UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

Geologic interpretation of gravity and magnetic data in the Salida region, Colorado

By

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This report is preliminary and has not been reviewed for conformity with U. S. Geological Survey editorial standards and stratigraphic nomenclature. Trade names are used for descriptive purposes only.

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INTRODUCTION

The Upper Arkansas Valley region, centered around Salida, Colorado, is a major structural knot in the Southern Rocky Mountains (fig. 1) where elements of several mountain ranges, large basins, and graben intersect. The region is of special economic interest because it includes large centers of Cretaceous-Tertiary igneous activity that are associated with mineralization in the central segment of the Colorado Mineral Belt (Tweto and Sims, 1963).

Gravity and aeromagnetic surveys were conducted over the region at intermittent intervals during 1962-1968 to provide control on concealed rock types and structure and on the dimensions and configuration of larger rock masses at depth. An interpretive report on data from the Leadville 30-minute quadrangle, just to the north of the Salida region, covers the main part of the central Colorado Mineral Belt (Tweto and Case, 1972). This report briefly summarizes the regional geology and the principal interpretations derived from the gravity and aeromagnetic data over the Salida region. The geophysical maps (plates 1 and 2) are superimposed on a screened topographic and geologic base at scale 1:125,000. Other geophysical surveys in the region will be listed on p. 12 .

Several large structural-geomorphic blocks have been identified in the area. In the central and northern part of the area, a major anticlinal uplift, cored with Precambrian rocks, extends from near Salida and Monarch northward into the Leadville 30-minute quadrangle (fig. 1 and plates). The Sawatch Range is carved in the western part of the anticline and a southern extension of the Mosquito Range in the eastern part. Between the two mountain ranges, a large graben, part of the Greater Rio Grande rift system, has formed along the approximate crest of the anticline. The Arkansas River flows through the graben, and its valley is filled with thick Tertiary and Quaternary terrestrial deposits. In the north-eastern part of the area, a major structural and topographic basin forms the southern part of South Park. To the south, the northern end of the San Luis Valley is an asymmetrical graben which is a northern segment of the main Rio Grande rift system. East of the northern San Luis Valley, the northern Sangre de Cristo Range trends northwest as a tilted block of Precambrian rocks having Paleozoic sedimentary rocks preserved on its northeastern flank. Precambrian rocks are exposed in patches west of the San Luis Valley and may represent a southern extension of the Sawatch Range block. Most of the area immediately west of the San Luis Valley area, however, is dominated by extensive volcanic deposits of the Bonanza Caldera, the northeastern part of the San Juan volcanic field. A graben filled with Tertiary sedimentary rocks nearly connects the San Luis Valley graben with the Arkansas Valley graben, and both graben are regarded as part of the Rio Grande rift system. Another basin or graben filled with Tertiary sedimentary rocks occurs in the lower valley of the Arkansas River near Stout Creek School in the southeastern part of the region. A complex syncline and anticline occur between the Mosquito Range and South Park Basin in the Cameron Mountain and Antero Reservoir quadrangles. Many structural features, especially the uplifts and depressions, are Neogene. Deformation also occurred in Laramide time, during Late Paleozoic, and during several Precambrian intervals (Tweto, 1975).

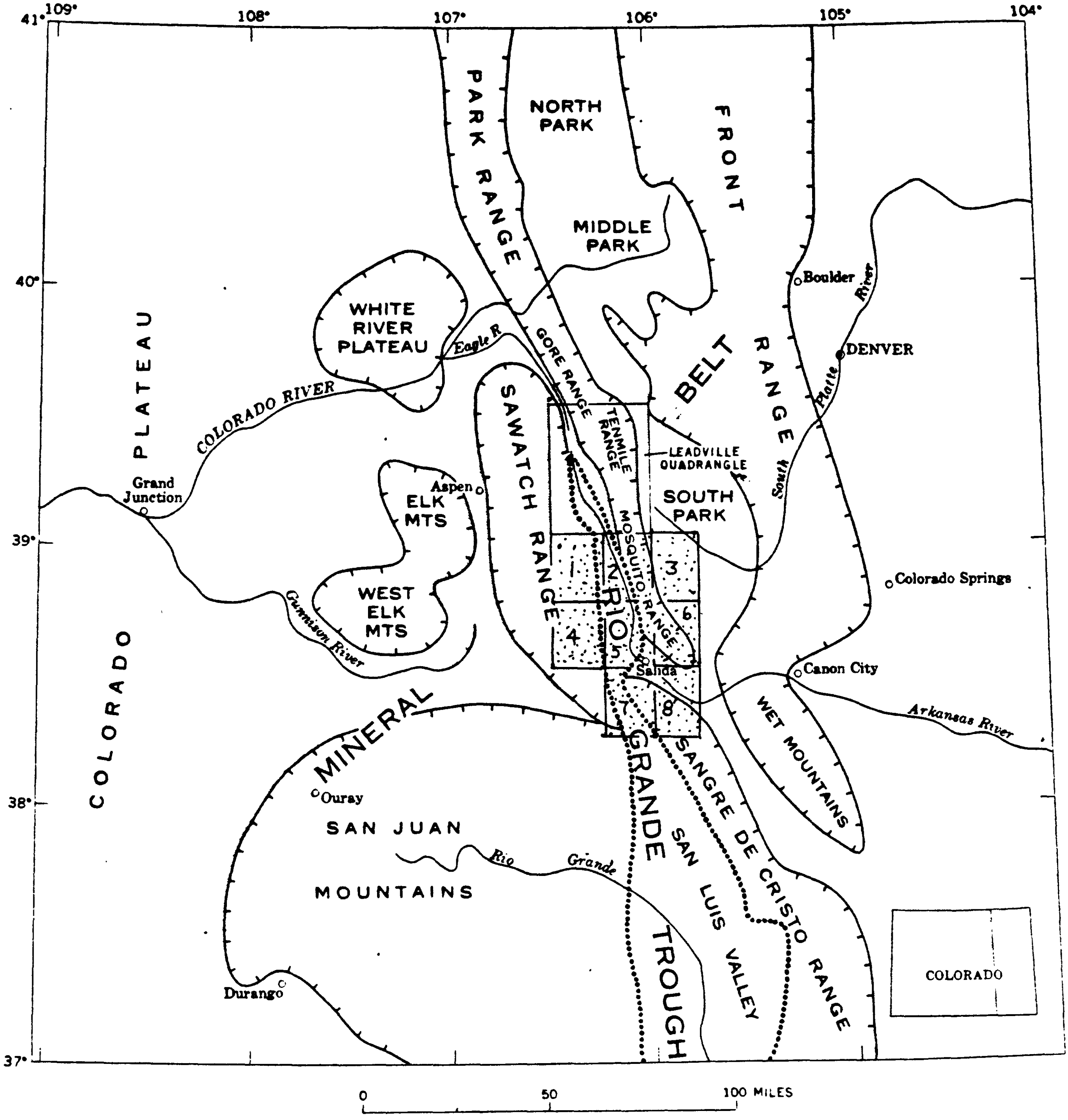


Figure 1.-Index map of central and western Colorado, showing location of the Salida region (dots) and the Leadville 30-minute quadrangle in relation to the Colorado mineral belt and the Rio Grande trough. Fifteen-minute quadrangles are: 1. Mt. Harvard, 2. Buena Vista, 3. Antero Reservoir, 4. Garfield, 5. Poncha Springs, 6. Cameron Mountain, 7. Bonanza, and 8. Howard.

Summary of Major Rock Units

Because many of the rock units of the Salida region (table 1) are like those in the Leadville 30-minute quadrangle to the north, one may conveniently refer to a more detailed regional summary prepared by Tweto and Case (1972). For the geologic base for plates 1 and 2 within the Salida region, the principal sources were maps at scale 1:250,000 for the Montrose 1° X 2° quadrangle (Tweto and others, 1976,), the Pueblo 1° X 2° quadrangle (Scott and others, 1976, 1978), and the geologic map of Colorado, scale 1:500,000 (Tweto, 1979). More detailed maps cover the Antero Reservoir quadrangle (De Voto, 1971); Buena Vista quadrangle, (Scott, 1975); Mt. Harvard quadrangle, (Brock and Barker, 1972); Cameron Mountain quadrangle (Wrucke and Dings, 1979); Poncha Springs quadrangle (Van Alstine, 1969; Scott and others, 1975); Garfield quadrangle (Dings and Robinson, 1957); Howard quadrangle (Taylor and others, 1975); and Bonanza quadrangle (Knepper, 1973, Marrs, 1973, Knepper and Marrs, 1971, and theses of several areas by students at the Colorado School of Mines).

Precambrian rocks.--The oldest Precambrian rocks exposed in the region are metasedimentary and metaigneous rocks of relatively high metamorphic grade (units Xbg and Xvf on geologic base). The rocks include extensive exposures of micaceous feldspathic gneiss, amphibole gneiss, and amphibolite. Schistose rocks are locally abundant, especially in the northern Sangre de Cristo Range and in the southern Sawatch Range.

The older complex of metasedimentary and metaigneous rocks has been intruded by Precambrian granitoid rocks of two types and ages. The older intrusive rocks (unit YXg) are of the "Boulder Creek" type, which generally are mafic quartz monzonite or granodiorite that are foliated in many

Table 1.--Generalized geologic column, Leadville 30-minute quadrangles
(Note that thicknesses differ somewhat in the Salida region)

Age	Unit (Symbol on geologic base in parenthesis)	Thickness (feet) (meters)	Character and remarks
Quaternary	Alluvium, morainal deposits, and outwash gravels 'QT)	0-500+ (0-152+m)	
	Various upper Tertiary sedimentary units (QT)	0-2000(?) (0-610(?)m)	Loosely consolidated sandy silt, sand, and gravel. Miocene and Pliocene in age; may be underlain by unexposed older Tertiary units in Arkansas valley.
Tertiary	Terrestrial sedimentary rocks (T)	0-4000+(?) (0-1220+(?)m	Moderately consolidated conglomerate, tuff, sandstone.
	Extrusive igneous rocks (Tv)	0-8000+(?) (0-2440(?)m)	Wide variety of basalt, andesite, and rhyolite, and alkalic volcanic flows, ignimbrites, and associated volcaniclastic rocks; mainly Oligocene and Miocene.
	Intrusive igneous rocks 'TKi)		Porphyries of many varieties; mainly quartz monzonite, but range from granodiorite to granite in composition.
Cretaceous	Mancos Shale (Mz)	Several hundred feet	Shale, minor siltstone and sandstone.
	Dakota Sandstone (Mz)	0-200 (0-62m)	Sandstone, quartzite, and shale
Jurassic	Morrison Formation (Mz)	0-300 (0-91m)	Sandstone, shale, and limestone
Permian and Pennsylvanian	Sangre de Christo and Maroon Formations (uPz)	0-10,000(?) 0-3048(?)m)	Sandstone, grit, conglomerate, and shale. Local limestone and gypsum'(?)
Pennsylvanian	Minturn Formation (uPz)	0-4,000 (0-3048(?)m	Grit, conglomerate, sandstone, limestone, local evaporites.
	Belden Formation (uPz)	0-1,700 (0-518m)	Shale, sandstone, limestone, local evaporites.

(Table continues on following page)

Table 1 (Continued)

Mississippian	Leadville Dolomite or Limestone (lPz)	0-350 (0-107m)	Dolomite or limestone.
Mississippian and Devonian	Chaffee Group (lPz)	0-300 (0-91m)	Dyer Dolomite Gilman Sandstone Member, 15-25 ft., 0-80 ft; Parting Formation at base, 0-55 ft.
	Fremont Limestone or Dolomite (lPz)	0-135 (0-41m)	Limestone and dolomite.
Ordovician	Harding Sandstone (lPz)	0-40m (0-12m)	Sandstone, quartzite, and shale.
	Manitou Dolomite (lPz)	0-150 (0-46m)	Cherty dolomite.
Cambrian	Peerless Formation (lPz) (Absent in Salida region)	0-100 (0-30)	Sandstone and dolomite.
	Sawatch Quartzite (lPz) (Only thin edge occurs in Salida region)	0-190 (0-58m)	Quartzite.
	Younger granites, 1,400 m.y. (St. Kevin and Silver Plume types)(Yqm)		Quartz monzonite and granite.
Precambrian	Older granites, 1,700 m.y. (Denny Creek Granodiorite Gneiss and related rocks)(YXg)		Granodiorite and quartz diorite.
	Mafic, ultramafic rocks, and local diorite (Xm)		Gabbro, metagabbro, amphibole rock.
	Metasedimentary and metaneous gneisses and schists (Xbg and Xvf)		Biotite gneiss, migmatite, hornblende gneiss, calc-silicate gneiss, impure quartzites, amphibolite and micaeous schists.

places. The Denny Creek Granodiorite Gneiss (Brock and Barker, 1972) in the Mt. Harvard quadrangle is representative of the older, syntectonic plutons. The Boulder Creek types have been isotopically dated at about 1.7 b.y. by Peterman and others (1968). The younger granitic rocks (Yqm) are of the "Silver Plume" type, a porphyritic biotite quartz monzonite or granite. This group of granitic rocks has been dated at about 1.4 b.y. in many parts of Colorado (Pearson and others, 1966; Hedge and others, 1968). These rocks are commonly unfoliated or only weakly foliated. Small bodies of mafic rocks consist of dark-greenish-gray massive to foliated metamorphosed gabbro (Xm).

Sedimentary rocks

Paleozoic, Mesozoic, and Cenozoic sedimentary rocks are preserved in places in the area. Most of the preserved rocks are Paleozoic. Mesozoic strata are thin and are preserved only in the extreme northeastern corner of the Antero Reservoir quadrangle and extreme southwest corner of the Garfield quadrangle. Cenozoic strata are thickest in the intermontane basins and graben of South Park, Arkansas Valley, and San Luis Valley.

Paleozoic strata--Cambrian strata are mainly quartzite and are less than 100 feet (33m) thick. Ordovician strata include as much as 325 feet (99m) of cherty dolomite, sandstone, quartzite and shale; and limestone and dolomite. Devonian and Mississippian strata are mainly limestone, dolomite, and quartzite having an aggregate thickness of as much as 735 feet (224m). Most of these older Paleozoic units are shallow marine deposits. They have little influence on interpretations of the geophysical data because their densities are similar to those of underlying Precambrian rocks, and they are virtually nonmagnetic. These units are of considerable economic significance, however, because they are hosts for some ore deposits, and some units in south Park possibly may be prospective for oil or gas.

Late Paleozoic strata include locally thick sequences of marine carbonate and clastic deposits of Pennsylvanian age that grade upward into sandstone, grit, conglomerate, and shale of Pennsylvanian and Permian age that are continental deposits derived from erosion of the ancestral Rockies. These beds locally are more than 10,000 feet (3,048m) thick. The rocks are only weakly magnetic and their densities, especially the clastic facies, are probably somewhat less than those of the average Precambrian basement.

Mesozoic strata--Triassic and lower Jurassic rocks were either not deposited or have been eroded from the region. The Late Jurassic Morrison Formation, present only in the northeast and southwest corners of the map area, consists of as much as 300 feet (91m) of sandstone, shale, and minor limestone lying on Precambrian rocks. It is overlain in small areas by the Dakota Sandstone and overlying Mancos Shale of Cretaceous age.

Cenozoic strata--Thick sequences of moderately consolidated conglomerate, tuff, sandstone, and poorly consolidated sandy silt, sand, and gravel occur in all major structural depressions of the area. Thickness probably exceed 4,000 feet (1219 m) in South Park, Arkansas Valley, and San Luis Valley. The sediments for these accumulations were derived not only from Cenozoic erosion of the rising mountain ranges but also from volcanic ejecta from centers within the area, such as the Bonanza Caldera, and from the San Juan Mountains volcanic field to the west and southwest. These deposits produce few, if any, magnetic anomalies, but their density is low in comparison to the Paleozoic and Precambrian rocks, and major gravity lows are associated with the larger Cenozoic basins.

Quaternary glacial deposits are widespread along the flanks and interior of the higher mountains. Alluvium, terrace deposits of several varieties, and colluvial deposits are common, but these deposits are generally so thin that they have little influence on the gravity and magnetic anomalies.

Cenozoic volcanic rocks

Two general groups of Tertiary volcanic rocks are present in the area: in the southwest, a wide variety of flows, ash-flow-tuffs, tuff, and volcanogenic sedimentary rocks are associated with the Bonanza Caldera, one of the most easterly centers of the greater San Juan Mountains volcanic field (Steven, 1975). Most of the rocks are andesitic to rhyolitic. In the eastern part of the area, thinner, more sporadic patches of volcanic rocks, including parts of the Thirtynine Mile volcanic field, occur in the Mosquito Range, South Park, and along the east margin of the Arkansas Valley depression. Volcanic rocks include: The Wall Mountain Tuff (older than tuffs of San Juan provenance; age 35-36 m.y.), the early ash-flow tuff of the Sawatch Range province; pre-ash-flow andesitic flows, breccias, tuffs (general age 30-35 m.y.); intra-ash-flow andesitic flows; ash-flow tuff of main volcanic sequence (age in San Juan Mountains 26-30 m.y.; in South Park 29-32 m.y.). Volcanic units are relatively thin, less than 1,000 feet (305m), in most of the area, except in the vicinity of the Bonanza Caldera where thicknesses of as much as 8,000 feet (2,440m) may occur.

Cretaceous and Tertiary intrusive rocks

The Whitehorn Granodiorite (Wrucke, 1974), on the east side of the Arkansas Valley, forms a pluton with three small satellitic bodies. It ranges in composition from syenogabbro to quartz monzonite, but granodiorite is the most common composition. Potassium-argon ages range from about 69 to 70 m.y. (Late Cretaceous). In the northwest part of the area, the southern part of the Twin Lakes stock is exposed (Wilshire, 1969; Brock and Barker, 1972); granodiorite is the commonest composition but it is a quartz diorite in places. It is locally coarsely porphyritic, but in the Mt. Harvard quadrangle it tends to be more equigranular. Isotopic ages by various methods range from about 42 to 56 m.y. (summarized by Tweto and Case, 1972). Middle Tertiary intrusive rocks (Miocene and Oligocene) include granodioritic, quartz monzonitic, and granitic rocks in stocks, dikes, sills, laccoliths, and irregular bodies in the western part of the area (Tweto and others, 1976), and a small body of sodium rich granite (Miocene?) in the extreme southeastern part of the area.

Physical Properties of Rock Units

Summaries of measured density (fig. 2) and magnetic properties (fig. 3) of samples from the Salida region were included with data from the Leadville quadrangle (Tweto and Case, 1972) and will be discussed only briefly here. Map symbols of the various units are shown in parentheses.

Densities of four samples of amphibole gneiss (from units Xvf and Xbg) range from about 2.95 to 3.1 g/cm^3 and average 3.0 g/cm^3; 20 samples of biotite gneiss and migmatite (Xvf and Xbg) range from about 2.6 to 2.95 g/cm^3 and average 2.75 g/cm^3; 12 samples of older granitoid rocks (Denny Creek Granodiorite Gneiss, and other granites, YXg) range from 2.6 to 2.9 g/cm^3 and average 2.71 g/cm^3; 23 samples of younger granitic rocks (St. Kevin and Silver Plume types, Yqm,) range from 2.55 to 2.70 g/cm^3 and average 2.64 g/cm^3 (fig. 3). Isaacson and Smithson (1976) reported a mean density of 2.71 g/cm^3 for Precambrian rocks, undivided.

Densities of 15 samples of lower Paleozoic [pre-Beldon] quartzites, sandstone, and calcareous sandstone average 2.63 g/cm^3, and those of six samples of limestone and dolomite average 2.80 g/cm^3. Inasmuch as these two

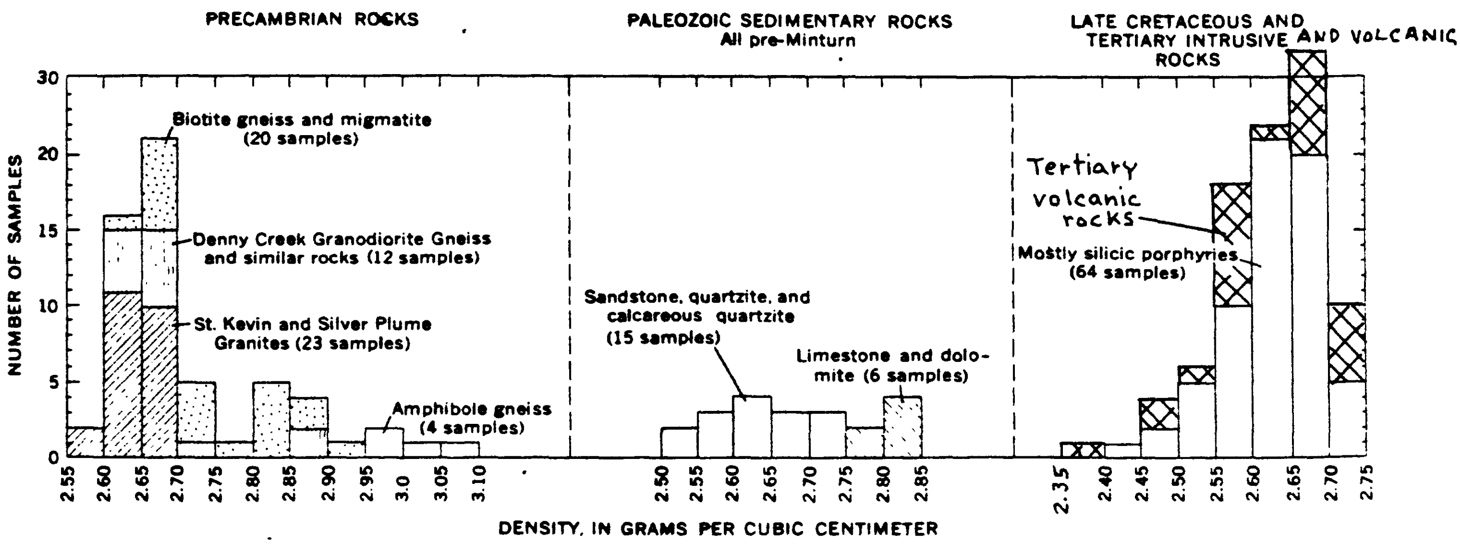


Figure 2.-Densities and total samples of major rock units.

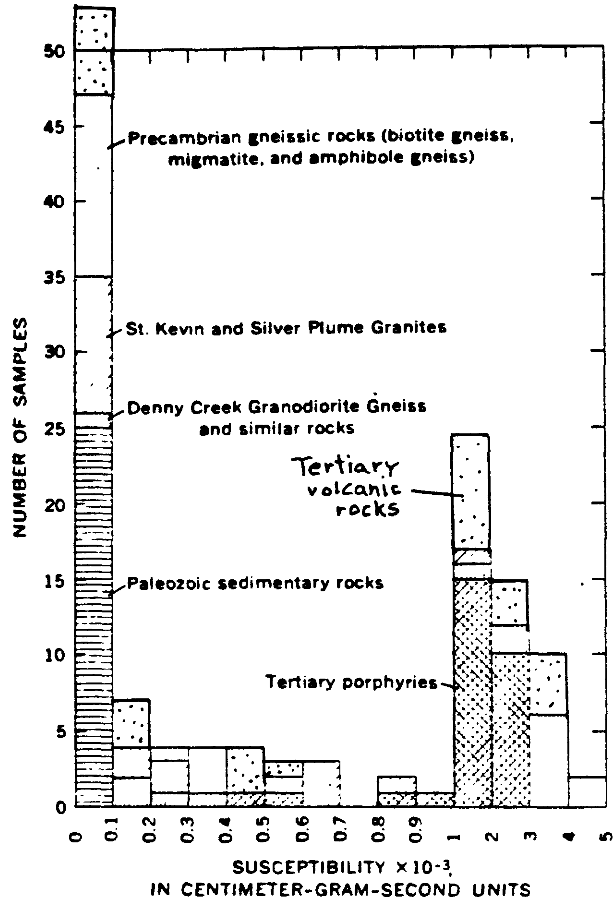


Figure 3.-Magnetic susceptibilities of rocks from the Leadville quadrangle and Salida region, Colorado.

general lithologies are about equally abundant in the lower part of the stratigraphic section, the average density for the pre-Belden rocks, thus, is about 2.71 g/cm^3. Although the number of samples measured is small, this value seems reasonable. The point to be emphasized is that the density of this thin unit (500-1,000 ft., 152-304m) is not greatly different from the average for the Precambrian rocks.

The clastic rocks of the Belden, Minturn, and Maroon Formations are quartzo-feldspathic sandstone and siltstone and some shale. 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/cm^3 (Byerly and Joesting, 1959, p. 41).

The average density of 64 samples of Tertiary and Cretaceous intrusive rocks from 37 localities in the region is 2.64 g/cm^3. Most of these samples are from the Mount Princeton batholith, which represents the largest exposed sample of the batholith presumed to underline the Colorado mineral belt. Isaacson and Smithson (1976) measured a mean density of 2.63 g/cm^3 for 27 samples of Tertiary granitic rocks.

Densities of 25 samples of Tertiary volcanic rocks range from 2.35 (a dacite breccia) to 2.75 g/cm^3 and average 2.61 g/cm^3. Few measurements are available for densities of such Tertiary sedimentary rocks as the Dry Union, Santa Fe, Antero, and Wagontongue Formations. Values of about 2.1 to 2.37 g/cm^3 have been commonly assumed for the several gravity investigations in the region (Tweto and Case, 1972, Snyder, 1968, Gaca and Karig, 1965, Isaacson and Smithson, 1976; Davis, 1979).

Magnetic Properties

Most of this discussion is modified from Tweto and Case (1972).

Numerous samples of the various Precambrian rock units, Tertiary and Cretaceous intrusive rocks, and Tertiary volcanic rocks 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 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 four major magnetic units--Precambrian granitic rocks, Precambrian metamorphic rocks, Tertiary and Cretaceous intrusive rocks, and Tertiary volcanic rocks--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.

The 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 3. 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 X 10^{-3} cgs (centimeter-gram-second) units shown on the histogram (fig. 3). Another major cause of low susceptibility is deuteric or hydrothermal alteration of rock samples in which magnetite may be converted to weakly magnetic oxide or sulfide 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 X 10^{-3} cgs units are nonmagnetic to weakly magnetic; (2) rocks whose susceptibilities range from 1.0 to 3.0 X10^{-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 X 10^{-3} cgs units are moderately to strongly magnetic and cause anomalies of several hundred gammas, as observed at the flight level of the aircraft (14,500 feet, 4,429 m).

Precambrian gneiss--Susceptibilities of Precambrian gneiss samples show a bimodal distribution (fig. 3). Sixteen samples have susceptibilities below 1.0 X 10^{-3} cgs units and eight samples have susceptibilities above 3.0 X 10^{-3} cgs units. Migmatitic gneiss in the Sangre de Cristo Range appears to be somewhat more magnetic than most gneiss units of the Salida region, as determined from its expression on the aeromagnetic map.

Remanent magnetization of the gneiss is extremely variable in both intensity and direction. Intensities range from 0.001 to 0.854 X 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. so that 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 granitoid rocks--Magnetic susceptibilities of the Denny Creek Granodiorite Gneiss and similar rocks average about 0.86 X 10^{-3} cgs units, and those of the St. Kevin and Silver Plume types average 0.32 X 10^{-3} cgs units. All but one sample of the St. Kevin and Silver Plume types have susceptibilities less than 1 X 10^{-3} cgs units and that one has a susceptibility less than 2 X 10^{-3} cgs units. Many granitoid rocks are moderately to strongly magnetic as clearly indicated by large positive anomalies associated with them.

Paleozoic sedimentary rocks--Figure 3 shows that the Paleozoic sedimentary rocks have magnetic susceptibility values of less than 0.1 X 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 have a wide range of magnetization from less than 0.4 x 10^{-3} to more than 3 x 10^{-3} cgs units. Fresh samples generally have moderately high values of magnetic susceptibility, but altered ones have low values. Thus, both magnetic highs and lows are found over the plutons; magnetic lows may reflect either alteration or a low original content of magnetite in fresh rock.

Remanent magnetization of Tertiary intrusive rocks is generally weak and variable; no measured samples have reversed directions of remanent magnetization. Most remanent directions are northeastward. Their apparent inclination is somewhat greater than that of the earth's present field in the region but no samples were demagnetized. Q values are variable and range from 0.02 to 1.27. Samples were not demagnetized, so these results should not be used for paleomagnetic investigations.

Magnetic properties of the Whitehorn stock will be briefly discussed in the intepretation section (p. 31).

Tertiary volcanic rocks--Magnetic properties of only a few scattered samples of Tertiary volcanic rocks were measured. Susceptibility values of 27 samples range from about 0.02 to 3.99 X 10^{-3} and average 1.3 X 10^{-3} cgs units. Remanent magnetization has a huge range--from 0.02 X 10^{-3} to more than 300 X 10^{-3} emu/cc. I suspect that lightning is responsible for high values of remanent magnetization of these undemagnetized specimens. Inspection of the aeromagnetic map suggests that volcanic rocks (relatively thin) in the eastern part of the area are only weakly to moderately magnetic as they appear to have little magnetic expression at the flight elevation of 14,500 feet (4,420 m), but they are well-expressed on a low level survey flown at 1,000 feet (305 m) above the surface (U.S. Geological Survey, 1979). Volcanic rocks in the vicinity of the Bonanza Caldera appear to be somewhat more magnetic, and some negative anomalies there may be produced by hydrothermal alteration or by reversed remanent magnetization, as discussed in the interpretation section.

Other geophysical surveys

A consideragle amount of geophysical work has been conducted in the Salida region and adjacent areas since 1965.

Reconnaissance gravity data over the southern Sawatch Range and vicinity were briefly discussed by Case (1965, 1967). Gravity surveys in South Park were interpreted by Snyder (1968). Gaca and Karig (1965) and Karig (1965) described general features of the northern San Luis Valley and of the Bonanza Caldera. Marrs (1973) also presented a brief discussion and interpretation of geophysical data over the Bonanza area. Isaacson and Smithson (1976) interpreted gravity features of the western part of the area, especially the anomaly associated with the Mt. Princeton batholith. Plouff and Pakiser (1972) described the gravity field of the San Juan volcanic field, which extends into the Bonanza region. The broader regional setting of the gravity field of the area can be seen on the gravity anomaly map of Colorado by Behrendt and Bajwa (1974) and of the magnetic field by Zietz and Kirby (1972a, 1972b). Resistivity surveys have been conducted in the Arkansas Valley by Zohdy and others (1971), and two-dimensional gravity analyses across the Arkansas Valley were prepared by Donald Peterson (unpublished data included with this report). A Bouguer anomaly map of the Pueblo 1° X 2° quadrangle was released on open-file by Peterson, Kleinkopf, and Wilson (1974) and Boler and others (1982), and aeromagnetic and gravity anomaly maps and interpretations to accompany a resource appraisal of the quadrangle have been prepared by Boler and Klein (1982a, 1982b). Aeromagnetic surveys over the Cameron Mountain and Antero Reservoir quadrangles, flown at 1,000 feet (304m) above the ground surface, were released on open-file (U.S. Geological Survey, 1979a). A gravity survey of the San Luis Valley region included a resurvey and reinterpretation of parts of the Bonanza and Howard quadrangles (Davis, 1979). An aeromagnetic survey of the Maroon Bells area, northwest of the Salida region, was released on Open-File in 1979 (U.S. Geological Survey, 1979b).

DESCRIPTION OF SURVEYS

Gravity Survey

Gravity stations were established during 1961-65 along nearly all roads accessible by vehicle and, also, by foot traverse along many ridges. Worden gravity meter no. 90 with scale constants of about 0.5 mgal per scale division were used throughout the survey. A 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 (location shown by Tweto and Case, 1972, fig. 5). The value of observed gravity assumed for 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).

Locations of gravity stations were plotted on the Mt. Harvard, Buena Vista, Antero Reservoir, Garfield, Poncha Springs, Cameron Mountain, Bonanza, and Howard 15-minute quadrangles (scale 1:62,500).

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 determined from the Garfield quadrangle map, are subject to greater uncertainty than those from the other maps.

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 which utilized the 1930 International Gravity formula and datum. Bouguer anomalies based on the more recent absolute gravity standard "IGSN 71" and Geodetic Reference System 1967 (GRS 67) are about 2.5 mGal more negative for the latitude of the Salida region than those based on the old system (see discussion by Oliver, 1980). Terrain corrections, determined for all stations, ranged from 0.6 mGal at lower stations in the open flat valleys to more than 40 mGal at the highest peaks. 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, 1977) which utilizes digitized terrain on a geographic coordinate basis of 1 minute for Hammer zone I (2.6146 km) through 21.9 km, and a 3-minute basis for 21.9-166.7 km.

Principal facts for gravity stations were released on open-file (Case, 1973). Stations for which large errors in Bouguer anomalies are suspected, probably the result of erroneous elevation or observed gravity, are indicated by triangles on plate 1.

Errors in the Bouguer anomalies--In mountainous regions where topographic relief is great, as in the Salida region, 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 (0.3m) at the better bench marks to as much as 50 feet (15m), 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 (6m), 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 less than 0.1 mGal for stations in the flat valleys to more than 4 mGal at higher peaks.

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. At a few stations, the gravity meter may have been misread.

The normal expected error in the Bouguer anomaly value at an individual station is about 2 mGal, as a subjective estimate, although the total error might be as great as 5 mGal at a few high peak stations. 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 hand-drawn as smooth lines between control points, without any special attempt to reflect known geologic features.

Aeromagnetic Survey

Aeromagnetic surveys over most of the northern part of the area were flown in a twin-engine aircraft at an elevation of 14,500 feet (4,420 m) 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 about 2 miles (3.2 km) 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 parts of the Pueblo and Montrose 1° X 2° quadrangles (1:250,000). The aeromagnetic map, contour interval 20 gammas, was compiled by standard methods (Balsley, 1952). The southern part of the area was flown in 1968 by similar methods but the flight lines were spaced at about 1 mile (1.6 km) apart. The compilations were released on open-file by the U.S. Geological Survey (1978).

General Features of the Bouguer Anomaly Map

One of the outstanding gravitational features of the region is the general change in level of the Bouguer anomaly field east of the Arkansas Valley and San Luis Valley as compared with values to the west. Bouguer anomalies over Precambrian areas of the Mosquito Range and Sangre de Cristo Range, in the eastern province, are about -250 to -270 mGals. In contrast, Bouguer anomalies over the Sawatch Range have values of -270 to -290 mGals, or even more negative, over Precambrian rocks. Although part of this difference may be related to differences in mean topographic elevation, and part to the influence of low-density Tertiary and Cretaceous (?) batholithic masses in the Sawatch Range, it appears that the change may also coincide with a change in gross crustal or upper mantle properties. Refraction evidence (Prodehl and Pakiser, 1980) suggests that the average crustal thickness is about 48 km in the Sawatch Range and Park Range and 52 km in the Front Range; unless the crust is thicker beneath the Sawatch Range than beneath the Front Range, the mean crustal-upper mantle density is probably lower beneath the Sawatch Range than beneath the eastern area to account for lower gravity anomaly values beneath the Sawatch Range.

Superimposed on this regional pattern are high-amplitude lows that coincide with the Twin Lakes pluton in the northwest (G14), with the Mt. Princeton batholith in the west-central part of the area (G17), and with the Bonanza Caldera complex in the southwest (G43).

Either closed lows or areas of flattened gravity gradient occur over the major basins of the Arkansas Valley, San Luis Valley, and South Park. Adjacent to these areas are relative gravity highs over the Mosquito Range, Sangre de Cristo Range, and Sawatch Range which are related to relatively dense uplifted basement blocks.

Several conspicuous gravity highs occur over Precambrian terranes having a high proportion of mafic rocks--amphibolites (not shown on geologic map) and metagabbros. A large high is evident in the western part of the Sawatch Range near Cottonwood Pass (G15), and another near Chipeta and Ouray Peaks (G38), southeast of Monarch Pass. This latter anomaly, however, may be more apparent than real, due to the relative negative anomaly (G35) over the block of Tertiary sediments near Cleveland Mountain.

Another prominent gravity high (G25) occurs near Cameron Mountain, over the Whitehorn granodiorite pluton and local mafic Precambrian rocks near Salida.

Several zones of steepened gravity gradient clearly indicate major fault zones. The most prominent of these occur along the east side of the Upper Arkansas Valley (G8), along the south side of the Arkansas Valley (G47), and along the east side of the San Luis Valley (G34).

General Features of the Magnetic Map

As is the situation in the Leadville 30-minute quadrangle to the north, the intrusive, extrusive, and metamorphic rocks in the Salida region have wide ranges in magnetic properties: some of the igneous rocks are magnetic and some are not; some of the metamorphic rocks are magnetic and some are not. Moreover, as in the Leadville quadrangle (Tweto and Case, 1972), the pattern of magnetic anomalies is strongly influenced by the extreme topographic relief of the region--up to 5,000 feet (1,524 m) in short horizontal distances. Several magnetic anomalies have composite rock sources. The Earth's regional field was not removed. It increases northward about 500 gammas across the area.

Most of the major basins are characterized by relatively negative magnetic anomalies, in keeping with the great depth to magnetic basement.

For some units, particularly the Tertiary intrusive rocks, alteration has locally lowered the susceptibility, and local magnetic lows develop, even at high elevations. Such magnetic anomalies may constitute indirect clues to ore deposits, as discussed below for specific areas.

Interpretation of the Geophysical Anomalies

In the following discussion, anomalies will be generally interpreted from east to west and north to south. An M-prefix refers to a feature shown on the magnetic anomaly map and a G-prefix to a feature on the gravity anomaly map.

South Park and Mosquito Range--It should be noted that Snyder (1968) has a very detailed gravity survey of the northern part of the Antero Reservoir quadrangle. The contours on his Bouguer anomaly map and residual anomaly map (shown here as fig. 4) differ only in minor detail from those anomalies shown on plate 1 of this report. To the northeast, a prominent pair of positive magnetic anomalies (M1 and M2) and gravity anomalies (G1 and G2) occur over the structurally high block that lies east of the South Park Basin. Although Tertiary volcanic rocks are widely exposed in this area, they are relatively thin, and Precambrian granitic rocks crop out under anomaly 1 and on the west flank of anomaly 2. Thus it appears that the anomalies are caused principally by structurally shallow Precambrian basement as interpreted by Boler and Klein (1982a) who estimated that sources are buried at depths of 0.5 to 1.0 km below the ground surface. From the steepness and linearity of gradients along the west flanks of magnetic anomalies 1 and 2, shown on the low-level survey (U.S. Geological Survey, 1979a), a concealed fault, downthrown to the west, is interpreted. The fault lies close to segments of concealed faults postulated by De Voto (1971).

Just to the west, major magnetic (M3 and M4) and gravity (G3 and G4) lows occur over the South Park Basin. Both gravity and magnetic lows are interrupted by a saddle of high values (M5, G5) near the boundary between Tps. 13 and 14 S., R. 76 W. The residual gravity anomaly (G3) to the north is about 20-24 mGals depending on how the regional field is chosen (fig. 5). The axis of the gravity anomaly coincides closely with the axis of Antero Reservoir syncline. Snyder (1968) computed the gravitational effects of a model along profile H-H' (figure 5), in which a density contrast of -0.25 g/cm^3 was assumed for older sedimentary rocks with respect to the basement, and a contrast of -0.30 g/cm^3 between the older sedimentary rocks and the low-density Tertiary deposits. These contrasts, then, are consistent with mean densities of 2.7 g/cm^3 for the basement rocks, 2.45 g/cm^3 for the older sedimentary rocks, and 2.15 g/cm^3 for the younger Tertiary deposits. With these assumptions, the younger Tertiary deposits have a thickness of about 3,000 feet (914 m), and the older sedimentary rocks (presumably mainly Pennsylvanian and Permian strata) a thickness of about 4,000 feet (1,220 m). To the south, the residual anomaly (G4) is about 15-18 mGals. These relations suggest that the main South Park basin has a considerable thickness of low-density fill--perhaps as much as 4,000 feet (1,220m) of Tertiary material as shown on De Voto's geologic section A-A' (1971, plate 1). But the main basin may be subdivided into two smaller basins by a structural high that coincides with the saddles in the gravity and magnetic anomalies (M5, G5) where the fill may be only 1,000 or 2,000 feet (304 or 610m). It should be pointed out that the southern negative gravity and magnetic anomalies do not coincide with the axis of the Antero Reservoir syncline as mapped by De Voto (1971), and a deep trough of low-density sedimentary rocks is interpreted from the gravity data to extend southeast into the NW 1/4 T. 15S., R. 75W.

A simplified gravity model has been computed along profile A-A' (fig. 6). If the density of the Tertiary deposits is about 2.2-2.3 g/cm^3, that of Mesozoic sedimentary rocks about 2.4-2.5 g/cm^3, and that of upper Paleozoic clastic rocks is about 2.5 g/cm^3, the mean density of the sequence may be about 2.4 g/cm^3. Precambrian and pre-Belden Formation (Pennsylvanian) basement rocks probably have a mean density of about 2.7 g/cm^3. Assuming that the anomaly is two-dimensional along profile A-A' and assuming a density

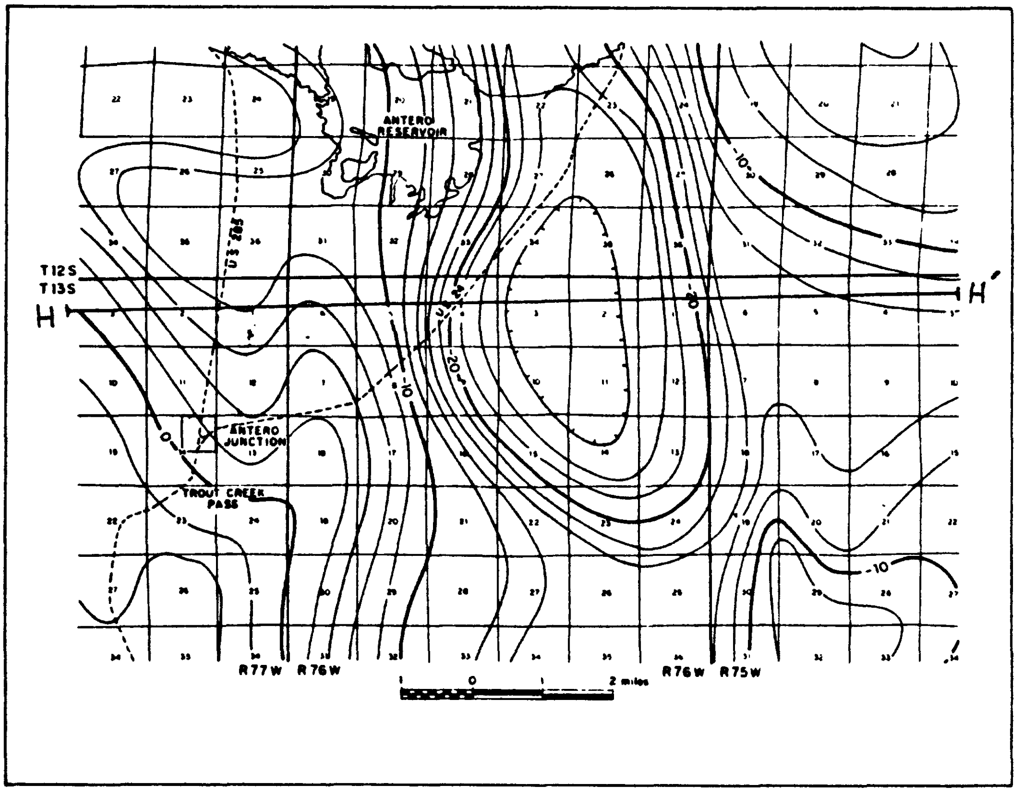


Figure 4.-Residual gravity anomaly map, north part of Antero Reservoir quadrangle (from Snyder, 1968, pl. 4). Contour interval=2 milligals. Modified from De Voto, 1971

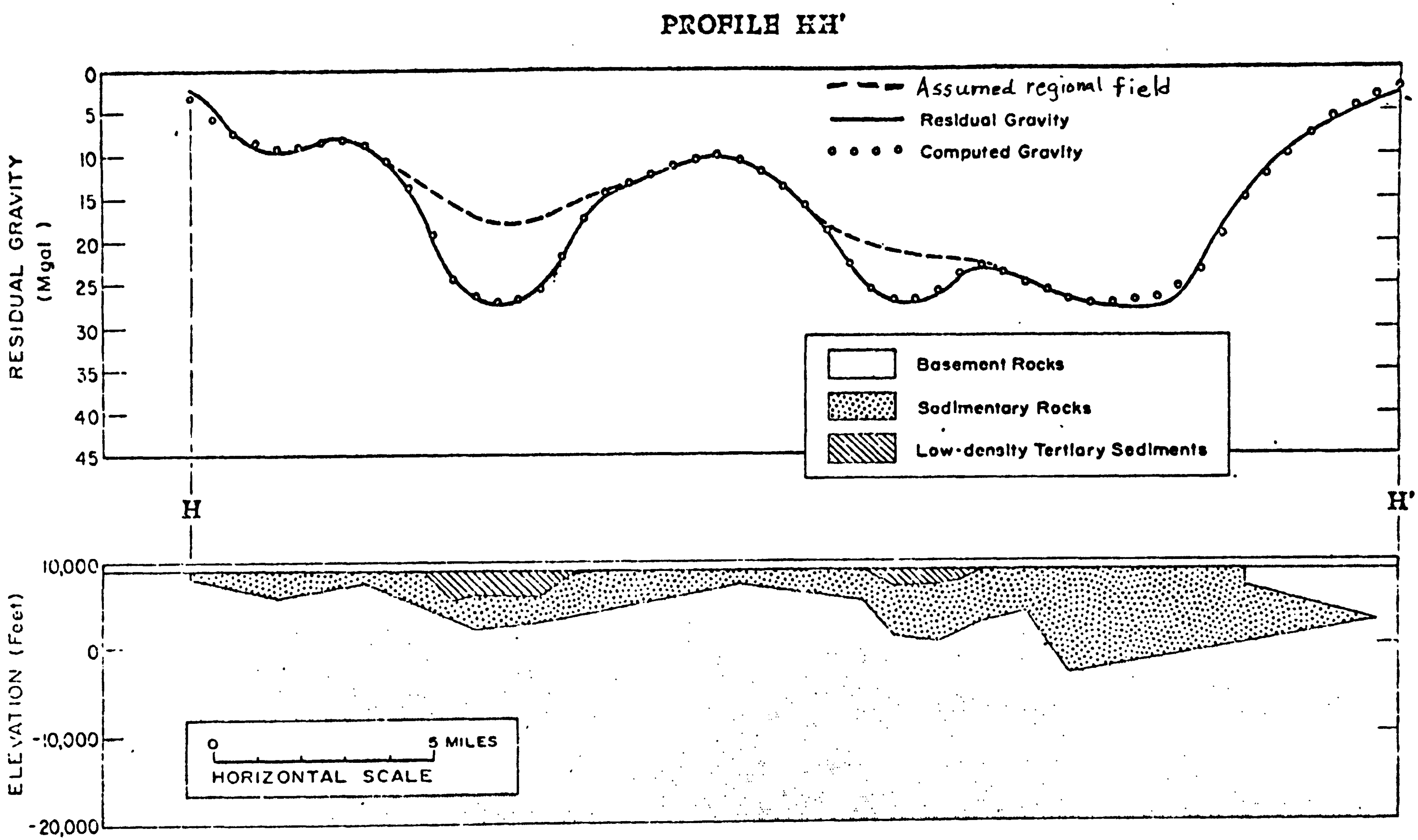


Figure 5.-Interpretation of residual gravity anomaly along profile H-H', after Snyder, 1968. Stipple pattern is for a density contrast of $-0.25\ g/cm^3$, and diagonal rule pattern is for a density contrast of $-0.3\ g/cm^3$ within the sedimentary sequence and for a density contrast of $-0.55\ g/cm^3$ with respect to basement.

contrast of $-0.3\ g/cm^3$ between the low-density sedimentary rocks and adjacent older Paleozoic and Precambrian rocks (fig. 6), then fill could be as much as 6,500 feet (2,000 m). This is only a crude estimate because of lack of subsurface control. There are no drill data to confirm this estimate.

If suitable source and reservoir rocks are present at depth, especially in the Paleozoic section, the postulated basement or structural high near G5, and M5 would constitute a potential target for oil or gas exploration. According to De Voto (1971), exploration programs have been conducted in and near the Antero Reservoir quadrangle for gypsum and potash in the Maroon Formation (Sangre de Cristo Formation), and for uranium in Tertiary volcanic conglomerate and tuffaceous siltstones, especially in the vicinity of Antero syncline. East of the area, hows of oil and gas have been found in the Pierre Shale and Dakota Sandstone; just north of the area, gas seeps emanate from the Belden Formation in places, and gas and hot water were encountered in a drill hole in the Leadville Limestone in a drill hole in the S 1/2 sec. 18, T. 13S., R. 76W.

A few miles southwest of Antero Reservoir, a small negative residual anomaly (fig. 4) of about 3-4 mGals (G 3A) may be related to salt. In the area a thin volcanic sequence (±200 feet; ±60m) caps a mesa near the anomaly and rests on upper Paleozoic sedimentary rocks. A north-trending anticline occurs just north of the apparent anomaly. Because of absence of Tertiary sedimentary rocks as a cause for the low, and because of known evaporites in the area, a small evaporite dome may be present. A detailed gravity survey over the feature is merited to verify the presence and exact location of the anomaly and to provide an estimate of depth and dimensions of the source of the anomaly. From the reconnaissance gravity data, it appears that a dome on the order of 1 to 1.5 miles (1,609-2,414 m) in diameter can be postulated.

Farther west, poorly-defined gravity (G6) and magnetic (M6) highs crudely coincide with an upthrown block near Kaufman Ridge. Whether these anomalies are indeed caused primarily by the structural relief (roughly 2,000 feet; 610 m) or by intrabasement contrasts in density and susceptibility is not known. Bohler and Klein (1982a) estimated the depth to the source at about 1.1 to 1.5 km below the ground surface. More detailed gravity surveys and analysis of the low-level aeromagnetic survey (U.S. Geological Survey, 1979a) are required for resolution of the question.

The high level aeromagnetic survey (plate 2) shows that the south flank of anomaly M6 is a northeast-trending steepened gradient. The low-level survey shows a steepened gradient that trends more easterly. These zones of steepened gradient are close to mapped faults that trend east-northeast near the Trout Creek mining district where minor deposits of gold; silver; lead ores in Paleozoic rocks have been mined (Marsh and Queen, 1974, Vanderwilt, 1947).

Still farther west, over the Mosquito Range, the most prominent magnetic anomaly (M7) of the region occurs over granitic (locally gneissic) rocks assigned to the Denny Creek Granodiorite. A series of similar magnetic highs are found over granitic and gneissic rocks at sporadic intervals over the Mosquito Range to the north in the Leadville quadrangle (Tweto and Case 1972). It seems likely that the magnetization of the Precambrian rocks along the Mosquito varies along the trend of the range. This variation is independent of the topography and, hence, may reflect differences in rock type or degree of metamorphism that have not yet been defined geologically. More detailed geologic control and ground magnetic studies are required for

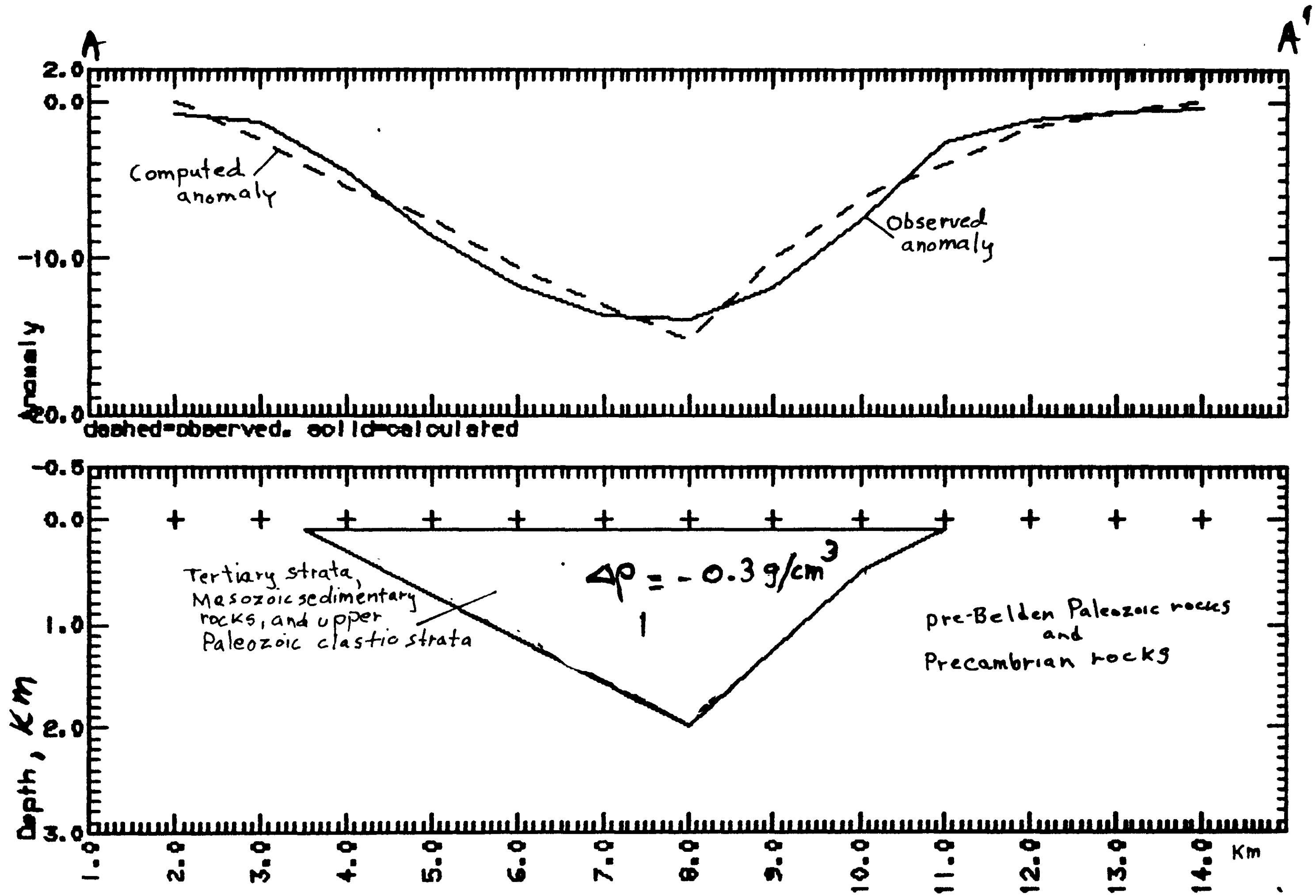


Figure 6.- Interpretation of the gravity anomaly along profile A-A', plate 1

resolution of this question.

The small gravity anomaly (G7) does not correlate with the position of the magnetic high, hence mafic rocks probably are not the cause of the magnetic anomaly.

Arkansas Valley Basin--Steepened magnetic (M8) and gravity (G8) gradients coincide reasonably well along the eastern margin of the Arkansas Valley Basin down to about latitude 38°42'N, but farther south, the magnetic gradient diverges greatly from the gravity gradient and trends more southeasterly. It thus appears that the gravity gradient is an expression of the large density contrast between the valley fill and the Precambrian rocks, and is related to structural relief across the fault system on the east side of the valley. The magnetic gradient only partly expresses the structural relief; a substantial fraction of the gradient is caused by contrasts in magnetization within the Precambrian rocks. Where the magnetic gradient diverges, Precambrian rocks are principally metamorphic rather than granitic, and the influence of the Whitehorn stock may be a factor. This is especially evident in Tps. 50 and 51N., Rs. 8 and 9E.

Estimation of the thickness of fill in the Arkansas Valley is of considerable importance in resource evaluations. Not only may mineral deposits occur in the older pre-fill rocks, but the depth of fill relates to the potential for ground water in the region, and patches or blocks of Paleozoic sedimentary rocks, perhaps hosts for mineral deposits or oil and gas, could occur at depth. Although gravity anomalies have commonly been used to estimate depth of valley fill in many parts of the world, it is a particularly difficult technique to employ in the Arkansas Valley region. The negative gravity anomaly (G9) over the valley is distorted by the influence of (1) the steep gradient (G8), an apparent crustal anomaly that slopes from east to west across the area and (2) the negative anomaly (G17) over the Mt. Princeton batholith west of the Valley. Isolation of a residual anomaly caused only by the valley fill requires an estimate of some "regional" gradient and this is exceedingly difficult because of the interferring anomalies of similar or greater magnitude.

Two-dimensional analyses have been made across the valley along profiles B-B' and C-C' by Donald Peterson (oral comm., 1968, figs. 7 and 8). Linear regional gradients were assumed. Along profile B-B', the valley fill is estimated to be about 4,000 feet (1,220m), if a density contrast of 0.5 g/cm^3 is assumed. Such a density contrast would be reasonable if the main density of the fill is 2.2 g/cm^3 and the mean density of the "basement" is 2.7 g/cm^3. Tweto and Case (1972) assumed a density contrast of 0.5 g/cm^3 farther north across the Arkansas Valley, near Leadville. An estimate of 4,000 feet from the gravity model for a density contrast of 0.5 g/cm^3 is uncertain because the anomaly across the valley near B-B' poorly approximated by a two-dimensional model. It is perhaps reasonable to postulate fill depth in the range 3,000-5,000 feet (910-1,520m) near profile B-B'. Fill is thin or lacking at the extreme north edge of the area, where Precambrian rocks are exposed, so the question arises as to the location of the site of maximum thickening. One troublesome problem, moreover, is that the gravity low (G9) under the valley near Buena Vista may be partly caused by an extension of the Mt. Princeton batholith beneath the fill. A prominent positive gravity anomaly (G10) trends across the valley near North Cottonwood Creek and the

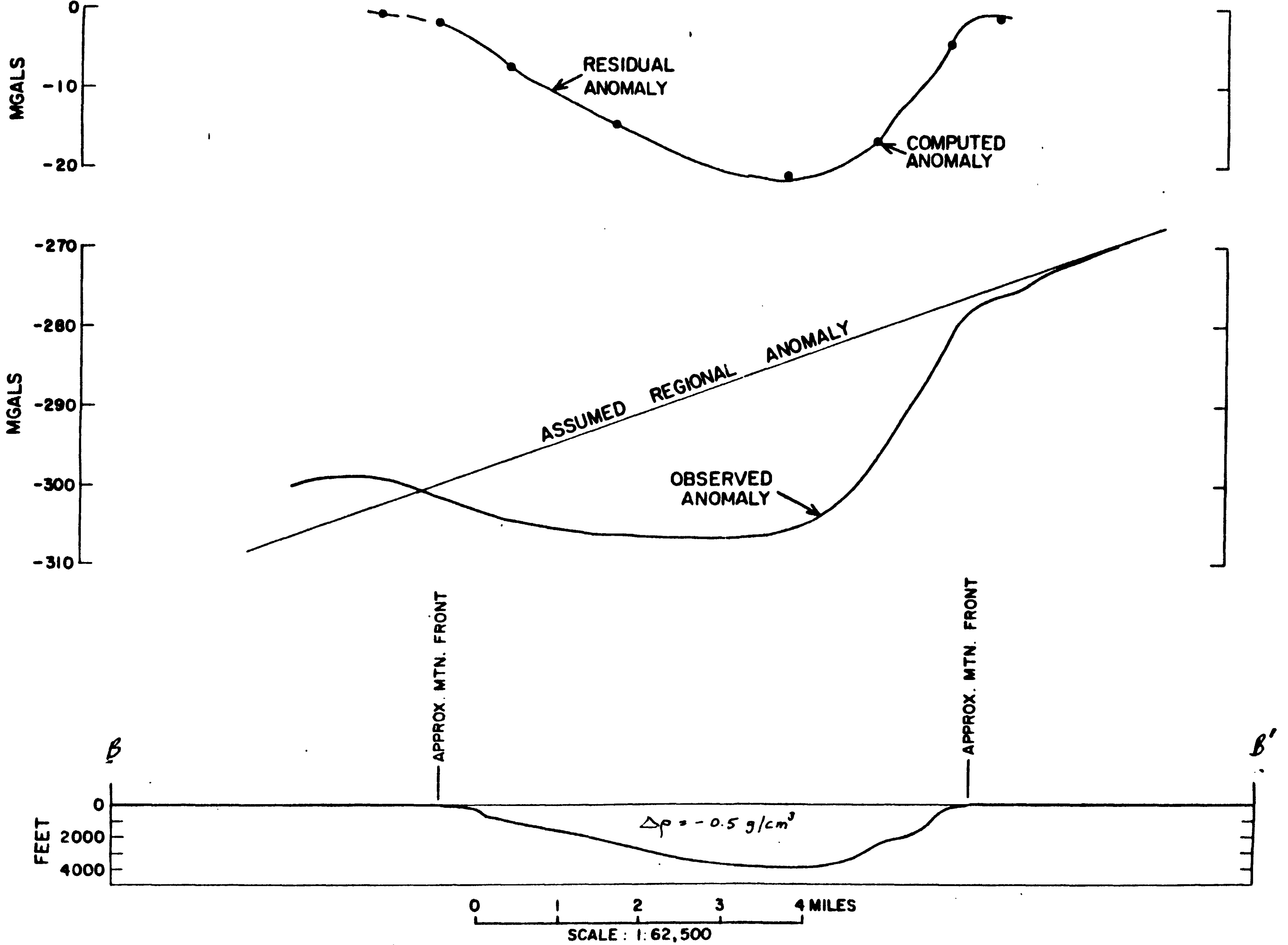


Figure 7.-Two-dimensional model computed along gravity anomaly profile B-B', plate 1. Assumed density contrast=-0.5 g/cm^3. From unpublished data of Donald Peterson.

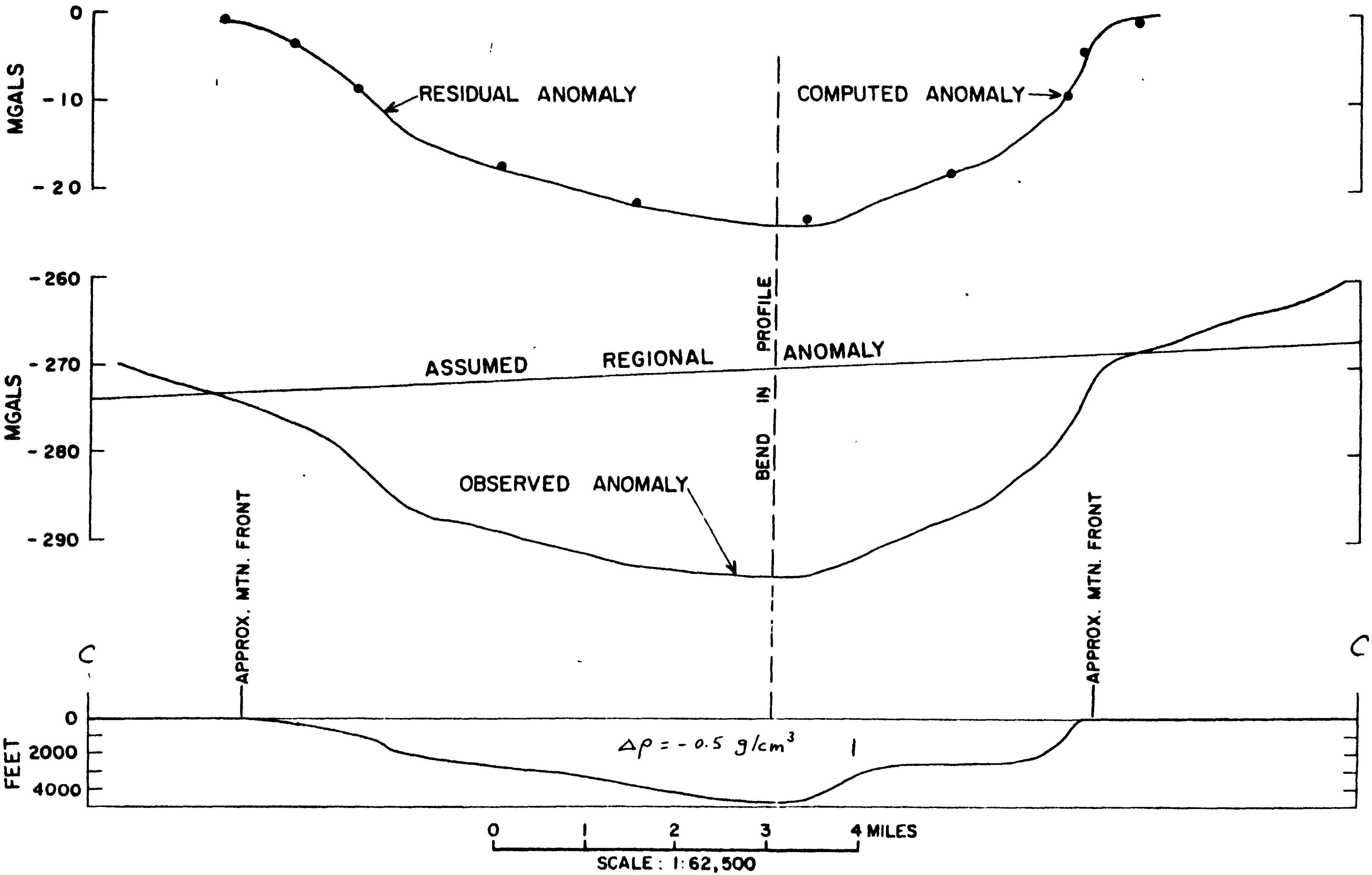


Figure 8.-Two-dimensional model computed along gravity anomaly profile C-C', plate 1. Assumed density contrast=-0.5 g/cm^3. From unpublished data of Donald Peterson.

southward gradient on the south side of the nose might reflect a zone of local thickening of fill, unless the anomaly has an intrabasement origin. A small magnetic high (M10) occurs in the same area. Whether it defines an area of shallow basement or represents intrabasement magnetic contrasts is unknown.

Resistivity soundings were conducted by Zohdy and others (1971) in T. 14S., Rs. 78W and 79W., just south of Buena Vista. They obtained a depth of fill of about 4,200 feet (1,280 m) near the line between secs. 29 and 30, T. 14S., R. 78W., in excellent agreement with Peterson's estimate of 4,000 feet (1,220m) based on the gravity model.

To the south, where the valley is widest, between Shavano Peak and Salida, Peterson's two-dimensional analysis along profile C-C' (fig. 8) suggests about 4,600 feet (1,402m) of fill for a density contrast of -0.5 g/cm^3. Again, this is a highly uncertain result because the anomaly is not well-approximated by a two-dimensional model.

Magnetic anomalies (M9) over the Arkansas Valley are generally of, amplitude and gentle gradient in keeping with the great depth of basement beneath the flight level of the aircraft. In Missouri Park, west of Salida, where the dense basement may be buried 4,500 feet (1,372) below the surface (fig. 8), magnetic rocks may be as much as 11,500 feet (3,505m) below the flight elevation.

Van Alstine (1969) and Scott and others (1975) have mapped a northwest-trending horst in T. 51N., R.8E. which is poorly expressed by a positive gravity nose (G11), but this horst has no magnetic expression in high altitude data on the one flight line that crossed it (see M11). Although the surficial horst is truncated by a north-trending valley margin fault, the gravity nose may extend several miles to the northwest, based on the anomaly at a single station.

Fluorspar deposits of the Browns Canyon district occur along a northwest-trending fault that separates Tertiary volcanic rocks on the southwest from Precambrian rocks to the northeast. This fault appears to have no magnetic expression on the high level survey.

Sawatch Range--The western margin of the Arkansas Valley is poorly defined, both gravitationally and magnetically. To the north, a very prominent magnetic high (M12) on the west side of the valley is centered over a Tertiary granodiorite pluton (Brock and Barker, 1972) and trends parallel to the pluton. This anomaly has no gravitational counterpart (see G12). Farther west in the Sawatch Range. in an area of Precambrian Denny Creek Granodiorite, a magnetic low (M13) occurs near a northwest-trending fault in the vicinity of Huron Peak and Emerald Peak; although, as contoured, the magnetic low partly coincides with a topographic low. This general area is moderately mineralized, probably part of the Twin Lakes gold district, and it is also on the fringe of a molybdenum-bearing area. One may suspect that the granodiorite has been altered, accompanying the mineralization. Gravity coverage was not obtained near the axis of the magnetic low (see site G13).

One of the largest negative gravity and magnetic anomalies of the area is in the extreme northwest corner of the Mt. Harvard quadrangle (G14, M14). The gravity anomaly is a continuation of the mineral-belt gravity low over the Twin Lakes granodiorite pluton in the Leadville 30-minute quadrangle. According to the gravity anomaly map of Colorado (Behrendt and Bajwa, 1974) and Isaacson and Smithson (1976), this low extends westward to the West Elk Mountains. From regional gravity surveys, the amplitude of the low is 25-30 mGals, and the Bouguer anomalies (-332 mGals) are among the most negative in the conterminous United States. The mineral-belt gravity low has long been interpreted as caused by an intracrustal batholithic mass of low density (Case, 1965, 1966, 1967; Tweto and Case, 1972; Isaacson and Smithson, 1976).

The magnetic low near Winfield Peak and Huron Peak (M14) correlates only in part with low topography. Some of the magnetic values are low even over the higher mountains. In this area the rocks are mineralized and altered. It seems clear that the original magnetite in the Twin Lakes Quartz Monzonite has been thoroughly altered to less magnetic or nonmagnetic minerals. These relations may constitute regional ore guides in areas covered by glacial or alluvial deposits or by thin veneers of sedimentary rocks as pointed out by Herness (1955) and Case (1967). In the area covered by this survey, every negative magnetic anomaly should be examined with care to determine its correlation with topography. If lows occur in areas of high topography, rock alteration may be suspected. It is, of course, always possible that the rock mass beneath the low has a small original magnetization, but this can be checked by careful field sampling (which could well accompany a geochemical sampling program).

The Mt. Harvard mining district has produced gold, silver, lead, and copper from veins in Precambrian granitic rocks (Vanderwilt, 1947, Marsh and Queen, 1974). Shear zones in the vicinity of old mines trend north-northwest. A poorly-controlled magnetic low (M14A) trends northeast between Mt. Harvard and Mt. Oxford. Although the low is partly correlative with low topography, detailed ground magnetic surveys might be warranted in the area.

In the area near and just north of Texas Creek, the gravity anomaly contours form the south border of the mineral-belt low, and the several small negative magnetic anomalies (unnumbered) appear to correlate with low topography.

South of Texas Creek a major gravity high (G15) trends north-northeast over a geologically complex terrane that includes amphibolite, mica schists, and granitic masses. This high, having values up to -294 mGals, is in part an anomaly over a block of Precambrian rocks between the Twin Lakes pluton to the north and the Mt. Princeton batholith to the south, both of which cause major gravity lows. This apparent anomaly of as much as 15 mGals is enhanced by the presence of the dense amphibolite masses (see Brock and Barker, 1972, for locations). The magnetic anomalies (M15, 15A) in the same area show little correspondence with the gravity anomaly. For example, in the area of the crest of the positive gravity anomaly, near the boundary between Tps. 14S. and 15 S., R. 81 W., the magnetic anomalies are relatively low (M15A), despite high topography. The low magnetic values are crudely concentrated over the main amphibolite masses. Elsewhere in the southern Rocky Mountains many amphibolites and amphibole gneisses are surprisingly nonmagnetic (Tweto and Case, 1972, p. C18; Case, 1966; Plouff and Pakiser, 1972, p. B189).

Ore deposits in the Tincup district at the west edge of the area are chiefly silver-lead-gold "blanket" replacement deposits in the Leadville Dolomite and Dyer Dolomite of the Chaffee Group and silver-lead gold veins (Vanderwilt, 1947, Tweto, 1968). A zone of steepened gravity gradient trends north-northwest through the district, and a poorly-controlled magnetic gradient trends roughly east-west. A prominent north-south trending magnetic gradient between magnetic low M19A and magnetic highs M19 and M20 lies close to, but does not coincide well with, the eastward-dipping Tincup fault. The Quartz Creek mining district, west of the fault, includes silver and lead deposits as well as some gold, copper, zinc, molybdenum, and tungsten deposits. Deposits occur in fissure veins, many of which trend easterly, and in replacement deposits in Paleozoic limestone and dolomite. The district occurs in a poorly-controlled magnetic low and in the gravity low associated with the Mt. Princeton batholith (G 17).

Near Mt. Yale, a prominent positive magnetic anomaly (M16) occurs over the gneissic rocks and a Tertiary pluton that form a high ridge. It appears that both gneiss and porphyry are about equally magnetic and that the anomaly is caused by the extreme topographic relief along the flight line that defines the anomaly. The apparent lows to the north and south are along flight lines over major valleys. Inadequate gravity coverage is available to determine if a significant correlative anomaly occurs, though there is a hint of a positive nose between G10 and G16.

The dominant gravity feature in the southern part of the Sawatch Range is a negative anomaly over the Mt. Princeton batholith (G17). The batholith is a complex of several types of intrusive rocks and is variably altered. Bouguer anomalies range from about -300 mGals around the periphery of the batholith to -315 to -320 mGals near the valley of Chalk Creek. Superimposed on the general gravity low are several small highs and lows of 1 to 8 mGals. Most of these small anomalies are in the Garfield quadrangle on "spot" elevations obtained by topographic surveys during the interval 1938-1940. If some of these elevations are in error by as much as 50 feet, the map contour interval, the error in the Bouguer anomaly may be as much as 3 mGals. Thus, many of the small anomalies in the Garfield quadrangle must be suspect. If any of them appear to have special scientific or economic importance, the area should be resurveyed to determine correct elevations, and the gravity stations should be reoccupied.

Isaacson and Smithson (1976) have presented generalized crustal models across the Colorado Mineral belt gravity low, one of which crosses the Mt. Princeton batholith ((their profile B-B', not on plate I, see figs. 9 and 10). In their analysis, the total range of Bouguer anomalies decreases from -250 mGals, near Gunnison, Colorado, to about -312 over the Mt. Princeton batholith, then rises to -265 over the edge of the Mosquito Range, east of the Mt. Princeton batholith. They assumed an overall crustal thickness of 45-50 km.

In two alternative models (fig. 10) they assumed very complex sets of density distributions within the batholith and included a dense stoped block at the base of the crust. Their premise for model B was that density increases from a surficial density of about 2.62 g/cm^3 to greater values at depth in the batholith. Density contrasts of various blocks in batholith vary from -0.04 to -0.14 g/cm^3. The stoped block at the base of the crust was assumed to have a density of 3.1 g/cm^3. A batholithic "thickness" of 23 or 25 km was calculated. Such detailed vertical density zonation was inferred from conceptual petrologic models of batholithic emplacement. Although the negative anomaly over the Mt. Princeton batholith is a three-dimensional feature, they used a two-dimensional approximation, which introduces further uncertainty in details of their models. For comparison, the gravity anomaly over the inferred batholith beneath the Colorado Mineral Belt in the Leadville quadrangle was modeled by a single low-density mass having a density contrast

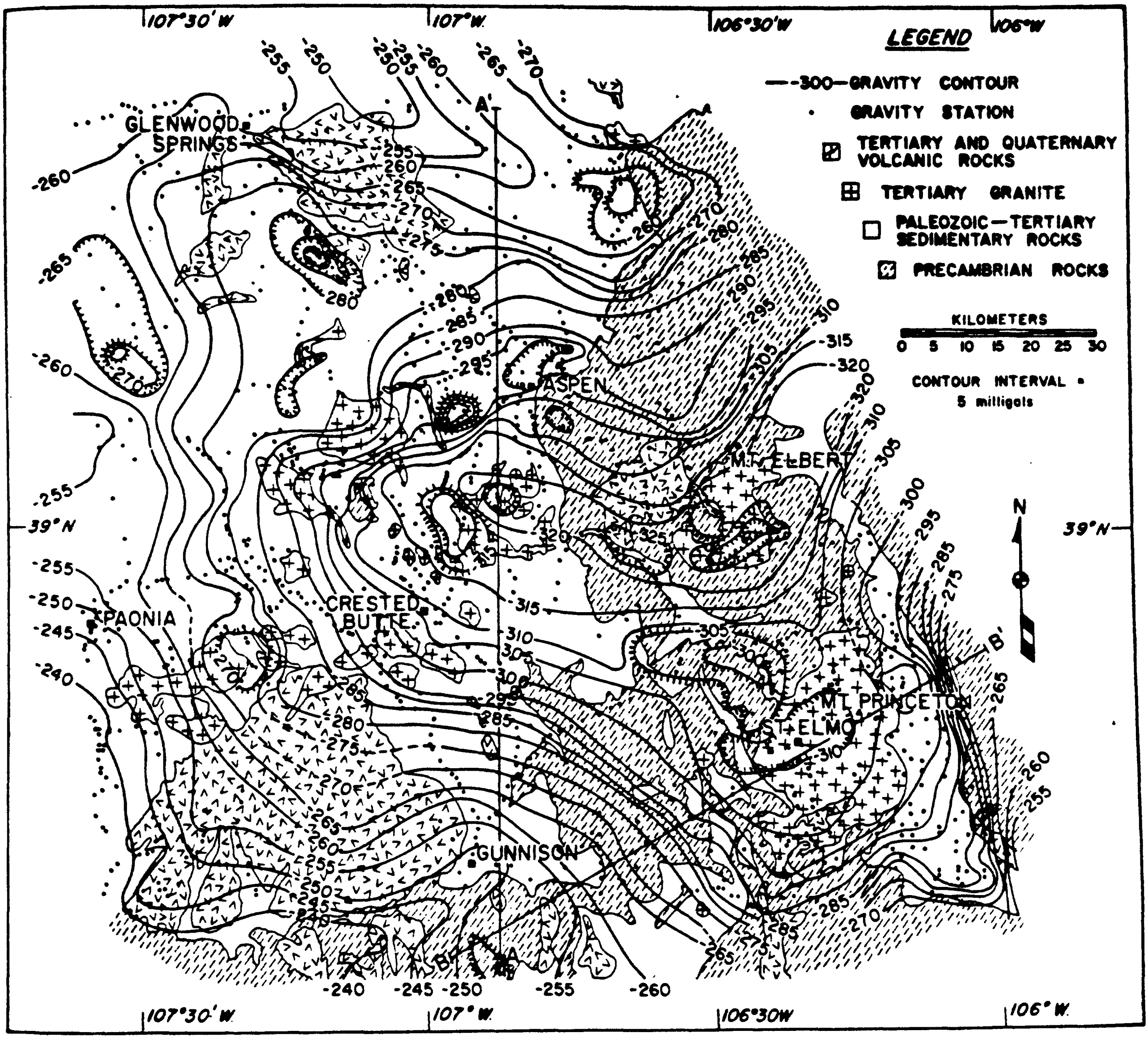


Figure 9.-Bouguer gravity anomaly map of west-central Colorado. From Isaacson and Smithson, 1976, figure 2.

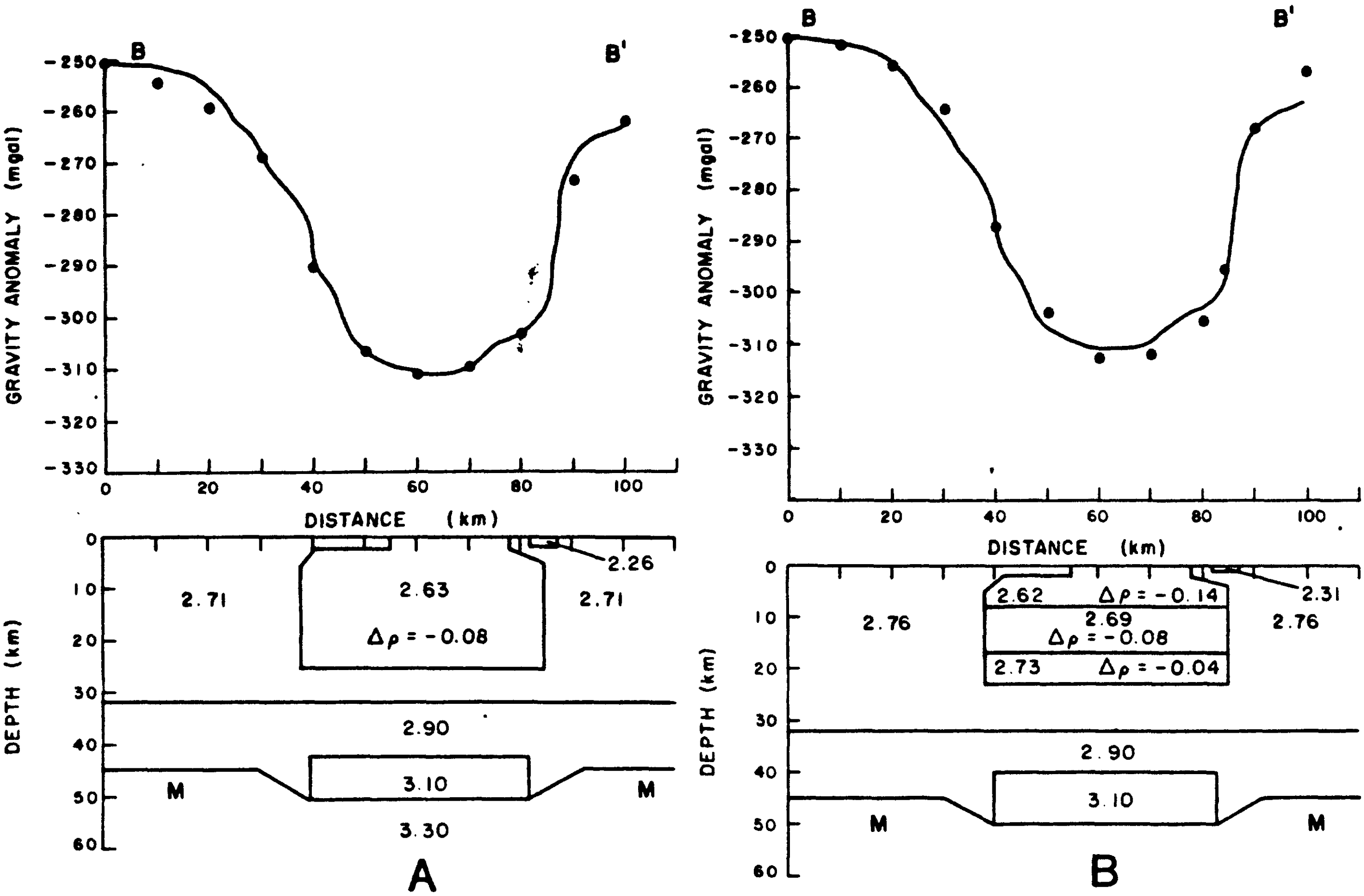


Figure 10.-Gravity profiles along B-B'(fig. 9) and gravity model for Mount Princeton batholith. A high-density mass is shown at base of crust, representing stoped material. Model for batholith uses minimum-density contrast. Block of low-density Tertiary sedimentary rocks just east of the batholith is 1 km thick. B, Model uses vertical density stratification and represents vertically zoned batholith. Deep stoped mass is at base of crust. From Isaacson and Smithson, 1976, figure 5.

of -0.12 g/cm^3 with respect to adjacent rocks and a vertical extent of about 15 km (Tweto and Case, 1972). Perhaps the main point of the analysis of Isaacson and Smithson is that such an anomaly can be readily produced by a large intracrustal mass having a density slightly less than that of adjacent crustal rocks.

Major negative magnetic anomalies (M17) occur over the batholith, but the lows along South Cottonwood Creek and Chalk Creek, south of St. Elmo, correlate fairly well with low topography. Magnetic highs around the northern and western periphery of the batholith (M18, M19, M20) are not reflected by corresponding gravity anomalies (G18, G19, G20). A magnetic high (M21), interrupted by a local low related to low topography, may correspond to a small gravity high (G21) near the central part of the batholith. As pointed out previously, however, low-amplitude gravity highs controlled by one or two stations are suspect. A prominent gravity high (G18A) on the eastern edge of the exposed batholith is unexplained. Perhaps it correlates with a local dense phase of the batholith.

Some of the magnetic lows over the Mt. Princeton batholith correlate only in part with low topography. They also correlate with zones where many mines or prospects are located (fig. 11). Ore deposits in the Chalk Creek-St. Elmo district are veins in the Mt. Princeton batholith that carry gold, silver, copper, lead, and zinc (Vanderwilt, 1947, Marsh and Queen, 1974, Dings and Robinson, 1957). The main production is in or near the main negative gravity and magnetic anomalies (G17, M17), where rock alteration is common.

A large magnetic low (M22) has been contoured over the eastern part of the Mt. Princeton batholith. The low occurs in the vicinity of Mt. Antero, (an area of small beryllium deposits), Mt. White, and Carbonate Mountain. Only four flight lines define the low, and it is clear that part of the low is a simple topographic effect--for example, the minimum value (2,000 gammas) occurs along Browns Creek, south of Mt. White. Yet some of the profiles show magnetic lows, or gentle gradients over relatively high topography. Thus, it appears that there are hints in the magnetic data of anomalous lows which may point to hydrothermal alteration and hence to potential ore deposits in the vicinity of anomaly 22.

A poorly-controlled positive gravity nose (G22) occurs in the region of the negative magnetic anomaly (M22). No surficial rock units capable of causing the anomaly are known at the site of the gravity nose, so if the anomaly is real, and not the result of an elevation error, a dense phase of the batholith occurs or a block of dense, perhaps Precambrian, rocks occurs at depth within this segment of the Mt. Princeton batholith.

Farther south, near the south margin of the batholith, a prominent negative magnetic anomaly (M23) occurs near Clover Mountain and Bald Mountain and may indicate alteration of the Mt. Princeton batholith or of the small patches of volcanic rocks that occur under the anomaly. The anomaly does not correlate well with topography. The Monarch district has produced silver, lead, zinc, gold, and copper, chiefly in replacement deposits in Paleozoic limestone and dolomite and locally in veins. The district occurs mainly in the eastern part of magnetic low M23, which is over low topography. A northeast-trending steepened gravity gradient crosses the mining district. Deposits of silver, lead, and zinc and minor gold and copper in the Tomichi district occur as replacement types in Paleozoic limestone and dolomite near

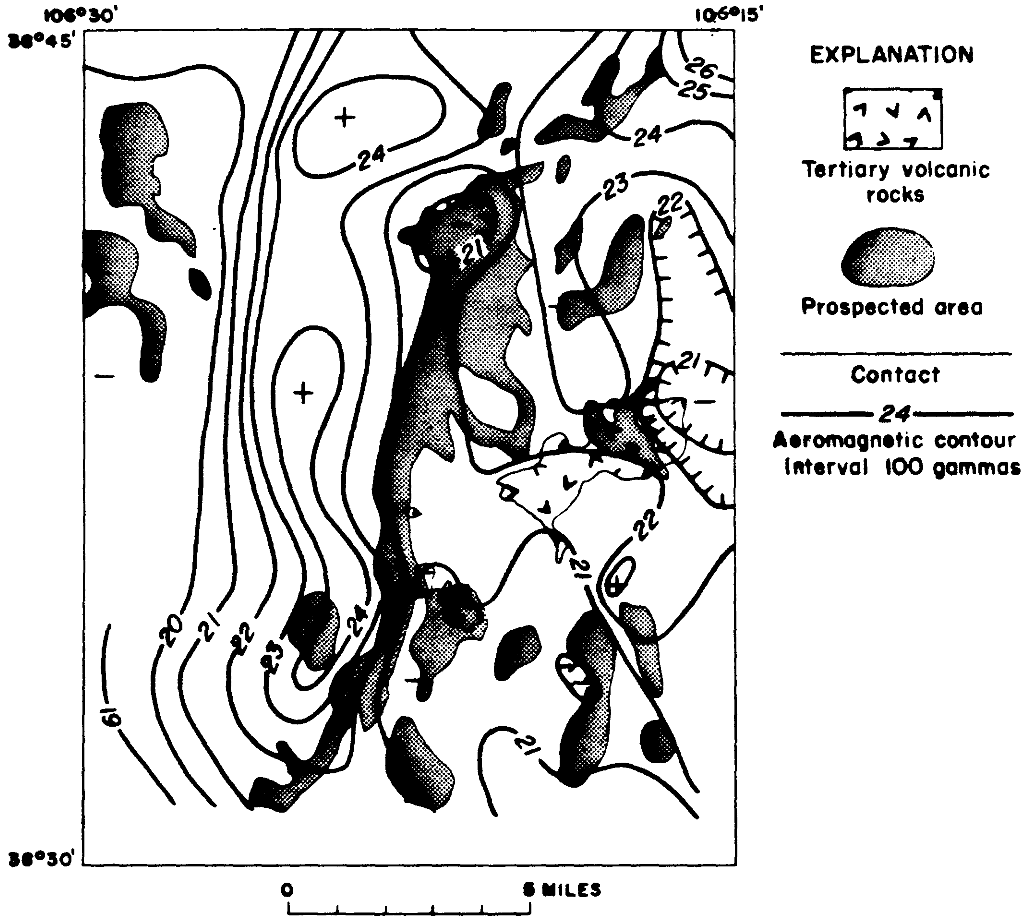


Figure 11.-Map showing aeromagnetic anomalies and distribution of heavily prospected areas in the Garfield 15-minute quadrangle. Simplified from Dings and Robinson (1957, pl.1) and Case (1967, fig. 8).

fault zones or along bedding; fissure veins occur in other rock types. The district lies principally along a zone of steepened gradient between magnetic positive M20 and magnetic low M23. A small positive gravity nose (G23A) occurs near the central portion of the negative magnetic anomaly. Again, the cause of the postive gravity anomaly is not explained by surficial rock units.

Southern Mosquito Range--In the Mosquito Range, just west of southern South Park, a prominent postive magnetic anomaly (M24) occurs over Precambrian granite and gneissic granite. The volcanic units in the area are too small and thin to contribute to the anomaly as defined by the high-level survey, but some anomalies attributable to volcanic rocks occur on the low-level survey (U.S. Geological Survey, 1979a). The positive anomaly extends southward over cover of Paleozoic and Tertiary sedimentary rocks. Steep gradients on the low-level survey suggest fault boundaries on the southwest, southeast, and northeast sides of the anomaly. Boler and Klein (1982a) interpreted the elevation of the top of the source at 1.98 km, but Precambrian granodiorite crops out at elevations of about 3 km in the northwest part of the anomaly, so the top of the source plunges south and southeast. Absence of a positive gravity anomaly indicates that mafic rocks are not the cause of the magnetic high, so that rocks of average crustal density and magnetic, such as quartz monzonite, may be suspected.

Farther south, the Whitehorn Granodiorite body, which ranges from syenogabbro to quartz monzonite (Wrucke, 1974), produces both positive magnetic (M25) and gravity (G25) anomalies. Densities of seven samples of the Whitehorn pluton range from 2.77 to 2.90 g/cm^3 and average 2.82 g/cm^3 and thus are probably substantially denser than the adjacent upper Paleozoic clastic rocks which are estimated to have a mean density of about 2.5 g/cm^3 (Tweto and Case, 1972). Susceptibilities of six samples of the pluton range from 3.05×10^{-3} to 7.26×10^{-3} and average 5.43×10^{-3}, rather high values which readily account for the prominent associated magnetic anomaly. The value of 6.37×10^{-3} units, derived in the analysis below of Boler and Klein (1982a), fits nicely in the range of measured samples. The magnetic high has maximum amplitude over the topographic crest of Cameron Mountain. The magnetic anomaly corresponds well with the mapped extent of the body in its central and southern portions, but the anomaly diminishes greatly over the northern part of the body. Either the magnetite content of the body is quite variable or the body thins considerably toward the north. Similarly, the associated gravity anomaly is highest in the central and southern portions and diminishes in amplitude northward. These combined effects suggest that the northern part of the pluton is sill- or laccolith-like. Wrucke (1974, p. 3) suggested that the pluton has a subhorizontal floor on Paleozoic strata and was fed by a steeply inclined conduit.

In a three-dimensional analysis of the anomaly, Boler and Klein (1982a) assumed a laccolith-like body and adjusted the susceptibililty to obtain an optimum least-squares value and then adjusted the geometry of the body to produce a satisfactory field fit to the residual magnetic intensities. Their model produced a satisfactory fit of computed and observed anomalies where the elevation of the base to the body varied from 1,500 to 2,500 meters above sea level. The ground surface varies from about 2,400 to 3,100 meters, so the thickness was computed at about 600 to 1,600 meters, with the thickest part being beneath the maximum anomaly, near Cameron Mountain. The best-filling susceptibility was 6.37×10^{-3} cgs unit (0.08 S.I. unit).

Ore deposits of the Turret-Calumet district are mainly on the steep gradient on the southwest flank of M25. They include iron ore (magnetite), gold, silver, and copper (Marsh and Queen, 1974, Vanderwilt, 1947) in contact replacement deposits along the west margin of the pluton.

The small gravity closure (G26) west of the main high over the Whitehorn pluton is probably caused by dense phases of the amphibolitic Precambrian rocks (not shown on geologic base). Local flattening of the magnetic gradients (M26) suggests that the terrane may be weakly magnetic.

A gravity high (G27) in Tps. 49 and 50N., R. 11E. is present over a complex of Precambrian gneiss, amphibolite, and granodiorite. A magnetic high nose (M27) coincides with part of the anomaly. A mafic or an amphibolitic mass at depth may be largely responsible for the gravity anomaly. Magnetic low M27A is over gneiss and mafic rocks and a topographic high. Cause of the low is unexplained, but alteration may be suspected. A gradient trending northwest on the flank of the anomaly lies close to the contact between Precambrian rocks and Tertiary volcanic rocks.

Along Badger Creek in T. 49N., R. 11W., a poorly-controlled gravity low (G28) occurs over a thick sequence of Upper Paleozoic redbeds. The redbeds are less dense than adjacent Precambrian rocks to the east and Precambrian and pre-Pennsylvanian Paleozoic rocks to the west. The influence of the Whitehorn pluton at depth appears to mask any substantial magnetic expression (M28) of the crudely synclinal block of redbeds.

Major gravity (G29) and magnetic (M29) lows are present over the complex graben near the Stout Creek School and Coaldale along the lower part of the Arkansas River Valley. The magnetic low is caused by the relatively great depth of the magnetic bedrock beneath the Paleozoic sedimentary rocks and the block of Tertiary valley fill deposits. The gravity low results from the low-density Tertiary deposits and Paleozoic clastic rocks. No attempt has been made to model the thickness of Tertiary fill because of poor control on the flanks of the gravity anomaly.

A prominent magnetic gradient (M30) trends northerly across the Arkansas Valley near the southeast edge of the area discussed above (M29). The gradient locally parallels the contact between granitic rocks on the east and gneissic rocks on the west. Assuming that the granitic rocks are more magnetic than the gneiss, as is common elsewhere in the Salida region, the contact projects south past Coaldale in the subsurface. No gravity data are available in that area. From inspection of the aeromagnetic map of Colorado (Zietz and Kirby, 1972), and the aeromagnetic map of the Pueblo quadrangle (Boler and Klein, 1982a) the gradient extends southeast to at least latitude 38°N, separating a strongly magnetic province on the east from a weak to nonmagnetic province on the west. The smoothness and linearity of the gradient may indicate that the contact is a fault, probably the Pleasant Valley Fault which has vertical displacement of 10,000 feet (3,049 m) or more (Scott and others, 1978). Boler and Klein (1982a) termed the southern extension the "Alvarado Fault Gradient".

Sangre de Cristo Range--A general gravity high (G31) over the east and northeast slope of the Sangre de Cristo Range seems split into a high (G32) that trends northerly and one that trends northwest (G33). Only a relatively small magnetic high (M31) occurs near the axis of the apparent gravity high. Precambrian gneiss, granodiorite, and minor amphibolite are exposed at the site of the magnetic high; the basement source of the anomaly extends eastward under the cover of Paleozoic sedimentary rocks. Boler and Klein (1982a) estimated the elevation of the top of the source at about 2 km; surface elevations near the anomaly are 2.8-3.7 km. A north-trending gravity high nose (G32) partly coincides with a structurally high block of Precambrian and Paleozoic rocks that crosses the Arkansas Valley along the line between T.49N., R.9E., R.10E. Both a magnetic positive nose (M32A) and saddle are present near the site of the gravity nose, and these do not correlate with topography, so the anomalies may be partly of intrabasement origin rather than related solely to the uplifted block.

A prominent magnetic high (M33) lies close to the crest or just west of the crest of the northern Sangre de Cristo Range. Evidently the gneiss that is the major unit in the core of the range is moderately to strongly magnetic. Much of the anomaly is caused by relief of the magnetic basement, which lies only 1,000-2000 feet (305-610 m) below flight elevation at the crest of the range but is more than 8,000 feet (2,440m) below the flight elevation under the San Luis Valley and 9,000 feet (2,740m), or more, beneath the lower Arkansas Valley in the vicinity of Stout Creek School. Structural relief of the basement is on the order of 10,000 feet (3,049m) (Taylor, 1975, Tweto, 1978a). The positive gravity nose at the northern end of the range (G33) probably reflects the relative basement high at the northern end of the range rather than dense intrabasement rocks. Steepened magnetic (M34) and gravity (G34) gradients coincide with the faulted southwestern flank of the mountain front, but segments of the steepened magnetic and gravity gradients over the alluvium of the San Luis Valley suggest that other faults lie southwest of the main mountain front.

San Luis Valley and vicinity--The mapped graben that connects the San Luis Valley graben with the Arkansas Valley graben near Cleveland Mountain is expressed a gravity low (G35) of at least 4-6 mGals. However, a magnetic high (M35) at the same site indicates that concealed magnetic rocks exist beneath the graben.

A small, probably thin, patch of Tertiary fill in the central part of T.48N., R.8E., just south of Poncha Pass, may be partly expressed by a magnetic low (M36) but the positional correlation is not good. An apparent residual low gravity nose or flexure (G36) may likewise reflect the fill in this small graben. The gravity anomaly is complicated, however, as it is superimposed on the much larger negative anomaly associated with the Bonanza caldera.

A residual negative gravity anomaly (G37) of at least 10 mGals occurs over the main graben of the San Luis Valley. Low magnetic values (M37) occur near the main gravity low. The amplitude of the negative gravity anomaly (figs. 12 and 13) increases a short distance southward then values rise to a saddle (Gaca and Karig, 1965, Davis, 1979), south of the area of this report. Taylor (1975, fig. 5) estimated the structural relief from the base of Pre-Neogene fill in San Luis Valley to an Eocene erosion surface above the Sangre de Cristo Range at about 15,000 feet (4,572 m) at about latitude 38°. From analysis of two-dimensional profile across the deepest part of the low to the south (figs. 12 and 13), Gaca and Karig (1965, p. 15) estimated that the minimum thickness of low-density fill in the San Luis Valley is 16,000 feet (4,880m) if the density contrast between the fill and basement is 0.7 g/cm^3, but the thickness may be as much as 40,000 feet (12,200m) if the mean density contrast is 0.44 g/cm^3 (figs. 12 and 13). Davis (1979) computed a complex

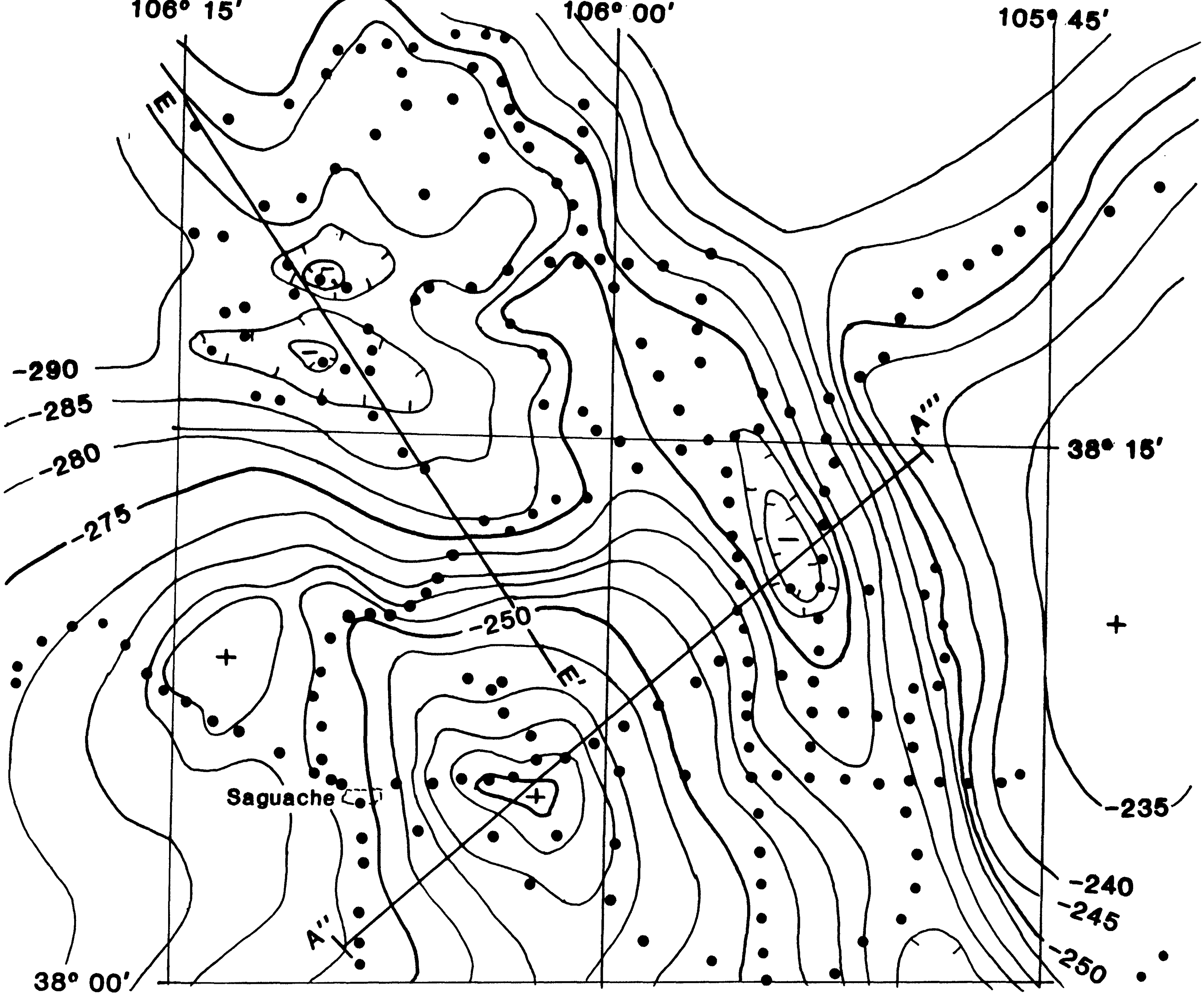


Figure 12.-Bouguer anomaly of the Bonanza area and upper San Luis Valley, modified after Gaca and Karig (1965).

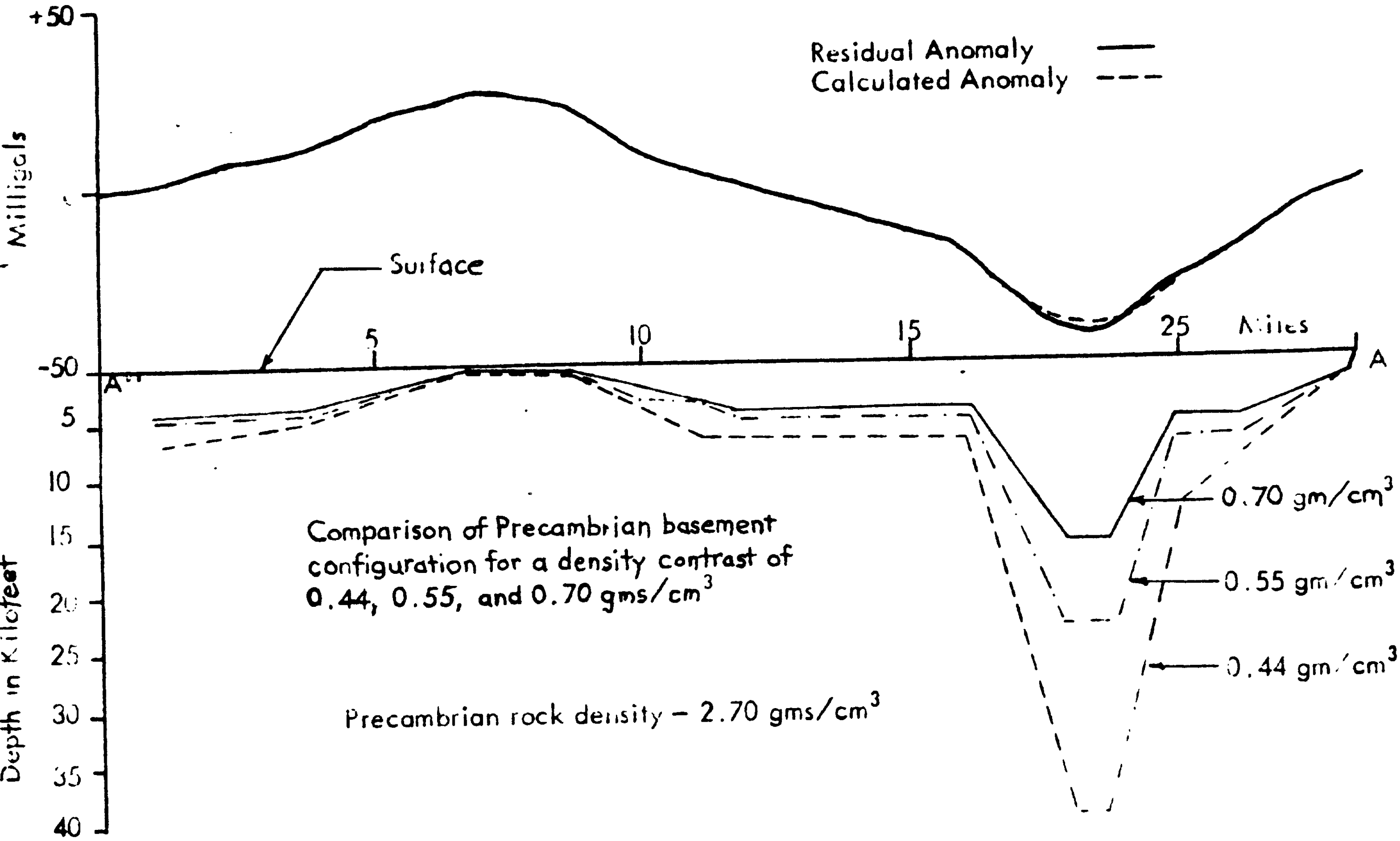


Figure 13.-Interpretive profile A"_A'", from Gaca and Karig (1965).

gravity model far south of the area near the high saddle of the anomaly at about latitude 38°05'N., and derived a thickness of fill of about 12,200 feet (3,500m) for a density contrast of 0.6 g/cm^3. At about the same latitude, Boler and Klein (1982a) modeled the depth of fill (susceptibility = 0) as about 5,740 feet (1,750m).

Bonanza Caldera and vicinity--Several conspicuous positive magnetic anomalies (M38-41) lie parallel to the west side of the part of the San Luis Valley and graben included on the map. They also occur close to the northeast margin of the general gravity low associated with the caldera. The most northerly anomaly (M38) is associated with amphibolites (not distinguished on the geologic map) and has an amplitude of 400 gammas near Ouray Peak. Although poorly controlled, a positive gravity nose near Ouray Peak (G38) is probably caused by the relatively dense amphibolites. Magnetic anomalies (M39-M41) on the same trend, however, are over volcanic and plutonic rocks of the Bonanza volcanic center. Measurements of susceptibility of a few samples of volcanic rocks indicate that some andesites are magnetic, having susceptibilities as high as 0.0039 x 10^{-3} cgs units. Other samples of altered dacite have low susceptibilities. Thus, it isn't clear whether anomalies M39-M41 are principally caused by the volcanic complex or by Precambrian rocks below the complex. Anomaly M40, for example, appears to extend from the volcanic-plutonic terrane over an area of Precambrian granite. Anomaly M41 occurs partly over a pluton of probable Tertiary age as well as volcanic rocks and correlates poorly with the outcrop pattern of the pluton. Gradients on the flanks of anomaly M41 suggest that the source could outcrop at about 5,000 feet (1,524m) below the flight elevation or have a deeper source. No gravity control exists at the site of anomaly M39, but a small questionable positive gravity nose occurs over the site of M40 and M41. A gravity high (G42) separates the low over the San Luis Valley graben from the low over the Bonanza caldera. The high occurs over a basement structural high in which Precambrian granite and Paleozoic sedimentary rocks are exposed. A poorly developed magnetic nose extends over the granite body, but this may be related to the source of M41 in the volcanic-plutonic complex.

A major gravity low (G43) of at least 26 mGals occurs over the Bonanza volcanic center. This low extends both south and west of the area covered in this report (Karig, 1965; Davis, 1979) and is caused by the low-density volcanic rocks in the collapsed caldera. Karig (1965) made a three-dimensional analysis of the anomaly (figs. 14 and 15) and concluded that the mass causing the anomaly "....is an elliptical cylinder centered about 2 miles northwest of Bonanza with a maximum radius of about 5 miles trending northwest and a minimum radius of about 4 miles". If the density contrast between the volcanic complex and the exterior basement rocks is 0.2 g/cm^3, the low-density material is about 8,000 (2,438m) feet thick. An alternative model (fig. 16) was computed by Marrs (1973). To account for extension of the gravity low to the northwest, he assumed that the caldera floor is tilted toward the northwest so that the caldera fill may be as much as 15,000 feet (4,572m) on the northwest.

The magnetic pattern over the caldera is complex. In addition to the positive magnetic anomalies M39-M41 on the eastern side, magnetic lows (M43 and M44) and highs (M45 and M46) are present. The magnetic lows may be caused by alteration or remanant magnetization as correlation with low topography is poor. The most northerly magnetic high (M45) is in an area of no gravity coverage. The southerly high (M46) may be expressed by the high gravity

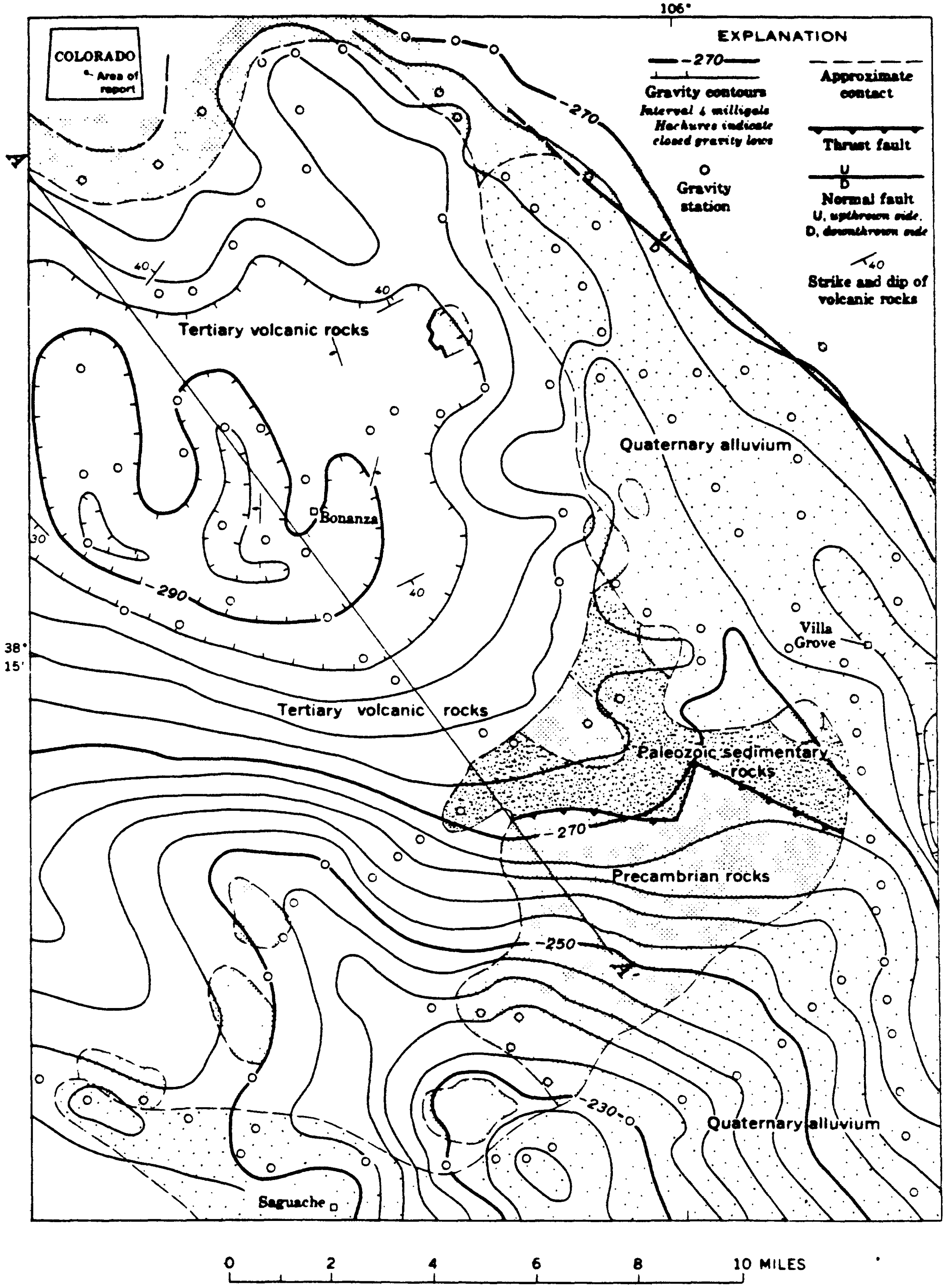


Figure 14.-Combined gravity and geologic map of the Bonanza region, Colorado, from Karig, 1965.

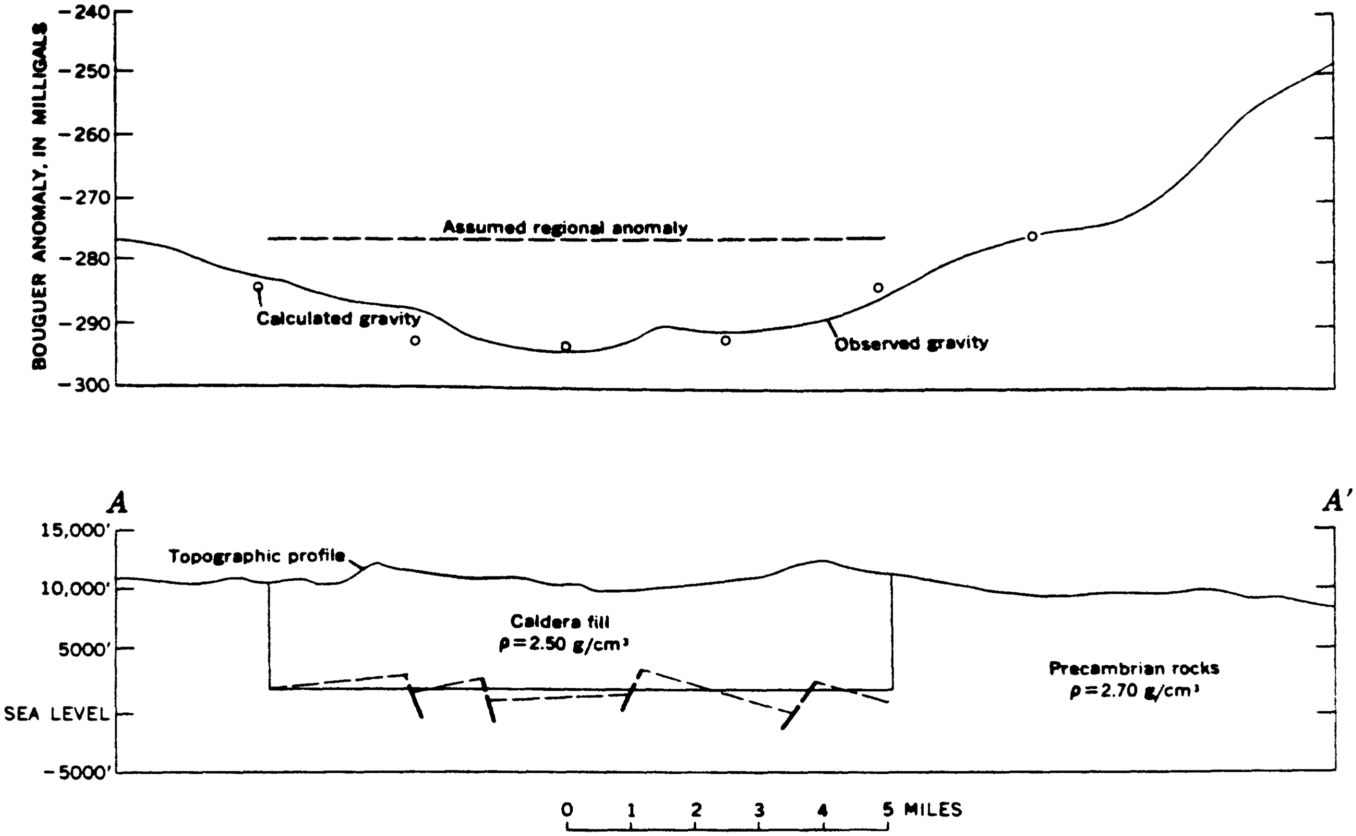
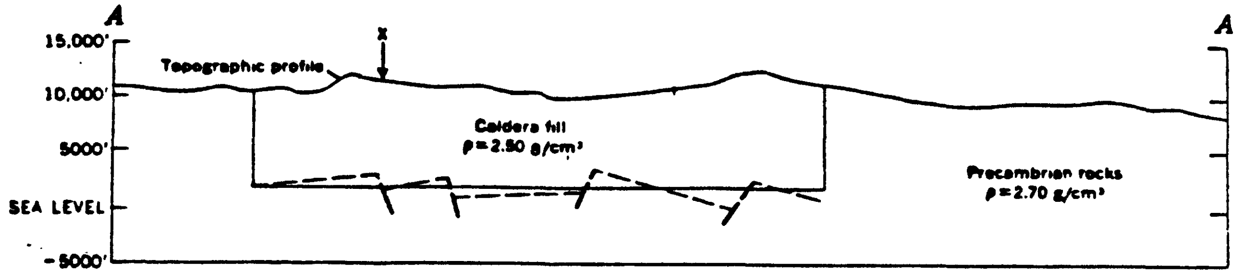
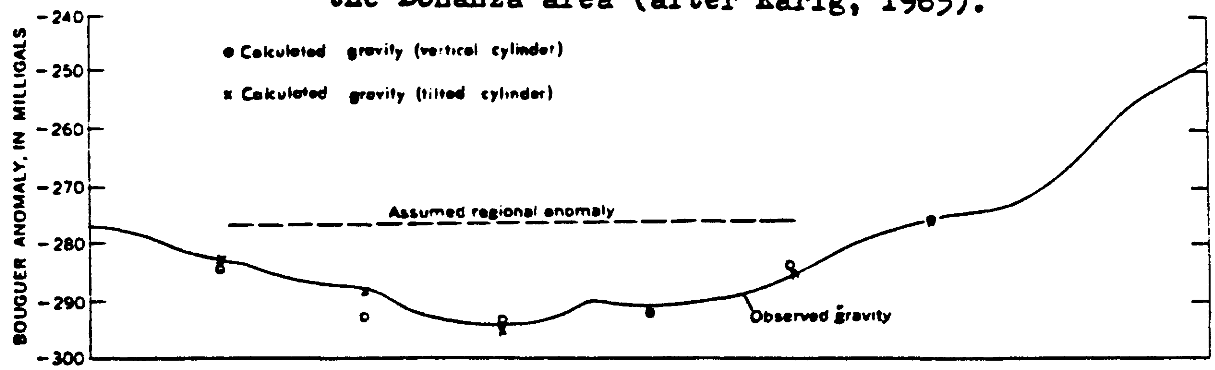


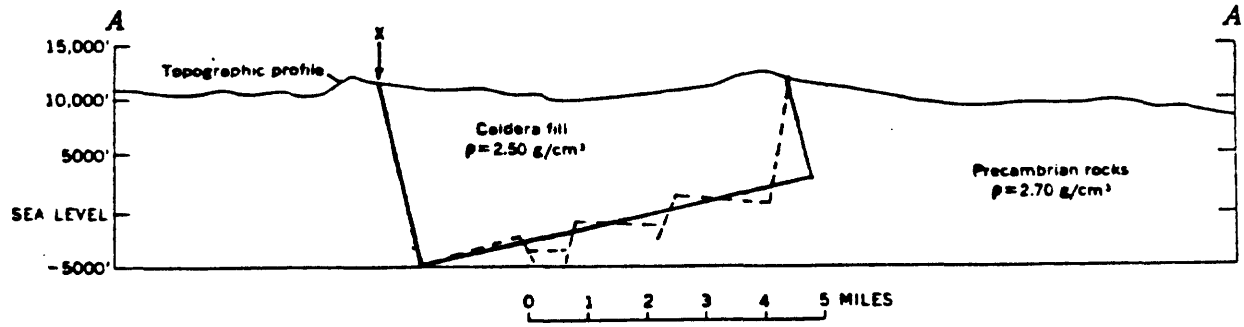
Figure 15.-A section through a mass distribution that will produce the gravity anomaly observed across the Bonanza district along profile A-A', from Karig, 1965.



A section through a vertical cylindrical mass that will produce a gravity anomaly similar to that observed along profile A-A' (fig. 34) in the Bonanza area (after Karig, 1965).



Comparison of observed gravity and computed gravity profiles for vertical and tilted cylindrical models.



A section through a tilted cylindrical mass that will produce the observed gravity anomaly along profile A-A' and is confined to the mapped boundaries of the central caldera.

Note: **Body A (hypothesized by Karig, 1965) extends beyond point X (representing position of Western Boundary Fault). Body B allows better correlation between the observed and calculated gravity profiles and does not extend beyond point X. Model B was computed using the Lachenbruch (1957) solid-angle graticule as employed by Karig (1965).**

Figure 16.-Comparison of two models across the Bonanza area; modified from Marrs, 1973.

anomaly nose (G46) having a Bouguer value of about -290 mGals.

Ore deposits of the Bonanza caldera include silver, lead, copper, zinc, and gold (Burbank, 1947, in Vanderwilt, 1947; Burbank, 1932, Marsh and Queen, 1974) which occur in various ore minerals in quartz-sulfide veins and quartz-rhodochrosite-fluorite veins that cut the volcanic rocks which are locally highly altered. Some of the veins are probably fault-or fissure-controlled. Many of the mines are located in or on the flanks of the major gravity and magnetic lows (G43, M43), and rock alteration is probably a principal cause of low M43.

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