moreover, any

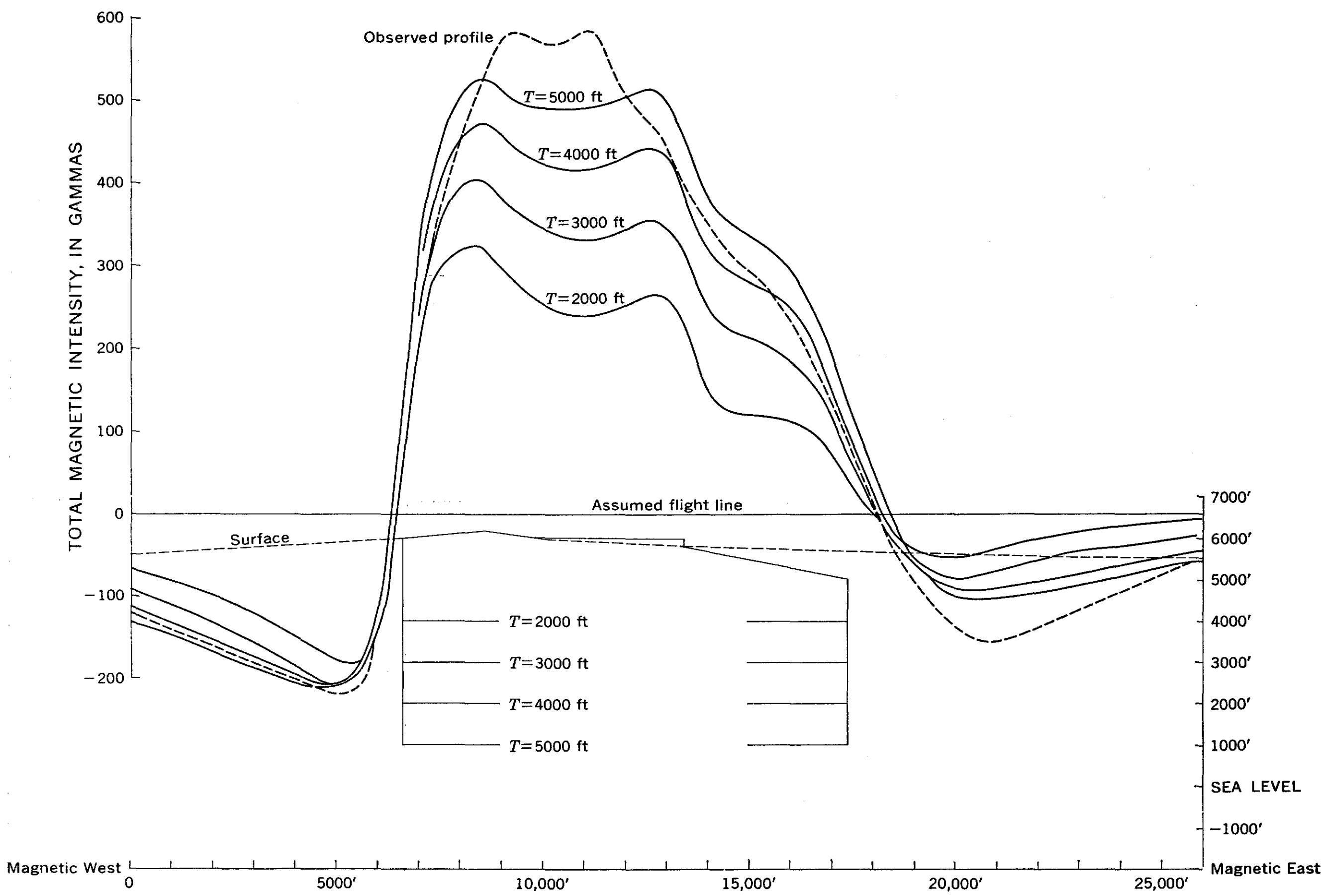

FIGURE 3.—Total intensity aeromagnetic anomalies generated by hypothetical two-dimensional models of the Three Peaks intrusion, $k=4\times10^{-3}$ cgs units. Observed aeromagnetic and topographic profiles C–C' are indicated by dashed lines.

increase in the displacement of the porphyry surface at the East fault would produce a worse fit. A modification of the shape of the east side of the model is evidently necessary to reconcile the observed and computed curves near the eastern minimum; another step fault may be present, the intrusive body may extend farther east, and the side is probably not vertical.

The susceptibility used for the curves in figure 3, $k=4\times10^{-3}$ cgs units, is less than that computed for selvaged-zone rock from the traverse of Irene monocline but is rather high for normal interior rock as obtained from the traverse of Big Peak. Other combinations of susceptibility and thickness could of course be used to produce a satisfactory amplitude match of theoretical and observed profiles. However, for thicknesses much less than 3,000 feet the required susceptibility is unreasonably large and the discontinuity at the East fault is exaggerated; for thicknesses much greater than 5,000 feet the required susceptibility for the amplitude match might be satisfactory, but the shape of the western minimum is unacceptable. A more precise knowledge of susceptibility and natural remanent-magnetization values and their distribution is required before a more refined quantitative interpretation would be meaningful.

EAST FAULT

As a test of the validity and significance of the East fault, the trend of this inferred structural feature was traversed at right angles with a Worden gravimeter. Observations were made along approximately east-west roads, and the reduced values were projected onto true east-west profiles. The results are reproduced in figure 4, together with magnetic profiles taken from the isomagnetic contour map. Profiles D–D' show a distinct gravity discontinuity at the indicated fault trace amounting to about 3 milligals and a steep magnetic gradient having a point of inflection somewhat farther west. The magnetic profile may be influenced by magnetic inhomogeneities in the porphyry. Profiles E–E' also show a gravity step across the fault trace and an associated steep magnetic gradient.

The gravity data reflect the density contrast between alluvium and bedrock but do not distinguish between the porphyry and the Homestake Limestone Member;

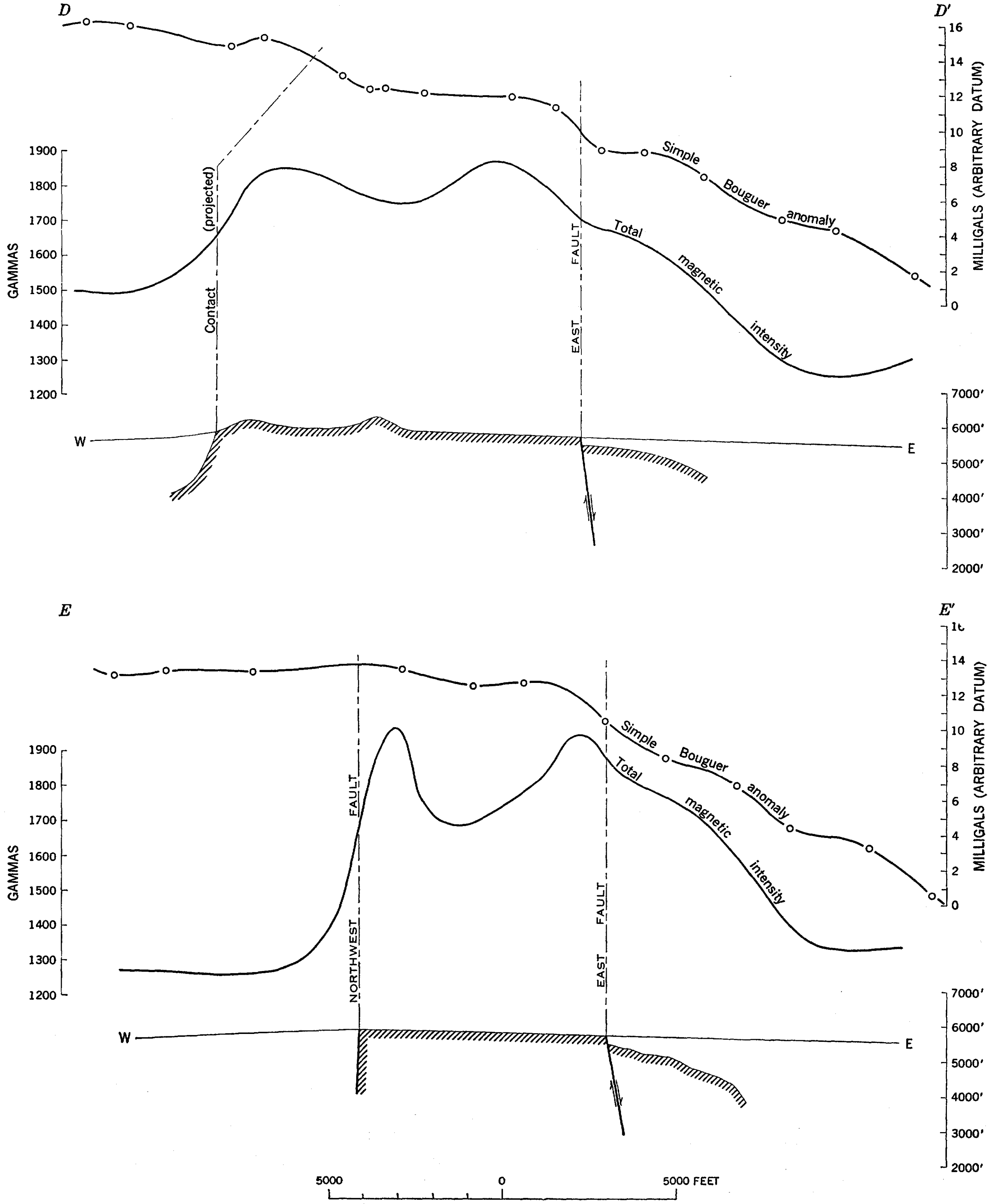

FIGURE 4.—Gravity and aeromagnetic profiles across the East fault, Three Peaks intrusion. Gravity traverses by H. R. Blank, Jr., assisted by G. W. Greene, 1964.

the magnetics are sensitive to the surface configuration of the intrusive body only. In combination, the data suggest that a small displacement of the porphyry surface, downward to the east, coincides with the trace of the East fault. The density of the porphyry is about 2.65 grams per cubic centimeter (Leith and Harder, 1908, p. 47). If the surficial material is assumed to be dry unconsolidated sediments with a density of 1.85 grams per cubic centimeter, a displacement of about 300 feet satisfies the gravity discontinuity. The fault apparently dies out to the south where the magnetic break disappears. Local disturbances of the magnetic field in this vicinity are most likely caused either by irregularities in the bedrock topography or by changes in the effective susceptibility in the porphyry, such as would be produced by concentrations of magnetite veinlets.

The presence of porphyry at a shallow depth east of the East fault suggests that this area has potential economic significance. The contact of intrusive porphyry with Homestake limestone—a favorable environment for ore deposition—could be concealed beneath a thin cover of alluvium, and therefore local magnetic anomalies could also represent replacement ore bodies amenable to exploitation. The 1,940-gamma high, apparently superimposed on the linear anomaly associated with the fault, may be produced by a replacement body just east of the fault zone and should probably be investigated further with a ground-magnetometer survey.

LOCAL ANOMALIES

Most of the local magnetic anomalies within the exposed margins of the Three Peaks intrusion are due to magnetic inhomogeneity of the porphyry, magnetite veins, steep intrusive contacts, and topographic relief. In general the zone of selvaged joints indicated on the geologic base map is represented by a magnetic high. The high cannot be only an edge effect because it diverges from the margin of the intrusive body and follows the Irene monocline. It is most pronounced where magnetite veins and iron-coated joints are most numerous. Some maximums (the 2,060- and 2,110-gamma anomalies) coincide with vein ore. The Great Western vein deposits, perhaps the largest in the area, occur in what is contoured as a magnetic saddle on the selvaged-zone high (immediately south of the 2,063-gamma anomaly), but they were not crossed by a flight line. Even in the area of rather homogeneous interior rock, a weak magnetic ridge (containing the 1,885- and 1,870-gamma maximums, near the East fault) follows a zone of abundant mineralized joints extending south of Big Peak. Two of the three negative closures in interior rock occur where there are fewest joints (1,735-gamma minimum); the third (1,675-gamma minimum) is in part a polarization low associated with the positive anomaly of Irene monocline.

Because selvaged-zone rock is generally more resistant to erosion than normal rock of the interior, and has a higher effective susceptibility, there is a partial correlation between local magnetic highs and topography; however, topographic relief in interior rock is not reflected by the magnetic pattern. The effect of peripheral shell porphyry on the western and southern margins is merged with that of the selvaged zone. Isolated outcrops of peripheral shell on Big Peak or elsewhere do not disturb the magnetic field appreciably at the elevation flown.

GRANITE MOUNTAIN AREA

GEOMETRY OF THE INTRUSION

Previous studies of the Granite Mountain intrusion (Mackin, 1954) indicate that the area of outcrop represents the easternmost, and structurally highest, part of a largely concealed mass. The isomagnetic contours show that porphyry extends beneath the sedimentary and alluvial cover for about 4 miles southwest of the southwesternmost exposures (near Desert Mound) along the major Laramide trend and northwest of Desert Mound approximately to the limits of the survey. The maximum amplitude of the anomaly over exposed intrusive rock is comparable to that of the Three Peaks maximum; a slightly lower maximum is present at the buried southwest end. Like the Three Peaks intrusion, the Granite Mountain intrusion probably has the overall form of an elongated slab several thousand feet thick, whose upper surface is locally upbulged.

The exposed southeastern intrusive contact is a high-angle reverse fault (Cory-Armstrong fault) placing porphyry against the Cretaceous and Tertiary sedimentary sections. The magnetics suggest that this fault, or at least a steep intrusive contact, continues to the southwest beneath alluvium. In the alluvium-covered area intrusive rock is probably also present on the southeast side. Similarly the intrusive fault on the northwest side of Granite Mountain (Clive fault) can be extrapolated through a zone of steep magnetic gradient past Desert Mound toward the southwestern end of the intrusion. These two structural features define an upbulged area, which can be regarded as an intrusive horst on the surface of the intrusive body. They give way at the northeastern end to an intrusive nose, where the porphyry contact dips to the north beneath the sedimentary cover. The presence of the nose is reflected by a partly exposed plunging anticlinal flexure in the sedimentary rocks, designated the Iron Springs arch. According to the aeromagnetics, the axis of the nose swings sharply to the northwest. The axial trace as inferred here was not entirely included in the Bureau of Mines ground-magnetometer surveys previously cited. Because such a structural feature may contain selvaged feeder joints produced by late distension of the outer part of the intrusion, the supra-adjacent limestone beds constitute a favorable environment for replacement ores and should be thoroughly tested.

This nose is only about 1 mile from the southwest nose of the Three Peaks intrusion. The intervening terrane is probably also floored by intrusive rock, so that the Three Peaks and Granite Mountain intrusions are connected. Depth to porphyry in the gap probably exceeds 2,000 feet.

A broad magnetic anomaly, the 1,660-gamma high, occurs immediately northwest of the community of Iron Springs. The anomaly is attributed to porphyry constituting a second upraised part of the largely unexposed Granite Mountain intrusive slab. Although the body is too deeply buried to produce strong magnetic detail, it seems to be bounded by rather steep contacts (intrusive faults?) on three sides, and its surface probably dips gently to the southwest. It does not affect the dip of Cretaceous rocks on the nearest exposures and consequently could not be detected by surface mapping. The peak of the anomaly was outlined by private ground-magnetometer surveys; the presence of subsurface porphyry (as well as ore in the Homestake) is reportedly confirmed by commercial drilling.

The aeromagnetic survey does not encompass the entire Granite Mountain anomaly, but it is evident that the northwest perimeter of the intrusion is deeply buried. The broad poorly defined 1,615-gamma anomaly is roughly at the center of the body.

At the southwestern end of the Granite Mountain intrusion, another major upbulge is indicated by the 2,035-gamma anomaly. This feature is partly isolated from the main intrusive horst, although it is alined with it and is likewise bounded by steep contacts on the northwest and southeast sides. The upbulge is probably responsible for the arcuate pattern traced by the northwest-facing scarp of the volcanic sequence in the Swett Hills. Drilling near the magnetic maximum reportedly located high-grade replacement iron deposits in limestone of the roof rock and bottomed in quartz monzonite porphyry. The magnetic expression of the ore would be merged with that of the porphyry.

LOCAL ANOMALIES

The Granite Mountain anomaly also shows local irregularities over exposures of porphyry. All the exposed rock is either the selvaged or peripheral-shell type and should have a relatively high effective susceptibility. Topography must therefore make some contribution to the anomalies. Comparison with a detailed geologic map of the intrusion (Mackin, 1954) shows that the 2,195-gamma maximum coincides with a zone in which vein magnetite is most abundant; the remainder of the pattern is probably caused by a combination of edge effect, mineralized joints, and topography. Exceptions are the 1,860-gamma maximum on the north nose, which is produced by the so-called Pioche replacement ore body, and the 2,005-gamma anomaly in the vicinity of Desert Mound, which probably is largely due to a group of replacement deposits.

Flight traverses passed directly over some replacement ore bodies that do not disturb the isomagnetic contour pattern. Glicken (1955) presented an interesting illustration of the effect of the Short Line replacement body (due west of the Desert Mound pit) on an airborne magnetometer at different flight levels. At 1,000 feet or more above the terrane the anomaly of this deposit is not distinguishable from the anomaly due to the porphyry intrusion.

SOUTHWEST TERMINATION

One of the most interesting features of the Granite Mountain anomaly is the pattern of isomagnetic contours produced by the concealed southwestern end of the intrusion. The pattern implies that the termination of the intrusion is alined with an extension of the Woolsey Ranch fault which forms the southwestern border of the Swett Hills.

This fault is, however, genetically associated with the Iron Mountain intrusion rather than with the Granite Mountain intrusion; it marks the northern boundary of a zone of chaotic structure formed by gravity sliding from Iron Mountain (Mackin, 1960, p. 119–122, and fig. 8). Within this zone (south of the fault) the structural relation of the Iron Springs Formation to the Claron Formation, the multiple repetition of the Claron section, and the presence of tectonic breccias, considered as a whole, indicate that the bulk of the post-Cretaceous section moved generally east-southeastward, accompanied by shearing off and rotation of the Claron. Vertical displacement on the Woolsey Ranch fault is greatest near Iron Mountain and decreases rapidly to the east; the movement becomes largely translational before dying out altogether. The fault is not found northwest of Iron Mountain at the foot of the Antelope Range. The geologic evidence strongly implies that the fault was formed in conjunction with the gravity movements.

Combined lithologic and structural evidence suggesting that the Iron Mountain intrusion was emplaced prior to the Granite Mountain intrusion was adduced in a previous paragraph. The aeromagnetic data tend to rule against a shallow subsurface continuity of the two bodies or a vertical displacement of the Granite Mountain intrusion by the fault. On the premise, then, that the Granite Mountain intrusion is a discrete body that postdates the fault movement, it seems reasonable to suppose that the Woolsey Ranch fault served as a structural barrier to southwestward extension of the Granite Mountain magma. Examples of other early faults which influenced the shape of the spreading intrusions are the Cory-Armstrong fault on the north side of Granite Mountain and the Northwest fault of Three Peaks.

The origin of the east-southeast trend of the Woolsey Ranch fault is purely speculative, but the trend may represent a Laramide line of weakness approximately transverse to the axis of the Iron Springs Gap anticline.

IRON MOUNTAIN AREA

GEOMETRY OF THE INTRUSION

The position of the Iron Mountain aeromagnetic anomaly corresponds rather closely to the area of porphyry outcrop. The anomaly has the general form which would be produced by a thick ovate slab elongated slightly in the direction of the main Laramide trend and dipping west-southwestward. The magnetic margin and outcrop margin of the intrusive body in the northwest, north, and northeast, although obscured by the pattern of local anomalies, are approximately coincident. Only in the south and west is there a significant discrepancy.

The curving southeastern boundary of the intrusion is a near-vertical intrusive monocline having a throw of several thousand feet, which corresponds in position to a steep magnetic scarp. This scarp is not completely delineated by the survey, but probably continues along the southern border of the intrusion; the effect of the Mount Stoddard intrusion to the south of the area flown distorts the southernmost contours. On the west, the porphyry surface slopes downward beneath a cover of sedimentary rock and alluvium to form what appears to be a nose analogous to the southwest nose of Three Peaks. The base of the Homestake (the horizon of intrusion) has been calculated from the westerly dip of Claron and Iron Springs rocks to be about 4,500 feet below the nearest outcrops of the Claron (more than 2 miles west of the exposed margin of the intrusion). The steep magnetic gradients associated with the Iron Mountain anomaly disappear within about half that distance.

Surface geologic evidence, on the other hand, suggests that intrusive rock occurs west of the region of steep gradient. The westward continuity of south-dipping rocks of the Claron Formation tangent to the southeastern and southern margin of Iron Mountain, and the arcuate pattern (convex to the north) of the Claron northwest of Iron Mountain, are strong structural indications of an intrusive body beneath the alluvium. Moreover, porphyry has reportedly been penetrated by deep test drilling in this region. Although the critical area is not thoroughly covered by the aeromagnetic survey, the data suggest that the weak magnetic ridge with a 1,330-gamma maximum and the high of plus 1,400 gammas at the western edge of the map area are expressions of deeply buried porphyry, probably continuous with the Iron Mountain body proper. Thus Iron Mountain, like Granite Mountain, is apparently the highest part of a more extensive intrusive body.

LOCAL ANOMALIES

Although phases of intrusive rock at Iron Mountain are not distinguished on the geologic map, all exposed porphyry represents either peripheral or selvaged interior phases. The relation of local anomalies to magnetic inhomogeneities in the porphyry cannot be demonstrated. It is apparent, however, that both topographic relief, which is as great as 1,700 feet, and major ore deposits make significant contributions to the local pattern.

The 2,705- and 2,260-gamma highs at the southwest end of the intrusion are produced by one of the most commercially important ore deposits in the district, a group of replacement bodies in the Homestake Limestone Member of the Carmel Formation. Ore and Homestake limestone are exposed only at the southern end of the positive anomaly. The well-defined polarization low (1,000-gamma minimum) shows that the strike of the total magnetization vector is approximately true north. No aeromagnetic flight path crosses the rather sizable workings immediately to the southeast of the deposit; the 1,800-gamma minimum closure shown there may have little meaning. The plus 2,200-gamma high on the southern periphery and the 2,540-gamma high near the eastern margin also represent major replacement ore bodies. Mineralization in the area of the 2,540-gamma high has occurred at the base of an infolded septum of the roof rock.

Two local highs in the central part of the intrusion probably reflect the topography to some extent but require an additional explanation. A 2,640-gamma magnetic peak is associated with a magnetite vein system that crops out just north of the traverse; this anomaly probably is largely caused by the veins. A 2,765-gamma high—much broader than the 2,640-gamma high—is crossed by the trend of a high-angle reverse fault which is believed to extend from the infolded septum of roof rocks southwestward across the intrusion. (For a schematic section of this structural feature see Mackin, 1960, fig. 8, sections B and C.)

Mineralized Homestake limestone crops out in several places along this trend and near the anomaly. The anomaly is conceivably produced (at least in part) by mineralization of a large infolded or infaulted roof pendant almost wholly concealed by quartz monzonite porphyry. Alternatively, the anomaly could be caused by an increase of effective susceptibility due to abundant mineralized joints and veinlets.

The magnetic trough just east of Iron Mountain is interpreted as an edge anomaly associated with polarization of the intrusive body. Local irregularities in the western part of the trough, including three distinct lows (the 1,030-, 1,000-, and 1,035-gamma minimums) should probably be attributed to the irregular margin of the porphyry and to variations in effective susceptibility. Where the porphyry is concealed, the local anomalies may have economic significance. However, the precise configuration of these anomalies is not represented by the isomagnetic contours.

SUMMARY AND CONCLUSIONS

1. The aeromagnetic survey roughly delineates the lateral subsurface extent of the Three Peaks, Granite Mountain, and Iron Mountain intrusions. Granite Mountain is an upbulged part of a largely concealed body; two additional upbulges on this body are indicated by the isomagnetic contours but do not crop out at the surface.
2. Analysis of the Three Peaks anomaly suggests that the intrusive body is floored at relatively shallow depth, probably less than 1 mile.
3. The zone of selvaged and mineralized joints in the exposed Three Peaks intrusion has a higher effective susceptibility than normal interior rock and is associated with a belt of local magnetic highs; maximums occur where magnetite fissure veins are most abundant. Such anomalies in the Three Peaks and Granite Mountain bodies are larger than those produced by exploitable replacement deposits, some of which are not detected by the survey.
4. The East fault of Three Peaks probably produces a maximum displacement of several hundred feet on the surface of the porphyry. The area east of the fault is underlain by intrusive rock at relatively shallow depth and could be a favorable target for further prospecting.
5. The axis of the concealed northern nose of Granite Mountain (Iron Springs arch) lies partly to the west of the area covered by published ground-magnetometer surveys and may also be favorable for further prospecting.
6. Quartz monzonite porphyry is continuous at depth from Granite Mountain to a northwest-trending line possibly representing an extension of the Woolsey Ranch fault which forms the southern margin of the Swett Hills. The fault may have determined the limit of southwestward expansion of this intrusion.
7. Weak but incompletely delineated anomalies west of Iron Mountain probably represent deeply buried extensions of the main body of porphyry.
8. A local anomaly associated with a structural trend crossing the interior of Iron Mountain may be caused by mineralization of a concealed infolded septum of the Homestake Limestone Member of the Carmel Formation.

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