Gravity and Magnetic Features as Related to Geology in the Leadville 30-Minute Quadrangle, Colorado

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By OGDEN TWETO *and* J. E. CASE

GEOPHYSICAL FIELD INVESTIGATIONS

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A summary and correlation of geologic and geophysical data on the most productive part of the Colorado mineral belt

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GRAVITY AND MAGNETIC FEATURES AS RELATED TO GEOLOGY IN THE LEADVILLE 30-MINUTE QUADRANGLE, COLORADO

By OGDEN TWETO and J. E. CASE

ABSTRACT

Regional gravity and aeromagnetic surveys were made in the Leadville 30-minute quadrangle, Colorado, to supplement and extend geologic studies in a highly productive segment of the Colorado mineral belt. The quadrangle lies at the intersection of the mineral belt with the Arkansas valley graben, a northern extension of the Rio Grande and San Luis Valley graben system of New Mexico and southern Colorado.

Almost the entire quadrangle is a part of the eastern flank of the huge Sawatch anticline. The Sawatch Range, in the western part of the area, is carved in the Precambrian rocks in the core of this anticline. The Arkansas River valley, at the foot of the range, is an elongate downfaulted block, or graben, high on the eastern flank of the anticline. The Mosquito and Tenmile Ranges, which occupy a broad central belt through the length of the quadrangle, constitute an upthrown fault block east of the Arkansas valley graben. They consist of Precambrian rocks capped by Paleozoic sedimentary rocks. The sedimentary rocks dip eastward into South Park, a broad structural basin.

The Precambrian rocks and the Paleozoic sedimentary rocks are cut by numerous bodies of intrusive porphyry of Late Cretaceous and Tertiary age. These porphyry bodies and related mineral deposits — such as those of Climax, Leadville, and several other mining districts — characterize the Colorado mineral belt, which here forms a broad northeast-trending belt that occupies much of the quadrangle. A deep fill of upper Tertiary alluvial deposits and mantling Pleistocene glacial deposits in the Arkansas valley covers the bedrock along the axial trend of the mineral belt for several miles southwest of Leadville.

The dominant gravity anomaly is a huge low of 30–50 milligals which trends northeast across the quadrangle. From analysis of steep gradients on the flanks of the anomaly, the low is inferred to be caused by a shallow batholith of relatively low density. This batholith is concluded to extend to within a few thousand feet from the surface and to be the source of the numerous Upper Cretaceous and Tertiary intrusive bodies.

Superimposed on the main gravity anomaly is a low of 5–20 milligals over the Arkansas valley graben. This anomaly is attributed to a density contrast of 0.4–0.5 grams per cubic centimeter between the bedrock and fill and indicates a maximum thickness of about 4,000 feet of fill in the graben.

A general magnetic low occurs along the same trend as the main gravity low, from Climax southwest to the Twin Lakes stock of Tertiary porphyry. Magnetic highs and lows occur both over Precambrian granitic and gneissic rocks and over porphyry intrusives. The magnetic susceptibilities of these rocks have overlapping ranges; thus, many of the anomalies can be confidently interpreted only where the sources are exposed. Many magnetic highs correlate with topographic highs developed in crystalline rocks, but other highs are nearly independent of topography, and reflect strong magnetization of the rocks.

The Precambrian Homestake shear zone, which trends northeast in the northwestern part of the quadrangle, is expressed by a strong magnetic gradient that reflects magnetic biotite gneiss and migmatite within, and northwest of, the shear zone, and less magnetic amphibole and quartz gneiss southeast of the shear zone. The gradient indicates both continuity and location of the shear zone beneath areas covered by Paleozoic sedimentary rocks.

Magnetic and gravity highs are found over a fault block near Sheep Mountain and Round Hill, reflecting dense and magnetic rocks, possibly mafic intrusives, in the block. Gravity and magnetic lows are found in the southeastern part of the quadrangle, where Paleozoic rocks are several thousand feet thick.

Neither the Climax nor the Leadville mining district has a gravity or total-intensity-magnetic expression, but both are marked by weak residual magnetic lows, probably reflecting alteration of the crystalline rocks. Many of the mining districts are located near the axis of the main gravity low, and, thus, it may be postulated that mineralization arose from the apical region of the batholith at depth.

INTRODUCTION

The Leadville 30-minute quadrangle is in the most productive part of the Colorado mineral belt, a belt of Upper Cretaceous and Tertiary intrusive rocks and ore deposits that extends diagonally across the mountains of Colorado and contains most of the State's ore deposits (fig. 1). The intrusive rocks and ore deposits that characterize the belt generally have been regarded as manifestations of an underlying batholith (Crawford, 1924; Lovering and Goddard, 1938; Tweto, 1968a, p. 570–571). Location of the belt and presumably of the underlying batholith coincides

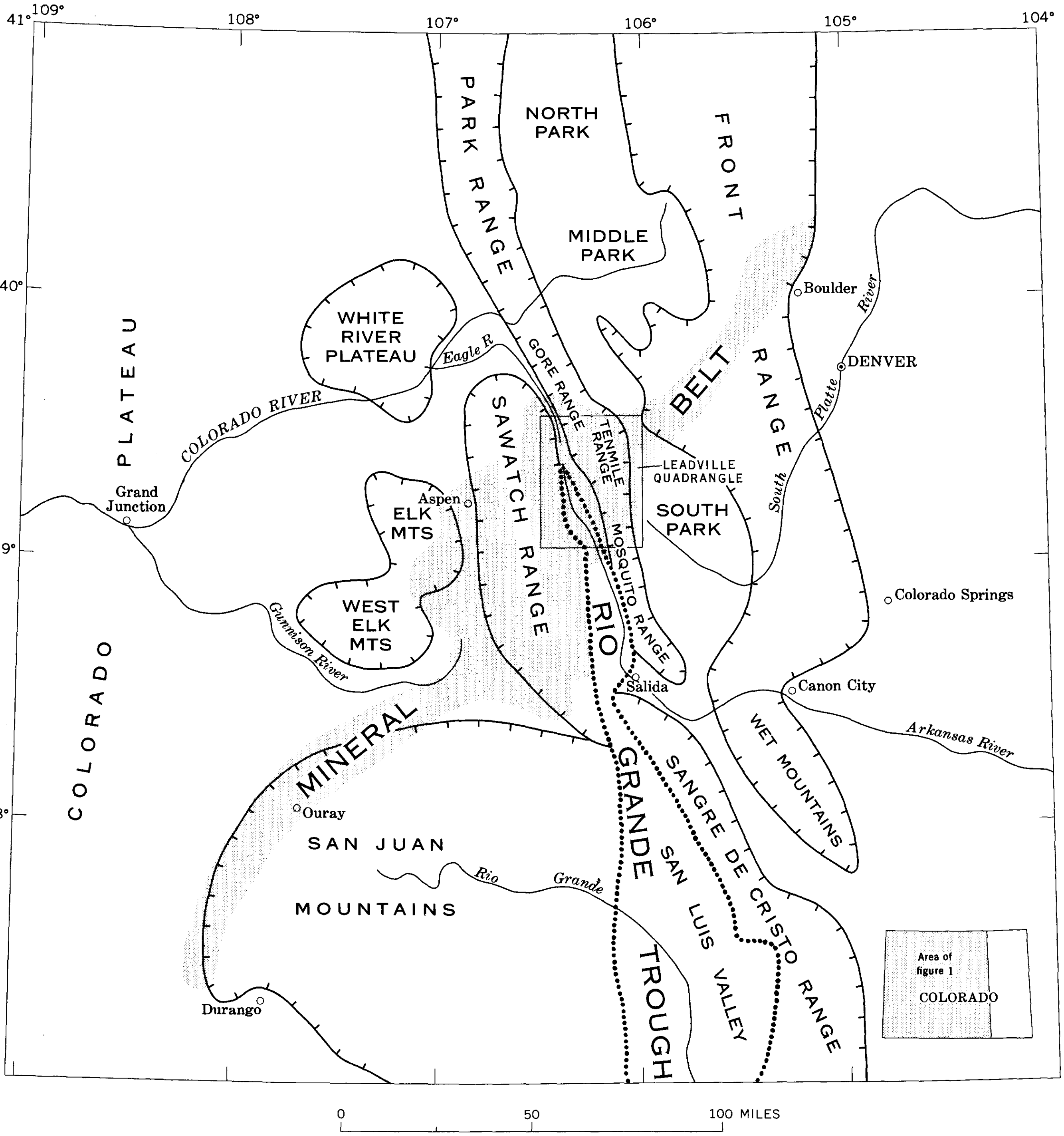

FIGURE 1. — Index map of central and western Colorado, showing location of the Leadville 30-minute quadrangle in relation to the Colorado mineral belt and the Rio Grande trough.

with a system of Precambrian shear zones in the basement rocks (Tweto and Sims, 1963). In the quadrangle the mineral belt intersects basin-and-range faults of the Rio Grande trough or graben system and widens abruptly, as compared with its northeastern part (fig. 1).

A program of gravity and magnetic surveys was begun in 1962 in this area of intersection and southward along the basin-and-range fault system of the upper Arkansas River valley. These geophysical studies were undertaken to complement and extend the geologic studies by defining more clearly the nature of the mineral belt in depth, and to serve as an aid in the geologic and economic appraisal of an areally significant segment of the belt that is buried beneath thick alluvial deposits of the downfaulted upper Arkansas River valley. This report on the Leadville 30-minute quadrangle presents the results of the geophysical surveys in the northern part of the area investigated.

The Leadville quadrangle is centered over the Mosquito-Tenmile Range, an element of the Park Range, in the heart of the mountain province in Colorado. (The Mosquito-Tenmile Range is a single range, but the part of it south of the Continental Divide is called the Mosquito Range, and the part north of the Divide is called the Tenmile Range.) In the northern part of the quadrangle, the Tenmile Range is overlapped on the west by the south end of the Gore Range, also an element of the Park Range (fig. 1). The western part of the quadrangle, west of the valleys of the Arkansas and Eagle Rivers, is in the Sawatch Range. The southeastern corner of the quadrangle is in South Park, and the northeastern corner is on the western toe of the Front Range.

The crests of both the Mosquito–Tenmile and the Sawatch Ranges are generally above 13,000 feet in elevation, and they include many peaks that exceed 14,000 feet. The intervening valleys of the Arkansas and Eagle Rivers are at elevations of 9,000–10,000 feet, as is South Park. Thus, most gravity observations were subject to large terrain corrections, and aeromagnetic flight lines, flown at a constant barometric elevation of 14,500 feet, varied greatly in height above the ground.

GEOLOGY

MAJOR FEATURES

Geologically, almost the entire area of the Leadville quadrangle is a part of the eastern flank of the huge Sawatch anticline. The Sawatch Range, which extends both west and south beyond the quadrangle (fig. 1), is carved in Precambrian rocks in the core of this anticline. The eastern flank of this crystalline-rock core is cut longitudinally by a major graben that constitutes the valley of the upper Arkansas River. The graben and valley, deeply filled with Tertiary deposits, extend far to the south of the quadrangle, and the graben continues southward through the San Luis Valley (fig. 1) to a continuation with the Rio Grande graben of New Mexico, a major arm of the basin-and-range structural province. The graben tapers to an end in the Leadville quadrangle, but the fault system along its east side continues northward beyond the quadrangle.

The upthrown block on the east side of the graben constitutes the Mosquito–Tenmile Range. This range consists of Precambrian rocks capped by Paleozoic sedimentary rocks. As part of the Sawatch anticline, the sedimentary rocks dip eastward into South Park, forming a homoclinal eastern flank of the Mosquito Range. South Park is a broad structural basin separating the Mosquito and Front Ranges.

Precambrian rocks occupy about half of the quadrangle area (pl. 1). In the other half, Paleozoic and younger sedimentary rocks, having a preserved thickness of as much as 10,000 feet, overlie the Precambrian rocks. Both the Precambrian and the sedimentary rocks are cut by many bodies of hypabyssal intrusive rocks of Late Cretaceous and Tertiary age and of granodioritic to granitic composition. Upper Tertiary alluvial deposits and Pleistocene glacial deposits occupy a large part of the upper Arkansas valley, and glacial deposits mantle many of the valley bottoms elsewhere in the quadrangle.

PRECAMBRIAN ROCKS

The Precambrian rocks are divided, for geophysical analysis, into metasedimentary gneisses and granitic rocks. The metasedimentary gneisses are largely biotite gneiss and migmatite, but in the northern part of the quadrangle they include hornblende gneiss, calc-silicate gneiss, and impure quartzites that are markedly less magnetic than the bordering biotite gneiss and migmatite. Most of the biotite gneiss is biotite-quartz-plagioclase gneiss, but sillimanite- and garnet-bearing varieties also are common. Gneisses of the Tenmile Range were described by Koschmann (1960) and by Bergendahl (1963). Those elsewhere in the quadrangle are generally similar to the gneisses in the Front Range, as described by Sims and Gable (1964, 1967).

The granitic rocks are of several varieties, but are principally the St. Kevin Granite in the west-central part of the area, the Denny Creek Granodiorite Gneiss in the southern part, and the Silver Plume Granite in the northeastern part. The St. Kevin Granite consists of at least five distinct textural and compositional varieties (Tweto and Pearson, 1964), but most of it is an even-grained to markedly porphyritic granitic rock that compositionally is near the borderline between granite and quartz monzonite. It is characterized by the presence of muscovite, in addition to biotite. Other varieties range from this composition to one near the borderline between quartz monzonite and granodiorite. The Denny Creek Granodiorite Gneiss (Barker and Brock, 1965) ranges in composition from biotite granodiorite to biotite-quartz diorite, and it generally contains some hornblende and unevenly distributed augen of microcline perthite. Silver Plume Granite, as applied in the Climax-Alma area (Butler and Vanderwilt, 1933; Singewald and Butler, 1941), is a porphyritic biotite-muscovite-quartz monzonite (Koschmann, 1960). The Denny Creek belongs to the group of older, syntectonic Precambrian granites of Colorado, exemplified by the Boulder Creek Granite of the Front Range, 1.7 b.y. (billion years) in age (Peterman and others, 1968). The St. Kevin and Silver Plume belong to a middle, late syntectonic–early posttectonic group, about 1.4 b.y. in age (Pearson and others, 1966).

SEDIMENTARY ROCKS

The pre-Tertiary sedimentary rocks are grouped in two units on the map. The lower unit consists of quartzites and dolomites that range in age from Cambrian through Mississippian (table 1). It is only 500–1,000 feet thick, but it is of prime interest economically because it contains the host rocks of major ore deposits, as at Leadville. The upper unit consists principally of sandstones, conglomerates, and shales of Pennsylvanian and Permian age and is as much as 10,000 feet thick. Near Breckenridge the lower unit is absent, and the upper unit consists only of a thin sequence of Pennsylvanian or Permian rocks and of overlying Mesozoic formations.

The contrast in the sedimentary sequence in the Breckenridge area as compared with that in the rest of the quadrangle reflects the effects of the late Paleozoic and early Mesozoic Front Range highland, an element of the so-called ancestral Rockies. Most of the Leadville quadrange is in the area of a basin of sedimentation on the southwest side of this highland. This area is characterized by a thick sequence of Pennsylvanian and Permian rocks constituting the Belden, Minturn, and Maroon Formations, as well as by the presence of pre-Pennsylvanian sedimentary rocks (table 1). The Breckenridge area, in contrast, was on the edge of the highland; consequently, the pre-Pennsylvanian rocks were stripped from it in Pennsylvanian time, and only a few hundred feet of the Maroon and Chinle Formations are preserved beneath the Morrison Formation there (Lovering, 1934; Singewald, 1951). As judged from the distribution of pre-Jurassic rocks, the boundary of the highland extended generally westward from the Breckenridge area to the vicinity of Copper Mountain (pl. 1), where it turned north-northwestward. Thus, only a few square miles in the northeast corner of the Leadville quadrangle was on the highland proper.

The Cenozoic sedimentary rocks, shown as a single unit on the map (pl. 1), consist at the surface of the upper Tertiary Dry Union Formation and extensive Pleistocene glacial deposits (Tweto, 1961). This unit reaches a geophysically significant thickness only in the Arkansas valley, although the glacial deposits are widespread. In the Arkansas valley, unexposed older Tertiary deposits may lie beneath the Dry Union Formation. The Dry Union, of Miocene and Pliocene age, is known—from surface exposures, mine shafts, and drill holes—to be at least 1,000 feet thick in the area just southwest of Leadville. Farther out in the Arkansas valley, the Tertiary sediments may be as much as 4,000 feet thick, as indicated by the geophysical data presented in this report. It is unlikely that all these strata belong to the Dry Union Formation. They may include equivalents of the Miocene Browns Canyon Formation of the Salida area (Van Alstine, 1969) and possibly even of the Oligocene Antero Formation of Stark and others (1949), which occurs on the east side of the Mosquito Range, in South Park (Stark and others, 1949; DeVoto, 1964).

Near-surface stratigraphy of the fill in the Arkansas valley is discussed in a following section on geology of the Arkansas valley bottom.

UPPER CRETACEOUS AND TERTIARY INTRUSIVE ROCKS

Intrusive igneous rocks of Late Cretaceous and Tertiary age occur in stocks, plugs, crudely laccolithic bodies, sills, and dikes. The sills and dikes number in the thousands, but owing to limitations of scale, only the largest among them are shown on the map (pl. 1). Most of the intrusive rocks are porphyritic, and rocks of the group as a whole are generally referred to as porphyries. Compositionally, the porphyries range from diorite to granite, but most of them are granodiorite or quartz monzonite. More than 50 different varieties of porphyry have been distinguished in the quadrangle.

Many of the porphyries fit into an empirical age sequence as determined from geologic relations (Tweto, 1960). Radiometric dating by the K–Ar (potassium-argon) method has established the presence of two main age groups among the porphyries — an early one that is Late Cretaceous and early Tertiary (Paleocene) in age (Pearson and others, 1962), and a later one that is middle Tertiary (Oligocene) in age (Tweto, 1968a; Wallace and others, 1968). A few radiometric dates corresponding to an Eocene age raise a question as to whether intrusion was fairly continuous from Late Cretaceous to the end of the Oligocene, or whether the intermediate age values reflect argon leakage from Late Cretaceous and Paleocene intrusives by heating during the Oligocene intrusive episode. This question is thus far

TABLE 1.—*Generalized geologic column, Leadville 30-minute quadrangle*

Era	Age	Unit	Thickness (feet)	Character and remarks	
Cenozoic	Quaternary	Alluvium, morainal deposits, and outwash gravels	0–500+		
	Tertiary	Dry Union Formation	0–2,000(?)	Loosely consolidated sandy silt, sand, and gravel. Miocene and Pliocene in age; may be underlain by unexposed older Tertiary units in Arkansas valley.	
		Intrusive igneous rocks		Porphyries of many varieties; mainly quartz monzonite, but range from granodiorite to granite in composition. Mainly of two general ages: (1) Late Cretaceous and early Tertiary and (2) Oligocene.	
Mesozoic	Cretaceous	Pierre Shale	Maximum of 500 ft preserved	Shale	Present only in area near Breckenridge.
		Niobrara Formation	350	Calcareous shale and limestone	
		Benton Shale	360	Shale	
		Dakota Sandstone	125–175	Sandstone, quartzite, and shale	
	Jurassic	Morrison Formation	200–300	Sandstone, shale, and limestone	
		Entrada Sandstone	20–50	Sandstone	
	Triassic	Chinle Formation	250–400	Siltstone	
Paleozoic	Permian and Pennsylvanian	Maroon Formation	1,000–4,500	Sandstone, grit, conglomerate, and shale.	
	Pennsylvanian	Minturn Formation	3,600–6,000	Grit, conglomerate, sandstone, limestone.	
		Belden Formation	0–1,200	Shale, sandstone, limestone.	
	Mississippian	Leadville Dolomite	0–210	Dolomite; Gilman Sandstone Member at base, 15–25 ft.	
	Devonian	Chaffee Formation	0–135	Dyer Dolomite Member at top, 0–80 ft; Parting Quartzite Member at base, 0–55 ft.	
	Ordovician	Harding Sandstone	0–40	Sandstone, quartzite, and shale.	
		Manitou Dolomite	0–150	Cherty dolomite.	
	Cambrian	Peerless Formation	0–100	Sandstone and dolomite.	
		Sawatch Quartzite	0–190	Quartzite.	
Precambrian		St. Kevin and Silver Plume Granites		Quartz monzonite and granite.	
		Denny Creek Granodiorite Gneiss and related rocks		Granodiorite and quartz diorite.	
		Metasedimentary gneisses		Biotite gneiss, migmatite, hornblende gneiss, calc-silicate gneiss, and impure quartzites.	

unresolved. Minor late intrusive activity, suggested by geologic relations to be late Tertiary, produced small rhyolite dikes and, at Leadville, rhyolitic explosion breccia pipes (Emmons and others, 1927).

Porphyries of the older group occur principally as widespread sills or subconcordant sheets in the sedimentary-rock terrane (pl. 1) and as a few small stocks. The earliest of all the porphyries, the Pando Porphyry (including the White and Mount Zion Porphyries of earlier usage), is the most widespread. It occurs throughout the length of the quadrangle as sills or sheets, some of which are more than 1,000 feet thick, and as a small stock just north of Leadville (Prospect Mountain stock, fig. 2). Other major porphyries that occur principally as sills are the Elk Mountain Porphyry of the Kokomo area, the

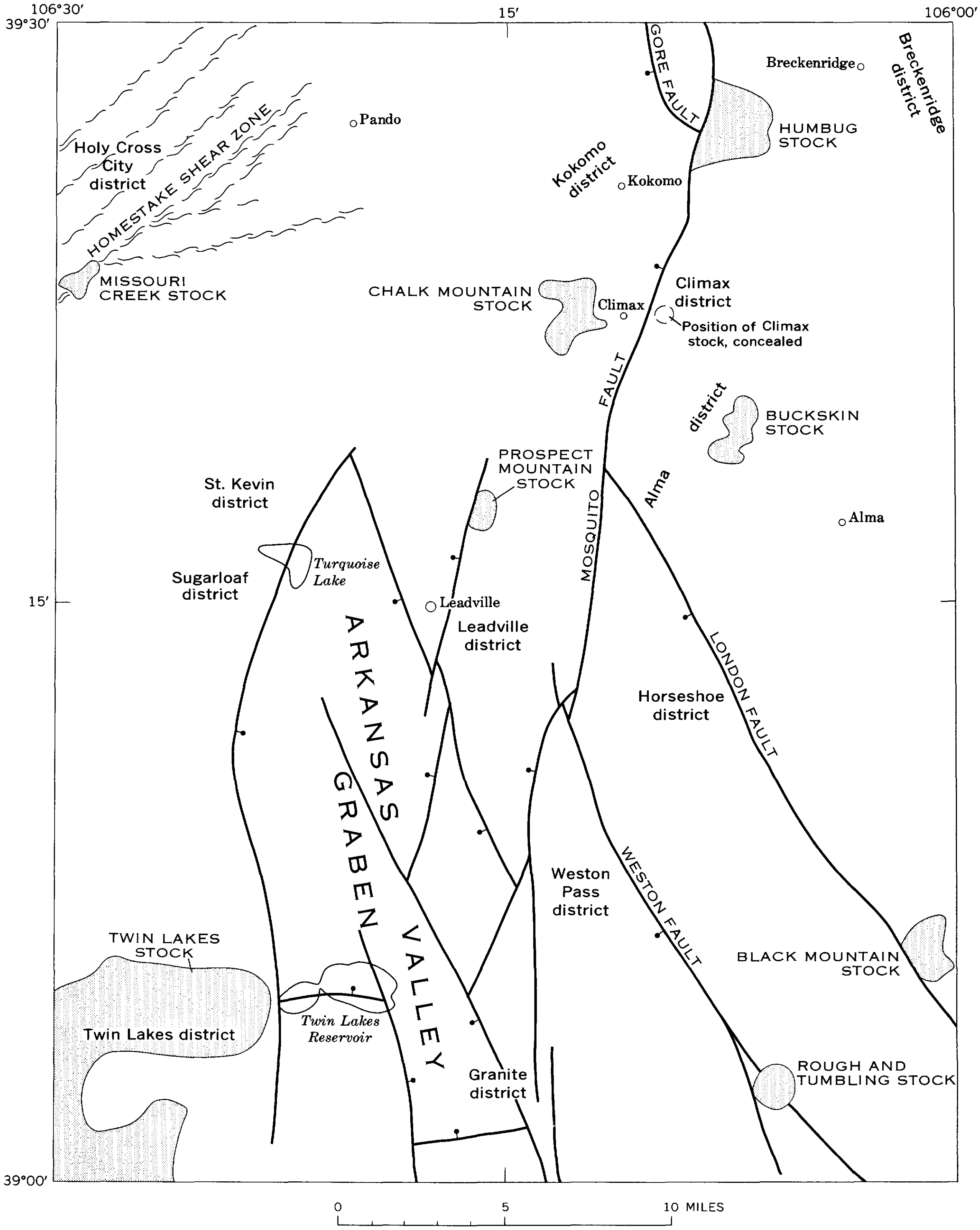

FIGURE 2. — Major structural features, stocks, and mining districts in the Leadville 30-minute quadrangle. Bar and ball symbol indicates downthrown side of fault.

Lincoln and Sacramento Porphyries of the areas north and east of Leadville, the Evans Gulch and Johnson Gulch Porphyries of the Leadville district, and the various unnamed porphyries in the Alma and Breckenridge districts. Chemically, all these porphyries are near the borderline between granodiorite and quartz monzonite, although the Pando Porphyry is abnormally siliceous (72 percent SiO_2) for such a composition. The composite Buckskin stock, west of Alma, has been shown by Singewald (1932) and by Kuntz (1968) to consist of successively intruded quartz diorite, granodiorite, and quartz monzonite inferred to have been derived from a quartz diorite body at depth. The quartz monzonite facies was correlated with the Lincoln Porphyry by Singewald (1932).

If the porphyries that have yielded intermediate or Eocene K–Ar ages are, in reality, older, as noted in the preceding paragraphs, then the older group of porphyries also includes the two largest stocks in the quadrangle — the Twin Lakes stock and the Humbug (or Bald Mountain) stock (fig. 2). The Twin Lakes stock, only part of which lies within the quadrangle, consists of coarsely porphyritic granodiorite (Wilshire, 1969) that chemically resembles the Pando Porphyry in its high content of SiO_2 and low content of Fe_2O_3, FeO, MgO, and CaO. The Twin Lakes stock is cut by fine-grained white dikes that closely resemble the Pando. Biotite from the granodiorite porphyry has been dated as 41.7±1.2 m.y. (million years) in age by the K–Ar method, and 49.7±4.5 m.y. by the Rb–Sr (rubidium-strontium) method (Obradovich and others, 1969), and also as 56±10 m.y. by the Rb–Sr method (Moorbath and others, 1967).

The Humbug stock occupies an area of 4–5 square miles on the western slope of the Tenmile Range, about 5 miles north of Climax. The rock of the stock has been described as quartz monzonite by Crawford (1924) and Bergendahl (1963). Four K–Ar age determinations made for the Climax Molybdenum Co. (V. E. Surface, written commun., 1970) yielded disparate results ranging from 35 to 47 m.y. If the stock is older than the Lincoln Porphyry, as indicated by Bergendahl (1963, p. 15 and map), its true age should exceed 64 m.y. (Pearson and others, 1962).

Porphyries of middle Tertiary age occur mainly in crosscutting bodies, such as stocks, plugs, and dikes, but also in a few domed sills of limited extent. Most notable of these younger intrusives is the Climax stock, to which the great Climax molybdenum deposit is genetically related (Wallace and others, 1968). The stock is not exposed at the surface, but it is known from subsurface exploration to be about 3,000 feet in diameter and to be a sodic granite in composition. Several K–Ar determinations indicate that its age is about 30 m.y. (Wallace and others, 1968). Rhyolite or nevadite porphyry of the Chalk Mountain stock, just west of Climax, has a K–Ar age of 27±1.9 m.y., and a plug of rhyolite porphyry a few miles to the north has been dated as 35.2±1.4 m.y. in age (V. E. Surface, written commun., 1970). Other intrusive bodies assigned to this age group are (1) numerous dikes of "late white porphyry" in the Mosquito Range east of Climax (Singewald and Butler, 1941, pl. 1) and east of Leadville (Behre, 1953, pl. 1); (2) late leucocratic porphyries in the intrusive complex in the eastern part of the Leadville district (Tweto, 1968b, p. 700); (3) a rhyolitic breccia plug near the head of Lake Fork, in the Sawatch Range; and (4), tentatively, two rhyolite porphyry stocks near the southeast corner of the quadrangle, in South Park. Possibly also of this age, but more likely of younger age still, are rhyolitic dikes and a small elongate plug along a north-trending fault on the lower slopes of the Sawatch Range northwest of Leadville.

The change with time from granodioritic to granitic or rhyolitic compositions among the exposed porphyries suggests progressive differentiation of the underlying source batholith, and this implies that the batholith itself is compositionally zoned. Its upper part may approximate granite in composition, and the composition probably changes progressively downward to quartz diorite or diorite at a depth of a few miles. Evidence of a composition as mafic as diorite is seen in the early quartz diorite facies of the Buckskin stock, and in scattered dikes and small plugs and sills of diorite as mafic as augite diorite. For purposes of geophysical computations in later sections of the report, the average composition of the batholith is assumed to be that of the early porphyries — that is, granodiorite near quartz monzonite.

TERTIARY VOLCANIC ROCKS

Near the southeast corner of the quadrangle, Tertiary volcanic rocks cover an area of about 1 square mile (pl. 1). These rocks are a part of a small volcanic field at Buffalo Peaks on the crest of the Mosquito Range, ½–1 mile south of the quadrangle. The volcanic rocks, described by S. F. Emmons (in Cross, 1883), consist of hypersthene andesite, hornblende andesite, tuffs, and breccias that have an aggregate thickness of as much as 1,500 feet. They lie horizontally on tilted Paleozoic rocks and on Precambrian granite. The volcanic rocks apparently cover strands of the Weston fault (pl. 1; also Gould, 1935), but the distribution of the hypersthene andesite, as compared with the other volcanic rocks described by Emmons, would permit a major fault through the volcanics. No direct data on the age of the volcanics — within the Tertiary — are available. The rocks are tentatively classed as outliers of the extensive Thirtynine Mile volcanic field of southern South Park, which is Oligocene in age (Epis and Chapin, 1968).

STRUCTURE

PRECAMBRIAN HOMESTAKE SHEAR ZONE

Aside from an intricate fold structure in the metasedimentary gneisses, not considered in this report, the principal Precambrian structural feature in the quadrangle is the Homestake shear zone (fig. 2). This master shear zone, which has a pronounced magnetic expression, consists of many individual shear zones of northeast trend in a belt 7–8 miles wide. The individual shear zones range in width from a few feet to several hundred feet. Collectively, the shear zones are characterized by a wide variety of cataclastic rocks, ranging from completely recrystallized biotite gneisses through phyllonites, blastomylonites, pseudotachylyte, and mylonites to gouge (Tweto and Sims, 1963). Some of the individual shear zones contain scattered small lenses of hornblendite, and the master shear zone is bordered on the southeast by a swarm of metalamprophyre dikes. The Homestake shear zone disappears beneath Paleozoic sedimentary rocks east of the Eagle River, but elements of it reappear in the Precambrian rocks of the Gore Range, north of the Leadville quadrangle (Tweto and others, 1970).

LARAMIDE AND YOUNGER STRUCTURE

Structural features considered in this report are principally the faults. The sedimentary rocks are folded only locally, near faults, and have a regional easterly dip (pl. 1, sections *A–A′* and *B–B′*) that reflects the location of the quadrangle on the eastern flank of the huge Sawatch anticline.

A complex system of faults, only the largest of which are shown on plate 1, characterizes the Mosquito Range and both sides of the Arkansas valley. Many of these faults originated during the Laramide orogeny, but they were reactivated later to serve as elements of the basin-and-range fault system. Some, however, seem to be principally Laramide, and some may be principally basin-and-range in time of major movement.

The master fault along the west side of the Mosquito–Tenmile Range, from Iowa Gulch northward to the quadrangle boundary and beyond, is the Mosquito fault. This is an early Laramide west-dipping normal fault that was in existence before intrusion of the porphyries. A concentration of intrusive rocks in a belt along the fault, particularly on its west side, suggests that it was a conduit at depth for porphyry magmas (Tweto, 1968a, b). Near the north boundary of the quadrangle, the fault shows indications of Precambrian ancestry (Tweto and Sims, 1963), as does the intersecting Gore fault (fig. 2), but no indications of this early history are known farther south.

Near Leadville, total vertical displacement on the Mosquito fault and on the many subsidiary faults to the west of it is about 12,000 feet. Near Climax, the displacement may be as much as 14,000 feet (pl. 1, section *A–A′*). Of this amount, a significant part is post-Laramide. On the basis of one interpretation of faulted ore bodies, Wallace and others (1968) estimated that 9,000 feet of displacement has occurred on the main strand of the Mosquito fault since the mineralization stage in Oligocene time. Alternative interpretations might be made, but they would still indicate a post-Laramide displacement of at least a few thousand feet. Two miles south of Climax, slices of the Dry Union Formation (too small to be shown on pl. 1) occur in the Mosquito fault zone, indicating that much of the late displacement was Pliocene or younger. These slices are at an elevation of 11,900 feet, nearly 2,000 feet higher than the Dry Union of the Arkansas valley; thus, they also indicate extensive displacement on subsidiary faults between the Mosquito fault and the valley, as do faults at Leadville (Tweto, 1968b).

Near Iowa Gulch the north-northeast-trending Mosquito fault intersects the north-northwest-trending Weston fault. The main line of Laramide displacement extends south-southeastward along the Weston fault from this locality, and the line of younger fault displacement, possibly following Laramide faults, continues southward along the Mosquito fault trend to a connection with the border faults of the Arkansas valley (pl. 1). The Weston fault, a steep reverse or vertical fault, has a displacement of about 4,000 feet, with the east side upthrown (pl. 1, section *B–B′*). The displacement decreases south of Weston Pass, where the fault crosses the present drainage divide of the Mosquito Range. At the south edge of the quadrangle, the fault is in several strands that have displacements only in the hundreds of feet, and some of these fault strands are evidently covered by the Oligocene(?) volcanic rocks of Buffalo Peaks.

The principal fault on the east side of the Mosquito Range is the London fault. From an intersection with the Mosquito fault, northeast of Leadville (pl. 1; fig. 2), this fault extends south-southeastward for many miles into South Park. The London is an eastward-dipping reverse fault that has a displacement of about 3,000 feet (pl. 1, section *B–B′*).

The Mosquito, London, and Weston faults all have had stocks intruded along them (fig. 2), and their relations to the oldest porphyries indicate that they existed before porphyry intrusion began. Many of the faults subsidiary to these main faults, as at Leadville, are somewhat younger, having formed during the period of intrusion of the early porphyries (Tweto, 1960, 1968b). Many of these subsidiary faults, particularly those of near northward trend, and the Mosquito fault evidently underwent repeated movements in later time, in conjunction with the sinking of the Arkansas valley graben. Major movement on them occurred in Miocene or earlier time, forming one flank of the structural valley in which the Dry Union and possibly older formations accumulated. Still later movements displaced the Dry Union Formation and even the glacial deposits (Tweto, 1961).

Evidence of such a history on the west side of the graben is not as clear because rocks younger than Precambrian are virtually absent. However, one of the north-trending faults characteristic of the slope of the Sawatch Range contains dikes that indicate a generally similar history. This fault, which extends from Sugarloaf Mountain to West Tennessee Creek (pl. 1), contains local dikes of two or three different porphyries, all of which are crushed and altered, indicating movement on the fault since their emplacement. One of the porphyries is the Lincoln Porphyry, which indicates that the fault is at least as old as the early porphyries. An irregular dike of undeformed rhyolite also follows the fault. This dike is characterized by wide chill zones of flow-banded vitrophyre, suggesting that it was emplaced close to the present surface and, hence, that it is very young.

GEOLOGY OF THE ARKANSAS VALLEY BOTTOM

The Arkansas valley has a graben structure (fig. 2) that constitutes the northern tip of the great Rio Grande–San Luis Valley graben system of New Mexico and southern Colorado (fig. 1). Near the south edge of the Leadville quadrangle, a local high block of Precambrian rocks forms a ridge across the bottom of the graben, thus creating a subbasin that extends from the ridge northward to the tip of the graben, about 3 miles northwest of Leadville. This basin is deeply filled with sediments of the Dry Union Formation and mantling glacial deposits. Similar deposits fill the valley south of the constricting ridge, which extends for about 1 mile south of the quadrangle boundary.

The geology of the valley bottom is of special concern because the bedrock along a 12-mile-long axial segment of the mineral belt is buried beneath the thick fill. The fact that the Leadville and Sugarloaf–St. Kevin mineralized areas are directly across the valley from each other (fig. 2) and extend to the edge of the valley fill suggests that some potential for mineralization exists beneath at least that part of the valley. Geology of the valley bottom is discussed here in somewhat greater detail than for other areas or geologic units because of its pertinence to any physical or geophysical exploration that might be undertaken in this covered area.

Most of the fill in the valley consists of the Dry Union Formation plus whatever unexposed older Tertiary units may be present beneath it. The Dry Union (Tweto, 1961) is varied in character, but its principal component is brown sandy silt, or pebbly silt, which occurs in structureless layers 5–50 feet thick. Lenses and beds of coarse sand and gravel are scattered among the silt beds, and some of these are cemented to a tough sandstone or conglomerate by the calcium carbonate of old caliche zones. Across most of the width of the valley, the Dry Union consists of assorted materials derived, in part at least, from the Mosquito Range; only in a narrow zone along the west side of the valley does it consist exclusively of materials derived from the Precambrian rocks of the Sawatch Range. Wherever seen in outcrop, the Dry Union dips westward. Even as far west as the slope north of the western, or upper, lake of Twin Lakes Reservoir, less than a mile from the western border fault of the valley, the Dry Union dips 9° W.

After extensive fault movements that placed Dry Union against bedrock in many places (Tweto, 1961) and, also, after deep stream dissection of the Dry Union, extensive parts of the valley were covered by an ancient till (till No. 1). Except in the vicinity of Twin Lakes, where it contains abundant volcanic rocks derived from the Sawatch Range near the head of Lake Creek, this till is characterized by the presence of quartzite, phenocrystic quartz crystals from porphyries, and other resistant materials derived from the east side of the valley. The till is also characterized in most places by a thick, intensely weathered zone at its top that consists of tough reddish-brown gumbo.

After deposition of the No. 1 till, extensive pediments formed on the sides of the valley, cut on till No. 1 and the Dry Union Formation. These pediments have subsequently been displaced by faults, giving an impression of terrace remnants at various levels. After some dissection of the pediments, an extensive glacial advance produced till No. 2 in massive moraines, and also a very extensive blanket of outwash gravel. This gravel, called the Malta Gravel (Tweto, 1961), is more than 300 feet thick in the Leadville area, where it fills old valleys and caps the earlier, somewhat eroded pediments. The gravel also formed a thick blanket over the bottom of the Arkansas valley westward to the slopes of the Sawatch Range. Large parts of the present valley bottom from the mouth of the East Fork Arkansas River southward are floored on this gravel.

After an erosion interval during which till No. 2 and the Malta Gravel were weathered and dissected and were also displaced by fault movements, successive glacial advances produced tills No. 3, 4, 5, 6, and 7. Stratigraphic relations of these tills are evident from the positions of various moraines but are best shown in test holes drilled by the U.S. Bureau of Reclamation in the Turquoise Lake and Twin Lakes areas. Test holes 500 feet deep on the large moraine enclosing Turquoise Lake showed as many as four superposed tills to a depth of 380 feet, below which is the Dry Union Formation. Each till is marked by a weathered and stained top. In places in the Twin Lakes area, black soils are present at the tops of some weathered zones. In this same area, tills Nos. 4 and 5 are separated by as much as 225 feet of lacustrine ashy silts and sands and blue clay, indicating both a pronounced break in glacial deposition—presumably, the break between the Bull Lake and Pinedale Glaciations—and, possibly, the occurrence of local volcanism at that time.

Data on depth and configuration of the bedrock surface beneath the valley fill are scant, except along the borders of the valley bottom. In the area just west and southwest of Leadville, scattered shafts and drill holes and a single small outcrop of Leadville Dolomite at the pediment surface (pl. 1) indicate that the depth to bedrock ranges from zero to more than 600 feet, and that the bedrock surface is extensively faulted. No information is available on the depth or character of the bedrock in the area from the edge of the pediment on the east side of the valley westward to Lake Fork and Turquoise Lake, except that the depth probably considerably exceeds 500 feet. "Bedrock" was reported by the drillers at average depths of 40–60 feet in 88 churn-drilled placer test holes bored in this area in 1946–47, but it was interpreted at the time by Tweto as probably being hard layers in what is now known as the Dry Union Formation. Partly on the basis of the reported bedrock, refraction seismic data obtained by the U.S. Bureau of Reclamation (Conwell, 1950) were interpreted to indicate bedrock at depths of 25–35 feet beneath the valley bottom due west of Leadville, as *P*-wave velocities of 7,000–8,000 feet per second were obtained for a layer at this depth. Subsequent drilling by the U.S. Bureau of Reclamation has proved that the placer and seismic "bedrock" is the gumbo at the top of till No. 1. The drilling also established that various other seismically refractive layers in the moraine area at Turquoise Lake, distinguished by *P*-wave velocities of as much as 10,500 feet per second, are till sheets with weathered tops.

Detailed gravity, magnetic, and seismic surveys made in 1969 by Earth Sciences, Inc., of Golden, Colo. (Duane Bloom, written commun., 1970), indicated faults in the bedrock and (or) overlying materials in the part of the valley discussed in the preceding paragraph. These data support the inferred north-northwest-trending faults that pass just west and east of Malta (pl. 1).

At Lake Fork just below Turquoise Lake, several drill holes proved that the Malta Gravel, till No. 1, and the Dry Union Formation are faulted against Precambrian rocks along the main western border fault of the Arkansas valley. The fault there is complex and consists of at least three or four strands in a zone a few hundred feet wide. A mile to the south, a vertical drill hole penetrated outwash gravel that is tentatively correlated with till No. 3 and bottomed in a gouge zone 40 feet thick in shattered Precambrian rocks. A few hundred feet southwest of this locality, a ditchbank exposure at the foot of the slope of the Sawatch Range shows the Malta Gravel to be in fault contact with Precambrian rocks.

Refraction seismic investigations, largely experimental, were made by the U.S. Geological Survey in 1941–42 in the area between Leadville and the mouth of Iowa Gulch.[1] Many of the interpretations of subsurface geology based on the seismic survey were questionable even at that time (J. H. Swartz, oral commun., 1942), and, viewed in light of the subsequent drilling and seismic work at Turquoise Lake, they are now even more questionable. However, the survey did show a high-velocity refracting surface (12,500–15,800 feet per second) at a depth of about 1,300 feet near the mouth of Iowa Gulch that probably represents bedrock, presumably either Precambrian rock or lower Paleozoic quartzites and dolomites. The data also showed abrupt changes of as much as 750 feet in the level of this surface, suggesting fault scarps or deep, steep-sided canyons in the bedrock surface.

[1]Swartz, J. H., Farnham, F. C., Scharon, J. L., and Raspet, R., 1943, Report of a geophysical survey of proposed drainage-tunnel routes in the Leadville mining district, Colorado: U.S. Bur. Mines unpub. report, 18 p.

Test holes drilled by the U.S. Bureau of Reclamation near the Twin Lakes Reservoir established a complex fault pattern in the bedrock and valley fill in that area. Although a canyon topography in the bedrock surface cannot be precluded completely, the drill-hole data strongly suggest that the fill is deeply downfaulted against Precambrian rocks east and south of the lakes. Within the area of deep fill is at least one elevated block of Precambrian rocks, beneath the eastern part of the eastern lake. Granite is exposed at the surface in a small area along the north shore of the lake (pl. 1), but drill holes a few hundred feet to the west and north bottomed in the Dry Union Formation at depths of as much as 150 feet. A drill hole on the east shore of the lake reached Precambrian bedrock at a depth of 271 feet. Possibly, this locality is part of the block that crops out at the north edge of the lake. Half a mile north of this hole, however, and half a mile east of the granite outcrop, a 503-foot hole bottomed in till No. 1 (or possibly an even earlier till). This till, which was continuous from a depth of 75 feet to the bottom of the bore hole at 503 feet, seems to be in a block bounded by Precambrian bedrock on one side and by the Dry Union Formation on the other. The block is interpreted as a fault block, although it conceivably could be a prism of fill in a steep-walled canyon. The ridge that is about 500 feet high on the north side of the Twin Lakes Reservoir has long been classed as a huge moraine (Westgate, 1905; Capps, 1909; Ray, 1940). In reality, however, it is a valley wall cut in the Dry Union Formation. This valley wall is only thinly mantled by moraines, as shown by both surface exposures and drill holes. Large areas of the valley wall have been modified by intraglacial and postglacial landslides.

ORE DEPOSITS

The Leadville 30-minute quadrangle is in the heart of the most productive part of the Colorado mineral belt, and all parts of it, except the southeast corner, show evidence of mineralization to some degree. Productive areas constituting generally recognized but vaguely defined mining "districts" are indicated in figure 2. Somewhat mineralized areas between these districts, as well as the numerous districts themselves, constitute a large and promising hunting ground for exploration targets of the future. Most of the districts have been described in detail in various reports that are referred to in the following brief outlines.

Climax district. — The Climax district, or molybdenum deposit, occupying an area of no more than 1 square mile, is the premier district of the quadrangle in terms of production and of known production potential. Total value of molybdenum produced from the district through 1969 probably exceeded $1.5 billion; in addition, significant amounts of byproduct tungsten and pyrite and a small amount of tin were produced. The Climax deposit (described by Wallace and others, 1968) is in Precambrian rocks above a small stock of sodic granite, of Oligocene age, in the footwall of the Mosquito fault. The ore is in stockworks in silicified and feldspathized rocks in three overlapping dome-shaped ore bodies related to three phases of intrusion of the underlying Climax stock (Wallace and others, 1968).

Leadville district. — Prior to the period of great productivity at Climax, which began in 1940, Leadville was the leading district in the quadrangle and, indeed, the most productive mining district in Colorado. Production from the district from 1859 through 1963 was about $512 million (as valued at time of production) in silver, zinc, lead, gold, copper, and various minor metals (Tweto, 1968b). Mining operations in the district closed in 1957, but in 1969 development work in preparation for relatively large scale operations was started in the eastern part of the district. Ore bodies at Leadville are mainly replacement bodies in the pre-Pennsylvanian dolomites (table 1), but some are in veins and in minor stockworks. The sedimentary rocks are complexly intruded by porphyries and broken by numerous faults, many of which had both preore and postore movement. The district was described by Emmons (1886), by Emmons, Irving, and Loughlin (1927), and by Tweto (1968b). Bordering areas to the east and south were described by Behre (1953).

Breckenridge district. — The Breckenridge district has produced about $35 million in gold, zinc, lead, and silver; nearly half of the total was in placer gold. The lode deposits are principally veins in Cretaceous rocks (table 1) and in porphyries that intrude these rocks. The district was described by Ransome (1911) and by Lovering (1934), and the area to the south of the district was described by Singewald (1951).

Kokomo district. — The Kokomo district has produced about $25 million in lead, zinc, and silver. The ore deposits are principally replacement deposits in limestone beds in the Minturn Formation, but a few are in veins. The districts also has some low-grade molybdenum deposits — thus far unexploited — in porphyry. Geology and ore deposits of the district were described by Koschmann and Wells (1946) and by Bergendahl and Koschmann (1971).

Holy Cross City district. — The Holy Cross City mining district is a small district characterized by small gold-bearing feldspathic veins that cut Precambrian rocks. Production probably has not exceeded $1 million (Ogden Tweto and R. C. Pearson, unpub. data).

Alma district. — The ore deposits of the Alma district (Singewald and Butler, 1941; Singewald, 1947) are scattered over a wide area on the eastern slope of the Mosquito Range, opposite the Climax and Leadville districts, but 70 percent of the lode-mineral production has come from a small area along the London fault. Total production from the district is approximately $45 million, of which $35 million was in gold, silver, and lead from lode deposits and about $10 million in placer gold (including placer production from downstream, in South Park). The principal deposits are veins in porphyries and Paleozoic sedimentary rocks, but significant production was also made from replacement deposits in the sedimentary rocks. Placer and minor lode deposits in the area east of Alma were described by Singewald (1942, 1950).

Horseshoe district. — The Horseshoe district (Singewald and Butler, 1941) has produced silver, lead, and zinc ores from vein and replacement deposits in the Paleozoic dolomites. Total production is variously estimated to be $2–$5 million. The district was being actively explored in 1969.

St. Kevin and Sugarloaf districts. — The St. Kevin and Sugarloaf districts, west of Leadville, are credited with a production of $10–$15 million, primarily in silver, from veins in Precambrian rocks. The ore deposits were described by Singewald (1955) and the geology was mapped in detail by Tweto and Pearson (1958).

Weston Pass district. — The Weston Pass district (Behre, 1932) is a minor district that has produced silver, lead, and zinc with an estimated value of about $125,000 from replacement deposits in the Leadville Dolomite.

Granite district. — The Granite district, thus far not studied in detail, has produced somewhat over $1 million from gold placer deposits west of the town of Granite, and probably less than $1 million in precious-metal ores from veins in the Precambrian rocks east of the town.

Twin Lakes district. — Widely scattered mines in the valley of Lake Creek, constituting the Twin Lakes district, have made a small output of gold-silver ores from veins in Precambrian rocks or in the granodiorite of the Twin Lakes stock. Low-grade molybdenum deposits in the part of the district just west of the quadrangle have not been mined. The ore deposits were briefly described by Howell (1919).

DENSITIES AND MAGNETIC PROPERTIES OF THE MAJOR ROCK UNITS

Densities and magnetic properties were measured on samples collected from some of the major rock units in the Leadville quadrangle and vicinity to aid interpretation of the geophysical maps. Sampling was not systematic, and the samples may not represent true values of all the geophysicially significant units; nonetheless, some useful information on the values of these properties was obtained for the crystalline rock units. Densities were measured by W. E. Huff and Lee Peck. Magnetic properties were measured by W. E. Huff; measurements were conducted by standard techniques, and the results are shown in figures 3 and 4.

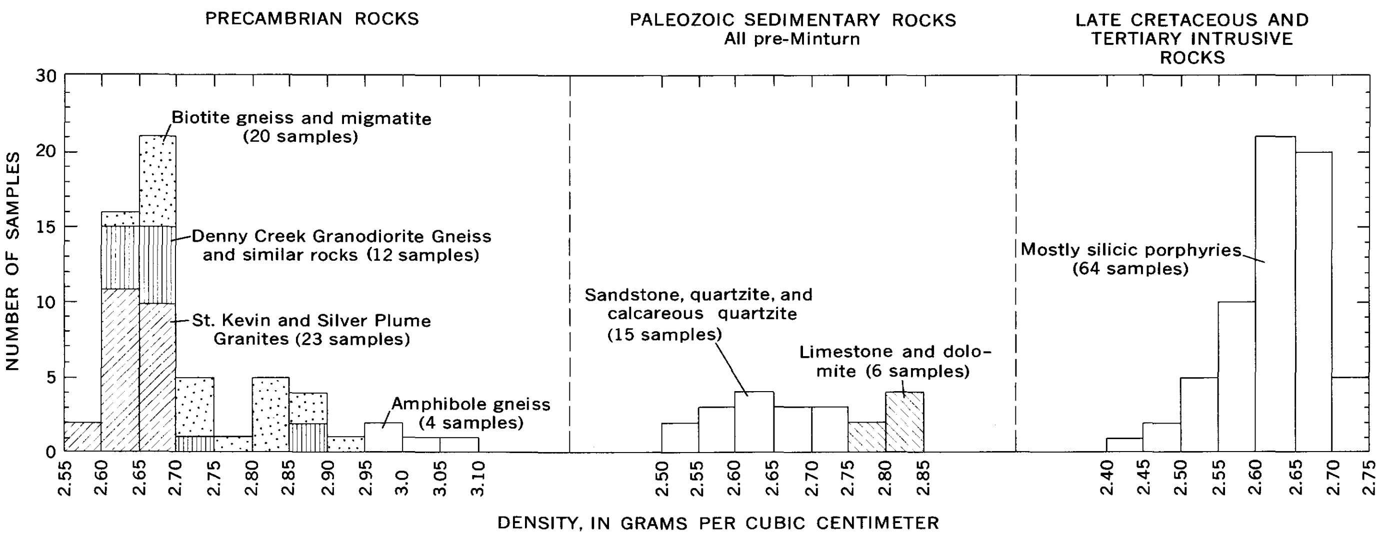

FIGURE 3. — Densities and total samples of major rock units.

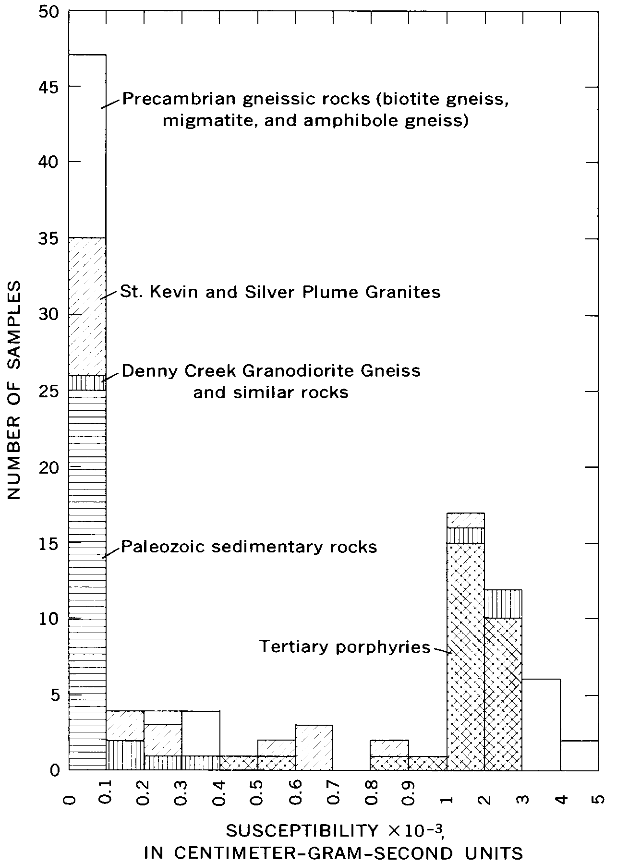

FIGURE 4. — Magnetic susceptibilities of rocks from the Leadville quadrangle and upper Arkansas River valley areas, Colorado.

The Precambrian granitic rocks are not subdivided on the geologic map (pl. 1), because of a lack of data for doing so in many places. However, the Denny Creek Granodiorite Gneiss and similar rocks differ significantly in both density and magnetic properties from the St. Kevin and Silver Plume Granites. Consequently, the Denny Creek and the St. Kevin and Silver Plume are treated separately in the discussions that follow. In general, the data for Denny Creek rocks will apply to the granitic rocks of the southern and south-central parts of the quadrangle, and the data for the St. Kevin and Silver Plume rocks will apply to the granitic rocks of the west-central and northeastern parts of the quadrangle.

DENSITIES

The Precambrian rocks consist of four major lithic units, each of a different density. The following tabulation lists average densities determined for each of these units and the estimated volume proportion of each in the Leadville quadrangle, from which a weighted average density of 2.76 g/cm³ (grams per cubic centimeter) is calculated for the Precambrian rocks of the quadrangle as a whole.

Rock	Number of samples	Average density (g/cm³)*	Estimated volume proportion (percent)	Fractional density product
St. Kevin and Silver Plume Granites	23	2.64	20	0.53
Denny Creek Granodiorite Gneiss	12	2.71	25	.68
Biotite gneiss and migmatite	20	2.75	40	1.10
Amphibole gneiss	4	3.00	15	.45
Weighted-average density	....	....	....	2.76

*g/cm³, grams per cubic centimeter.

Only four samples of amphibole gneiss were collected from the Leadville quadrangle, but an average density of 3.00 g/cm³ is nearly the same as, or slightly greater than, samples of similar rocks from the Front Range (Tooker, 1963, table 18; Sims and Gable, 1964, table 19). If the average density of the amphibole gneiss is 2.9, the weighted average density of all Precambrian rocks would be 2.74 g/cm³.

Densities of 15 samples of lower Paleozoic quartzites, sandstone, and calcareous sandstone average 2.63 g/cm³, and those of six samples of limestone and dolomite average 2.80 g/cm³. Inasmuch as these two general lithologies are about equally abundant in the lower part of the stratigraphic section, the weighted average density for the pre-Belden rocks, thus, is about 2.71 g/cm³. Although the number of samples measured is small, this value seems reasonable. Perhaps the point to be emphasized is that the density of this thin unit (500–1,000 ft.) is not greatly different from the average for the Precambrian rocks.

The clastic rocks of the Belden, Minturn, and Maroon Formations are quartzo-feldspathic sandstones and siltstones containing some shales. Densities of these rocks were not measured. The lithology is generally similar to that of the Cutler Formation of the Colorado Plateau, for which measured dry densities average 2.50 g/cm³ (Byerly and Joesting, 1959, p. 41).

Densities of the Upper Cretaceous and Tertiary porphyries present some uncertainties, primarily because completely fresh samples of many varieties are unobtainable. The weighted average density of porphyries in the Leadville quadrangle is about 2.62 g/cm³, as calculated from 53 samples shown in the following tabulation.

Porphyry body	Number of samples	Average density (g/cm³)*	Estimated volume proportion (percent)	Fractional density product
Pando Porphyry	4	2.61	20	0.52
Lincoln Porphyry	9	2.61	18	.47
Sacramento Porphyry	3	2.63	8	.21
Elk Mountain Porphyry	5	2.57	7	.18
Johnson Gulch Porphyry	2	2.59	7	.18
Twin Lakes stock	10	2.65	15	.40
Humbug stock	5	2.64	5	.13
Breckenridge-Alma area	5	2.67	10	.27
All others	10	2.63	10	.26
Weighted-average density	..	....	....	2.62

*g/cm³, grams per cubic centimeter.

The average density of 64 porphyry samples from 37 localities elsewhere in the Arkansas valley region is 2.64 g/cm³. Most of these samples are from the Mount Princeton batholith, which represents the largest exposed sample of the batholith presumed to underlie the mineral belt. Perhaps an average density of 2.63 g/cm³ is reasonable for the porphyries of the region.

Little information is available on densities of the Dry Union Formation and of glacial deposits. A sample of typical sandy silt from the Dry Union in drill core had a dry density of 1.81. Another sample from the same core, but containing abundant fragments of Pando Porphyry, had a density of 2.02. As reported by Birch, Schairer, and Spicer (1942, tables 2–6), sandy silts from the Fort Union Formation range in density from 1.81 to 2.15 g/cm³, and sandstones of the Fort Union range from 2.14 to 2.59 in saturated bulk density. Pakiser, Kane, and Jackson (1964, p. 23–24) assumed an average density of 2.2 to 2.3 g/cm³ for Cenozoic deposits in the Owens Valley, Calif., region. A mean density of 2.3 g/cm³ was assumed for 7,000–8,000 feet of beds in the Rio Grande trough near Albuquerque, N. Mex., by Joesting, Case, and Cordell (1961). Perhaps a mean saturated density of 2.2 g/cm³ is reasonable for the Dry Union Formation. As judged from limited seismic data, the older glacial deposits may have similar densities; however, in most places the glacial deposits are too thin to influence the gravity interpretations.

To summarize, the weighted average density of the Precambrian rocks is about 2.75 g/cm³, although the St. Kevin and Silver Plume Granites average only about 2.64 g/cm³. The average density of the porphyries is about 2.63 g/cm³, making a density contrast of about 0.12 g/cm³ between average Precambrian rocks and the Cretaceous and Tertiary porphyries. The older sedimentary rocks have average densities very near those of the Precambrian rocks, and the thick upper Paleozoic rocks have assumed densities of about 2.50 g/cm³. The Dry Union Formation is estimated to have a saturated density of 2.2 g/cm³, making a density contrast of −0.4 to −0.5 g/cm³ with the adjacent crystalline rocks along the Arkansas valley.

MAGNETIC PROPERTIES

Numerous samples of the Precambrian rock units and of the porphyries were collected for measurement of induced and remanent magnetization. Such measurements provide merely a rough idea of the magnetization of a given rock unit. Where good exposures of the rock units are available, their expression on the magnetic map is a better indication of combined magnetic properties. These properties can then be used as a guide for interpreting anomalies from buried sources. From analysis of the magnetic map and from laboratory measurements, the three major magnetic units — Precambrian granitic rocks, Precambrian metamorphic rocks, and the porphyries — have a wide range of magnetization. Some of them are virtually nonmagnetic, and others are very magnetic. Sedimentary rocks of the region are effectively nonmagnetic.

Influence of surficial weathering on the magnetic properties of rock units should be kept in mind in evaluation of the magnetic data presented in figure 4. Magnetite, the commonest accessory magnetic mineral in crystalline rocks, is readily oxidized to such iron oxides as hematite, limonite, or goethite, which are only weakly magnetic. The rock samples collected were of varying degrees of freshness, so the measured magnetic susceptibilities collectively are probably lower than in rocks at depth, and some may be abnormally low because of surficial weathering. This may account for the peak of susceptibility values below 0.1×10^{-3} cgs (centimeter-gram-second) units shown on the histogram (fig. 4). Another major cause of low susceptibility is deuteric or hydrothermal alteration of rock samples in which magnetite may be converted to weakly magnetic iron minerals. This significant effect can be observed in samples collected from altered and mineralized zones.

From the combined analysis of the aeromagnetic map and the laboratory determinations, the following generalizations can be made: (1) rocks whose susceptibility is less than 1.0×10^{-3} cgs units are nonmagnetic to weakly magnetic; (2) rocks whose susceptibilities range from 1.0 to 3.0×10^{-3} cgs units are moderately magnetic and cause anomalies of a few tens of gammas to several hundred gammas; and (3) rocks whose susceptibilities are greater than 3.0×10^{-3} cgs units are moderately to strongly magnetic and cause anomalies of several hundred

TABLE 2. — *Summary of magnetic properties of the major rock units*

[cgs units, centimeter-gram-second units]

Rock unit	Number of samples	*K* Susceptibility × 10^{-3} (cgs units)		Number of samples	*J* Remanent magnetization × 10^{-3} (cgs units)		Number of samples	$Q = \frac{J}{KH}$, H = 0.56 oersteds	
		Range	Average		Range	Average		Range	Average
Upper Cretaceous and Tertiary porphyries	29	0.46 –2.67	1.58	21	0.032–1.52	0.23	21	0.02– 1.27	0.21
Precambrian Silver Plume and St. Kevin Granites	19	.03 –1.64	.32	16	.022– .601	.44	16	.87–17.93	5.1
Precambrian Denny Creek Granodiorite Gneiss and similar rocks	8	.073–2.07	.86	7	.016– .159	.084	7	.14– 0.86	.40
Precambrian gneisses	24	.015–4.52	1.37	18	.001– .854	.278	18	.25– 2.70	1.30
Paleozoic sedimentary rocks	25	.012– .06	.02	....	Generally weak.		....	....	....

gammas, as observed at the flight level of the aircraft.

The magnetic properties of major rock units are summarized in table 2.

PRECAMBRIAN GNEISS

Susceptibilities of Precambrian gneiss samples show a bimodal distribution (fig. 4). Sixteen samples have susceptibilities below 1.0×10^{-3} cgs units and eight samples have susceptibilities above 3.0×10^{-3} cgs units. In the Leadville 30-minute quadrangle, this bimodal distribution is reflected by the aeromagnetic expression of the lithologic units: biotite-rich gneisses and migmatites in and northwest of the Homestake shear zone are more magnetic than the amphibole and quartz gneisses southwest of the shear zone. The average susceptibility of all the gneisses is 1.37 cgs units.

Remanent magnetization of the gneiss is extremely variable in both intensity and direction. Intensities range from 0.001 to 0.854×10^{-3} cgs units. Remanent orientations fall generally in northeast or southwest quadrants, but the azimuths are widely scattered. The average Q value for 18 samples is 1.3. On the average, remanent magnetization exceeds induced magnetization by a small amount. However, most of the samples with a high total magnetization have low Q values; therefore, magnetic anomalies shown on the aeromagnetic map reflect, for the most part, the induced component of total magnetization. Because the specimens were not demagnetized, the data are not suitable for paleomagnetic analysis.

PRECAMBRIAN GRANITIC ROCKS

Magnetic susceptibilities of the Denny Creek Granodiorite Gneiss and similar rocks average about 0.86×10^{-3} cgs units, and those of the St. Kevin and Silver Plume Granites average 0.32×10^{-3} cgs units. All but one sample of the St. Kevin and Silver Plume Granites have susceptibilities less than 1×10^{-3} cgs units and that one has a susceptibility less than 2×10^{-3} cgs units.

Remanent magnetizations of the Denny Creek trend north to northwest, and the azimuths are widely scattered. Inclinations are generally steep. Remanent magnetizations are low and range from 0.016 to 0.159×10^{-3} cgs units. Q values range from 0.14 to 0.86, and average about 0.4. Thus, remanent magnetization makes very little contribution to the total magnetization.

Remanent magnetization of the St. Kevin and Silver Plume Granites ranges from 0.022 to 0.601×10^{-3} cgs units. The magnetization generally has a reversed, low inclination, and the direction in most samples is northeast. Q values range from 0.87 to 17.93, but only two of the 16 samples have values below 1.0, and the rest exceed 2.1. The average Q is 5.1; thus, remanent magnetization is clearly dominant for these rocks. It should be emphasized that none of the Denny Creek rocks show reversed remanent magnetization, whereas the St. Kevin and Silver Plume rocks do exhibit reversed magnetization.

Magnetic data may aid in distinguishing rocks of the St. Kevin and Silver Plume Granites from those of the Denny Creek Granodiorite Gneiss. Three magnetic features may serve as a supplement to petrographic, chemical, and field criteria: (1) Q values of rocks of the St. Kevin and Silver Plume are much greater than those of the Denny Creek. (2) The magnetic susceptibilities of biotite-quartz monzonites and granodiorites of the Denny Creek are somewhat greater than those of the granites of the St. Kevin and Silver Plume. (3) Reversed remanent magnetization is commonly present in rocks of the St. Kevin and Silver Plume and seems to be rare in rocks of the Denny Creek.

These potentially significant correlation techniques merit much further investigation by concerned specialists.

PALEOZOIC SEDIMENTARY ROCKS

Table 2 shows that the Paleozoic sedimentary rocks have magnetic susceptibility values of less than 0.1×10^{-3} cgs units and, thus, that these rocks are effectively nonmagnetic. Therefore, the sedimentary rocks can be excluded as a significant source of magnetic anomalies.

UPPER CRETACEOUS AND TERTIARY INTRUSIVE IGNEOUS ROCKS

These rocks — the porphyries — have a wide range of magnetization. Fresh porphyries generally have moderately high values of magnetic susceptibility, but altered porphyries have low values. Thus, both magnetic highs and lows are found over the porphyries; magnetic lows may reflect either alteration or a low content of magnetite in fresh rock.

Remanent magnetization of Tertiary porphyries is generally weak and variable; no samples have reversed directions of remanent magnetization. Most remanent directions are northeastward. Their inclination is somewhat greater than that of the earth's present field in the region. Q values are variable and range from 0.02 to 1.27.

GRAVITY FEATURES

One of the largest regional negative gravity anomalies in the United States trends northeast across Colorado, from the San Juan Mountains to the Front Range, near Boulder. This low, as shown on the U.S. Bouguer anomaly map (Woollard and Joesting, 1964), is interrupted by a saddle near the Gunnison River. Thus, two main negative anomaly areas can be recognized: one centered over the upper Arkansas valley area, and one over the San Juan Mountains. The origin or source of this regional negative anomaly and its relationship to the Colorado mineral belt constitute one of the major geophysical problems of the Rocky Mountain region. Regional gravity maps of Colorado have been presented by Holmer (1954), and an isostatic anomaly map and analysis based on Holmer's data were prepared by Qureshy (1960, 1962), who considered the low to be caused by crustal thickening. Behrendt (1968) identified the low as the most negative gravity anomaly in the conterminous United States, and Case (1965) interpreted the low as caused by a batholithic mass of low density.

GRAVITY SURVEY

Gravity stations were established by Case during 1961–65 along nearly all roads accessible by vehicle and, also, by foot traverse along many ridges. Worden portable gravity meters with scale constants of about 0.5 mgal (milligal) per scale division were used throughout the survey. A master gravity base network was established which extends from Leadville through Buena Vista to Poncha Springs and Monarch Pass, from Buena Vista through Fairplay to Breckenridge, and from Beckenridge through Climax to Leadville (fig. 5). The value of observed gravity at Leadville is 979.1855 gals, as determined by D. J. Stuart, of the U.S. Geological Survey (oral commun., 1961), in connection with establishment of a Southern Rocky Mountains gravity profile tied to the international gravity network (Stuart and Wahl, 1961). All gravity values in the Leadville quadrangle were determined with respect to the Leadville value.

Locations of gravity stations were plotted on the Holy Cross, Mount Lincoln, and Mount Elbert 15-minute quadrangles; the Mount Sherman, Fairplay West, South Peak, and Jones Hill 7½-minute quadrangles; the Tenmile mining district (scale 1:12,000) and Leadville mining district (scale 1:9,600) special topographic sheets (pl. 1, index map); and preliminary 7½-minute maps covering parts of the Holy Cross and Mount Lincoln quadrangles prepared by the U.S. Army Map Service. Locations of gravity stations are considered to be correct to within 0.1 mile for most stations.

Elevation control was provided by bench marks of the U. S. Geological Survey and U.S. Coast and Geodetic Survey, by photogrammetric elevations shown on the modern topographic maps, by leveling data along the main highways provided through the courtesy of the Colorado Highway Department, and by surveyed "spot elevations" shown on the older topographic maps. A few elevations were determined by altimetric surveys. Elevations shown on older maps, especially the Mount Lincoln and Mount Elbert quadrangles, are subject to greater uncertainty than those shown on the modern maps. As a result, the greatest errors in Bouguer anomalies are to be expected in the Mount Lincoln and Mount Elbert quadrangles.

Gravity values were reduced to Bouguer anomalies by standard methods. (See Oliver, 1965, p. 218.) A density of 2.67 g/cm^3 was assumed in the reductions. Terrain corrections, determined for all stations, ranged from 2.4 mgal at lower stations in the open flat valley southwest of Leadville to 52.3 mgal at Mount of the Holy Cross. Many corrections were in the 3- to 10-mgal range. The largest corrections were required at the higher, sharper peaks and in the floors of the deep, relatively narrow glacial valleys. Inner corrections through Hammer's (1939) zone H were obtained through use of the Hammer template system. Corrections for the outer zones were obtained by a computer method devised by Plouff (1966) which utilizes digitized terrain on a geographic coordinate basis of 1 minute for Hammer zone I (2.6146 km) (kilometers) through 21.9 km, and a 3-minute basis for 21.9–166.7 km.

ERRORS IN THE BOUGUER ANOMALIES

In mountainous regions where topographic relief is great, as in the Leadville quadrangle, errors in the Bouguer anomalies attain a maximum. Principal sources of error are the terrain corrections and the station elevations.

Elevation errors. — Elevation errors range from less than 1 foot at the better bench marks to as much as 50 feet, the map-contour interval, at spot elevations shown on the older quadrangles. An error of 50 feet is equivalent to an error in the computed Bouguer anomaly of about 3 mgal. Most elevations are believed to be correct to within 20 feet, equivalent to errors of 1.2 mgal.

Terrain correction errors. — Errors in terrain corrections are exceedingly difficult to estimate, but they probably do not exceed 10 percent of the total correction. Thus, these errors could range from 0.24 mgal for stations in the flat valley southwest of Leadville to as much as 5.2 mgal at Mount of the Holy Cross.

Location errors.—Virtually all locations are correct to within 0.1 mile, equivalent to errors of about 0.1 mgal or less in the latitude correction.

Errors in observed gravity. — The principal errors in observed gravity arise from instrumental drift and earth tides which occurred during daily traverses. Normal drift rate of the gravity meters did not exceed 1 mgal per daily traverse, and commonly was less than 0.5 mgal. During daily traverses, repeats were made at base stations and intervening stations where possible. Where such repeats were possible, relatively precise drift corrections could be applied; therefore, the values of observed gravity for these traverses are probably correct to within 0.2 mgal. On long mountain foot traverses, where repeats were made only at the end of the traverse, the error may be as much as 0.5 mgal.

The normal expected error in the Bouguer anomaly value at an individual station is about 2 mgal, as a subjective estimate. The Bouguer anomaly map (pl. 1) has been contoured with an interval of 2 mgal, because a 1-mgal map would reflect the many small errors unavoidably present in the data. No significance can be attached to apparent anomalies of 2 or 3 mgal, particularly in the high mountains, as these values are too close to the possible error inherent in the data.

The gravity anomaly contours were controlled by the values at the stations and were drawn as smooth lines between control points, without any special attempt to reflect known geologic features.

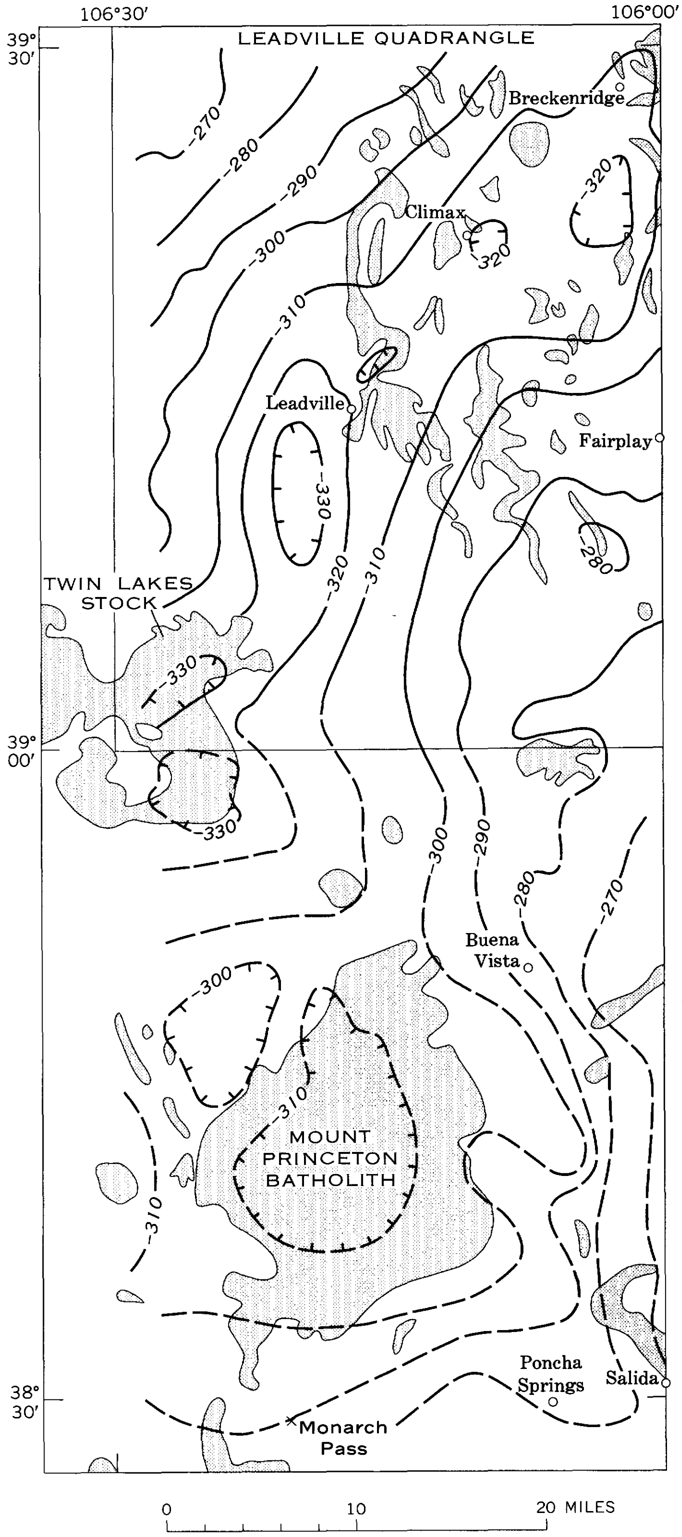

FIGURE 5. — Regional Bouguer anomaly map showing generalized anomaly contours (interval 10 mgal) and distribution of larger Tertiary igneous masses (shaded areas) in central Colorado. Dashed contours are preliminary.

INTERPRETATION OF THE GRAVITY ANOMALY MAP

Although the principal mountain ranges and valleys trend about north, the dominant gravity anomaly, a huge gravity low of 30–50 mgal, trends northeast, diagonally across the ranges, from La Plata Peak in the southwest corner of the quadrangle to Breckenridge in the northeast corner. Superimposed on the major regional low is a local low, the axis of which trends about north, over the alluvium-filled Arkansas valley southwest and west of Leadville. The steepened gravity gradients that border the major low flatten to both the west and northwest of the Leadville quadrangle, as indicated by reconnaissance gravity data and the United States gravity map (Woollard and Joesting, 1964) and to the east and southeast of the quadrangle, as indicated by detailed surveys in South Park (Rodgers, 1960). The major low, here termed the "mineral-belt low," together with its bordering zones of steep gravity gradients occupies all but the southeastern part of the quadrangle. The steep gravity gradients suggest that the source of the anomaly is shallow, perhaps within the upper 50,000 feet of the crust.

MINERAL-BELT GRAVITY LOW

The steepened gravity gradient that defines the northwest margin of the mineral-belt low extends (pl. 1) from Lake Creek, in the southwest corner of the area, north along the eastern flank of the Sawatch Range to the vicinity of Lake Fork and West Tennessee Creek. It then bends northeast, and extends across the south end of the Gore Range and the north end of the Tenmile Range to the vicinity of Breckenridge, in the northeast corner of the area. In the segment between Mount Elbert and the north slope of La Plata Peak, the gradients are as high as 6 mgal per mile. The average gradient from Mount of the Holy Cross to Tennessee Pass, across the Homestake shear zone, is about 3 mgal per mile.

The southeast margin of the low is defined by a zone of steepened gravity gradients that extends northeast from Quail Mountain in the southwest, across the Arkansas valley at Twin Lakes, and diagonally, northeast, across the Mosquito Range to the vicinity of Mosquito Creek; it then swings eastward to Alma and, thence, northward to Breckenridge. Again, gradients range from about 5 mgal per mile near Quail Mountain to an average of about 3 mgal per mile near Mosquito Creek.

The two zones of steepened gravity gradient that border the mineral-belt low cross a great variety of rock types of variable density; therefore, the relatively light rocks causing the low must be largely concealed. Sedimentary rocks cannot account for the gravity low because they are too limited in distribution with respect to the low. Steep gravity gradients, however, require that the anomaly source be relatively shallow, within the upper part of the crust. By using the limiting depth criteria of Bott and Smith (1958), the maximum depth to the top of the anomalous mass was calculated to be 40,000–50,000 feet, and the actual depth may be much less.

UNDERLYING BATHOLITH AS SOURCE

The most plausible source of the anomaly is an underlying shallow batholith of silicic rocks (Case, 1965). Such a batholith has long been postulated as a source of the hypabyssal intrusive rocks — and the ore deposits — that characterize the mineral belt (Crawford, 1924; Lovering and Goddard, 1938; Tweto and Sims, 1963). The density difference of about 0.1 g/cm^3 between the Precambrian rocks and the porphyries is sufficient to account for the anomaly, as discussed further in following paragraphs. Moreover, the fact that the larger intrusive bodies, such as the Twin Lakes stock and the Mount Princeton batholith, coincide with low closures (fig. 5; also Case, 1966, 1967) strongly suggests that the major gravity low is associated with a body of intrusive rock of batholithic proportions. The northwest margin of the low, characterized by relatively straight gravity contours and a very steep gravity gradient, coincides closely with the Homestake shear zone, which evidently exerted some control on this part of the Colorado mineral belt and its intrusive rocks (Tweto and Sims, 1963).

To determine the approximate dimensions and depth of the mass causing the mineral-belt low, a line of profile (pl. 1, *C–C′*) extending northwest-southeast across the area was selected for analysis (fig. 6). The profile is located approximately normal to the gravity contours and along a line where the alluvial and glacial deposits are either thin or absent. Thus, almost all of the low must originate within the bedrock. The regional Bouguer anomaly values at the ends of the profile are about −266 mgal near Mount of the Holy Cross, and about −280 to −290 in South Park. From the sparse regional gravity data to the northwest and good data to the southeast (Rodgers, 1960), it appears that the −266 values near Mount of the Holy Cross are part of a regional high at the north end of the Sawatch Range (Stuart and Wahl, 1961, fig. 245.1), and the values of −280 to −290 in South Park are regional lows, partly related to the thick sedimentary fill in South Park. Thus, a regional gradient, decreasing southeastward, of about 0.6 mgal per mile can be assumed along profile *C–C′*. However, note that other regional gradients may be more or equally applicable. Choice of different regional gradients would influence the amplitudes and gradients of the residual anomalies across the area, but a residual low of large amplitude and steep flanking gradients must be generated by any assumed regional gradient. The gradient picked along profile *C–C′* happens to be the simplest possible choice and yields a fairly symmetrical residual anomaly.

It is possible to set limits on some dimensions of the mass causing the anomaly. For a uniform density contrast, the margins of the light mass at depth should not be wider than the distance between the steep central parts of the flanking gravity gradients, or approximately 15 miles.

In the two-dimensional model established for the computation (fig. 6), the top of the anomalous mass is assumed to extend nearly to the surface at the axis of the gravity low, near the East Fork Arkansas River. The density contrast between the mass causing the low and the Precambrian rocks is assumed to be 0.12 g/cm³, the approximate density contrast between the Upper Cretaceous and Tertiary porphyries and the Precambrian rocks.

In computing gravitational effects of the model, both the gravity anomaly and the model are as-

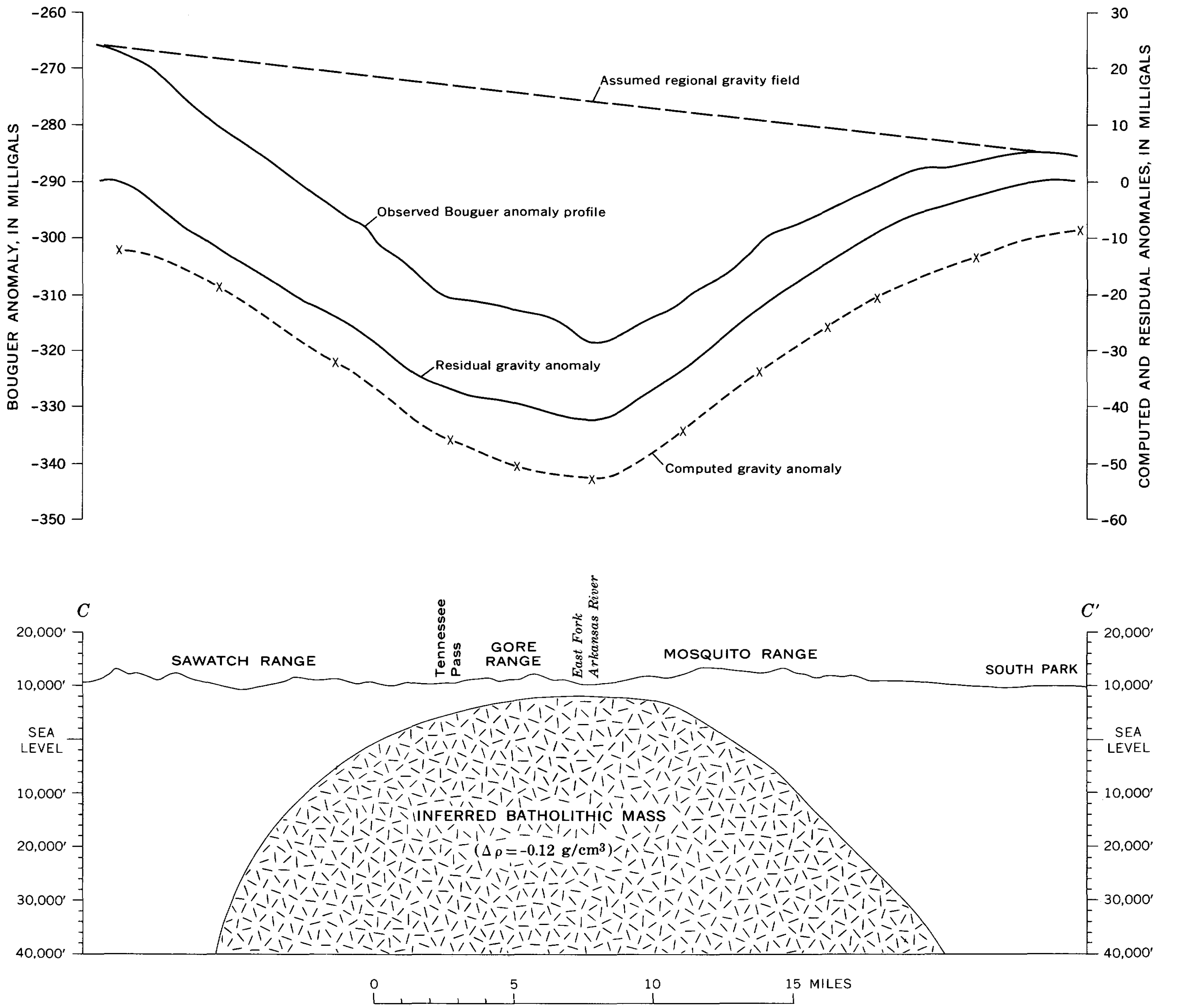

Figure 6. — Regional gravity anomaly and its interpretation along profile C–C′. Assumed regional gradient is about 0.6 mgal per mile. Line of profile shown on plate 1.

sumed to be two dimensional — that is, their lengths greatly exceed their width. Obviously, this assumption is not completely correct. Moreover, the gravity field related to the mass causing the mineral-belt low is somewhat influenced by the thick low-density fill in the Arkansas valley, west of Leadville. However, this gravitational disturbance can be no more than a few milligals along the line of profile, which is 5–6 miles northeast of the region of thick fill.

The observed gravity anomalies over the concealed low-density mass are shown in figure 6. If a linear regional gradient of 0.6 mgal per mile is assumed, the residual profile can be matched very closely by the computed anomaly of the model.

A geologically plausible model is a batholithic mass that averages 15–20 miles in width, that extends to depths on the order of 40,000 feet below sea level, whose apex is within a few thousand feet of the surface, and whose average density contrast is about -0.12 g/cm^3, which yields a computed anomaly that matches the observed anomaly both in amplitude and in steepness of gradient. Such a batholith could consist in part of the St. Kevin and Silver Plume Granites, inasmuch as these granites are only slightly more dense than the porphyries, but the continuity of porphyry intrusion along the mineral-belt low strongly suggests that the underlying mass is a continuous batholith of Late Cretaceous and Tertiary age.

No attempt was made to construct a model whose gravity anomaly exactly matches the observed anomaly. The discrepancy between the observed and the computed anomalies at specific points is generally less than 2 mgal, which is on the same order of magnitude as the error inherent in the Bouguer anomalies.

Note, however, that the observed anomaly could be matched by other models; in particular, the batholithic mass could extend to greater depth if the average density contrast is less than -0.12 g/cm^3, or a somewhat smaller mass at greater depth could be present if the density contrast is greater than -0.12 g/cm^3.

The closure of the gravity contours in the northeastern part of the area, near Breckenridge, and the generally narrow width of the mineral-belt low indicate that the batholithic mass may become smaller or that its roof may plunge downward toward the northeast.

DEEP CRUSTAL OR SUBCRUSTAL SOURCE

A general thickening of the crust beneath the high mountains of Colorado is indicated by the fact that the Bouguer anomalies increase with increasing mean topographic elevation, as is well illustrated by a map by Gilluly, Waters, and Woodford (1968, p. 176). From analysis of seismic data from a mine blast at Climax, Jackson and Pakiser (1965) determined a crustal thickness of about 50 km (30 miles) beneath the Southern Rocky Mountains in Colorado, as contrasted to a crustal thickness of 35–40 km in the Colorado Plateau and the Uinta Mountains to the west. However, they found little contrast in the crustal thickness between the mountains and the plains to the east.

The thickening implied by the regional gravity and seismic data applies to much broader areas than the mineral-belt low. The steep gravity gradients of the low and the narrow width of the low, about 15 miles, strongly suggest a local, shallow feature whose effects are superposed upon those of a regionally thickened crust. On the basis of only a few gravity stations, Qureshy (1960, 1962) concluded that the low was caused by local crustal thickening to about 52 km across a horizontal distance of 30 miles or more, but this width is too great. The average width of the anomalous mass causing the low cannot be greater than the distance between the positions of the steepest gradients on the flanks of the anomaly, or about 15 miles.

The requirement of a shallow position within the crust of the body causing the anomaly can be illustrated by comparison of observed gravity gradients with the calculated effects of a deep body. If a body 10 km thick, 20 km wide, and having a density contrast of -0.3 g/cm^3 were located at a depth of 30 km within the crust (fig. 7), the anomaly at the surface would be only -9.4 mgal, measured from a point at the center of the body to a point 30 km from the center. It is evident from the computed points shown in figure 7 that such a body would produce only a small anomaly, and that the gradients would be much flatter than those observed. A "root" of similar dimensions at the base of the crust would have even smaller effect, unless an unreasonable density contrast between crust and mantle (on the order of 1.5 g/cm^3) were assumed. From seismic studies, Jackson and Pakiser (1965, p. D90) concluded that "no pronounced crustal root [exists] under the Southern Rocky Mountains."

In summary, a deep crustal or subcrustal source of the anomaly (mineral-belt low) seems to be precluded. The source is concluded to lie at relatively shallow depth within the crust and to be superposed on a broader regional low related to the thickened crust of the mountain province as a whole.

LOCAL ANOMALIES ALONG THE MINERAL-BELT LOW

Local gravity anomalies, both relative highs and lows, are superimposed on the main mineral-belt

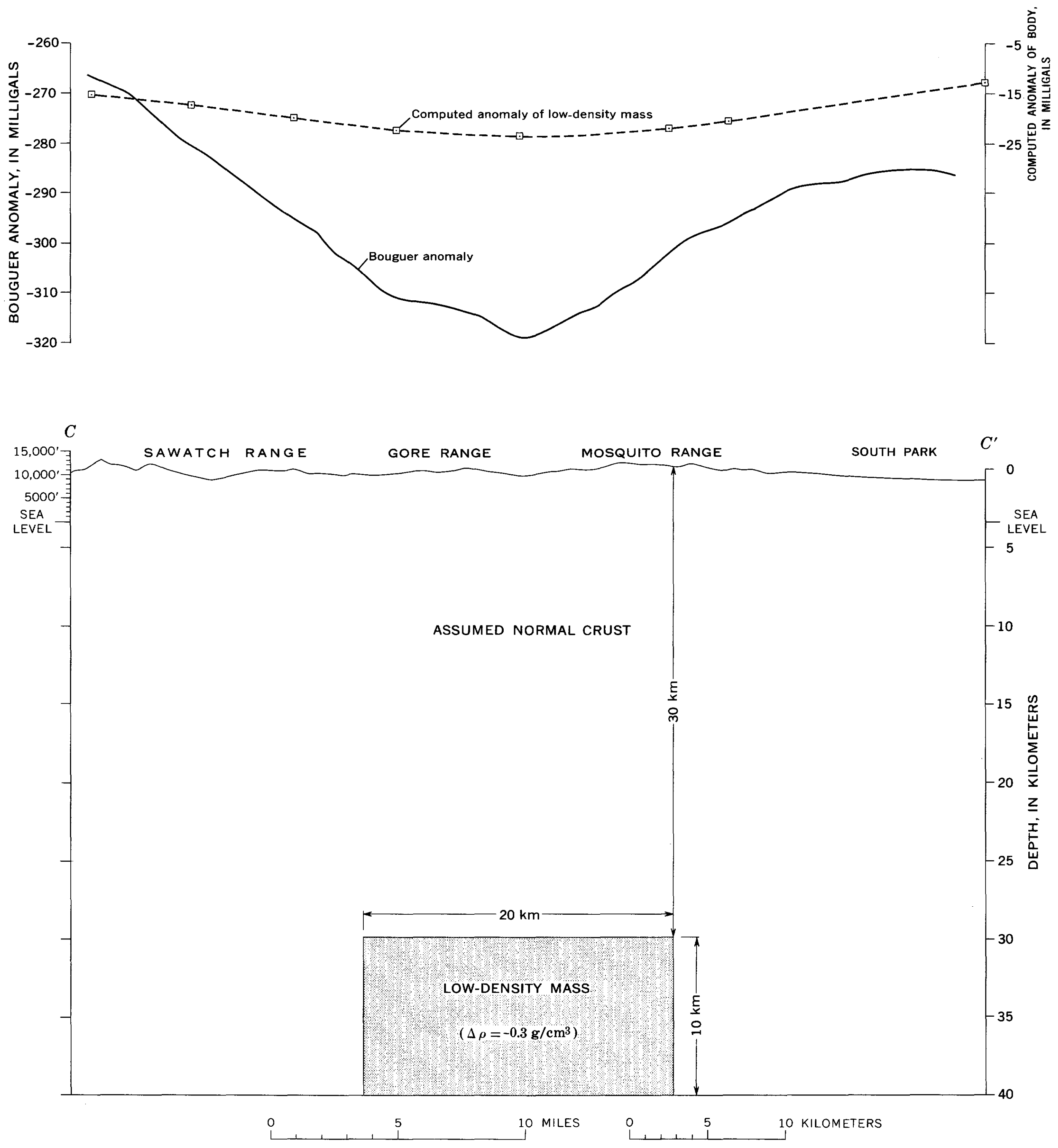

FIGURE 7. — Gravitational effects of a deep crustal-mass deficiency beneath the Colorado mineral belt.

low. Some, such as the low over the Arkansas valley graben, discussed in the following section, can be readily explained, but the origin of others is obscure.

A small low near Climax occurs, in general, over the Climax stock and adjoining areas of intensely altered Precambrian rocks. There seems to be little correlation of the low with the position of the Mosquito fault. The eastern limit of the low is poorly controlled, and additional gravity observations might establish that the —320 contour at Climax joins the —320 contour in the area along the Continental Divide, to the east. The fact that the low at Climax occurs over a variey of rock types suggests that this low may reflect a concealed igneous body of low density.

A conspicuous gravity high of about 4–5 mgal splits the main mineral-belt low where it crosses the Tenmile Range, northeast of Climax. This high may be caused by relatively dense gneissic (amphibolitic) rocks within the sequence of Precambrian gneiss, or it may be an "apparent" high between the two flanking lows, which presumably are caused by largely concealed silicic bodies of relative low density. For example, the Humbug stock may spread southward at shallow depth. The high is defined by only a few stations in a region where the elevations may be subject to large error. Thus, no attempt should be made to quantitatively interpret the anomaly unless additional gravity stations and more precise elevations are obtained.

A small low is found over a plug or stock of Pando Porphyry just north of Leadville. However, this low is controlled by only two gravity stations, and it cannot be readily isolated from the effects of the main source of the mineral-belt low or of the fill in Arkansas valley.

A well-defined low of about —10 mgal is correlative with the Twin Lakes stock in the southwestern part of the quadrangle. The low is interrupted by a gravity high that coincides with a prong of Precambrian rocks projecting into the stock from Quail Mountain to La Plata Peak.

GRAVITY LOW OVER THE ARKANSAS VALLEY GRABEN

In the Arkansas valley graben, the low-density fill of alluvial and glacial materials adds to the effects of the mineral belt low, creating the most conspicuous low in the quadrangle and, indeed, the deepest low known in the conterminous United States. Identification of that part of the low due to the fill is difficult, but necessary, in order to evaluate the thickness of the fill, which is otherwise unknown. The problem is compounded by lack of knowledge of the bedrock beneath the valley fill. For purposes of analysis, it was assumed that the buried bedrock consists primarily of Precambrian rocks. If fault blocks of sedimentary rocks are present, as they may be, they probably are mainly lower Paleozoic rocks, of about the same density as the Precambrian rocks. If the bedrock consists in large part of intrusive porphyry of low density, such as that of the Twin Lakes stock, its effect would be to reduce the calculated thickness of the Cenozoic fill in the valley.

A residual low over the Arkansas valley can be isolated by assuming near-linear variations in the Bouguer anomaly field between bedrock areas on the two sides of the valley. Bouguer anomalies over bedrock areas decrease from about —320 mgal in the area 3–5 miles northeast of Leadville to —325 to —330 mgal in the area near the Twin Lakes stock. Thus, one can assume, as the simplest situation, a near-linear decrease in minimum values along the axis of the mineral-belt low across the Arkansas valley graben. Similarly, Bouguer anomalies over bedrock decrease from about —300 mgal, near Tennessee Pass, to —310 mgal at the south-central edge of the quadrangle, 5 miles south of Twin Lakes. Values over bedrock along the eastern and western flanks of the graben are about —310 mgal. These regional Bouguer anomaly values were used to aid in constructing a smooth regional map (fig. 8). The differences between gravity values on the smooth map and the Bouguer anomaly map were then obtained and contoured to prepare a residual anomaly map (fig. 8) over the graben. This method yields a maximum residual anomaly of about —20 mgal.

As an alternative method of obtaining a regional profile, one may smooth the anomaly values across the valley between inflection points of the profile (fig. 8). This method yields a residual anomaly of about 17 mgal along profile *B–B''*. This residual was fitted by a model in which the thickness of valley fill is about 3,200 feet for a density contrast of —0.45 g/cm^3. If the maximum residual anomaly in the valley is 20 mgal, the depth of fill would be somewhat greater, perhaps 3,800 feet.

Because of the uncertainties — the regional gravity field, the average density contrast, and the exact location of the steep residual gravity gradients on the flanks of the anomaly — the model shown must be regarded merely as a geologically and gravimetrically plausible model. The thickness of valley fill could be in error by as much as 25 percent. A thickness of 3,000–4,000 feet is adopted here as a reasonable estimate.

OTHER BEDROCK ANOMALIES

A gravity high of 6–8 mgal is centered over Round Hill, on the London fault, in the southeastern part of the area. From this high, a positive nose extends northwestward along the trace of the London fault at least as far as Sacramento Gulch. Farther northwest, a line of bending in the contours suggests a continuation of the nose, but this is more likely a reflection of the lows at, and east of, Climax.

The gravity high and positive nose along the London fault can be attributed, in some part, to the

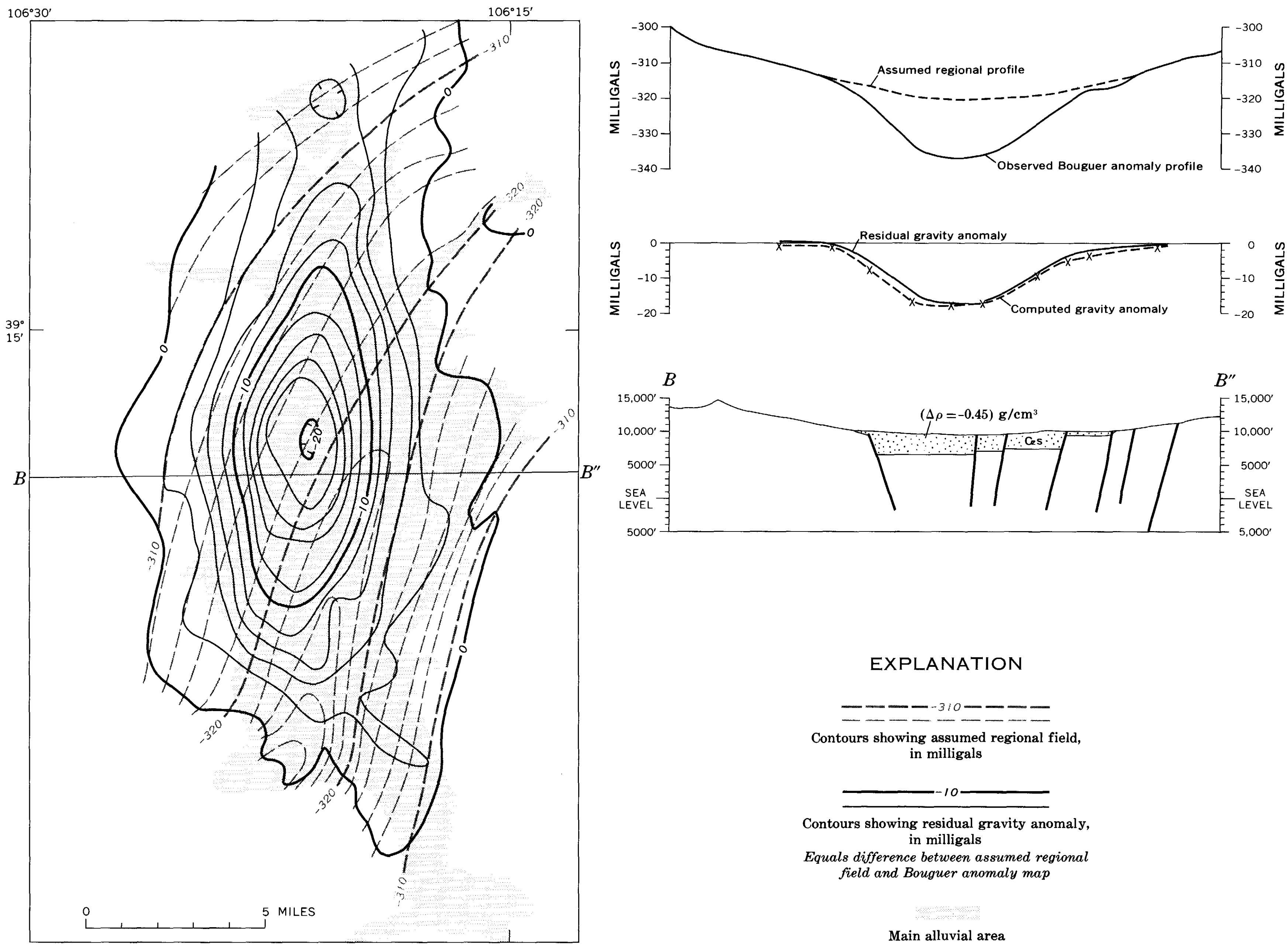

Figure 8. — Residual gravity anomaly over the Arkansas valley graben, and its interpretation. Czs, Cenozoic fill having density contrast of —0.45 g/cm³. Profile *B–B″* along western part of line of section *B–B′*, plate 1.

contrast between the relatively dense Precambrian and lower Paleozoic rocks on one side of the fault and the relatively light Pennsylvanian rocks and porphyries on the other side (pl. 1, section *B–B'*). However, this difference seems to be insufficient to be the entire cause. The anomaly may reflect a line of concealed mafic intrusions, as discussed further in the section on interpretation of magnetic anomalies.

AEROMAGNETIC SURVEY

Aeromagnetic surveys were flown in a twin-engine aircraft at an elevation of 14,500 feet above sea level. Total intensity of the magnetic field was measured by an ANASQ/12A fluxgate magnetometer mounted in a retractable "stinger," or boom, on the tail of the aircraft. Surveys were flown under the supervision of J. L. Meuschke and F. A. Petrafeso in 1963, and data were reduced under the supervision of J. R. Kirby and Jean Blanchett. Flight lines were flown east and west and were spaced 2 miles apart. The flight paths, controlled by strip film, were plotted on topographic base maps, scale 1:62,500 and 1:24,000. The data were compiled on an enlargement to a scale of 1:125,000 of the Leadville 1° by 2° quadrangle. The aeromagnetic map (pl. 2), contour interval 20 gammas, was compiled by standard methods (Balsley, 1952). Aeromagnetic surveys have been conducted in adjacent quadrangles to the north, east, and south of the Leadville quadrangle. A detailed aeromagnetic survey of the Climax area was described by Meyer (1968); the flight elevation was 14,000 feet, and lines were spaced about one-quarter mile apart. The resulting magnetic map shows many details not shown on plate 2.

INTERPRETATION OF THE MAGNETIC MAP

GENERAL FEATURES OF THE MAGNETIC MAP

[All anomaly letter designations refer to plate 2]

The magnetic map is contoured with respect to an arbitrary datum. A general northward increase in total magnetic intensity is caused by the earth's main magnetic field, which increases about 8.3 gammas per mile toward the north-northeast, according to the U.S. Coast and Geodetic Survey (1955, chart 3077F). Local magnetic anomalies, caused by topographic relief and by contrasts in rock magnetization, are superimposed on the earth's main field.

In regions where rugged topography has been carved in magnetic rocks, the aeromagnetic map must, to some extent, reflect variations in the distance from the flight elevation of the aircraft to the rocks below. This effect will be superimposed on the variations in the magnetic field resulting from contrasts in rock magnetization. An example of a rather crude, general terain effect is shown on plate 2, profile *A–A'*, the southernmost aeromagnetic profile in the Leadville 30-minute quadrangle, which extends from south of La Plata Peak and Mount Hope, near Quail Mountain and eastward across the valley, south of Clear Creek Reservoir, and across the Mosquito Range, to the region south of Pole Gulch. Magnetic values increase from about 2,250–2,260 gammas over the low point in the Arkansas valley to 2,596 gammas over the high part of the Mosquito Range—a magnetic increase of about 340 gammas across topographic relief of about 3,000 feet. A similar increase is found to the west of the valley, where magnetic values reach 2,616 gammas at Quail Mountain and 2,615 gammas near La Plata Peak, at elevations of 3,000–4,000 feet above the valley. Granitic rocks at Quail Mountain and over the Mosquito Range are dominantly biotite-quartz monzonites or granodiorites related to the Denny Creek Granodiorite Gneiss, and the average susceptibility contrast is about $2\text{–}3 \times 10^{-3}$ cgs units. The flight elevation of the aircraft was 14,500 feet; therefore, the magnetic rocks along the mountain ranges were 500–2,500 feet below the aircraft, and those in the valley were 5,500 feet below the aircraft. Yet, variations in amplitude of the magnetic anomalies over the high Sawatch Range are nearly as great as the amplitude variation from the Arkansas valley to the crests of the adjacent ranges.

The west half of the northernmost profile (pl. 2, profile *B–B'*) shows relatively little correlation between the topography and the variations in magnetic field. The magnetic high over the gneissic rocks northwest of the Homestake shear zone persists as a high, even though several thousand feet of relief is present in the terrain. The steepened magnetic gradient along the shear zone crosses several prominent ridges, and the lower values southeast of the shear zone are not reflected in the topography.

Many of the anomalies, thus, are independent of topographic relief and arise predominantly from contrasts in magnetization of the crystalline rock units. Perhaps half of the closed anomalies are the result of topographic relief. As indicated in the discussion of magnetic properties, the various igneous and metamorphic rock units have a wide range of magnetization. Positive anomalies are found over some of the Tertiary porphyries, Precambrian gneisses, and Precambrian granitic rocks. Relative magnetic lows may be found over the same units as a result of the low original magnetite content or of the alteration of magnetite.

In the following discussion, specific anomalies are identified by letters keyed to plate 2. The amplitudes assigned to the anomalies generally refer to the difference in magnetic intensity from the crest or trough of the anomaly to the adjacent regions of flat gradient, near the flanks of the anomaly. One should bear in mind that the contours are controlled only along the positions of the flight lines; hence, contours between flight lines are approximations.

ANOMALIES OVER THE ARKANSAS VALLEY

The general magnetic low over the Arkansas valley is expectable from the relatively low topographic setting and the great thickness of glacial and alluvial deposits in the valley.

The minimum anomaly in the region is found north and west of the Hayden Ranch, suggesting that the greatest thickness of valley fill is in the southwest quarter of T. 10 S., R. 80 W., and the northwest quarter of T. 11 S., R. 80 W. As noted previously, the minimum gravity values are in the area immediately south of Malta. The combined gravity and magnetic data suggest that the maximum thickness of fill lies in the west half of T. 10 S., R. 80 W. However, it is also possible that the low magnetic values over the valley might be caused, in part, either by nonmagnetic crystalline rocks or by reversely magnetized rocks, such as the St. Kevin Granite, at depth beneath the fill.

An apparent constriction of the magnetic low over the valley is present in the area due west of Leadville (anomaly *N*). This small positive anomaly may mark an area of major thinning of the valley fill, but it could also reflect the presence in the bedrock of a fine-grained granodioritic facies of the St. Kevin Granite. This granite is exposed in broad dikelike bodies southwest of Turquoise Lake and extends beneath the moraines. A similar constriction west of the town of Granite (anomaly *P*) coincides with a fault block of granitic rock projecting into the valley fill.

Calculation of the magnetic effects of a model across the Arkansas valley is not feasible, because the susceptibilities, as well as the depth, of the crystalline rocks beneath the valley would be only a guess.

The area of the Leadville mining district is magnetically flat. If a residual magnetic map were constructed, the principal mines would lie in a magnetic low (anomaly *T*) on the southern flank of a weak magnetic high.

ANOMALIES RELATED TO THE HOMESTAKE SHEAR ZONE

Much of the Homestake shear zone exposed in the Leadville quadrangle cuts through gneissic rocks. A prominent magnetic high (anomaly *M*) is present over the region northwest of Homestake Creek, in the vicinity of Mount of the Holy Cross and Whitney Peak. This anomaly is evidently caused by the magnetic migmatite and biotite gneiss, as well as by the high elevations of this part of the range. In many places in this area, the migmatite is so magnetic as to make a compass unreliable or even unusable. To the southeast of the main zone of shearing, the gneissic rocks consist of more weakly magnetic amphibole gneiss, calc-silicate gneiss, and impure quartzite or quartz gneiss. Unlike the amphibolites of North Park, Colo., which are magnetite-bearing and magnetic (Behrendt and others, 1969) and are probably of igneous origin, the amphibole-bearing gneisses southeast of the Homestake shear zone are magnetite-poor rocks of sedimentary origin. Thus, most of the magnetic high and the prominent northeast strike of the magnetic contours are caused by the contrast between the high susceptibility of the migmatite and biotite gneiss and the low susceptibility of the amphibole gneiss and accompanying rocks. However, the shear zone itself may be magnetic relative to bordering rocks.

The magnetic ridge, or high, along the northwest side of the shear zone and the line of steepened magnetic gradient that borders it extend across the region of nonmagnetic Paleozoic sedimentary rocks northeast of Camp Hale and into the Gore Range, where the shear zone is again exposed (Tweto and others, 1970). Thus, the shear zone can be inferred to persist beneath the sedimentary rocks east of the Eagle River. In the area of concealment, the width of the zone of steepened magnetic gradient does not indicate the width of the shear zone, but only provides a general indication of its location.

ANOMALIES ALONG THE SAWATCH RANGE

In the southwestern part of the quadrangle, positive anomalies over high parts of the Sawatch Range are separated by a magnetic low (anomaly *F*) over Lake Creek and the Twin Lakes stock. This low projects as a lobe from the main Arkansas valley magnetic low. The low is caused in part by low topography, but it also reflects a low magnetite content of the main body of the Twin Lakes stock, as contrasted with its border zones, particularly the north border (Wilshire, 1969). South of Lake Creek, positive anomalies *A*, *C*, and *E* form a line along the high ridge from La Plata Peak to Quail Mountain. This line of magnetic anomalies coincides with a gravity high over Precambrian gneisses that evidently project as a deep-rooted septum into the Twin Lakes stock. Negative anomaly *B*, between La Plata

Peak (anomaly *A*) and Mount Hope (anomaly *C*), seems to reflect a projecting arm of porphyry of the Twin Lakes stock. The magnetic saddle (anomaly *D*) coincides with a topographic saddle between Mount Hope and Quail Mountain (anomaly *E*) and may be caused, in part, by alteration along the faults in this area.

In the area of Halfmoon Creek, between Mount Elbert and Mount Massive, is a deep magnetic low (anomaly *H*). The cause of this anomaly is not immediately evident. The anomaly may reflect alteration, inasmuch as the rocks throughout much of the area weather yellowish brown, suggesting widely disseminated pyrite, especially in the north fork of Halfmoon drainage. The moderately productive Mount Champion gold mine, on main Halfmoon Creek, is only 1 mile west of the quadrangle boundary. The low might also be interpreted to reflect a concealed porphyry body that is similar in magnetic properties to the Twin Lakes stock or that is related to it. However, the magnetic low coincides approximately with a gravity high of several milligals. Assuming that the magnetic and gravity anomalies are due to the same cause, this would preclude an intrusion of the composition of the Twin Lakes stock, which generates a pronounced gravity low. Clearly, further geologic and geophysical investigation of this area is warranted, especially as there may be direct economic applications.

A magnetic high marked by positive anomalies *G* and *I*, separates the low just discussed from that of the Twin Lakes stock (anomaly *F*). The high is over Precambrian gneisses in a topographically high area, and it stands out mainly because of its contrast with the bordering lows.

Positive anomaly *J* is a long magnetic high that coincides approximately with the high topographic ridge that extends north-northwestward from the crest of Mount Massive. Hence, the anomaly is at least partly topographic in origin. However, it is in an area of the St. Kevin Granite, which—owing to strong reversed remanent magnetization — should produce magnetic lows rather than highs. The anomaly is coextensive with a system of strong north-northwest-trending faults, some of which contain lenticular plugs or large dikes of quartz porphyry. The fault zone may overlie an intrusive body at shallow depth, as indicated diagrammatically on plate 1, section *B–B′*. Such an intrusive body might account, in part, for the magnetic anomaly.

Negative anomaly *K*, a magnetic low over the valley of Lake Fork and the low hills of the St. Kevin mining district, probably reflects three factors in combination: (1) low topography, (2) reversed remanent magnetization in the St. Kevin Granite, and (3), extensive alteration of the rocks in the St. Kevin district. The north end of the Arkansas valley magnetic low, north of the constriction at anomaly *N*, is continuous with anomaly *K*, and may be due to these same causes, supplemented to some degree by the effects of the valley fill.

Negative anomaly *L*, near the forks of Homestake Creek, straddles a topographically high ridge in an area characterized by: (1) actinolitic quartzite and calc-silicate gneisses in a vertically standing belt nearly 1 mile wide, (2) numerous irregular bodies and very large dikes of leucocratic St. Kevin Granite, (3) many rusty zones reflecting sparsely disseminated iron sulfides in some calc-silicate layers, and (4) numerous lamprophyre and diorite dikes. The low most likely reflects a body of weakly magnetic, or reversely polarized(?), St. Kevin Granite at shallow depth, especially as it coincides with a small, but distinct, gravity low. The weakly magnetic gneisses might supplement the effect of the granite, but the swarm of mafic dikes should have the opposite effect. Conceivably, a Laramide intrusive similar to the Missouri Creek stock 2 miles to the north could lie beneath the magnetic low, but no porphyry dikes exist at the surface, and the iron sulfide mineralization in the gneisses predates the lamprophyre dikes, which are known to be Precambrian in age.

ANOMALIES IN THE SOUTHERN GORE RANGE

Other than the zone of steepened magnetic gradient related to the Homestake shear zone in the buried Precambrian rocks, the dominant magnetic anomaly in the southern part of the Gore Range is a very prominent magnetic low (anomaly *Q*) associated with the Chalk Mountain stock, west of Climax. This stock consists of rhyolite porphyry that contains very little iron in any form and, thus, is virtually nonmagnetic. The magnetic low is centered a little to the south of the stock, over a slight gravity high, and includes an area of Minturn Formation extensively intruded by Lincoln Porphyry (Tweto, 1956, section *C–C′*). This area is characterized by strong alteration and widespread weak mineralization. Thus, the magnetic low might be caused in part by altered basement rocks, as well as by the body of rhyolite porphyry.

ANOMALIES ALONG THE MOSQUITO-TENMILE RANGE

A large magnetic high (anomaly *R*), the most conspicuous anomaly of the quadrangle, is centered over the Humbug stock of quartz monzonite porphyry, but extends into adjacent areas of Precambrian rocks in the Tenmile Range. Samples collected from this stock indicate moderately magnetic to magnetic rock. It seems evident that this porphyry body is not severely altered and, thus, is not an encouraging site for prospecting. Elsewhere along the Tenmile Range, a general magnetic high, closely following the crest of the range, is found over Precambrian gneissic and granitic rocks. Positive anomaly *S* is apparently caused by the Buckskin stock, which consists of porphyries that range in composition from quartz diorite to quartz monzonite. The high continues southeastward to Alma, indicating that the magnetic unit extends at depth in that direction.

The Climax district has no distinctive magnetic expression that is evident on plate 2, but it is located in the zone of steep magnetic gradient between the high along the crest of the Tenmile Range and the low of the Chalk Mountain stock (anomaly *Q*). This zone of steep gradient marks the Mosquito fault, and it extends north and south of Climax along the fault. A detailed aeromagnetic survey of the Climax area (Meyer, 1968) showed a slight trough in the total-magnetic-intensity contours over the Climax mine area, but no closed negative anomaly. However, second derivative and residual maps yielded closures.

A general magnetic high (anomaly *U*) extends south along the crest of the Mosquito Range from the latitude of Leadville to the south edge of the quadrangle. The positive anomaly varies in amplitude along the range and reflects variations in topography, as well as zones of higher or lower susceptibility in the Precambrian granitic rocks that make up most of this part of the range. The Weston fault is locally expressed by a steepened magnetic gradient (for example, west of Peerless Mountain and Horseshoe Mountain), and sedimentary rocks west of the fault are expressed as a magnetic bench. The Union fault—the southern continuation of the Mosquito fault—is also marked by a line of steepened gradient. The small stock of Tertiary porphyry on the Weston fault at the line between Tps. 11 and 12 S., R. 78 W., apparently is nonmagnetic to weakly magnetic, as it causes no deflection of the magnetic contours.

Except for the Humbug and Buckskin stocks, none of the porphyry bodies in the Mosquito and Tenmile Ranges are marked by magnetic highs. This reflects the generally altered character of many of the porphyry bodies and, also, the fact that most of these bodies are sills and, hence, have a limited vertical dimension.

ANOMALIES IN THE EASTERN PART OF THE QUADRANGLE

A weak magnetic high (anomaly *V*) is found over the area of closely spaced porphyry intrusions northeast of Breckenridge, and a small positive anomaly (anomaly *W*) occurs over similar intrusive rocks a few miles southeast of Hoosier Pass. Thus, in their magnetic expression, these porphyry intrusions resemble the Humbug and Buckskin stocks to the west.

The most prominent anomaly along the west margin of South Park is the high (anomaly *X*) over Sheep Mountain and Round Hill. The ridgelike magnetic high coincides with a ridgelike gravity high, although the peak of the magnetic high is over Sheep Mountain, and the peak of the gravity high is over Round Hill. Both the gravity and the magnetic highs are probably caused, in part, by the crystalline rocks comprising the core of the fault block elevated along the northeast side of the London fault. However, farther northwest the fault does not show, or only weakly shows, such gravity and magnetic features, although the displacement is the same (Singewald and Butler, 1941, p. 26). A relatively dense and magnetic body of rock must underlie Sheep Mountain and Round Hill along the London fault. Such a body could be either a Precambrian rock or a younger intrusive. If Precambrian, it may be an intrusive rock, such as diabase or gabbro, along an ancestral London fault, or perhaps an isolated body of dense and magnetic gneiss, such as amphibolite. If a younger intrusive, it would seem to be unrelated to the exposed igneous rock at Sheep Mountain, as this is typical porphyry of quartz monzonitic composition. Such porphyry, like that of the Humbug and Buckskin stocks, could be the source of the magnetic anomaly, but not of the gravity anomaly. Significantly, the rhyolitic porphyry stock at Black Mountain, just south of Round Hill, has no magnetic expression, but coincides with a slight gravity low. Further studies in this area will be necessary before the anomalies along the London fault can be fully understood.

A large magnetic low (anomaly *Y*) in the southeast corner of the quadrangle is undoubtedly caused by the relatively greater depth to the crystalline basement beneath the thick cover of sedimentary rocks in this area.

SUMMARY AND CONCLUSIONS

The segment of the Colorado mineral belt that extends northeastward across the Leadville quadrangle is characterized by numerous porphyry intrusives of Late Cretaceous and Tertiary age and by major ore deposits; it coincides with a deep gravity low, or gravity valley. This gravity low is interpreted to reflect an underlying batholith. From the combination of gravity data and known geologic relations, this batholith is visualized to be greatly elongate, extending beyond the northeast and southwest corners of the quadrangle; to be 15–20 miles wide; to have an apex within a few thousand feet of the surface; to extend to depths of at least 10 miles; to be Late Cretaceous and Tertiary in age; and to consist largely of granodiorite-quartz monzonite, although grading upward to compositions near granite at the apex and downward to quartz diorite or diorite at depth. This batholith was the source of the hypabyssal sills, stocks, plugs, dikes, and sublaccolithic bodies that are exposed at the surface, and of the associated ore deposits, such as those of Leadville, Climax, Kokomo, Breckenridge, and Alma, as has been predicated previously on purely geologic grounds (Crawford, 1924; Tweto and Sims, 1963).

Except for the Twin Lakes stock, none of the exposed intrusive bodies in the quadrangle have a marked gravity expression — that is, none affect more than one or two gravity contours. The evident reason for this is that the individual porphyry bodies are small in volume, and their density contrast with their surroundings is not great. The Twin Lakes stock, by far the largest exposed intrusive body in the quadrangle, has volume and density contrast large enough to affect the gravity contours, and it coincides with a pronounced negative gravity anomaly.

In the Arkansas valley graben, a deep fill of low-density Tertiary sediments and overlying Pleistocene glacial deposits accentuates the mineral-belt gravity low. Gravity data suggest that this fill may be 3,000–4,000 feet thick in the deepest part of the graben, 1–2 miles west of the Arkansas River. This thickness may be less if (as is possible) the gravity low over the valley is caused, in part, by a large intrusive body of porphyry in contact with Precambrian rocks in the bedrock beneath the fill. Data from shafts, drill holes, and limited seismic surveys near the margin of the valley fill indicate the presence of many faults that cut the valley fill materials and, therefore, must displace the underlying bedrock. In light of the mineral productivity of the area of intrusion and gravity low, from Leadville northeastward, the covered valley southwestward along the axis of the low is worthy of consideration for exploration. If exploration is undertaken, an uneven, block-faulted bedrock, with relief of at least many hundreds of feet, is to be expected. More detailed geophysical surveys, particularly resistivity and seismic, would be required to delineate the bedrock surface in advance of physical exploration. However, limited seismic exploration in the valley has shown that fossil caliche zones in the Tertiary sediments and the weathered tops of superposed tills present problems for the seismic method. A few miles south of the Leadville quadrangle, resistivity soundings have proved effective in determining the depth to bedrock acording to W. D. Stanley of the U.S. Geological Survey (oral commun., 1970).

The largest magnetic feature in the quadrangle is a low over the Arkansas valley. This low is attributed mainly to the combination of low topography and deep valley fill, but, inasmuch as it coincides approximately with the gravity low, it could also reflect the presence of such rocks as the St. Kevin Granite or porphyry similar to that of the Twin Lakes stock. Both of these rocks have densities and magnetic properties that cause gravity and magnetic lows.

A zone of steep magnetic gradient characterizes the Homestake shear zone, which extends northeastward across the northwestern part of the quadrangle. This gradient is attributed to difference in the Precambrian rocks on the two sides of the shear zone, and possibly to the magnetic properties of the shear zone itself. Gravity contours parallel the magnetic contours along the shear zone, reflecting the concealed batholith and the control of the northwest side of this batholith by the shear zone.

The porphyry intrusive bodies show a wide range in magnetic expression. A few, such as the Humbug and Buckskin stocks, are magnetic highs. Others, such as the Twin Lakes and Chalk Mountain stocks, are magnetic lows. Most of the intrusive bodies, however, have no magnetic expression. The reasons for this are varied. Many of the bodies are altered—deuterically or hydrothermally, or both — with consequent destruction of the magnetite in them. Many are in sills which, although thick by the standards for sills, have a negligible vertical dimension. A few, such as the stocks in the southeast corner of the quadrangle, evidently have a mineralogic composition that produces magnetic characteristics indistinguishable from those of the surrounding rocks.

Neither the highly mineralized and intruded Climax district nor the Leadville district has a distinctive magnetic expression at the scale of the survey reported here. The Climax district is in a zone of steep magnetic gradient along the Mosquito fault, and the Leadville district is in a magnetically flat area at the edge of the Arkansas valley magnetic low.

A small, high-amplitude magnetic low in the Half-moon Creek area may reflect rock alteration, possibly in combination with a concealed intrusive body, and is worthy of further investigation. An elongate magnetic high along a fault zone to the north, on Mount Massive, possibly reflects a buried intrusive body, though quartz porphyry dikes exposed at the surface probably are not magnetic. A pronounced magnetic high over the Humbug stock suggests that the rock in the stock is unaltered. Thus, if any part of the stock is mineralized, the mineralization would likely be "primary," in the sense of being of the same age as the intrusive rock. A magnetic high along the London fault at Sheep Mountain and Round Hill might be interpreted to reflect porphyry intrusions that are largely concealed, but a gravity high coincident with the magnetic high cannot result from such a cause. A concealed mafic intrusive body may be the cause of both anomalies.

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