DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

TO ACCOMPANY MAP I–1419–B

RESIDUAL BOUGUER GRAVITY AND INTERPRETATIVE MAPS OF THE PUEBLO 1°× 2°QUADRANGLE, SOUTH-CENTRAL COLORADO

By
Frances M. Boler and Douglas P. Klein

INTERPRETATION

INTRODUCTION

Gravity features that are interpreted to be significant in the Pueblo 1°×2° quadrangle (lat 38° to 39° N. and long 104° to 106° W.) in terms of crustal composition and structure are shown on map *B*. These features are superimposed on a modified version of the geologic map of Colorado (Tweto, 1979a), but more detailed geology is available on the geologic map of the Pueblo 1°×2°quadrangle by Scott and others (1978). Gravity features, semilinear or linear trends, steep gradients, and selected anomalies are shown, as well as mineral districts. Tables 1, 2, and 3 summarize information about the anomalies, trends, and mineral districts, respectively. Geothermal resource analysis is not part of this study, but known geothermal locations (U.S. Geological Survey, 1977) are shown on map *B* because of their possible relationship to structures delineated by the regional gravity interpretation.

The interpretation begins with a discussion of gravity features that have horizontal dimensions of hundreds of kilometers and are shown in the southern Rocky Mountains residual gravity map (fig. 1). This discussion emphasizes the regional setting of the Pueblo quadrangle. Later sections discuss the specific features of the quadrangle. The last section comments on the relationships between gravity and mineralization.

REGIONAL GRAVITY OF THE SOUTHERN ROCKY MOUNTAINS

The regional gravity map of the southern Rocky Mountains (fig. 1) is based on data extending 173 km beyond the Pueblo quadrangle. The second-degree polynomial surface (shown as regional gravity contours in fig. 1 and map *A*) was removed from the complete Bouguer gravity anomaly data to form the residual gravity data; this surface should correspond to the gravity response of density contrasts in the crust and upper mantle that have horizontal dimensions of about 4–6°. Thus, the contributions from upper mantle density contrasts and crustal thickness variations related to the transition from the Great Plains to the Rocky Mountains (Pakiser, 1963) should be minimized on the residual gravity map.

The physiography and geology of the area encompassed by figure 1 are commonly divided into two provinces: the Great Plains province, which lies roughly east of long 105°00′ W., and the Rocky Mountains province to the west. The physiographic and geologic transition is abrupt, and normal faults bound the easternmost mountain fronts (Curtis, 1960; Tweto, 1979a).

The regional gravity field in the Great Plains east of long 105°00′ W. is characterized by broad gravity highs, as in the Otero-Bent volcanic area and the region east of Denver, and by broad lows, one centered between Denver and Pueblo and the other lying on the east edge of the figure. In contrast, west of long 105°30′ W. the Rocky Mountains province is characterized by deep elongated lows, as in the Sawatch Range and the San Juan Mountains. The region of elongated lows is bounded on the west by highs such as the one in the region of the White River plateau uplift. The gravity transition between the Great Plains and Rocky Mountains province lies between long 105°00′ W. and 105°30′ W. This transitional region, which occupies the central part of the Pueblo quadrangle, is characterized by anomalies of intermediate to small horizontal extent, such as those west of Denver and in the Wet Mountains. There is a tendency toward northwest elongation of the gravity features in this transition region.

Qureshy (1962) found that the isostatic gravity field in Colorado indicates that the Great Plains area is nearly 100 percent compensated, whereas the mountainous regions are slightly undercompensated. Most of the undercompensation occurs in the transitional region, especially in the Pikes Peak and Wet Mountains uplifts, but the Colorado mineral belt, Sawatch Range, and San Juan Mountains areas are overcompensated. Qureshy correlated the undercompensated areas to regions of mantle upwarp, and he correlated the overcompensated areas with regions of crustal thickening due to the presence of intrusive or volcanic rocks.

The Colorado mineral belt (fig. 1) was defined by Tweto and Sims (1960, 1963) on the basis of mineral deposit locations in Colorado. They considered the localization of mineralization along this northeast-trending belt as evidence of a northeast-trending crustal weakness of Precambrian age. The mineral belt is coincident with an elongated gravity low in the Leadville region. Tweto and Case (1972) attributed this gravity low to a low-density batholith that was also the source of mineralizing fluids. However, the Colorado mineral belt gravity low also coincides with the region of elevations greater than 2,500 m, and this suggests that isostatic effects are contributing to the low. A low-density batholith, isostatic effects, or both may be responsible for the gravity low.

In the following interpretation, the Pueblo quadrangle is divided into three areas on the basis of the characteristic residual gravity expression in each (fig. 3). The three areas are: (1) the Great Plains area, a region of 50-km-wide east-trending anomalies east of long 105°00′ W.; (2) the Front Range area, a region of 25-km-wide north-northwest-trending elongated highs and lows between long 105°00′ W. and 105°30′ W.; and (3) the ridge-trough area, a region of 10-km-wide north- and north-northwest-trending elongate gravity ridges and troughs lying west of long 105°30′ W. These three areas correlate approximately with the Great Plains province, the transitional area, and the Rocky Mountains province of the regional gravity discussed above.

Within the Pueblo quadrangle, the Great Plains area is dominated in the north by the Denver basin low and in the south by an arcuate east-west high that lies between the Apishapa arch (Kleinkopf, Peterson, and Johnson, 1970) and the Las Animas arch (fig. 1).

The Front Range area is dominated by the Pikes Peak and Wet Mountains highs. These two highs are colinear with the highs west of Denver; all of these highs are regions of isostatic undercompensation identified by Qureshy (1962) as mantle upwarps.

The ridge-trough area is located on the eastern edge of the Rocky Mountains regional gravity low. This area is continuous with the Rio Grande rift to the south. Within the Pueblo quadrangle, the San Luis Valley and South Park have gravity lows that typify this area. The Colorado mineral belt intersects the northwest corner of this province, encompassing four of the mineral districts of the quadrangle (see map *B*). The low in the northwest corner correlates with one of Qureshy's (1962) regions of crustal thickening.

DISCUSSION OF GRAVITY IN THE PUEBLO QUADRANGLE

This section presents a gravity model along profile A′–A″ (fig. 4). Then we discuss the gravity characteristics of each of three areas: the ridge-trough area, the Front Range area, and the Great Plains area. The generalized topography and the locations of features mentioned in the text are shown in figure 3.

Profile A′–A″

The model along profile A′–A″ (fig. 4) consists of finite-length, two-dimensional bodies striking perpendicular to the profile. Each body is bounded horizontally perpendicular to the profile by material of density 2.67 g/cm^3, and each body terminates downward at 20 km below sea level. The downward termination is consistent with the assumption that the residual gravity represents lateral density contrasts within the upper crust. The bodies at both ends of the model extend outward 10,000 km from points A′ and A″, so that the effects of body truncation will not interfere with the part of the model of interest.

We made computations of the gravity field using a program that accounts for finite strike length of the model bodies by applying end corrections to the field calculated for infinite strike length bodies (Cady, 1980; Talwani and others, 1959). The procedure was to specify the model geometry and compute by least squares the density that produces the best fit between the computed and observed gravity fields. Geometries were altered until a reasonable model was obtained in terms of field fit, density, and geologic structure. Other combinations of geometry and density could be found that would produce a field fitting the observed field equally well. The "observed data" were interpolated numerically from the grid of gravity data used for contouring the map (*A*).

The basement in the western third of the model (body 1) has a density of 2.697 g/cm^3, the lowest basement-rock density in the model. This body underlies both the San Luis Valley and Sangre de Cristo Mountains. Body 2 represents the San Luis Valley sedimentary fill and has a density of 2.121 g/cm^3. The model indicates that the basement is close to the surface at point A′, although the topographic expression of the San Luis Valley extends 8 km farther to the west. The maximum basement depth in the San Luis

Valley is modeled at 1.9 km between 11.5 and 13 km along the profile. Beyond 13 km, the basement depth slopes upward roughly parallel to the topography toward the Sangre de Cristo fault at 19.2 km.

The Sangre de Cristo fault separates the Quaternary sedimentary rocks of the San Luis Valley from the Paleozoic sedimentary rocks of the Sangre de Cristo Mountains (represented by body 3). Body 3 has a density of 2.452 g/cm ^{3}. The top of the modeled body is shown by the solid topographic approximation line in figure 4. If the actual topography is used between 24 km and 37 km, a low is produced in the computed gravity field of the model. The number of stations across the crest of the mountains is insufficient to determine if this low actually exists. In order to diminish the misfit between the model results and the available data, five-point running averages of the true elevations were substituted for the top vertices of body 3.

The basement as modeled beneath the Sangre de Cristo Mountains rises from 0.6 km above sea level at the Sangre de Cristo fault to 1.7 km at 26 km along the profile, and it drops down to 0.8 km above sea level at 33 km, near the position of the Alvarado fault. The fault marks the contact between Paleozoic sedimentary rocks of the Sangre de Cristo Mountains on the west and Quaternary and Tertiary sedimentary rocks of the Wet Mountain Valley on the east. The modeled fault dips a few degrees toward the east. The observed gravity data do not require a density contrast in the basement rocks below this fault.

The magnetic field along the same profile (Boler and Klein, 1990) shows a positive anomaly at 18 km, where the gravity shows a low. The magnetic model places magnetic basement at 1.7 km above sea level between 18.5 and 25 km, but the gravity does not permit such a shallow basement. This apparent inconsistency could result from volcanic rocks having low density and high magnetization within the sedimentary rocks, or it could result from a relatively small intrusion along the Sangre de Cristo fault, whose mass does not contribute significantly to the gravity field. The magnetic profile also shows a low near 27 km, where the gravity profile shows a high. This is probably the reflection of thick and relatively dense carbonate rocks of the Sangre de Cristo Mountains, rocks that have negligible magnetization.

Body 4 represents the Wet Mountain Valley sediments, which have a density of 2.156 g/cm^3. The valley basement (body 1) slopes upward from 1.1 km above sea level at the Alvarado fault (35 km) to 1.3 km above sea level (1.1 km depth below the surface) at the Westcliffe fault (41 km).

Body 5 extends between the Westcliffe fault at 41 km and the Ilse fault at 65 km and is modeled as being at or near surface between 45 km and 57 km. Its density is modeled at 2.725 g/cm^3, higher than either of the two flanking bodies, in order to produce a gravity high that matches feature E. This body is interpreted to consist of Cambrian mafic-alkalic intrusions similar to those exposed at McClure Mountain (Shawe and Parker, 1967).

Two small, lower density bodies (labeled 1) are modeled within body 5 at the surface. Early Proterozoic gneiss (Xfh) crops out in these regions, and the density of these bodies is equal to that of the basement west of body 5. These bodies were incorporated to match some of the gravity variations in the high of body 5.

Body 6 represents the highest part of the Wet Mountains, as well as the floor of Florence basin to the east. Its density (2.707 g/cm^3) is comparable to that of body 1.

Body 7 (density of 2.451 g/cm^3) represents the Cretaceous and older sedimentary rocks in the Florence basin. The deepest point of the basin (0.9 km below sea level or 2.7 km below the surface) is at 78 km along the profile. The basement slopes upward to 0.8 km above sea level (0.8 km below the surface) at the east side of the model.

Body 8 (density 2.721 g/cm^3) is required at the northeast end of the profile to fit the observed increase in gravity east of the Florence basin. Part of this increase in gravity may be due to inadequate removal of the regional gravity field. This probably would lower the density of body 8, but would not eliminate its necessity.

The ridge-trough area

The structure of the ride-trough area is characterized by north- and north-northwest-trending horsts and grabens including the San Luis Valley, the Sangre de Cristo Mountains, the Wet Mountain Valley, the southern Mosquito Range including its lower lying extension in the Arkansas Hills (Curtis, 1960), and South Park (see fig. 3). This fault-bounded system of valleys and ranges interconnects the Rio Grande rift graben, which extends south from the San Luis Valley, with North Park, Middle Park, and South Park, the system of intermontane basins to the north of the quadrangle. Many of the faults in the ridge-trough area have had movement in Neogene time (Tweto, 1979b).

The lithology of rocks in the area is varied. Precambrian granites and metamorphic rocks are exposed in the Sangre de Cristo Mountains and southern Mosquito Range, as well as in outcrops within the volcanic rocks of South Park. Paleozoic sedimentary rocks lie along the crest and flanks of the southern Mosquito Range and Sangre de Cristo Mountains. The southern half of South Park is largely covered by Tertiary andesitic lavas, tuffs, and volcanic sedimentary rocks from the volcanic centers at Thirtynine Mile Mountain, Waugh Mountain, and Guffey. Upper Tertiary and Quaternary sediments fill the San Luis Valley and Wet Mountain Valley.

Mineral districts identified by Marsh and Queen (1974) and Vanderwilt and others (1947) are located in Paleozoic sedimentary rocks and Precambrian crystalline rocks in the Sangre de Cristo Mountains, the southern Mosquito Range including the Arkansas Hills, and the Arkansas River Valley.

Feature A. Feature A consists of several north- to north-northwest-trending gravity anomalies that are associated with South Park and the bordering mountains. The northern part of gravity trend a, a linear high along the west edge of the quadrangle, coincides with uplifts of Precambrian crystalline rock in the southern Mosquito Range. There is a break in the continuity of this trend near the Trout Creek mineral district (TC), and this may indicate intrusion and fracturing in the Precambrian basement.

South Park, northeast of trend a, shows the lowest gravity values in the Pueblo quadrangle. The lows occur along two linear trends b and d, which mark synclinal axes where the greatest thicknesses of Tertiary volcanic and volcanic sedimentary rocks have been mapped (Scott and others, 1978). Anomaly 1 and trend c mark gravity highs. Anomaly 1 coincides with exposures of Early and Middle Proterozoic granitic rocks (Xg and Yg). The occurrence of exposures of Precambrian granite at the north end of trend c suggests that this gravity trend may follow a similar trend of relatively shallow Precambrian basement.

Feature B. Both linear high e and the southeast continuation of linear low b trend northwest within feature B, a deviation from the principal north to north-northwest trends prevalent elsewhere in the ridge-trough area. Trends b and e are both truncated at the South Park-Front Range boundary gradient. Oligocene volcanic sedimentary rocks (Tpl) abut Early Proterozoic granitic rocks (Xg) at the southeast termination of trend b, and trend b is believed to mark a continuous trough of sediments and unconsolidated volcanic material. Trend e coincides with exposures of Early Proterozoic granitic (Xg) and metamorphic (Xfh) rocks.

Trend a, on the western boundary of feature B, corresponds to exposures of Precambrian crystalline rocks in both the Arkansas Hills and the northern Sangre de Cristo Mountains. The low gravity anomaly 2 and low trend f to the east of trend a coincide with an area of Paleozoic and Tertiary sedimentary rocks.

Feature C. Feature C is marked by parallel north-northwest-trending gradients that coincide geographically with the major ridges, valleys, and faults of the Sangre de Cristo Mountains region. The eastern boundary of feature C and of the ridge-trough area is a gradient that marks the Westcliffe fault, a normal fault that downdropped the Wet Mountain Valley relative to the De Weese plateau (feature E). The Westcliffe fault is largely concealed by Quaternary sediments, but the gradient approximately coincides with the mapped traces of this fault between lat 38°13′ and 38°05′ N. Thus, it is likely that the gravity gradient south of lat 38°05′ N. indicates the extension of the Westcliffe fault.

Trend f extends southeast from anomaly 2 along the west side of the Wet Mountain Valley, and it is coincident locally with the mapped trace of the Alvarado fault, a normal fault that downdropped the Wet Mountain Valley relative to the Sangre de Cristo Mountains to the west. Gravity profile model A′–A″ shows that the Wet Mountain Valley floor dips westward and has a maximum depth of 1.8 km at the Alvarado fault. An east-west resistivity profile model (Zohdy and others, 1971), which crosses the valley at lat 38°05′ N., also shows the valley floor dipping westward, but more steeply than indicated by gravity model A′–A″. The east end of the resistivity model is located 5 km east of the Westcliffe fault and shows the valley floor at 0.6 km below the surface, versus about 1 km on the gravity model. At the west end of the profile, 2 km east of the Alvarado fault, the resistivity model shows the valley floor at 1.8 km below the surface.

Trend g follows the gravity high approximately along the crest of the Sangre de Cristo Mountains. Precambrian rocks are exposed at the crest of the mountains north of lat 38°20′ N. At the position where profile A′–A″ crosses trend g, the crystalline basement is modeled at 1.5 km below the surface. A magnetic low in this area implies that the uplifted rock there is relatively nonmagnetic, although dense, as discussed in the section on profile A′–A″.

Anomaly 3, on the eastern slope of the Sangre de Cristo Mountains, is a 10-mgal high located over Paleozoic sedimentary terrane. A mapped thrust fault in the area of the anomaly (Scott and others, 1978) may have served as a conduit for an intrusive body that could provide the density contrast for the anomaly. Because there is no corresponding magnetic anomaly, the source of the gravity high must have negligible magnetization, which suggests a siliceous composition. The depth of the body is likely to be 2.0 km or less. This anomaly deserves further study to determine its cause and the possibility of related mineralization.

The Sangre de Cristo fault gradient generally coincides with the normal fault of the same name, which has downdropped the San Luis Valley relative to the Sangre de Cristo Mountains. The Crestone and Orient mineral districts (table 3) occur a few kilometers east of this fault gradient. The Crestone mineralization occurs in Precambrian rocks, and the Orient mineralization occurs in Paleozoic rocks lying within 5 km of exposed Precambrian rocks. Many of the faults in the Rocky Mountains are weaknesses of Precambrian age that have been reactivated repeatedly (Tweto, 1968). The Sangre de Cristo fault may be such a fault, one that has provided a conduit for the mineralizing fluids that formed the two nearby districts.

Trend h coincides with the San Luis Valley. Profile model A′–A″ places the valley floor at a depth of 1.9 km where it crosses trend h. Gravity values along trend h decrease both to the north and south of the profile; this indicates that the valley floor may be a few hundred meters deeper in those places. Gravity values increase west of trend h, and the model of profile A′–A″ shows the valley floor close to the surface at the west edge of the quadrangle.

South Park-Front Range boundary gradient. A relatively steep and generally north-trending gravity gradient lies at approximately long 105°30′ W. and separates the linear anomalies of the ridge-trough area from the broad high of the Front Range area. There is a magnetic gradient in the same position (Boler and Klein, 1990). A continuation of this gradient lies just east of the Elkhorn fault north of the Pueblo quadrangle (Snyder, 1968). The Elkhorn fault has been mapped within the Pueblo quadrangle to the south edge of Elevenmile Canyon Reservoir. The gravity gradient intersects the Elkhorn fault at the south end of Elevenmile Canyon Reservoir and continues south within the Thirtynine Mile volcanic field to Guffey. South from Guffey, the gradient coincides with a segment of the Currant Creek-Ilse fault for about 15 km. Farther south, the gradient is less distinct but appears to follow the contact between Early Proterozoic granitic rocks (Xg) of the Front Range area and Oligocene volcanic sedimentary rocks (Tpl) of the ridge-trough area. At the Arkansas River (lat 38°30′ N.), the gradient bifurcates around the high of feature E to intersect and follow the Westcliffe fault to the west and the Wet Mountains to the east.

We infer that the northern segment of this gradient reflects the Elkhorn fault or a related fault system that continues south from Elevenmile Canyon Reservoir to Guffey beneath the volcanic rocks. This fault or fault system is a probable crustal conduit for the Oligocene Thirtynine Mile Andesite and volcanic rocks of the Guffey area that buried the fault trace. This gradient may represent a fundamental crustal weakness that extends north across the quadrangle and marks the boundary between different tectonic regimes.

The Front Range area

The Front Range is a 40-km wide, north-trending mountain range that extends from Pikes Peak north to Wyoming. The northwest-trending Wet Mountains are a narrower and lower elevation en echelon extension of the Front Range southwest of Pikes Peak (Curtis, 1960). Flanking the Wet Mountains on the east is the Florence basin, a synclinal structure that extends northwest into the Canon City embayment. Both the Front Range and Wet Mountains are Late Cretaceous-early Tertiary structures bounded on the east by normal faults or high-angle reverse faults. Neogene movement has been documented on many of the Front Range faults (Taylor, 1975). Granitic and metasedimentary Precambrian rocks in the Pikes Peak area and Wet Mountains area make up 75 percent of the mapped outcrop in the Front Range area. Tertiary volcanic rocks make up 15 percent of the outcrop and host major mineral deposits at Cripple Creek, Rosita Hills, Silver Cliff, and Guffey; the remaining major deposit (Lake George) is in Precambrian rocks. Paleozoic sedimentary rocks are uncommon, occurring only in Fourmile Canyon graben and east of the Ute Pass fault. Cretaceous sedimentary rocks are abundant in the Florence basin. Several mafic-alkalic intrusive complexes of Cambrian age crop out within the predominant gneissic unit (Xfh) of the De Weese plateau. These intrusions are associated with thorium mineralization in carbonatite dikes (Christman and others, 1959).

The gravity pattern of the Front Range area shows broad highs in the Pikes Peak and Wet Mountains regions and a low in the Florence basin. Qureshy's (1962) Colorado State isostatic map shows highs both in the Pikes Peak and Wet Mountains areas, which indicate incomplete isostatic compensation of these features. Part of the local isostatic imbalance along the Front Range and Wet Mountains must result from the rapid topographic transition from mountains to plains. Compensating deep density contrasts would be unlikely to be so abrupt.

Feature D. Feature D consists of the gravity high associated with the Pikes Peak area. The gravity field is generally uniform across the older Early and Middle Proterozoic granites of the Pikes Peak region (Xg and Yg), which indicates little density contrast between these rocks. Gravity values over the Middle Proterozoic Pikes Peak Granite (Yp) are slightly lower relative to the older granites (Xg and Yg), which indicates that the Pikes Peak Granite is less dense than the other two units.

Anomaly 4 marks the highest gravity value of feature D; it probably results from the higher density of Early Proterozoic granite (Xg) relative to Tertiary volcanic rocks and volcanic sedimentary rocks (Tpl, Tial) to the west and (Tpl, Tiql) to the east, as well as Pikes Peak Granite (Yp) to the northeast. Low 5 encloses the southern part of the Cripple Creek volcanic center, where brecciated and altered rock contributes to a lower density here relative to the surrounding Precambrian granite. Kleinkopf, Peterson, and Gott (1970) attribute the Cripple Creek gravity low to a volcanic subsidence structure. The location of the Cripple Creek volcanic center at the junction of four Proterozoic units (Xb, Xg, Yg, and Yp) suggests a zone of intersecting weaknesses that allowed the rise of magma.

Trend j marks the axis of the broad gravity high over the northern part of the Pikes Peak region. Trend i, a high, includes anomaly 4 and extends southeast into features H and I. It coincides (within feature D) with the approximate center of the Xg and Yg granite exposures.

Low 6 is caused by a small graben containing Cretaceous sediments. High 16 appears to result from the exposure of older granite (Xg) and the abrupt changes in elevation and geologic terrane across the Ute Pass fault.

Feature E. The Wet Mountains and De Weese plateau, which comprise feature E, are characterized by a broad, plateaulike gravity high; there is a similarly shaped magnetic high in about the same position (Boler and Klein, 1990). This feature encloses several smaller dimension gravity and magnetic anomalies that in many cases are coincident with one another.

Three of the gravity anomalies within feature E are related to Cambrian mafic-alkalic intrusions. High 7 is associated with the McClure Mountain Complex; high 8 is associated with the Gem Park Complex (Parker and Sharp, 1970); and high 10 is 10 km south of the syenite complex at Democrat Creek (Scott and others, 1978). We infer, partly based on the magnetic data (Boler and Klein, 1990), that feature E reflects the subsurface extent of the Cambrian intrusions, an area of approximately 200 km^2. Most of the gravity high (feature E) is attributed to the density contrast between the Cambrian intrusions and the surrounding Early Proterozoic metamorphic rocks (Xfh) on the basis of the association between local anomalies and known intrusions. Part of the gravity high probably results from local isostatic imbalance.

The gravity values associated with Early Proterozoic metamorphic rocks (Xfh) and the inferred underlying Cambrian mafic-alkalic intrusions (Cam) of the Wet Mountains-De Weese plateau area are 15–20 mgal higher on the average than values in the Pikes Peak region. This indicates that the densities of the Early Proterozoic metamorphic rocks (Xfh) and Cambrian intrusions (Cam) in feature E are significantly greater than the Proterozoic granitic units (Xg, Yg, Yp) of the Pikes Peak batholith. Profile model A′–A″ places the inferred intrusive body (5), having a density of 2.725 g/cm^3, between the Westcliffe fault and the Ilse fault. The metamorphic unit (Xfh) to the east of the intrusion (body 6) is modeled with a slightly lower density, 2.707 g/cm^3.

Anomaly 12 is a high located on the northeast boundary gradient of feature E. The anomaly coincides with outcrops of the Early Proterozoic Xg unit in the Tanner Peak-Curley Peak area. Elsewhere, however, the boundary gradient indiscriminately crosses Early Proterozoic Xg contacts, which indicates that the anomaly is more the result of local isostatic imbalance than surface density contrasts.

Lows 9, 11, and 13 are associated with Tertiary volcanic rocks from the centers at Johnson Gulch, Silver Cliff, and Rosita Hills. Following the conclusions of Kleinkopf and others (1979), it is likely that all three are caused by low-density brecciated volcanic rocks.

The gravity highs of the Cambrian intrusions to the north (7, 8, 10) are separated from similar highs to the south (14, 15) by a somewhat indistinct linear low (trend 1). The end of low 1 enters the Rosita Hills volcanic center (anomaly 13) and corresponds approximately with a magnetic low (feature L in Boler and Klein, 1990). This low may mark an igneous venting zone, as suggested by Boler and Klein (1990).

Gravity high 15 coincides with magnetic anomaly 50 (Boler and Klein, 1990), the largest amplitude magnetic anomaly in Colorado. Taylor (1974) has mapped a few gabbroic rock outcrops in this area, and these imply a gabbroic intrusive source for the gravity and magnetic anomalies. Magnetic modeling has indicated a near-surface, stocklike body (Boler and Klein, 1990). Anomaly 14 is a high that may mark relatively elevated Early Proterozoic metamorphic rock (Xfh) surrounded by lower density Tertiary volcanic sedimentary rocks. There is no corresponding magnetic high in this position; instead, this anomaly occurs over a magnetic gradient defining two magnetic anomalies, anomalies 47 and 48 (Boler and Klein, 1990).

The axis of feature E is defined by the merging of the larger anomalies (7, 10, 15) and is marked by trend k. This trend presumably indicates the centroid of this massive mafic unit, possibly the locus of emplacement.

Feature F. This feature is a 20-mgal low corresponding to the thick sedimentary rocks of the Florence basin syncline. Trend m (located at 78 km on profile A′–A″) marks the axis of the gravity low which intersects the more sinuous mapped axis of the syncline (Scott and others, 1978) in several places. Profile model A′–A″ indicates that the maximum thickness of sedimentary rocks (2.6 km) occurs about 1 km east of the trend.

The Great Plains area

The Great Plains area encompasses the flat-lying area to the east of the Front Range. Mapped surface units are sedimentary rocks of Quaternary to Cretaceous age. The gravity is characterized principally by a broad low in the north and a similarly broad high in the south. The high trends west-northwest to merge into feature D of the Front Range area.

Features G, H, and I. Feature G is the broad gravity low caused by the deepening of the basement into the Denver basin. The minimum in gravity, low 17, corresponds closely to the area of thickest sediments within the quadrangle, as mapped by Scott and others (1978).

Feature H is a broad high that is continuous with feature D to the northwest and feature I to the southeast. The axis of this high (trend i) roughly follows the center of several fold axes mapped in the Cretaceous sedimentary rocks

(Scott and others, 1978; Tweto, 1979a). The gravity high indicates a region of basement that is arched upward in what may be the northward en echelon extension of the Apishapa arch. The model along profile A′–A″ shows the basement rising to 0.8 km below the surface at the northeast end of the profile, as well as a possible basement density increase associated with this arch. A trend of broad magnetic highs along this arch (Boler and Klein, 1990) is consistent with the gravity data. Gravity high 18 is in an area of numerous faults in the sedimentary rocks (Scott and others, 1978) and may indicate relatively minor and local uplift of basement rock.

Feature I is a broad northeast- to east-trending gravity high that is only partly included in the southeast corner of the quadrangle (see fig. 1). Trend n, at the southeast corner of feature I, marks a separate high that may be related to the north-northeast-trending Las Animas arch (Curtis, 1960) defined to the east of the quadrangle. The thickening of sedimentary rocks north and east of Pueblo, shown by Scott and others (1978), does not result in lower gravity values as expected.

GRAVITY AND MINERALIZATION

Three rock types host metallic mineralization within the Pueblo quadrangle (table 3): Tertiary volcanic rocks, Paleozoic sedimentary rocks, and Precambrian crystalline rocks. Three of the Tertiary volcanic districts (Cripple Creek, Silver Cliff, and Rosita Hills) occur within the Front Range area. The fourth (Guffey) lies on the western geophysical boundary of this area. Tertiary volcanic rocks occurring within the ridge-trough area, mainly at Thirtynine Mile Mountain and Waugh Mountain, are not associated with known mineralization.

The gravity expressions of the Cripple Creek and Silver Cliff-Rosita Hills volcanic centers are well defined by closely spaced stations and show gravity lows that reflect volcanic collapse structures and (or) low-density brecciated volcanic rocks (Kleinkopf and Peterson, 1969, 1977; Kleinkopf, Peterson, and Gott, 1970; Kleinkopf and others, 1979). The Guffey mineralization also is associated with a Tertiary volcanic caldera (Buchanan, 1967), but the available gravity coverage does not provide a good definition of the local signature.

Mineral districts occurring in Paleozoic sedimentary rocks are all within the ridge-trough area roughly along trends a and g (Trout Creek, Blake, and Orient). All are located on or near a gravity high of large horizontal dimension. The station density is insufficient to show if local anomalies exist in the areas of mineralization. It seems probable that the gravity highs reflect basement uplifts that create favorable regional structures for intrusions and the movement of mineralizing fluids.

The districts occurring in Precambrian rock (Cotopaxi, Turret, Calumet, Crestone, and Lake George) show no regional gravity identity other than the highs usually associated with Precambrian rocks. In the environments of these deposits, structural deformations and intrusive sources for mineralization have nearly the same density as the Precambrian host rocks. Base metal concentrations would have higher densities than their host rocks, but detailed gravity surveys would be required to define such metal concentrations.

Of the 13 main districts, 4 lie on or near major, quasi-linear gravity gradients (Guffey, Orient, Crestone, and Silver Cliff), and 6 more lie on or near moderate gradients (Trout Creek, Turret, Calumet, Whitehorn, Blake, and Rosita Hills). Typically, linear gravity (and (or) magnetic) gradients are the result of faulting that juxtaposes rocks of different densities and magnetizations. The Sangre de Cristo and Westcliffe faults are examples within the Pueblo quadrangle of faults that have corresponding gravity gradients. Gravity and magnetic gradients, whether or not they correspond to mapped faults, indicate lithologic contrasts and thus provide guides to zones of crustal weakness along which magmas and mineralizing fluids may reach the surface. This is the case at Guffey, which lies on the South Park-Front Range boundary gradient (the gradient is caused presumably by the buried Elkhorn fault or a related fault system, as discussed earlier). Neogene tectonic movements on the Sangre de Cristo fault (Tweto, 1979b), which lies near the Crestone and Orient districts, are probably a recent reactivation of an ancient weakness that has controlled the movement of mineral-bearing fluids.

We conclude that the most consistent regional gravity expressions of areas favorable for mineralization in the quadrangle are the major gradients associated with tectonic zones of weakness. Gravity lows associated with districts of Tertiary volcanic rocks are well documented (Kleinkopf, Peterson, and Gott, 1970; Kleinkopf and others, 1979), but the definition of these areally limited anomalies requires densely spaced gravity observations, which are undertaken only after other indications of mineralization are discovered.

ACKNOWLEDGMENTS

Numerous suggestions on the gravity, magnetic, and geologic relationships in the Pueblo quadrangle were provided by M. Dean Kleinkopf, Richard B. Taylor, Donald L. Peterson, Glenn R. Scott, Rudy C. Epis, and Reinhart A. Wobus. Lin Cordell pointed out the gravity work done by G.H. Davis in the San Luis Valley, which the authors had overlooked.

REFERENCES CITED

Boler, F. M., and Klein, D. P., 1990, Residual aeromagnetic and interpretative maps of the Pueblo 1°× 2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1419–C, scale 1:250,000.

Boyer, R. E., 1962, Petrology and structure of the southern Wet Mountains, Colorado: Geological Society of America Bulletin, v. 73, no. 9, p. 1047–1069.

Buchanan, R. H., 1967, Geology of the Guffey area, southwest Park County, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 95 p.

Cady, J. W., 1980, Calculation of gravity and magnetic anomalies of finite-length right-polygonal prisms: Geophysics, v. 45, no. 10, p. 1507–1512.

Christman, R. A., Brock, M. R., Pearson, R. C., and Singewald, Q. D., 1959 [1960], Geology and thorium deposits of the Wet Mountains, Colorado—A progress report: U.S. Geological Survey Bulletin 1072–H, p. 491–535.

Curtis, B. F., 1960, Major geologic features of Colorado, *in* Weimer, R. J., and Haun, J. D., eds., Guide to the geology of Colorado: Denver, Colo., Geological Society of America, Rocky Mountain Association of Geologists, and Colorado Scientific Society, p. 1–8.

Kleinkopf, M. D., and Peterson, D. L., 1969, Bouguer gravity map of the Cripple Creek mining district, Teller County, Colorado: U.S. Geological Survey Open-File Report 69–138, scale 1:24,000.

_______1977, Geophysical evidence for a volcanic subsidence feature near Silver Cliff, Colorado: Geology, v. 5, no. 7, p. 445–447.

Kleinkopf, M. D., Peterson, D. L., and Gott, Garland, 1970, Geophysical studies of the Cripple Creek mining district, Colorado: Geophysics, v. 35, no. 3, p. 490–500.

Kleinkopf, M. D., Peterson, L. L., and Johnson, R. B., 1970, Reconnaissance geophysical studies of the Trinidad quadrangle, south-central Colorado, *in* Geological Survey research 1970: U.S. Geological Survey Professional paper 700–B, p. B78–B85.

Kleinkopf, M. D., Peterson, D. L., and Mattick, R. E., 1979 [1980], Gravity, magnetic, and seismic studies of the Silver Cliff and Rosita Hills volcanic area, Colorado: U.S. Geological Survey Professional Paper 726–F, 17 p.

March, W. R., and Queen, R. W., 1974, Map showing localities and amounts of metallic mineral production in Colorado: U.S. Geological Survey Mineral Investigations Resource Map MR–58, scale 1:500,000.

Pakiser, L. C., 1963, Structure of the crust and upper mantle in the western United States: Journal of Geophysical Research, v. 68, no. 20, p. 5747–5756.

Parker, R. L., and Sharp, W. N., 1970, Mafic-ultramafic igneous rocks and associated carbonatites of the Gem Park Complex, Custer and Fremont Counties, Colorado: U.S. Geological Survey Professional Paper 649, 24 p.

Qureshy, M. N., 1962, Gravimetric-isostatic studies in Colorado: Journal of Geophysical Research, v. 67, no. 6, p. 2459–2467.

Scott, G. R., Taylor, R. B., Epis, R. C., and Wobus, R. A., 1978, Geologic map of the Pueblo 1°×2° quadrangle, south-central Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1022, scale 1:250,000.

Shawe, D. R., and Parker, R. L., 1967 [1968], Mafic-ultramafic layered intrusion at Iron Mountain, Fremont County, Colorado: U.S. Geological Survey Bulletin 1251–A, 18 p.

Snyder, D. D., 1968, A gravity survey of South Park, Colorado: Golden, Colo., Colorado School of Mines, M.S. thesis, 167 p.

Talwani, Manik, Worzel, J. L., and Landisman, M. G., 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone [Pacific Ocean]: Journal of Geophysical Research, v. 64, no. 1, p. 49–59.

Taylor, R. B., 1974 [1975], Reconnaissance geologic map of the Deer Peak quadrangle and southern part of the Hardscrabble Mountain quadrangle, Custer and Huerfano Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–870, scale 1:24,00.

_______1975, Neogene tectonism in south central Colorado, *in* Curtis, B. F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 211–226.

Tweto, Ogden, 1968, Geologic setting and interrelationships of mineral deposits in the mountain province of Colorado and south-central Wyoming, *in* Ridge, J. D., ed., Ore deposits of the United States, 1933–1967 (Graton-Sales Volume), v. 1: New York, American Institute of Mining, Metallurgy, and Petroleum Engineers, p. 551–588.

_______1979a, Geologic map of Colorado: U.S. Geological Survey Special Map, scale 1:500,000.

_______1979b The Rio Grande rift system in Colorado, *in* Reicker, R. E., ed., Rio Grande rift: Tectonics and magmatism: Washington, D.C., American Geophysical Union, p. 33–56.

Tweto, Ogden, and Case, J. E., 1972, Gravity and magnetic features as related to geology in the Leadville 30′ quadrangle, Colorado: U.S. Geological Survey Professional Paper 726–C, 31 p.

Tweto, Ogden, and Sims, P. K., 1960, Relation of the Colorado mineral belt to Precambrian structure, *in* Geological Survey research 1960: U.S. Geological Survey Professional Paper 400–B, p. B8.

_______1963, Precambrian ancestry of the Colorado mineral belt: Geological Society of America Bulletin, v. 74, no. 8, p. 991–1014.

U.S. Geological Survey and Colorado Geological Survey, 1977, Energy resources map of Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–1039, scale 1:500,000.

Vanderwilt, J. W., and others, 1947, Mineral resources of Colorado: Denver, Colo., Mineral Resources Board, 547 p.

Zohdy, A. A. R., Hershey, L. A., Emery, P. A., and Stanley, W. D., 1971, Resistivity sections, upper Arkansas River basin, Colorado: U.S. Geological Survey Water Resources Open-File Report 71–337, 16 p.