Gravity, Magnetic, and Seismic Studies of the Silver Cliff and Rosita Hills Volcanic Area, Colorado

GEOLOGICAL SURVEY PROFESSIONAL PAPER 726-F

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By M. DEAN KLEINKOPF, DONALD L. PETERSON *and* ROBERT E. MATTICK

GEOPHYSICAL FIELD INVESTIGATIONS

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Interpretation of gravity, aeromagnetic, and seismic anomalies in terms of volcanic geology and fault tectonics

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GRAVITY, MAGNETIC, AND SEISMIC STUDIES OF THE SILVER CLIFF AND ROSITA HILLS VOLCANIC AREA, COLORADO

By M. DEAN KLEINKOPF, DONALD L. PETERSON, and ROBERT E. MATTICK

ABSTRACT

Gravity, aeromagnetic, and seismic refraction data provide new information about the thickness distribution of volcanic rocks and geometry of volcanic structures in the Silver Cliff and Rosita Hills volcanic areas, south-central Colorado. Geophysical surveys consisted of gravity measurements at 318 stations, low-level aeromagnetic coverage flown at 0.8 km spacing, and two seismic-refraction profiles across the Silver Cliff volcanic area.

The gravity patterns are dominated by negative anomalies which mainly show the distribution of Tertiary volcanic rocks. At the Silver Cliff and adjacent Johnson Gulch areas, prominent negative anomalies of nearly 10 mgals amplitude were interpreted to be caused by thick sequences of low-density breccias, tuff, and glasses preserved in volcanic subsidence features in Precambrian crystalline terrane. Three-dimensional modeling of the gravity data gave 1,000-1,200 m thickness of volcanic rocks in the deepest parts of these areas. The negative gravity anomalies in the Rosita Hills are smaller, indicating more restricted volcanic subsidence, although this may be complicated by a greater percentage of higher density volcanic rocks, such as andesites and trachytes, compared with the Silver Cliff area.

The magnetic data reflect both lithologic variations of Precambrian crystalline gneisses and distribution of the Tertiary volcanic rocks. The anomaly patterns are somewhat similar to the gravity features. In the Silver Cliff and Johnson Gulch areas, negative magnetic anomalies generally are broad and pronounced and correlate with the negative gravity anomalies across the subsidence areas. In addition, negative magnetic anomalies over adjacent Precambrian terrane suggest the possibility of incipient volcanic features not evident in the surface geology. A prominent magnetic low across the southeastern Bull Domingo Hills probably reflects a nonmagnetic phase of Precambrian gneiss as suggested by magnetic susceptibility measurements. However, the presence of a small breccia pipe at the old Bull Domingo Mine may point to a more extensive volcanic feature in the subsurface. The magnetic patterns at the Rosita Hills consist mainly of low-relief short-wavelength positive and negative anomalies that reflect compositional variations of the volcanic rocks. A major exception occurs along the southwest side of the Rosita Hills, where a broad negative magnetic anomaly suggests geologic conditions somewhat similar to that at the Silver Cliff area.

Two north-south seismic-refraction profiles across the Silver Cliff volcanic area have provided more specific quantitative data that complement the gravity and magnetic studies in defining the configuration of the volcanic subsidence areas and in delineating possible associated local vents.

INTRODUCTION

Gravity, magnetic, and seismic surveys were made by the authors at the Silver Cliff and Rosita Hills volcanic areas of south-central Colorado in conjunction with geologic studies of the volcanic centers and ore deposits (fig. 1). The purpose of the geophysical studies was to provide information about the thickness distribution of volcanic rocks, the geometry of volcanic structures, and possible relationships of volcanism to mineralization in and around the Silver Cliff and Rosita Hills volcanic areas.

Geophysical and geological studies of the region have been conducted by various workers. Published areal reconnaissance maps of gravity data (Peterson and others, 1974; Behrendt and Bajwa, 1974) and high-level aeromagnetic surveys (Zietz, 1972) cover the Silver Cliff and Rosita Hills volcanic areas. Regional interpretations of the gravity and aeromagnetic data covering the Pueblo 1°×2° quadrangle, which includes the study area, were made by the authors and Richard B. Taylor and William N. Sharp (unpub. data, 1970). Preliminary interpretations of the geophysical data at Silver Cliff and Rosita Hills have been made (M. Dean Kleinkopf, R. B. Taylor, D. L. Peterson, R. E. Mattick, and W. N. Sharp, unpub. data, 1970; Kleinkopf, Mattick, and others, 1970). The geology and ore deposits of the Silver Cliff and Rosita Hills area have been studied by Cross (1896), Emmons (1896), Gabelman (1953), and Sharp (1978).

Geophysical techniques have been used in studies of other volcanic centers of the southern Rocky Mountains. At the Cripple Creek mining district, about 72 km to the northeast of Silver Cliff, the volcanic area showed a 10-mgal (milligal) negative gravity anomaly upon which were superimposed local gravity lows believed to be related to deep mineralized fissure zones of fractured and loosely packed volcanic breccia (Kleinkopf and others, 1970b). In addition, the pronounced negative magnetic anomaly across the Cripple Creek center provided information about the depth and configuration of the altered breccia fill contained in the so-called "volcanic subsidence basin" (a usage after Koschmann (1949)). In the Bonanza area, about 64 km west-northwest of Silver Cliff (Karig, 1965), a closed gravity low, along with geologic data, indicated an elliptical volcanic structure with near-surface horizontal dimensions of 12.8 km and 16 km. The feature was estimated to contain about 2,400 m of low-density material (Karig, 1965).

The local geology (pls. 1 and 2) was simplified from the detailed interpretive geologic map of Sharp (1978). Three major rock divisions are shown, Precambrian rocks, Tertiary volcanic rocks, and Tertiary and Quaternary alluvium and sedimentary rocks. The Tertiary volcanic rock unit includes lithologies mapped by Sharp that generally were not of sufficient contrast in physical properties to be individually discriminated by the geophysical surveys, although some minor magnetic anomalies reflect variations of volcanic lithology in the Rosita Hills. Most of the faults and eruptive centers mapped by Sharp are included since in many cases they had a direct bearing on the geophysical interpretations.

We thank Mr. Joseph Chellini of the Callahan Mining Company, Mr. D. W. Fieldman of the Congdon and Carey Company, and personnel of the Cleavenger Land and Cattle Company for allowing access to properties in the Silver Cliff and Rosita Hills area. We are indebted to William N. Sharp of the U.S. Geological Survey for the geologic information that he provided, for logistical help during the surveying, and for many helpful suggestions in preparing the report. The geology shown on plate 1 was generalized from Sharp (1978).

GEOLOGY

The Silver Cliff and Rosita Hills volcanic area lies on the western flank of the Wet Mountains near the east edge of Wet Mountain Valley (fig. 1). The Wet Mountains in this area consist mainly of Precambrian metasedimentary, migmatitic, and granitic gneisses, and schists. The Precambrian rocks are part of an en echelon extension of the ancient Front Range highland that was exposed by erosion following uplift of the Wet Mountains during the Laramide revolution (Christman and others, 1959; Lovering and Goddard, 1950; Cross, 1896).

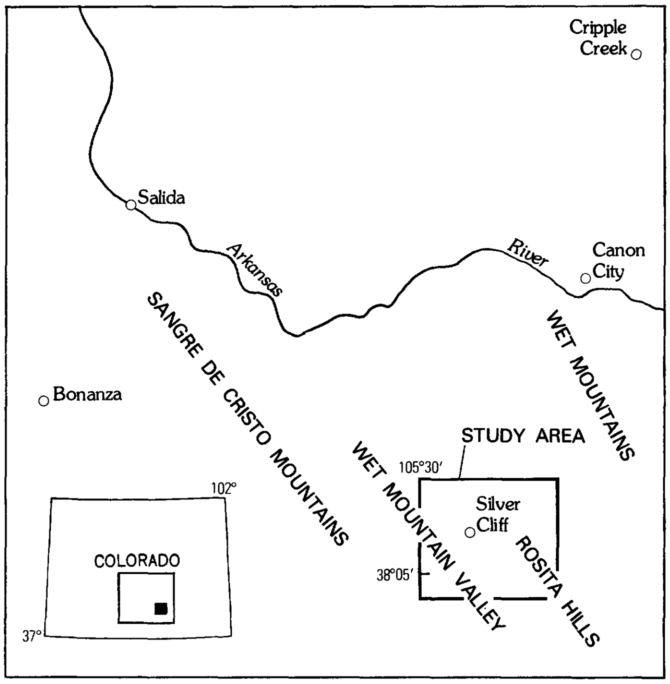


FIGURE 1.—Location of the Silver Cliff and Rosita Hills study area, south-central Colorado.

The Wet Mountain Valley is a tectonic basin that separates the Wet Mountains from the Sangre de Cristo Range on the west and appears to be related to the Rio Grande rift system of buried en echelon horsts and grabens. Scott and Taylor (1975) described the valley fill as composed of a variety of post-Paleocene Tertiary rocks and Quaternary volcanic debris that record the volcanic history of the region. The Eocene rocks consist of Echo Park Alluvium and of prevolcanic boulder alluvium equivalent to the Huerfano Formation of Huerfano Park. In Oligocene time, the basin fill changed abruptly from a sedimentary composition to an assortment of lava flows, ash flows, lahars, and volcanic-rich fluvial deposits derived from eruptions at the Rosita Hills volcanic center and other small volcanic fields in the area. The uppermost Tertiary deposit is a salmon-pink, basin-fill alluvium, which Scott and Taylor have called the Pliocene and Miocene Santa Fe(?) Formation.

The Silver Cliff and Rosita Hills volcanic centers form separate areas connected by a small isthmus and are surrounded by outcrops of Precambrian crystalline rocks. The emplacement of the Tertiary volcanic rocks was probably controlled by deep-seated, northwesterly trending, crustal fractures of Precambrian age reactivated during Tertiary uplift of the Wet Mountains (Siems, 1968). The Rosita Hills area consists of an early volcanic center surrounded by rhyolitic domes that formed by forceful intrusion of magma along ring faults (Siems, 1968). The probable boundaries of the early crater and the caldera as interpreted by Sharp (1978) are shown on plate 1. The volcanic rocks are made up of a complex structural association of flows, tuff, and ash that includes rhyolite, rhyodacite, latite, trachyandesite, and andesite. Siems (1968) described several phases: extrusives, subvolcanic intrusives, formation of stock and radial dikes, subsidence, and finally doming in the later stages to form a small, incompletely developed, resurgent cauldron. At Silver Cliff, early eruptions of rhyolite tephra, ash flows, breccias, and glass were accompanied by subsidence and formation of rhyolite domes along ring faults. As a result of subsidence, the volcanic rocks have been preserved from erosion.

The ore deposits occur mainly within the two volcanic areas, although many mineral occurrences are known in the adjacent Precambrian crystalline rocks. Deposits of silver, gold, lead, zinc, and copper associated with the Tertiary volcanic rocks have been mined. Emmons (1896) described three main types of ore bodies based largely on structural and alteration control. One type is the well-defined, fissure-vein deposits that occur along fault planes in the Rosita Hills district. A second type, mainly in the Silver Cliff district, is cavity fillings and replacements of highly altered, confining rock. A third, specialized type of ore body found in breccia pipes provided the most productive mines. The Bassick Mine, located on the south flank of Mount Tyndall, was in a breccia pipe composed of fragments of andesite with some granite and gneiss. Similarly, the Bull Domingo Mine in the Silver Cliff district was in a breccia pipe within Precambrian gneiss terrane.

COLLECTION OF DATA

GRAVITY SURVEY

Gravity measurements were made at 318 stations in the study area using a gravity meter with a scale constant of about 1 mgal per dial division, which could be read to one-hundredth of a dial division. Station elevations were obtained from bench marks, transit and rod surveying, and photogrammetric control shown on 7½ minute topographic maps. The gravity values were referenced to base station WU7 at the Colorado School of Mines, Golden, Colo. (Behrendt and Woollard, 1961). The measurements were reduced to complete Bouguer gravity values using an assumed rock density of 2.67 g/cm^3. Terrain corrections were made for each station through the H zone (2,615 m) of Hammer (1939) with hand templates and from the H zone to 167 km by means of a digital computer (Plouff, 1966). The precision of the contoured gravity map is estimated to be 0.5 mgal.

AEROMAGNETIC SURVEY

The magnetic data were collected by the U.S. Geological Survey in 1970 as part of a larger survey (U.S. Geological Survey, 1978) that extended northwesterly to the Arkansas River. Measurements were made with a continuously-recording ASQ-10 fluxgate magnetometer along flight lines oriented northwest-southeast and spaced 0.8 km apart. The flight elevation was 2,895 m above sea level. Topographic maps were used for position control of the aircraft and flight paths were recorded by a gyrostabilized, 35-mm continuous-strip camera (Evenden and others, 1967). Base lines were flown normal to the traverse lines for correction of diurnal and instrument drift. The magnetic contours (pl. 2) show the total intensity magnetic field of the Earth in gammas relative to an arbitrary datum. The gradient of the Earth's normal field was not removed from the data.

SEISMIC-REFRACTION SURVEY

Seismic-refraction surveys were made to supplement the information obtained from the gravity and magnetic surveys and, particularly, to determine the thickness of the alluvium and volcanic rocks. Two north-south seismic-refraction profiles were shot. *A–A′* extended through Westcliffe and *B–B′* passed through the east edge of Silver Cliff (pls. 1 and 2).

Seismograms were recorded on photographic paper using a 12-channel HTL 7000B[1] seismograph. For most of the field work a constant geophone spacing of 198 m was employed. The geophones were attached to a 2,180-m cable. In order to increase the profile length beyond 2,180 m, the following procedure was used. First, the 2,180-m geophone cable with 12 geophones was laid out along one end of the profile, and the P-waves propagated from the buried dynamite charges that were exploded at each end of the profile were recorded. The geophone cable was moved forward in increments of 2,180 m, and the previously used shotpoints at each end of the profile were reloaded and reshot. This procedure of moving the cable and

[1]Use of brand names in this report is for descriptive purposes only and in no way constitutes endorsement by the U.S. Geological Survey.

reshooting at the same shotpoints was repeated until the entire distance along a profile was covered. In addition, intermediate shots at 2,180-m intervals were used to record velocity changes in the near-surface rocks. The charges consisted of 23 to 91 kg of nitrate explosive that was detonated with a combination of electric blasting caps, primacord, and stick dynamite. The charges were loaded and covered to a depth of about 3 m in pits dug with a backhoe.

In general the resulting seismograms were of good quality and showed easily identifiable first arrivals on profile A-A'; some difficulty was encountered in picking first arrivals on profile B-B'. The traveltimes from shotpoint to seismometer were picked to the nearest 0.001 second, and traveltime curves were constructed (fig. 4). Velocities were determined by visual fitting of straight-line segments to the traveltime data. Since there was little relief along the profiles, no elevation corrections were applied. The intercept time of the first recorded velocity horizon was between 0.010 and 0.100 second on all traveltime curves. This intercept time, or weathering correction, was attributed to a thin surface layer of dry, unconsolidated, low-velocity material. Corrections for the weathering layer, assuming a velocity of 330 mps, were applied to the traveltime data prior to making depth calculations. The base of the weathering layer probably corresponds to the top of the water table. The graphical interpretation method of Slotnick (1950) and the time-depth method of Hawkins (1961) were used in calculating depths and dips of the refracting horizons. Final interpretations were made by fitting theoretical ray paths to the computed models.

INTERPRETATIONS OF GEOPHYSICAL DATA

The geophysical data give insights about the third dimension of the geology. The Bouguer gravity and magnetic anomalies provide information on the possible subsurface distributions of rock masses of various densities and magnetic susceptibilities. The seismic-refraction profiles directly provide quantitative data about the depths and thicknesses of various rock units based on their seismic velocities.

REGIONAL GRAVITY FEATURES

In order to show the broad gravity setting of the region covering the study area a small scale reconnaissance gravity map contoured at 5 mgals is included (fig. 2). Within the study area the contours were aproximated from the detailed gravity data shown at the larger scale (pl. 1). The reconnaissance map shows a northwesterly trending gravity high related to Precambrian crystalline rocks that comprise the uplifted Wet Mountains block. The associated regional gravity field dips toward the Sangre de Cristo Mountains rather uniformly in a southwesterly direction across the study area at about 2 mgal/km (Peterson and others, 1974), except for an increase of gradient across the low-density sedimentary rocks preserved in the Wet Mountain Valley basin. Local perturbations of the regional field can be observed and reflect anomalies attributed to the distribution of volcanic rocks in the Silver Cliff and Rosita Hills area.

REGIONAL MAGNETIC FEATURES

To show the regional magnetic setting, a small map (fig. 3) is included which shows high-level aeromagnetic survey data for the immediate region of the volcanic centers. The regional map shows a broad, complex magnetic high over the southern part of the Wet Mountains. The striking characteristic of the magnetic map is the plateau-like feature that is delineated by high gradient zones with a change of 150 gammas. The gradient zone along the southeastern flank of the Wet Mountains trends northeasterly and nearly bisects the Rosita Hills volcanic area. Perhaps this represents a lithologic boundary in the Precambrian subsurface between rock units of much different magnetic properties, such as gabbroic rocks, and less magnetic granitic rocks at San Isabel to the south (M. Dean Kleinkopf, R. B. Taylor, D. L. Peterson, R. E. Mattick, and W. N. Sharp, unpub. data, 1970). The coincidence of the volcanic complex with the magnetic gradient zone suggests that the volcanic activity may have been, in part at least, controlled by this postulated lithologic boundary.

The regional magnetic map shows a magnetic trough, defined by contour closures 2,220 and 2,240 gammas, which correlates with volcanic rock exposures located immediately southeast of the crater complex. This magnetic trough coupled with a nearly coincident gravity trough (fig. 2) may indicate a thick section of volcanic rocks preserved in a southeasterly trendind graben or volcanic-subsidence feature. Alternatively, the troughs could indicate a southeasterly trending lithologic unit of Precambrian rocks of low magnetization and relatively low density.

To the north, the major magnetic high defined by the 2,500- and 2,600-gamma closures probably represents a block of Precambrian gneiss that separates the volcanic centers at Silver Cliff and the Rosita Hills. The gravity data show a corresponding high, indicated by westerly nosings of the -215 and -220 mgal contours.

Although the reconnaissance aeromagnetic data are dominated by east-northeasterly trending features probably related to Precambrian lithology and struc-

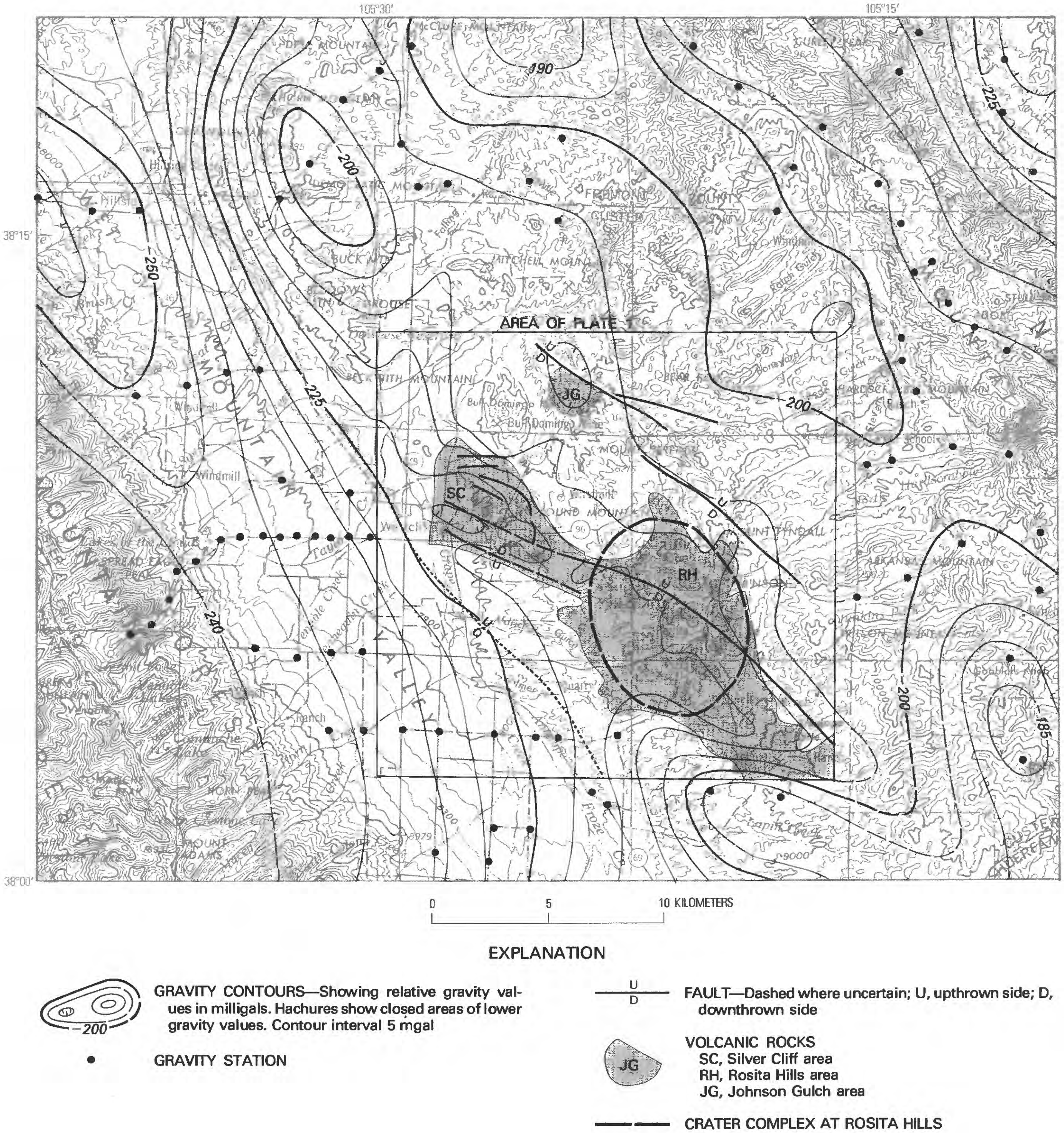
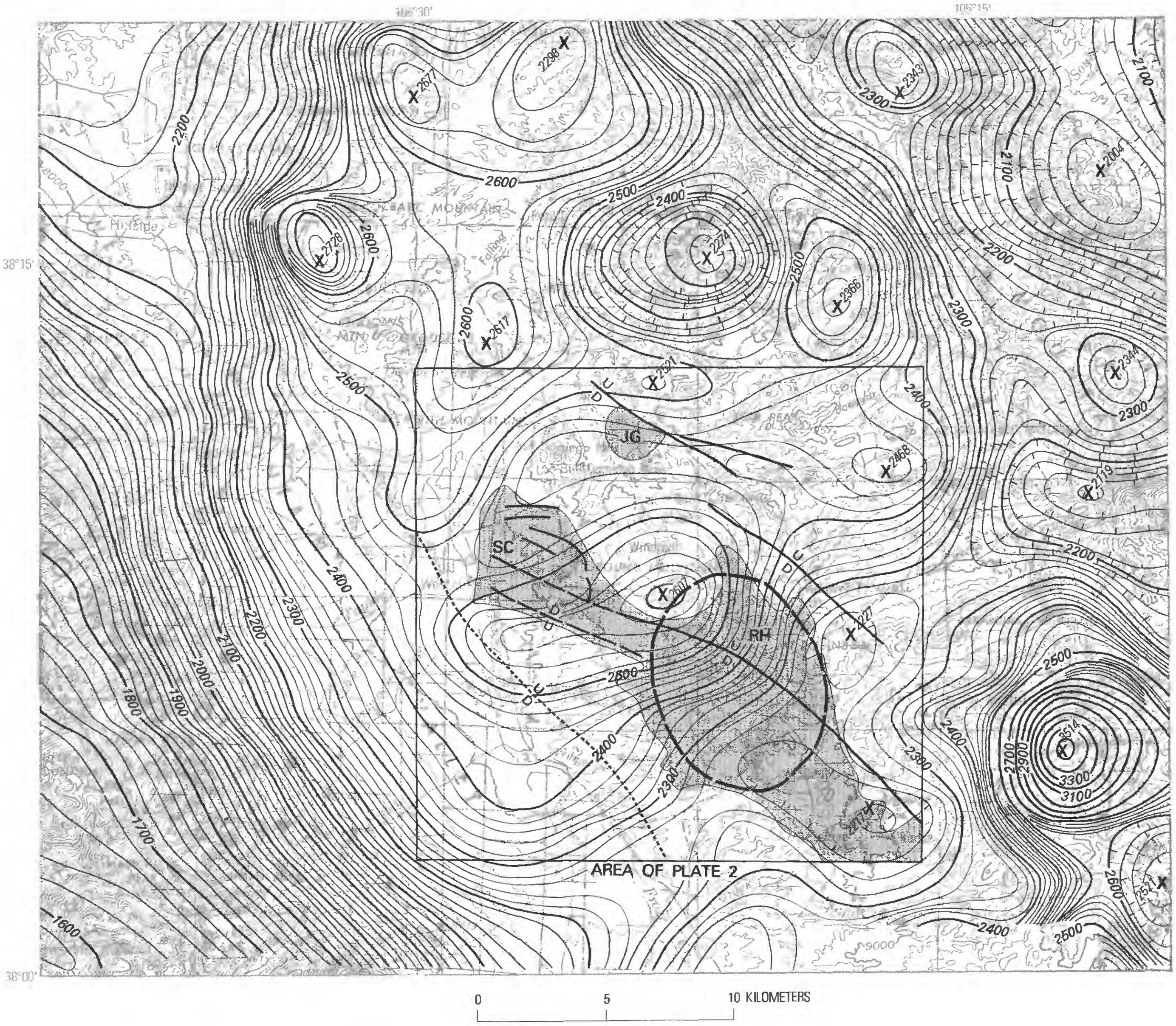


FIGURE 2.—Reconnaissance gravity map, modified from Peterson and others (1974).

ture in the subsurface, slightly negative expressions attributed to the volcanic deposits were observed over the Silver Cliff center. This was most evident just southeast of Silver Cliff village, where contours of 2,520 and 2,540 gammas show negative noses over volcanic rocks.



EXPLANATION

MAGNETIC CONTOURS—Showing total intensity magnetic field of the Earth in gammas relative to arbitrary datum. Hachured to indicate closed areas of lower magnetic intensity. Flight lines 4420 m above sea level, at 1.6 km spacing. Contour interval 20 gammas

LOCATION OF MEASURED MAXIMUM OR MINIMUM INTENSITY, IN GAMMAS, WITHIN CLOSED HIGH OR CLOSED LOW

FAULT—Dashed where uncertain; U, upthrown side; D, downthrown side

VOLCANIC ROCKS
SC, Silver Cliff area
RH, Rosita Hills area
JG, Johnson Gulch area

CRATER COMPLEX AT ROSITA HILLS

FIGURE 3.—Regional aeromagnetic map, modified from U.S. Geological Survey (1970).

DETAILED GRAVITY MAP

The Bouguer gravity map (pl. 1) is contoured at 1 mgal intervals and shows many local features not apparent on the 5 mgal map. The gravity pattern is dominated by high-gradient zones and by negative anomalies expressed as closed lows and residuals in the form of contour nosings. The gross northwesterly trend of the contours reflects the regional gravity field observed on the reconnaissance map. On the basis of correlations with known geology, most of the gravity anomalies can be interpreted in terms of lateral and vertical distribution of low-density Tertiary volcanic rocks in contact with high-density Precambrian gneisses (table 1) and are not related to lithologic variations in the Precambrian rocks. This is exemplified at the Silver Cliff and Johnson Gulch areas, where prominent negative anomalies apparently reflect thick sequences of highly altered volcanic breccias preserved in volcanic subsidence features. Conversely, the probable boundary of the early crater complex at the Rosita Hills, as outlined from geologic studies (pl. 1), is not clearly discernible in the gravity data. Instead, several smaller anomalies of less amplitude and areal extent may reflect a pattern of more restricted subsidence coupled with a greater percentage of denser volcanic rocks, including andesites and trachytes.

TABLE 1.—*Physical properties of rocks in the Silver Cliff and Rosita Hills volcanic area, Colorado*

Sample	*Density*[1]	[2]Magnetic susceptibility ($\times 10^{-4}$)
	Felsic gneiss	
1	2.61	0.58
2	2.61	*
3	2.62	*
4	2.61	*
5	2.63	.24
Average	2.62	0.16
	Mafic gneiss	
1	3.04	0.32
2	2.91	121.87
3	2.81	12.20
4	2.87	.53
5	2.94	18.74
Average	2.91	30.89
	Tuff	
1	2.04	*
2	1.95	65
Average	2.00	32
	Andesite	
1	2.73	0.48
2	2.96	10.97
Average	2.85	5.73
	Rhyolite	
1	2.46	0.43
2	2.51	.32
Average	2.49	0.38

[1]In grams per cubic centimeter.

[2]In electromagnetic units per cubic centimeter. *, values less than 10^{-6} emu/cm^3, the threshold of the measuring equipment.

DETAILED AEROMAGNETIC MAP

The detailed aeromagnetic map (pl. 2) is contoured at 50 gamma intervals and shows a number of prominent anomalies which reflect both lithologic and structural boundaries in the Precambrian gneissic complex as well as distribution of Tertiary volcanic rocks. Compared to the high-altitude survey (fig. 3), the information content of the low-altitude survey is considerably greater, since it was flown nearly 1,525 m closer to the ground surface and at one-half the flight-line spacing. The high-level data show broad smooth anomalies related to Precambrian rocks and the anomalies can be recognized on the detailed map as complex features complicated by the magnetic influence of the volcanic rocks. A good example is the major easterly trending positive anomaly that extends nearly across the map. Compare the smooth 2,500-gamma closure on the inset map of figure 3 with the rather contorted 2,500-gamma anomaly on the large-scale map.

The magnetic patterns are more complex than the gravity anomalies. The gross magnetic grain is northeasterly as would be expected since this trend is pronounced in the study area on the regional aeromagnetic map. In the northwestern part of the map, prominent negative anomalies occur over the volcanic deposits at Silver Cliff and Johnson Gulch. Interpretations of other negative features over adjacent Precambrian terrain will be discussed in the following section of this report. As was the case for the gravity data, the probable boundary of the early crater complex at the Rosita Hills is not distinctive in the magnetic data. The magnetic pattern is a rather nondescript mixture of low-relief highs and lows, except for a broad but well-defined negative anomaly along the southwest edge of the Rosita Hills. The positive features in the extreme southern and southwestern parts of the area are attributed to lithologic variation in the Precambrian basement rocks.

GEOLOGIC SIGNIFICANCE OF LOCAL GRAVITY AND MAGNETIC ANOMALIES

The gravity and magnetic features of interest are often referred to as "anomalies" in the discussions to follow. "Anomaly" is used in the customary way as a local deviation of geophysical values, such as milligals or gammas, above or below a regional field or background. An "anomaly" may be one of two types, first a high or low expression of various configurations portrayed by closed contours, or second, an expression portrayed by nosings or bowings in the contours in which no closed contours occur, but which nevertheless indicate a mass irregularity representing a geological disturbance of interest. The latter is referred to in the text as a "residual anomaly," or the local expression that occurs above or below the background field.

The interpretations were focused on the gravity data, which proved to be more diagnostic than the magnetic data in identifying and studying volcanic features in the third dimension. The magnetic data provided valuable qualitative information that often corroborated and thus strengthened the gravity interpretations. Because the magnetic patterns showed no indications of reversals, the magnetic anomalies were assumed to be caused by sources magnetized by induction in the Earth's field, and effects from remanent magnetization not in the direction of the field were considered negligible.

Possible correlations between topographic features and the gravity and magnetic anomalies were examined. The topographic relief of the area varies from low to moderate with a total relief of about 610 m: elevations range from less than 2,340 m at De Weese Reservoir to over 2,950 m at Mount Robinson in the Rosita Hills. Qualitative evaluations of the gravity and magnetic data across large topographic changes in both volcanic and granitic rocks showed no influences large enough to detract from the interpretation presented.

Density and magnetic susceptibility measurements were made (table 1) and showed marked contrasts between major rock units that are significant to the interpretations. However, in many cases, it was useful to assume average density and magnetic susceptibility values since the Tertiary volcanic rocks and Precambrian gneisses were a mixture of several lithologies.

Gravity anomaly 1.—The most prominent gravity feature is the large negative anomaly that corresponds to the Silver Cliff volcanic field in the west-central part of the area (pl. 1). The amplitude of the negative anomaly is nearly 10 mgals; two areas along the gravity trough where the gravity data indicate that the less dense rocks or volcanic rocks are thickest are located approximately by the −224 and −225 mgal closed contours. The deepest parts of the gravity trough define the Silver Cliff graben, which extends nearly to the Rosita Hills. On this basis, coupled with geologic field studies, the anomaly is interpreted to represent an area of substantial subsidence of Precambrian blocks, which resulted in accumulation and preservation of the volcanic rocks observed in outcrop. The gravity trough is terminated near the Rosita Hills by a cross-trending gravity high over near-surface Precambrian crystalline rocks that separate the Silver Cliff and Rosita Hills volcanic areas.

The magnetic data show a major negative anomaly that corresponds to the gravity feature. Particularly striking is the south side of the magnetic anomaly where it is elongated in a northwesterly-southeasterly direction as an axial low that correlated with the gravity trough. The magnetic trough is also terminated just west of the Rosita Hills, but a fingerlike extension of the negative anomaly suggests faulting that is not observed in the gravity data. The magnetic data have geologic significance in confirming the gravity interpretation of a structural depression filled with volcanic rock. The magnetic data indicate that most, if not all, of the volcanic debris are relatively nonmagnetic types, or that most of the magnetic character has been destroyed by alteration associated with later stages of the volcanism.

Gravity anomalies 2 and 3.—These anomalies are subsidiary negative residual anomalies formed from nosings in the contours along the steep gravity gradient zone that marks the north and northeastern flank of the major Silver Cliff feature, anomaly 1. The anomalies correlate with two volcanic vents, Upper Chlorite vent (anomaly 2) and Ben West volcano (anomaly 3). The eruptive vents are composed of chaotic volcanic debris that apparently is sufficiently porous to cause the gravity lows. Another center, Geyser vent, has been mapped in geologic field studies (pl. 1), but exhibits no gravity expression.

The magnetic data are significant. Magnetic low 2,185 nearly centers over Ben West volcano, but no observable magnetic expression of Upper Chloride vent or Geyser vent exists. The magnetic data strongly suggest that the volcanic alteration was more intensive at Ben West volcano, compared to the Upper Chloride and Geyser vents, where the magnetic character of the breccias apparently was not greatly changed. The seismic-refraction profile A-A' (fig. 4) across Ben West volcano confirmed the presence of low-velocity rocks in the subsurface and will be discussed subsequently in the section on seismic interpretations.

Gravity anomaly 4.—This is a negative residual anomaly that appears as a definite nosing in the contours over Precambrian outcrops. The amplitude of the anomaly is about 1 mgal. This could indicate an incipient volcanic feature in the subsurface, in which the magnetic properties of the Precambrian gneiss may have been destroyed by hydrothermal activity associated with the volcanism. Although the magnetic and surface data do not confirm such a feature, the anomaly is of interest because of the proximity of the main volcanic areas and the nearly adjacent reentrant of volcanic rocks along the northeastern end of the Silver Cliff graben.

Gravity anomaly 5.—Along the south side of the Silver Cliff graben, Precambrian crystalline rocks have been mapped in outcrop (pl. 1); and gravity anomaly 5 suggests that the crystalline rocks are in the near subsurface in a zone at least 2 km wide along the south side of the Silver Cliff graben. In fact, the seismic data along profile *A-A′* show crystalline rocks ranging in depth from 150-250 m between the graben and the Westcliffe fault. Magnetic high 2,965 generally correlates with gravity anomaly 5, and the apex of the magnetic anomaly is about 1 km southwest of the top of the gravity anomaly, as would be expected for a uniformly magnetized block. The gravity and magnetic highs appear to represent a unit of Precambrian gneiss of rather uniform lithology.

Gravity anomaly 6.—The Westcliffe fault is located along the southwestern margin of the study area (pl. 1) and shows subtle geophysical expressions. Scott and Taylor (1975) attached considerable importance to the fault and stated that it was one of the faults along which late Tertiary uplift uplift of the northern part of the Wet Mountains occured.

A local steepening of the gravity gradient occurs along the fault northwest of Aldrich Gulch; to the southeast, the gravity contours cross the fault with no noticeable deflection. The broad magnetic anomalies which were interpreted to reflect lithologic units in the Precambrian crystalline basement cross the fault without interruption. However, 1 km to the southwest of the fault, the magnetic gradients are noticeably broader, thus indicating that sources of the anomaly are deeper beneath the sedimentary rocks of this part of the Wet Mountain Valley. The seismic-refraction data do show about 30 m of offset, down to the southwest, near the end of profile *A-A′* (fig. 4). The lower velocities recorded in Precambrian rocks south of the Westcliffe fault suggest a change in the lithology of the crystalline Precambrian rocks. This is compatible with the magnetic data, which show evidence of decreasing magnetic susceptibility from magnetic high 2,965 southward to the negative magnetic trough (pl. 2).

Gravity anomaly 7.—This negative residual anomaly may represent an incipient volcanic center possibly containing brecciated and altered volcanic rocks. The anomaly, in the form of a nosing in the gravity contours, correlates with an apparent surface mantle of volcanic rocks over Precambrian crystalline rocks; and a similarity with the expression at the Bassick pipe (anomaly 13) exists both in configuration and in location, relative to the Rosita Hills volcanic area. The magnetic data show correlative low values in a saddle located between two prominent magnetic highs. A negative magnetic response might be expected from an incipient volcanic feature as postulated here.

Gravity anomaly 8.—This negative gravity anomaly is expressed by the −218 mgal contour closure and a trough-like extension, to the north. It is in an area of rhyolite flows, the source of which may have been the vent area at Rattlesnake Hill. The −218 mgal contour closure may reflect the thickest deposits of rhyolite. This possibility is reinforced by the magnetic data, which show a coincident negative feature elongated in an east-northeasterly direction along the axis of the gravity anomaly.

Gravity anomaly 9.—The shape of this negative gravity anomaly suggests a graben-like feature of less dense volcanic rocks in an area of predominantly rhyolite flows. The gravity trough extends to the southeast and is part of the regional gravity trough (fig. 2) that was discussed earlier in the section on regional features.

Magnetic low 1,960 is located on the southwest edge of the volcanic complex of Rosita Hills, and it appears to be related in part to gravity anomaly 9. There is a general similarity between magnetic low 1,960 and magnetic low 2,185, which centers over Ben West volcano and covers most of the Silver Cliff volcanic area. The east-west magnetic troughs at both the north and south edges of the anomaly resemble the patterns of the magnetic low associated with the Silver Cliff graben. Magnetic low 1,960 may represent a composite source ranging from volcanic rocks on the north to Precambrian lithologies of low magnetic intensities on the south. However, because of its location and its similarity to the magnetic anomaly at Silver Cliff, the locality of magnetic low 1,960, particularly the 2,000 gamma closure, seems worthy of detailed examination in the field for possible evidences of subsidence.

Gravity anomaly 10.—The pronounced nosing in the gravity contours results in a positive residual anomaly, about 2 mgals in amplitude, that correlates with an eruptive vent composed largely of Miocene Pringle Latite (Sharp, 1978; Siems, 1968). North-northeasterly trending faulting enhances definition of the western flank of the anomaly. The positive magnetic feature, magnetic anomaly 2,365, correlates with the gravity anomaly; the apex is offset to the southwest as would be expected, but it may in part be related to dike rocks along the fault zone. The northeast side of the anomaly is indistinctly bounded by the Rosita fault, which becomes a complex zone in its northwesterly trend, where the gravity data suggest that it connects with faulting along the north side of the Silver Cliff graben. Whether the Rosita fault may have been a controlling crustal fracture related to emplacement of the volcanic rocks (Siems, 1968) is a matter of speculation.

Gravity anomaly 11.—Over the eruptive vent mapped on geologic evidence (Sharp, 1978), a weak negative gravity residual is suggested, although it is based on one gravity station on the edge of the structure. No local magnetic anomaly is evident, although the vent is on the edge of a large magnetic trough, magnetic low 2,000. This suggests that the volcanic feature may narrow rapidly in a conelike fashion to a small diameter pipe or that the volcanic rocks within the center were not subjected to extensive alteration or brecciation sufficient to lower the density or magnetic susceptibility of the rocks.

Gravity anomaly 12.—The breccia vent mapped about a kilometer west of the townsite of Querida is expressed as a positive gravity residual or ridge. The ridge may be artificial and may have resulted from gradients associated with the lows to the east (anomaly 13) and to the west. No anomaly was detected in the magnetic data, which suggests, as in the case for anomaly 11, that there probably was not enough brecciation or alteration associated with the eruptive center to produce a density or magnetic susceptibility contrast with the surrounding rocks. In fact, the gravity data suggest the presence of somewhat denser rocks, possibly dacites or andesites at the eruptive center.

Gravity anomaly 13.—A pronounced negative gravity residual anomaly of 3-4 mgals amplitude correlates with the Oligocene breccia pipes located on the south flank of Mount Tyndall. The anomaly is part of a northeasterly trending gravity trough located along the northeast edge of the main volcanic field of the Rosita Hills. The anomaly is caused partly by volcanic agglomerates that form a reentrant into adjacent Precambrian gneiss outcrops.

The Bassick pipes area does not exhibit a corresponding magnetic low, but is located about 1.5 km northwest of the low point of a broader magnetic feature, magnetic low 1,940. It is surprising that there is not a sharp, high-amplitude magnetic low over the Bassick area because of the strong alteration expected with formation of the explosive breccia pipes.

Gravity anomaly 14.—The gravity expression over the monadnock-like mass of the Bull Domingo Hills is a broad elongate high that is poorly controlled. A prominent magnetic feature, magnetic low 2,060, centers over the southwest half of the hills, which consist of Precambrian rocks predominantly of hornblende and biotite gneiss. The magnetic low across this topographically high mass of dark-colored gneisses was unexpected. However, indications from two samples tested for magnetic susceptibility suggest that the Precambrian rocks of the southeastern hills may be relatively nonmagnetic compared to surrounding Precambrian terrane. The two samples averaged less than 1.0×10^{-4} emu/cm^3 compared with an average of 30.89×10^{-4} emu/cm^3 obtained for mafic gneisses of the study area (table 1). The possibility of a volcanic source for the magnetic anomaly is highly unlikely, but should be mentioned, since there is a small breccia pipe at the Bull Domingo Mine near the south end of the hills. The pipe could be the surface manifestation of volcanic activity that destroyed, through alteration, the magnetic properties of a large volume of rocks in the subsurface. If this were the case, it seems likely that there would be other areas of venting or alteration at the surface. None have been reported.

Magnetic low 2,060 is part of a broad pattern, a pronounced arc-like expression, that includes low 2,185 over Ben West volcano, low 2,195 just east at Johnson Gulch and low 2,235, some 6 km farther east. The lows at Ben West volcano and Johnson Gulch are both associated with gravity lows and correlate with areas of suspected volcanic subsidence. It is possible that associated with magnetic low 2,060 there may be a gravity low that was not detected in the reconnaissance control, owing to the broad spacing of the gravity stations in this area.

Gravity anomaly 15.—About 3 km east of the Bull Domingo Hills another volcanic feature has been identified along Johnson Gulch (Sharp, 1978; Kleinkopf and Peterson, 1976). The nearly coincident gravity and magnetic (2,195) lows (pls. 1 and 2) over outcrops of volcanic ash,coupled with geologic evidence (William N. Sharp, written commun., 1976), suggested the presence of a cauldron subsidence feature. Field evidence for subsidence was evident along the Precambrian-Tertiary tuff contact, where a zone of coarse breccia was composed of Precambrian rocks, along with some volcanic blocks, all tightly packed and angular with abundant iron staining. Three-dimensional modeling of the gravity anomaly indicated a column of low-density rocks extending about 1,000 m below the surface.

Gravity anomaly 16.—A negative gravity residual defined by a rather pronounced nose in the gravity contours is located about 3 km east of Ben West volcano. No surface evidence of volcanism has been reported in this area of Precambrian crystalline gneisses, Tertiary gravels, and conspicuous faults. However, a significant factor is the corresponding negative magnetic residual anomaly formed by a sharp nosing in the magnetic contours and controlled by two flight lines. Thus, gravity and magnetic expressions call attention to an area not far removed from the volcanic subsidence at Silver Cliff, and they may reflect a subsurface volcanic source that did not reach the present level of erosion.

SEISMIC INTERPRETATIONS

The two seismic-refraction profiles (*A-A′* and *B-B′*, figs. 4 and 5) shot across the major subsidence feature

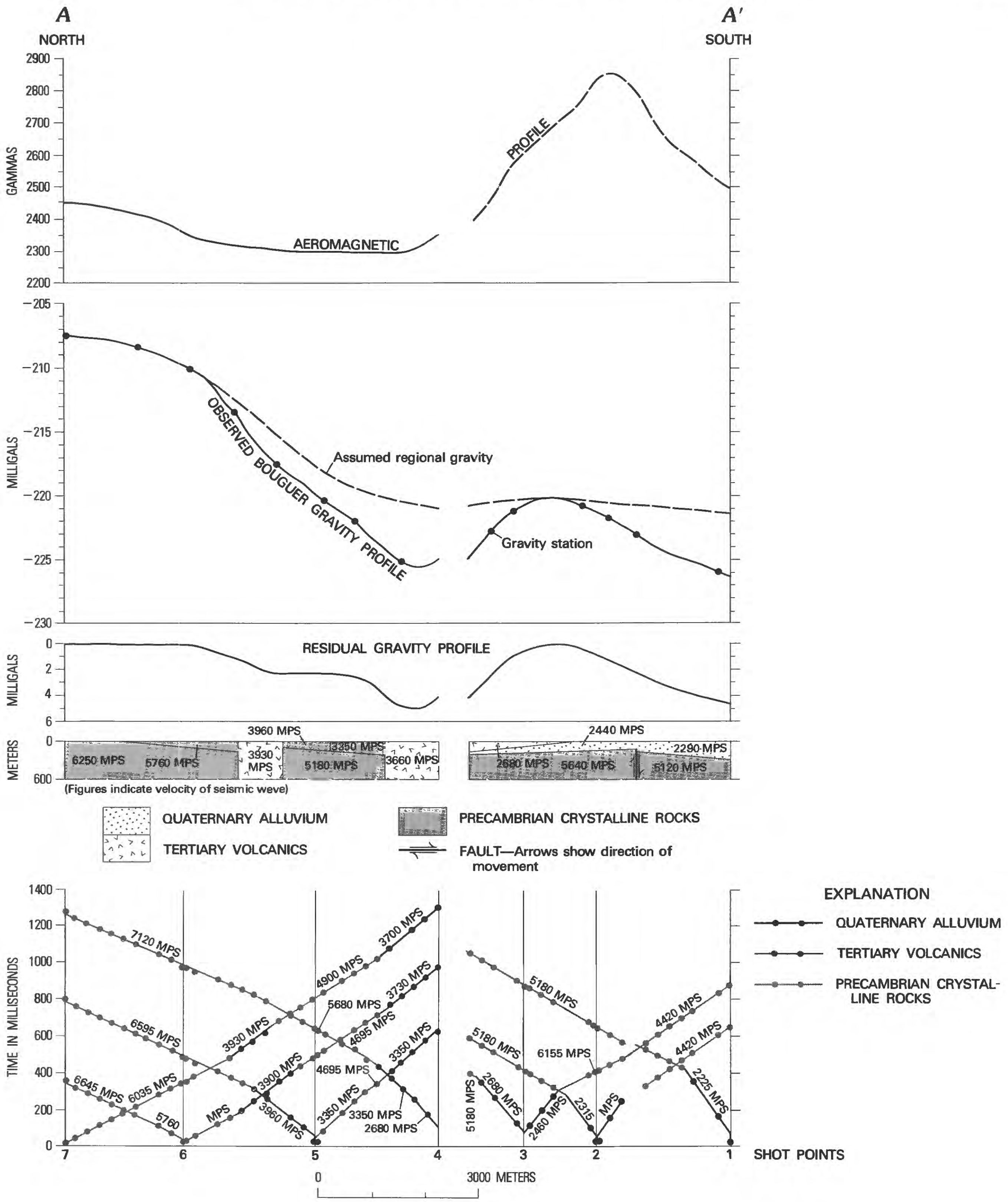


FIGURE 4.—Geologic section *A-A′*, constructed from seismic refraction data with time-distance plots, gravity, and aeromagnetic profiles.

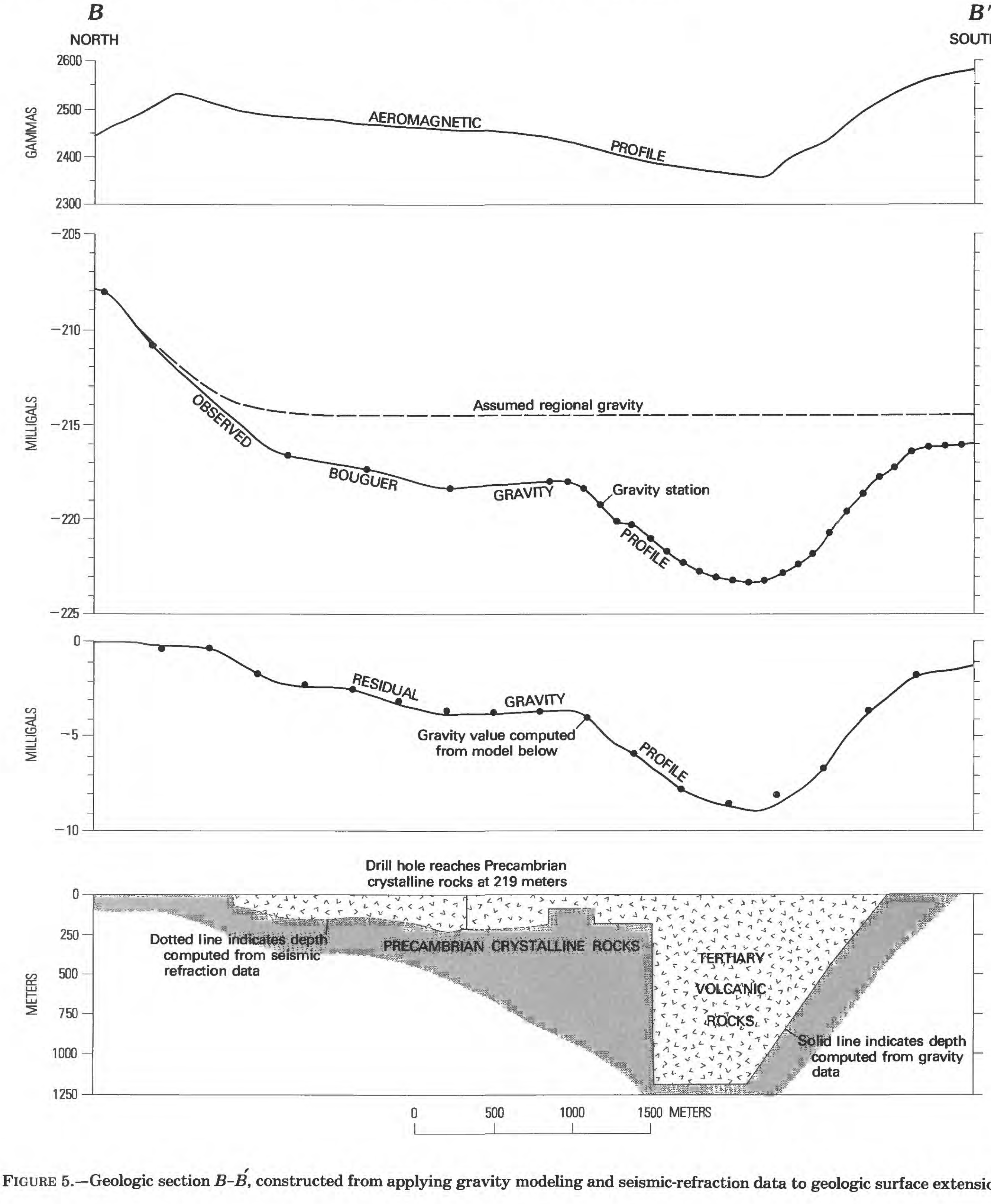


FIGURE 5.—Geologic section *B–B′*, constructed from applying gravity modeling and seismic-refraction data to geologic surface extensions.

at Silver Cliff (anomaly 1) provided quantitative information about the thickness and distribution of volcanic and alluvial deposits relative to Precambrian crystalline basement. The results from profile *A-A′* showed that the *p*-wave velocity measured in the Precambrian crystalline rocks varied from 3,350 mps to 6,250 mps, in the volcanic rocks from 2,680 mps to 3,930 mps, and in the overlying Tertiary sedimentary rocks from 2,290 mps to 2,440 mps. The notably low value of 3,350 mps velocity recorded for one area of outcropping Precambrian rocks was attributed to a high degree of fracturing. Disregarding this velocity measurement, the velocity in the Precambrian complex varied from 5,120 mps to 6,250 mps.

Seismic records from shotpoints 1-3 on profile *A-A′* (fig. 4) were of excellent quality, and interpretation was a straightforward procedure. Disregarding the thin weathering layer with a velocity of 330 mps and varying in thickness from 7 to 15 m, three refracting horizons were recorded with calculated velocities of 2,290–2,440 mps, 2,680 mps, and 5,120–5,640 mps. The three velocities were interpreted as representing sedimentary, volcanic, and crystalline rocks, respectively. Calculated depths to crystalline basement are about 300 m, 150 m, and 230 m at shotpoints 1, 2, and 3, respectively. A small offset on the time plot, located about 1,500 m south of shotpoint 2, was interpreted as indicative of the Westcliffe fault with displacement of about 30 m. On the upthrown side of the fault the velocity of the basement rock was calculated to be 5,640 mps and the velocity on the downthrown side was calculated to be 5,120 mps. This difference in velocity could be caused by a change in lithology, moderate alteration, or possibly a change in amount of fracturing and weathering.

The quality of the records obtained from shotpoints 4–7 (fig. 4) was not as good as from those obtained along the southern segment. Nonetheless a reasonable interpretation could be made. Between shotpoints 6 and 7, where Precambrian crystalline rock is exposed, the time-distance plot indicates two distinct velocity layers within the Precambrian complex with velocities of 5,760 mps and 6,250 mps.

Near shotpoint 4 a maximum velocity of 3,660 mps was measured. This velocity, not typical of Precambrian gneiss, is interpreted as reflecting a thick section of volcanic rocks that corresponds to the Silver Cliff graben shown on the gravity map (pl. 1). Similarly, the area just north of shotpoint 4, where velocities no greater than 3,930 mps were recorded, appears to correspond to the Ben West volcano. Between the two volcanic centers at the Silver Cliff graben and Ben West volcano the near-surface velocity varied from 3,350 to 3,960 mps and the deeper velocity was 5,180 mps. The thickness of the relatively low velocity surface volcanics is calculated to be at least 150 m; the surface volcanics overlie higher velocity material, which is interpreted to represent fractured crystalline rock of the Precambrian complex.

Along profile *B-B′* a schematic structure section was made from analyses of gravity modeling and the seismic-refraction data (fig. 5). The time picks of the seismic arrivals were variable in quality, but enough reliable information was obtained to construct the geologic section in conjunction with the gravity modeling. The volcanic rocks thicken from about 120 m near the north end of the profile to about 1,220 m in the trough, as calculated from the seismic-refraction data and the two-dimensional gravity modeling (fig. 5). The calculated thickness of the volcanic section was confirmed at one point by an existing drill hole that bottomed at the top of the Precambrian rocks at 219 m. The time-distance plots along profile *B-B′* suggest an average velocity of 5,790 mps for Precambrian rocks and 3,110 mps for the volcanic rocks—in good agreement with the corresponding velocities obtained on profile *A-A′*.

GRAVITY MODELING

Three-dimensional iterative modeling of the Silver Cliff volcanic area was done to obtain quantitative information about the thickness and configuration of the volcanic material. The gravity modeling involved several steps. First, a residual map was prepared by subtracting from the complete Bouguer gravity data (pl. 1) a regional field that was a smoothed approximation of the Bouguer gravity data. Figure 6 shows the arcuate dipping regional and the resulting residual gravity anomaly. The residual map then was gridded at a 0.5 km interval to obtain digitized data for input to a computer program (Cordell and Henderson, 1968). The horizontal reference plane chosen was the ground surface. After five iterations the solution was obtained as shown by the isopleths in figure 7.

A single average density contrast of 0.5 gms/cm^3 between Tertiary volcanic rocks and Precambrian gneisses was assumed based on the physical property determinations (table 1) coupled with the abundance of low-density tuffaceous and brecciated rocks in the volcanic suite at Silver Cliff. This order of magnitude of density contrast was confirmed by the large velocity differences measured during the seismic-refraction surveys. Along profile *A-A′* (fig. 4), velocities for volcanic rocks ranged from 2,680 to 3,960 mps and from 5,120 to 6,250 mps for Precambrian gneisses. The

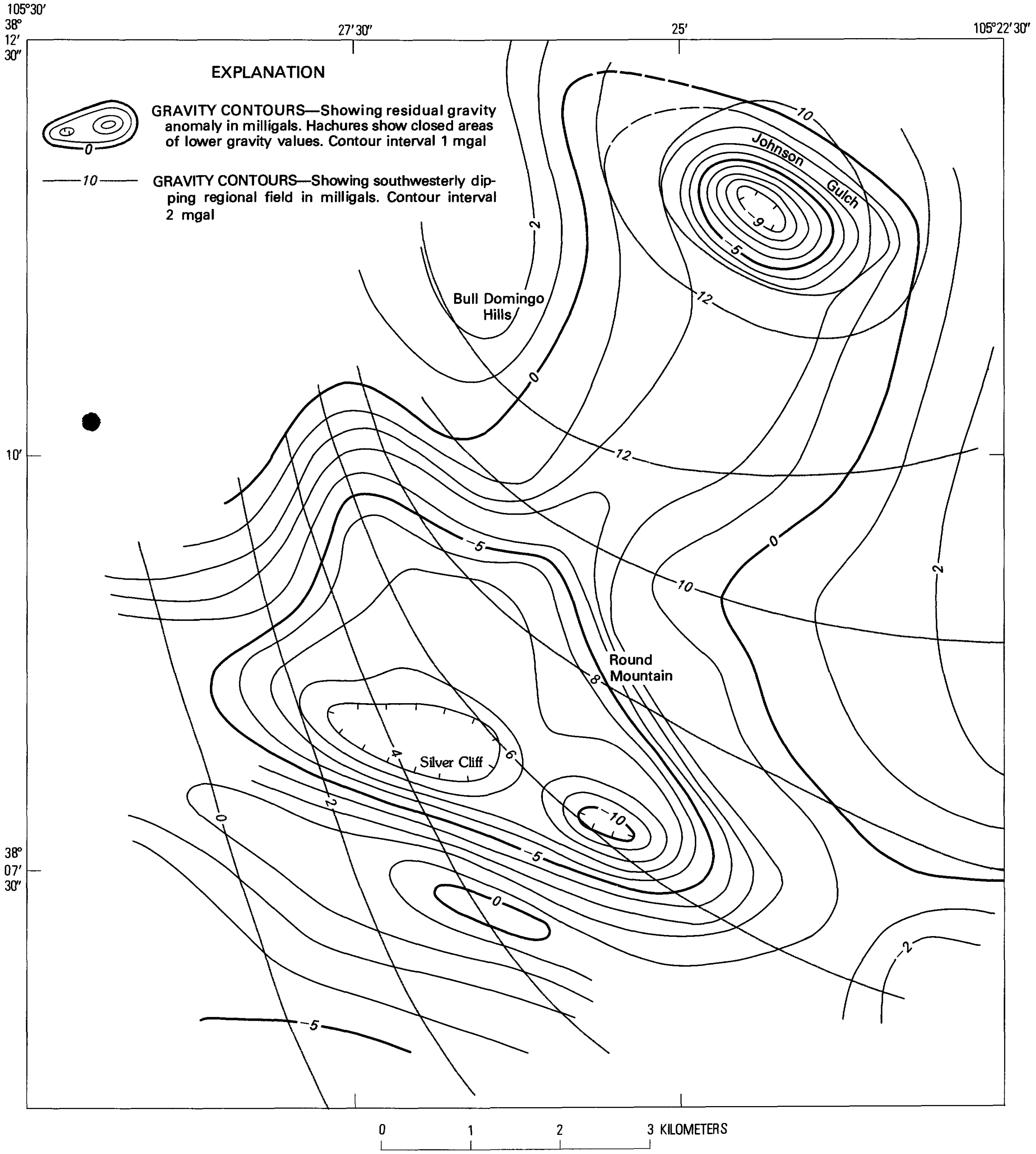


FIGURE 6.—Residual negative gravity anomaly over Silver Cliff and Johnson Gulch volcanic area. Anomaly derived by subtracting the southwesterly dipping regional field (shown by contours 0 to 12 in increments of 2 mgals) from the Bouguer anomaly (pl. 1).

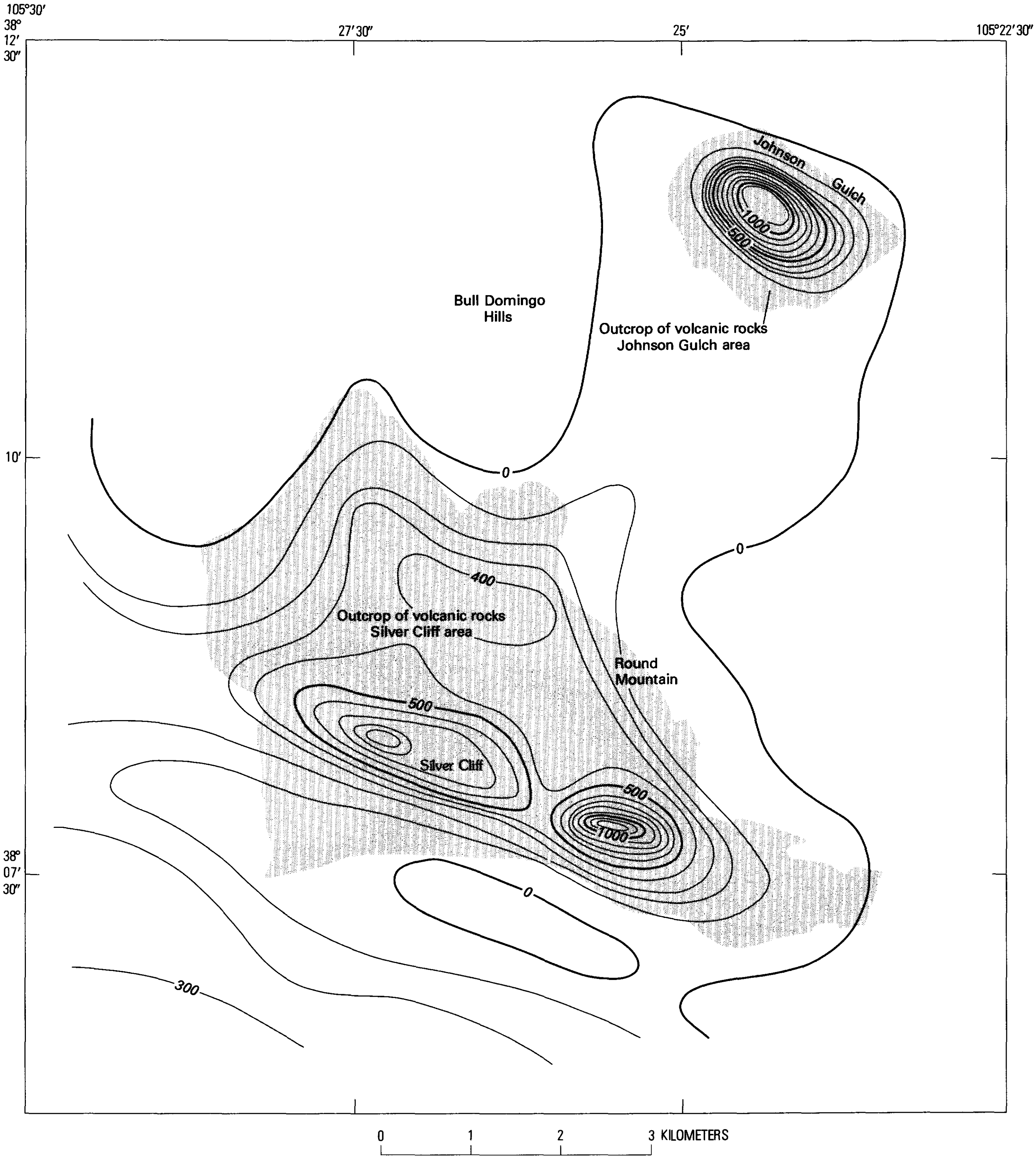


FIGURE 7.—Gravity model of configuration of volcanic rocks, Silver Cliff volcanic area. Thicknesses shown by isopleths of 100-meter intervals derived from 3-dimensional iterative modeling of the gravity data. (See fig. 6.)

results from profile B-B' (fig. 5) were in good agreement; 3,110 mps for volcanic rocks and 5,790 mps for Precambrian gneisses. The value of 0.5 gms/cm^3 is probably a maximum density contrast to be expected and would give minimal thicknesses of less dense volcanic rocks, since one might anticipate the contrast to decrease with depth.

The results of the modeling (fig. 7) show a wedge of low-density volcanic material with thicknesses reaching 900 and 1,200 m in the deepest parts of the Silver Cliff trough. These areas correspond to the −224 and −225 closures on Bouguer gravity map (pl. 1). The order of magnitude of the thickness values is in general confirmed by seismic-refraction profile A-A' (fig. 4) and the schematic-structure section made from seismic-refraction and two-dimensional modeling of detailed gravity data along profile B-B' (fig. 5). It is noteworthy that across Ben West volcano and Silver Cliff trough the seismic-refraction data did not resolve the bottom of the volcanic features, and it is probable that the gravity data show a minimum thickness since the depth extent apparently exceeds the width of the volcanic feature. Earlier results at Johnson Gulch (Kleinkopf and Peterson, 1976) indicated the presence of a low-density column of rocks shaped like an inverted and truncated cone which extended to a depth of approximately 1,000 m beneath the volcanic tuff outcrops. The Johnson Gulch gravity model is included here since the northeasterly trends in the gravity data, as well as the model results (fig. 7), suggests a possible connection in the subsurface between the Silver Cliff and Johnson Gulch areas. This is highly speculative, and such indication was not apparent from field geologic studies of the outcropping Precambrian gneiss, which showed no evidence of northeasterly trending structures. In fact, several northwesterly trending faults were mapped across this area (pl. 1). However, the gravity and magnetic evidence for a possible incipient volcanic vent occurring between the two areas should not be overlooked (gravity anomaly 16 with corresponding negative magnetic residual).

CONCLUSIONS AND RECOMMENDATIONS

Several exposed volcanic eruptive and cauldron subsidence features in south-central Colorado show well-developed negative gravity and magnetic anomalies. Examples are the Silver Cliff graben, Ben West volcano, and the Johnson Gulch features. For the study area in general. the relative amplitudes of the gravity and magnetic anomalies gave information about the degree of brecciation and intensity of alteration of volcanic rocks as well as their thicknesses. Variations in velocities recorded in the seismic refraction surveys were indicative of buried Tertiary volcanic deposits and highly fractured Precambrian rocks.

Several other localities besides those examples mentioned have distinct negative gravity or magnetic anomalies, possibly indicative of volcanic deposits in the subsurface; and these also seem worthy of careful studies. Additional geophysical and geological work seems warranted, in order to obtain more evidence of subsidence and alteration, possibly associated with mineralizaton. In particular the following anomalies are recommended for further considerations:

1. Gravity anomaly 7, located along the north side of the main Rosita Hills volcanic area.
2. Gravity anomaly 15, located at Johnson Gulch.
3. Gravity anomaly 16, located about 3 km east of Ben West volcano.
4. Magnetic low 2,235, located about 6 km east of Johnson Gulch (gravity anomaly 15).
5. Magnetic low 2,060, associated with the southeastern part of the Bull Domingo Hills.
6. Magnetic low 1,960, located along the southwestern boundary of the main Rosita Hills volcanic area.

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