# GRAVITY SURVEY OF THE GUFFEY VOLCANIC CENTER, THIRTYNINE MILE VOLCANIC FIELD, PARK COUNTY, COLORADO

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## Introduction

The Oligocene Thirtynine Mile volcanic field is the second largest volcanic field in the southern Rocky Mountain region, covering over 2000 $km^2$. The Guffey volcanic center, the largest center within the Thirtynine Mile field, is expressed as an elliptical topographic feature approximately 15 km in length along its east-west axis and 8 km in length along its north-south axis. Thirtynine Mile, Saddle, Castle, Witcher and Cover Mountains, exhibiting from 1000 - 2000 feet of relief, form the perimeter of this elliptical structure. These hills, composed of stratified volcanics that exhibit quaquaversal dips, are composed predominantly of mafic to intermediate flows and lahar deposits. Within the structure, numerous plugs, dikes, and vents cut these thick mafic deposits.

There are several possible origins of the elliptical topographic expression of the Guffey volcanic center. A single, large, volcanic edifice may have produced a subsidence caldera. Alternatively, the feature may be an erosional caldera (Williams, 1941). It is also possible that no large edifice existed and that the elliptical topography is the result of active imaginations. Collapse calderas are clearly reflected in the observed gravity in the nearby San Juan volcanic field (Plouff and Pakiser, 1972). In the summer of 1990 we conducted a local gravity survey of the Guffey volcanic center in order to determine if a subsidence caldera is evidenced by the local gravity field.

## Field Methods

### *Surveying*

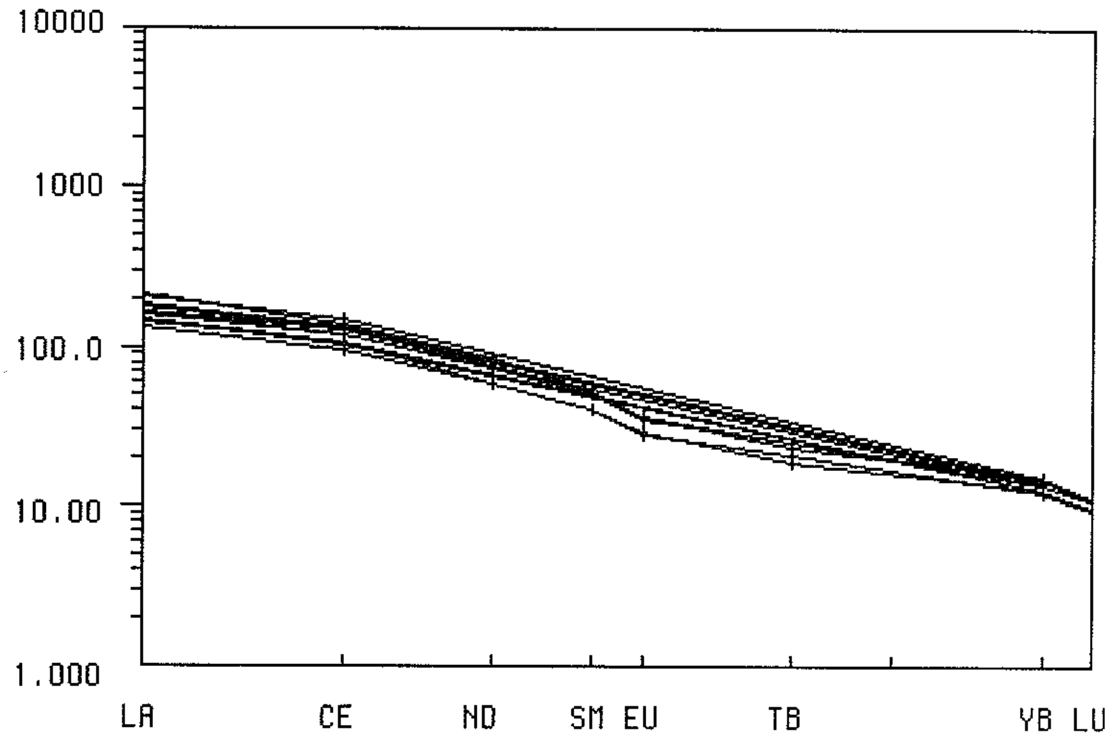
A gravity meter measures the difference in gravity between locations to a precision of one hundredth of a milliGal (mGal), or one part in one hundred million of the acceleration of gravity. If present, the gravity anomaly caused by a caldera structure might be as small as several milliGals. At the latitude of Guffey, a 400 ft change in latitude would result in a gravity change of approximately 0.1 mGal. An elevation change of one foot would produce a gravity change of approximately 0.06 mGal. Thus, elevations and locations taken from topographic maps would not allow us to achieve an overall accuracy of better than 0.1 mGal, and it was necessary to survey each gravity station. We employed a Lietz SET4 Total Station with an SDR electronic data collector. This system measures distances with an infrared beam reflected from a target prism. Horizontal and vertical angles are measured electromechanically to a precision of 5" of arc. The data was reduced using the data collector's topography program, which calculated and recorded station locations by easting, northing, and elevation with a precision of 0.001 ft. At the conclusion of each day, the data was downloaded from the electronic data collector into a Macintosh IICX.

The theodolite was set up at a base station, from which subsequent stations were shot at approximately 600 foot intervals. The maximum distance we shot from a base station was approximately 3000 feet; however, shots were usually limited to much shorter distances because of terrain obstruction. New base stations were established at previously surveyed stations, and back shots were performed to reestablish the azimuthal orientation of the theodolite. Each station was flagged and given a station number. Once a station was established, it could be reoccupied for gravity measurements whenever necessary (unless the flag was removed by animals or cranky ranchers).

### *Station locations*

One hundred and fifty eight stations were established in locations which would provide profiles crossing the margins of the elliptical topographic feature as well as good radial coverage of the northwestern quadrant of the feature. Station locations were chosen in as flat an area as possible in order to minimize terrain effects.

Benchmarks G290 and H290 along West Fourmile Creek were surveyed and defined a baseline for all subsequent surveying. Sixty-four stations were established along West Fourmile Creek, extending approximately 6.5 miles east from its intersection with Thirtynine Mile road. This set of stations extended across the eastern margin of the elliptical structure. Fifty stations were located along Thirtynine Mile Road, extending approximately 5 miles north from West Fourmile Creek crossing the northern margin of the elliptical feature. Two additional lines igure 6: REE plot



of stations were established running to the northeast, one on Saddle Mountain and the other between Saddle and Castle Mountains. These lines completed the radial coverage of the northeastern quadrant of the elliptical feature. Figure 1. is a map of the area showing the station locations and the approximate outline of the elliptical topographic feature.

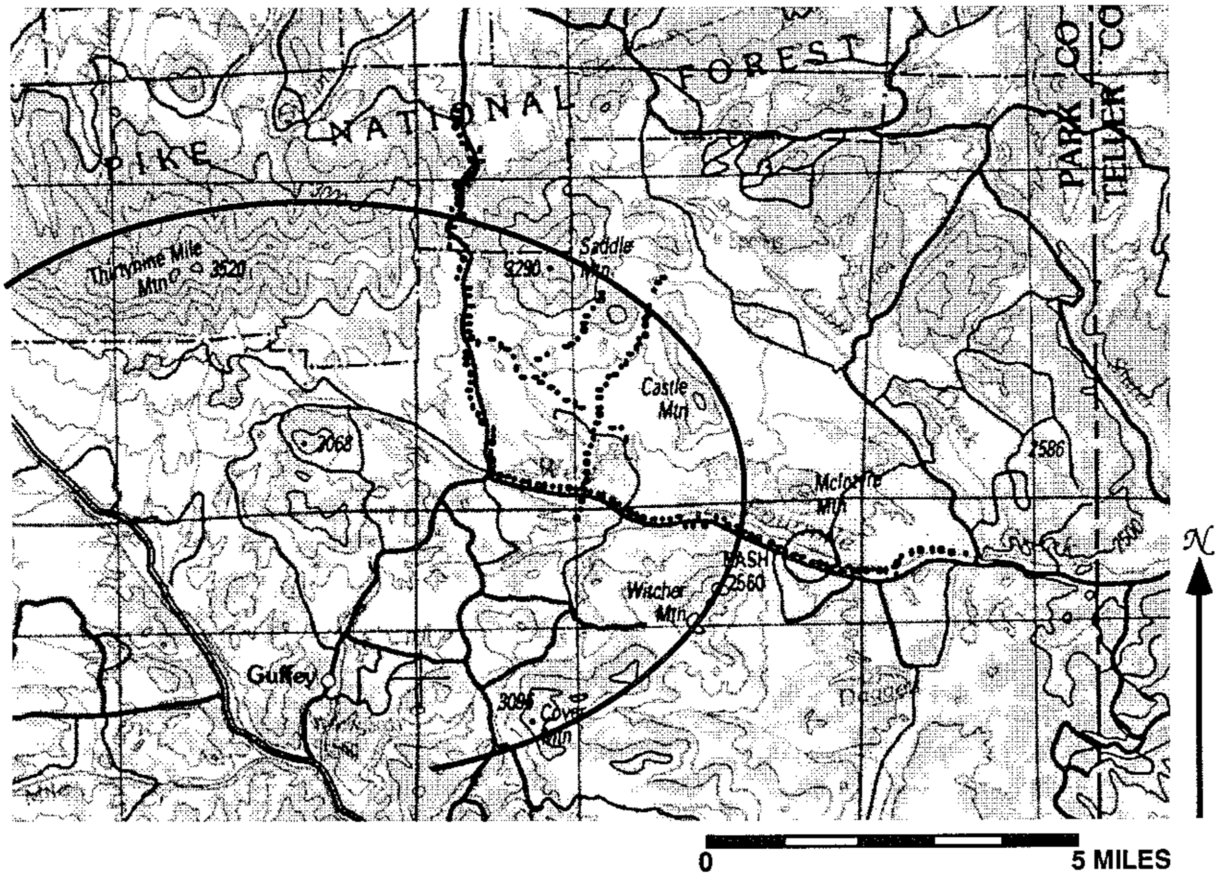



**Figure 1. Map of the station locations and their relation to the Guffey volcanic complex.**

*Gravity measurement*

We used two LaCoste and Romberg Model G gravity meters for the survey. The Trinity University meter was used for the majority of the measurements while the Franklin and Marshall College meter was used to check the consistency of the results from the Trinity meter. The station number, date, time, and gravity reading were recorded by hand in a field notebook. Over 450 gravity readings were made at 158 stations.

Due to the precision of the gravity meter, it was necessary to establish a careful procedure for taking gravity readings and thereby avoid tares in the data. The gravity meter required precise leveling to obtain an accurate reading. Bubble levels, built into the instrument, were used for this leveling. These bubble levels were very sensitive to sunlight, so it was necessary to shade the instrument under a large, red golfing umbrella with a fiberglass shaft. The person taking the reading would sit on the ground and straddle the meter. This position allowed the reader to fit under the umbrella and minimized disturbance of the meter reading due to the shifting of their weight. Finally, the gravity meter screw was always rotated in the same direction when approaching the final reading to eliminate the effect of mechanical play in the mechanism.

Temporal variations in the reading at a station are caused by the variation of tidal forces and instrument drift due to relaxation of the zero-length spring. To determine the drift, check for tares, and to allow for empirical removal of the tidal variation, base stations were reoccupied throughout the course of each field day. After five or so consecutive stations had been occupied, the base station was reoccupied. A repeat reading was then taken at the last station before proceeding to the next next series of new stations. New base stations were established frequently to reduce travel distance. Major base stations were occupied frequently, and the readings checked for consistency, five or six times a day. Vehicular transportation of the instrument, when possible, greatly reduced drift, prevented tares, and allowed for a greater daily occupation of stations. Repeatability of successive base station readings was usually better than 0.1 mGal. The stations forming the dominant gravity lines along West Fourmile Creek and Thirtynine Mile Road were occupied on numerous days to create a substantial data base for checking the accuracy and consistency of the data.

**Data Reduction**

We performed all of the data reduction on Macintosh™ II computers using the WingZ™ and Igor software packages. The first step was calibration. Each gravity meter has its own calibration curve mapping meter readings to actual values in milliGals. This calibration factor is close to, but not exactly, one.

After calibration, the data was corrected for instrument drift. A linear drift was determined for the time interval between each pair of successive base station readings. This linear drift was removed from all station measurements made in that time interval. Since our base station readings were closely spaced in time, variations in gravity due to tidal forces were small enough to be considered as part of this linear drift.

Since many base stations were used, and since the value of gravity at each base station varies over time, it was necessary to tie together all measurements in the survey. All measurements were corrected to an arbitrary base station (chosen for convenience) by adding or subtracting a constant value such that every reading of the same station would have the same gravity value. Due to random noise in the data, it was not always possible to achieve an exact match for every overlapping station. In such cases, we picked the constant that would produce the best overall match between station segments.

In some cases, we had only one data point for each station, but we measured many stations multiple times to provide tie points for the different segments of the survey as well as to provide a means to compensate for instrument drift. In most cases, the data were within approximately 0.1 mGal of each other. Occasionally, some points were obviously aberrant. Such points can be attributed to tares caused by bumping the meter and other such random factors. In all cases, we could either choose the best data values and average them to determine a mean value. This final canonical data set was the data set used in all subsequent analysis.

Next, a free-air anomaly was constructed to compensate for the effects of latitude and elevation (Dobrin and Savit, 1988). We corrected for latitudinal variation using a Chebychev approximation of the Gravity Formula 1967 of the International Association of Geodesy:

$$g=(978\,031.85)(0.005\,278\,895\sin^2\phi + 0.000\,023\,462\sin^4\phi)\ \text{mGal}$$

where $\phi$ is the latitude in radians. Since gravitational force varies with the distance from the center of the earth, it is also necessary to remove the effects of changes in elevation. This can be easily derived from Newton's law of gravitation:

$$\Delta g=(-0.09406)(\text{elevation in feet})\ \text{mGal}$$

The free-air anomaly would be sufficient if there were no material underneath the gravity meter as it changed elevation. Since this is not the case, the added attraction of additional material beneath the meter must be taken into consideration. The simple Bouguer anomaly assumes that the added material is a slab of uniform material of infinite extent. In regional surveys, an average crustal density of 2.67 g/cm$^3$ is usually employed. Due to the local nature of our survey, we estimated the density of local topography directly from the data. We determined an apparent density by applying a least-squares fit to groups of stations spanning clearly exposed rocks typical of the area and obtained a value of 2.64 g/cm$^3$. We thus applied the following simple Bouguer correction:

$$\Delta g=(0.01277)(2.64)(\text{elevation in feet})\text{mGal}$$

The effects of the Bouguer correction on the free-air anomaly can be seen in the accompanying graphs (figures 2 and 3). Figure 2 is a plot of the free-air and simple Bouguer anomalies of the readings taken along West Fourmile Creek projected on an east-west striking plane. Figure 3 is a similar plot of the free-air and simple Bouguer anomalies of the readings taken along Thirtynine Mile Road projected on a north-south striking plane. These planes are subparallel to the traverses along which the respective data were taken.

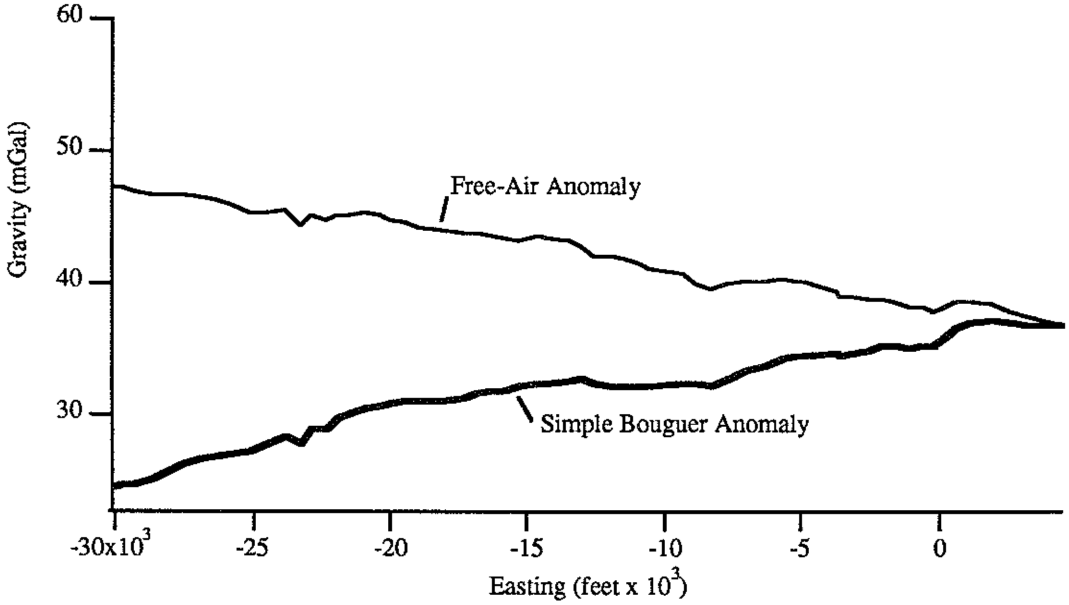



**Figure 2: Free-air and simple Bouguer anomalies for stations along West Fourmile Creek.**

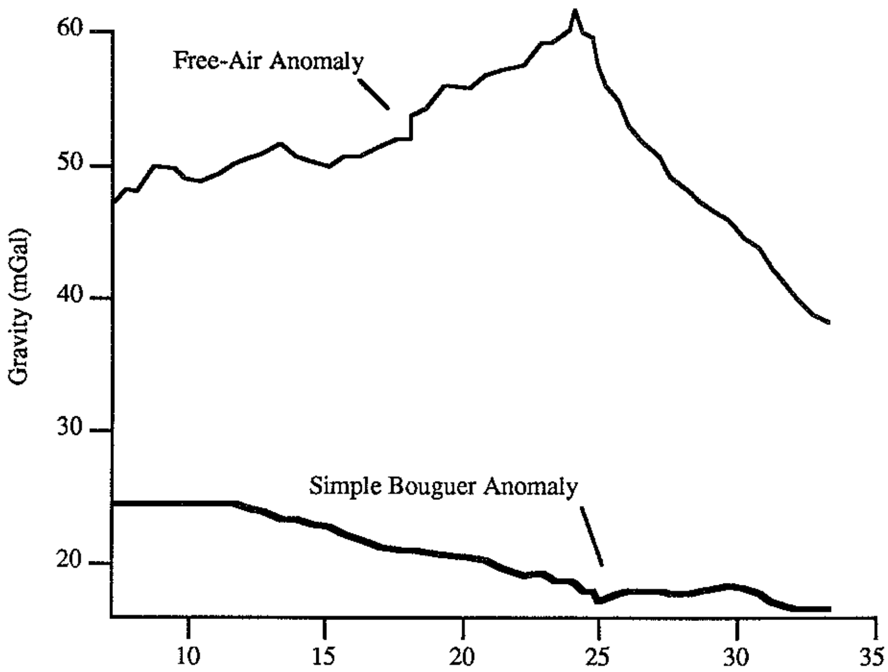



**Figure 3: Free-air and simple Bouguer anomalies for stations along Thirtynine Mile Road.**

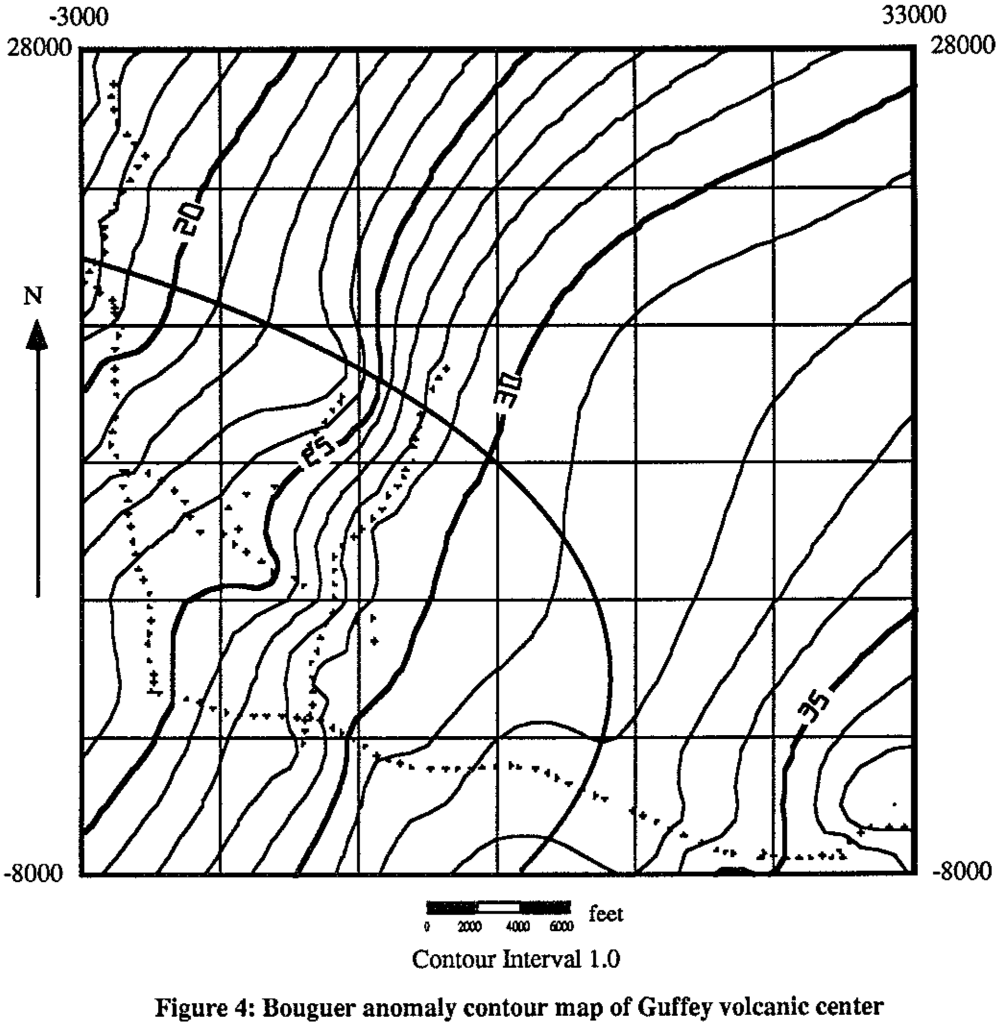
The free-air anomaly generally follows the topography of the area. This suggests that most of the observed variation in gravity is due to topography rather than subsurface variations in crustal density. The Bouguer anomaly represents the removal of the major portion of the topographic effect. The lower left corner of figure 2 and the lower left corner of figure 3 both represent the station at the intersection of West Fourmile Creek and Thirtynine Mile

Road. No symmetry is observed between these two profiles. If a radially symmetric caldera structure were present, it should produce some symmetry between these two profiles.

Ideally, a terrain correction that actually takes into account the shape of the surrounding topography would be applied to the data. We did not perform such a correction for two reasons. First, our survey was small enough and the relief low enough that we estimate that the terrain correction will not vary significantly along the survey lines. Second, we placed our stations in locations that were not likely to be affected by small, localized terrain effects such as culverts and steep slopes. Given the uncertainties in computing a terrain correction, the benefit of the correction would not outweigh the possibility of introducing systematic errors in the data set.

**Analysis**

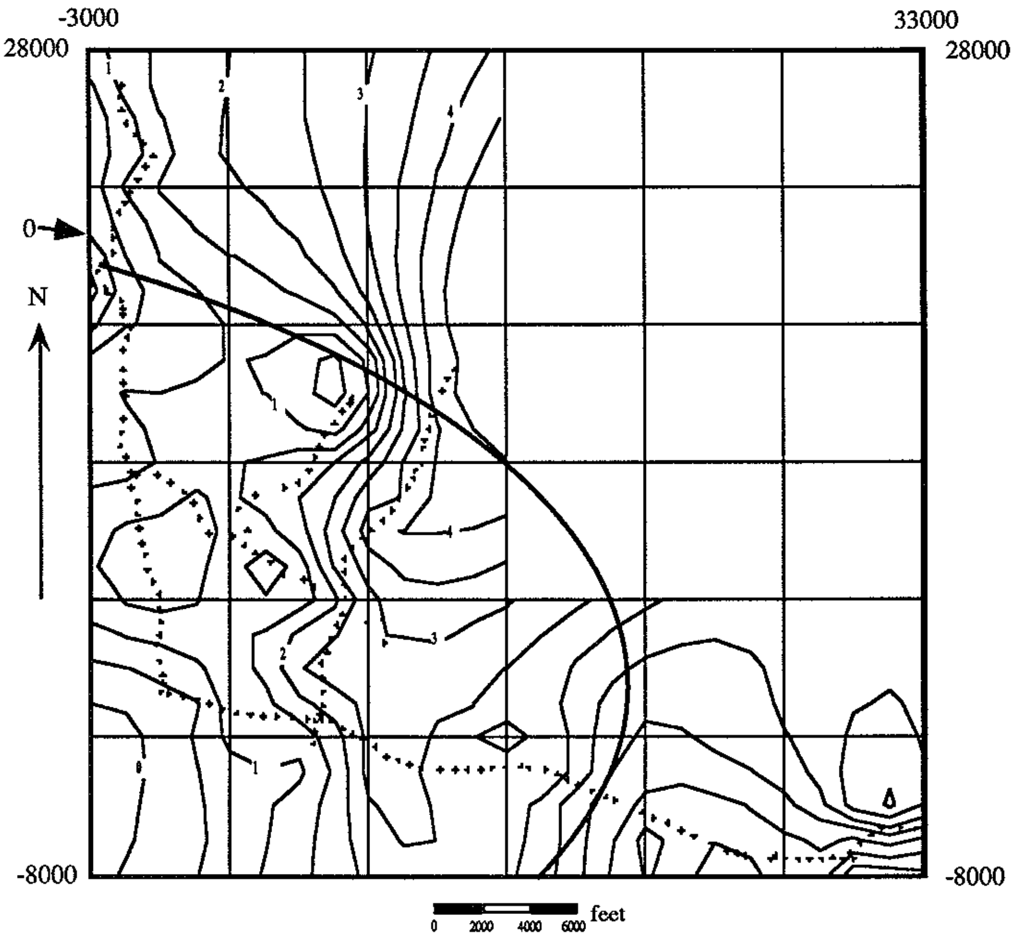
Since the profiles did not show any obvious radial structure, we generated a contour map of the data for interpretation. Using the GeoView™ software package, we generated a square data grid, 36000 feet on a side with 825 grid nodes. The gridded values were generated from our scattered data points using a first-degree, moving, weighted, least-squares function. Figure 4 is a smoothed contour map of the gridded data. The total range of values was approximately 20 mGal, with the highest values in the southeast corner of the map and the lowest values in the northwest corner of the map . Also shown on this map are the station locations and an ellipse approximating the outline of the proposed caldera.




Contour Interval 1.0

**Figure 4: Bouguer anomaly contour map of Guffey volcanic center**
**Contour values in mGal.**

The most obvious feature in Figure 4 is a strong trend striking towards the northeast with gravity decreasing almost linearly towards the northwest. The magnitude of this trend (approximately $4.17 \times 10^{-4}$ milliGal per foot) and its highly linear nature suggest to us that it is the result of large-scale regional anomalies and not related to any local anomalies caused by the presence of a collapsed edifice. Again using GeoView, we constructed a first-degree trend surface through the data. Figure 5 shows the residual signal left after the first-degree trend surface is removed.




Contour Interval 0.5

**Figure 5: Residual Bouguer anomaly contour map of Guffey volcanic center after removal of first-degree trend surface. Contour values in mGal.**

In the northeast quadrant of Figure 5, no contours are drawn because we did not establish any stations in that area. Any residual contours in that quadrant would result from the gridding algorithm. The residual gravity has an amplitude of no more than 4 mGal and shows no signs of the radial symmetry that would be expected from a subsidence caldera. In some areas the contours are tangential to the ellipse of the topographic features, while in other areas they are nearly normal to the ellipse. If there were a caldera present, we would expect that it would be expressed at this resolution.

**Interpretation**

The linear trend that we observed is consistent with the observations of Boler and Klein (1990). They did not note any anomaly in the Guffey region attributable to a caldera, although their stations were spaced approximately ten times less densely than ours. Presumably, a survey with a resolution as high as ours would have detected any such anomaly if it were present. They attribute the trends in the area of the Thirtynine Mile volcanic field to two separate and distinct features in the region: the South Park-Front Range boundary gradient and a local gravity high associated with the Proterozoic granites of the Pikes Peak region.

The South Park-Front Range boundary gradient is a linear feature that trends generally north at an approximate longitude of 105°30'W. In the region of the Thirtynine Mile volcanic field, it is associated with both the Elkhorn and Currant Creek-Ilse fault systems. It is also likely that a continuation of this fault trace would be found beneath the volcanic rocks of the Guffey area. Boler and Klein suspect that this gradient "may represent a fundamental crustal weakness that...marks the boundary between different tectonic regimes" and also may have served as the route to the surface for the rocks of the Thirtynine Mile field (1990).

The Pikes Peak high is associated with incomplete isostatic compensation of this portion of the Front Range. This highest gravity value of this feature is immediately to the east of the Thirtynine Mile field and is probably the result of the density contrast between the Thirtynine Mile volcanics and the Early Proterozoic granites located to the east. The data we obtained in our survey fully support these hypotheses.

The strike of the trend surface observed in our study does not suggest any association with the Currant Creek-Ilse fault system. The most likely explanation for the trend surface is the extension of the Elkhorn fault system southward under the Guffey volcanic center.

**Conclusions**

We are confident that the data collected in this survey would have revealed any systematic anomalies related to the collapse of a large volcanic edifice as the source of the topographic expression of the Guffey volcanic center. While the topography of the region is consistent with such a hypothesis, a true collapse structure should produce a distinct signal in the Bouguer anomaly of the area. The absence of any such signal leads us to believe that in fact there is no subsidence caldera associated with the Guffey volcanic center. The distinctive topography of the region must therefore be the result of other factors.

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