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Bouguer Gravity Study of Enumclaw/Pinnacle Peak, Washington

Abstract

A Bouguer gravity survey in the area of Enumclaw and Pinnacle Peak, Washington, which is located at the western edge of the Cascade Range, revealed a positive gravity anomaly associated with Pinnacle Peak and a continuous positive gravity anomaly associated with two lesser peaks. The two lesser peaks were interpreted as surface exposures of an Eocene or post-Eocene dike which was partly covered by Pleistocene deposits. The appendix of this paper presents the computer program used in this study to model the mass attraction of isolated peaks by subdividing the peak into a set of vertical prisms and summing the calculated mass attraction of each prism.

Introduction

Pinnacle Peak rises 350 m (1050 ft) above an otherwise featureless plain in the vicinity of Enumclaw, Washington. This plain is composed of Pleistocene glacial deposits and a recent mudflow (Osceola mudflow; 4700 BP) from Mount Rainier (Crandell, 1963). Because of this cover, except for outcrops on Pinnacle Peak and neighboring peaks, bedrock cannot be observed directly. Near the summit of Pinnacle Peak, outcrops of andesite with well developed columnar jointing are found. It has been hypothesized (Z. F. Danes, pers. comm.) that these peaks were derived as volcanic plug domes.

Many more small isolated peaks similar to those investigated in this survey are found to the north and south of this area. All of these peaks are found in a 5 km wide band along the western margin of the Cascade Range that extends for 20 km from 4 km south of Pinnacle Peak near Page Creek at the southern end to Palmer at the northern end. Vine (1969) has mapped the Cumberland Quadrangle, which includes the northern half of this band, and has described several igneous sills and dikes within this quadrangle. He has tentatively assigned these intrusions to an Oligocene age.

The topographic map (Fig. 1) shows the area covered by this survey. Pinnacle Peak is located at the southwest corner of sec. 31, and two lesser peaks are located in the northwest corner of sec. 36 and the southwest corner of sec. 25, respectively, T. 20N, R. 6E. The two lesser peaks are separated in a north-south orientation by 700 m.

The purpose of this study is to search for gravitational anomalies caused by possible volcanic conduits associated with Pinnacle Peak. Because of the overlying alluvium, we must rely on indirect means of exploration. Gravitational methods are based on the measurement at the earth's surface of small variations in the gravitational field which are caused by lateral variations in the distribution of mass in the earth's crust.

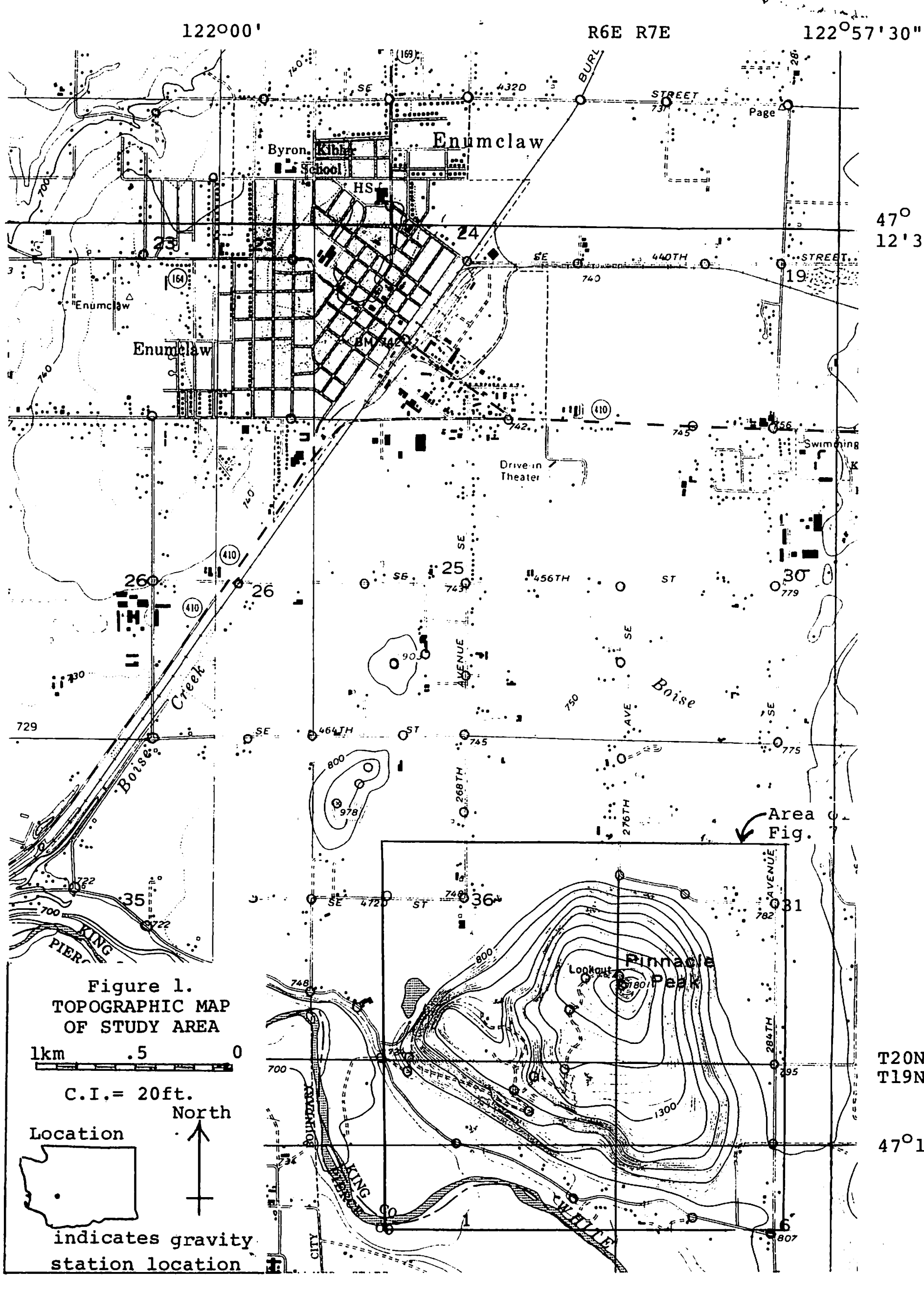


Figure 1. Topographic map of study area.

Data Acquisition and Reduction

Gravity measurements were taken at 71 locations throughout the 20.8 km^2 study area, giving a density of 3.4 stations per km^2. Station elevations were determined with an aneroid barometer with loops tied to road intersections where surface elevations are known from U.S. Geological Survey topographic maps. Elevations obtained from survey maps are accurate to ± 0.6 m (± 2 ft). Gravity observations have a precision of approximately ± 0.02 mgals. Barometric elevations are accurate to ± 6 m.

The observed gravity values were corrected for the variation of gravity with latitude and elevation as well as the attraction of mass above sea level.

The system used in this study for accounting for the attraction of material above sea level differs from the standard method. Normally, the attraction of the mass below a station and above sea level is approximated by an infinite slab of material. Then, if the topography is irregular, the attraction of all excess mass above the level of the station—as well as mass deficiencies from voids below the level of the station—is taken into account in a process of "sculpting." This is the "terrain correction."

In this study, conversely, the unique topographic setting of this area—characterized by isolated hills surrounded by flat plains—allowed for direct "building" of the terrain above sea level. The attraction of the material below the level of the plain for stations not near the peaks (below an elevation of 283 m (750 ft) for stations on Pinnacle Peak, and below 280 m (740 ft) for stations on the two lesser peaks) was approximated by an infinite plate with an assumed density of 2.67 gm/cm^3. For stations on and near the peaks, a computer was used to model (by the method of prisms (see appendix and Danes, 1960)) the gravitational attraction of the material of the peaks above the level of the infinite plate. For this determination, a density of 2.52 gm/cm^3 was used. This density value was found in a laboratory analysis of rock samples. (This density could be too low and would perhaps be greater if fresher samples were obtained.) The calculated mass attraction of the peaks was added to the attraction of the infinite plate below to achieve the total mass attraction.

Results

The resulting Bouger gravity anomaly map of the Enumclaw/Pinnacle Peak area is shown in Figure 2. Residual gravity was derived from the Bouguer gravity by subtracting the regional anomaly derived from Danes' data (to be published). The resulting gravity map is shown in Figure 3.

The residual gravity values show slight variations over the area ranging from +3 mgals to –1.5 mgals. Positive gravity anomalies are correlated with Pinnacle Peak and the two lesser peaks.

Interpretation

The magnitude of the Pinnacle Peak anomaly proved to be much less than anticipated. In addition, the location of the center of this anomaly with respect to the peak is difficult to define.

Attention was diverted from the Pinnacle Peak anomaly because of the above-mentioned problems and also because a full profile could not be constructed across the peak since the area to the east and south is not accessible by road.

Instead, the anomaly associated with the two lesser peaks was chosen for analysis in this report. This oval shaped anomaly is 1.5 mgals in magnitude and encloses both peaks. The authors attribute this anomaly to a north-south oriented dike which is exposed at the surface in the form of the two peaks. To demonstrate this possibility, we will model the dike—in the first approximation—as a horizontal cylinder. This

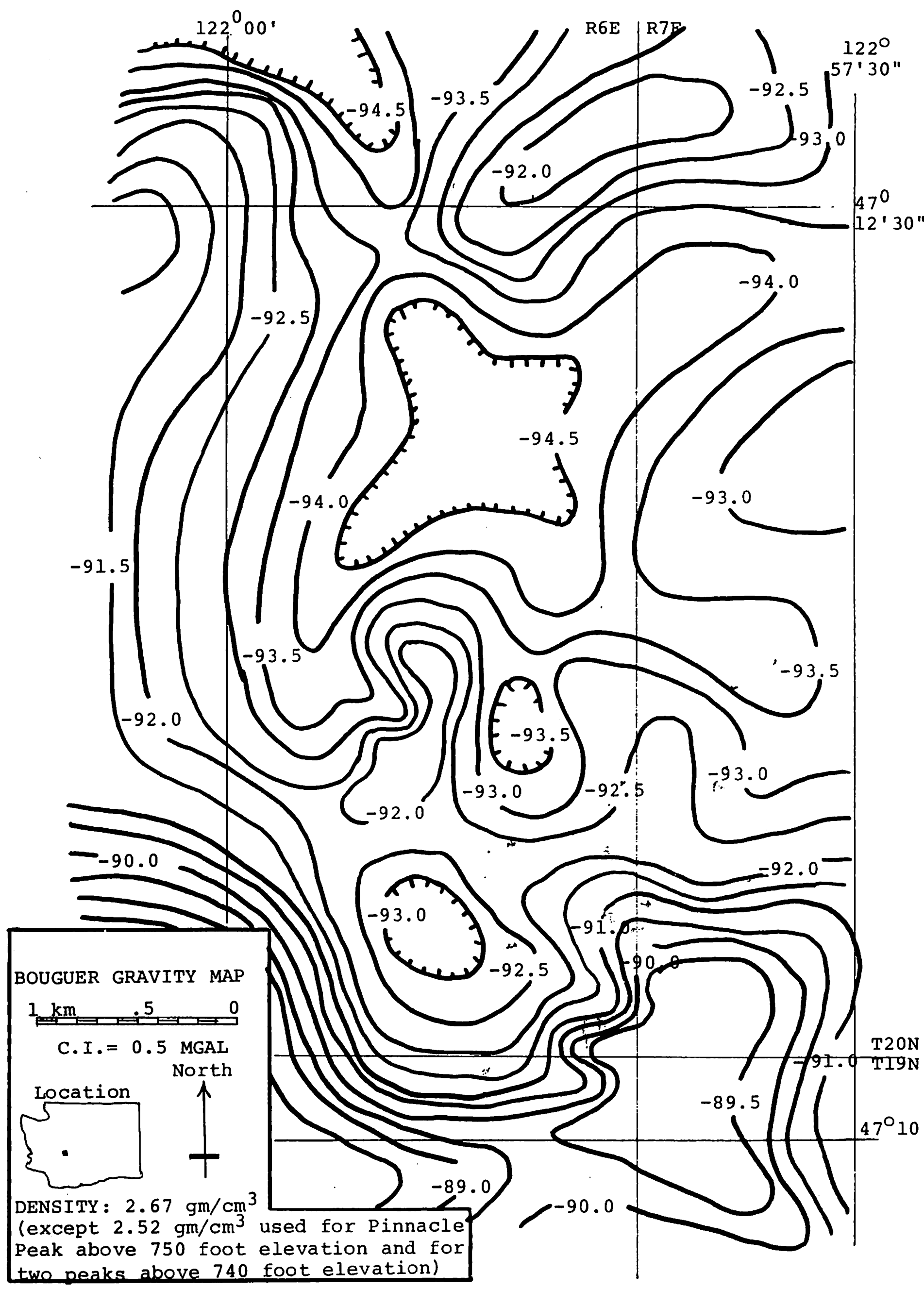


Figure 2. Bouguer gravity map of study area.

formation may not be geologically realistic but should be sufficiently so to determine if the postulate is reasonable.

Figure 4 shows two profiles across the anomaly associated with the two peaks. The

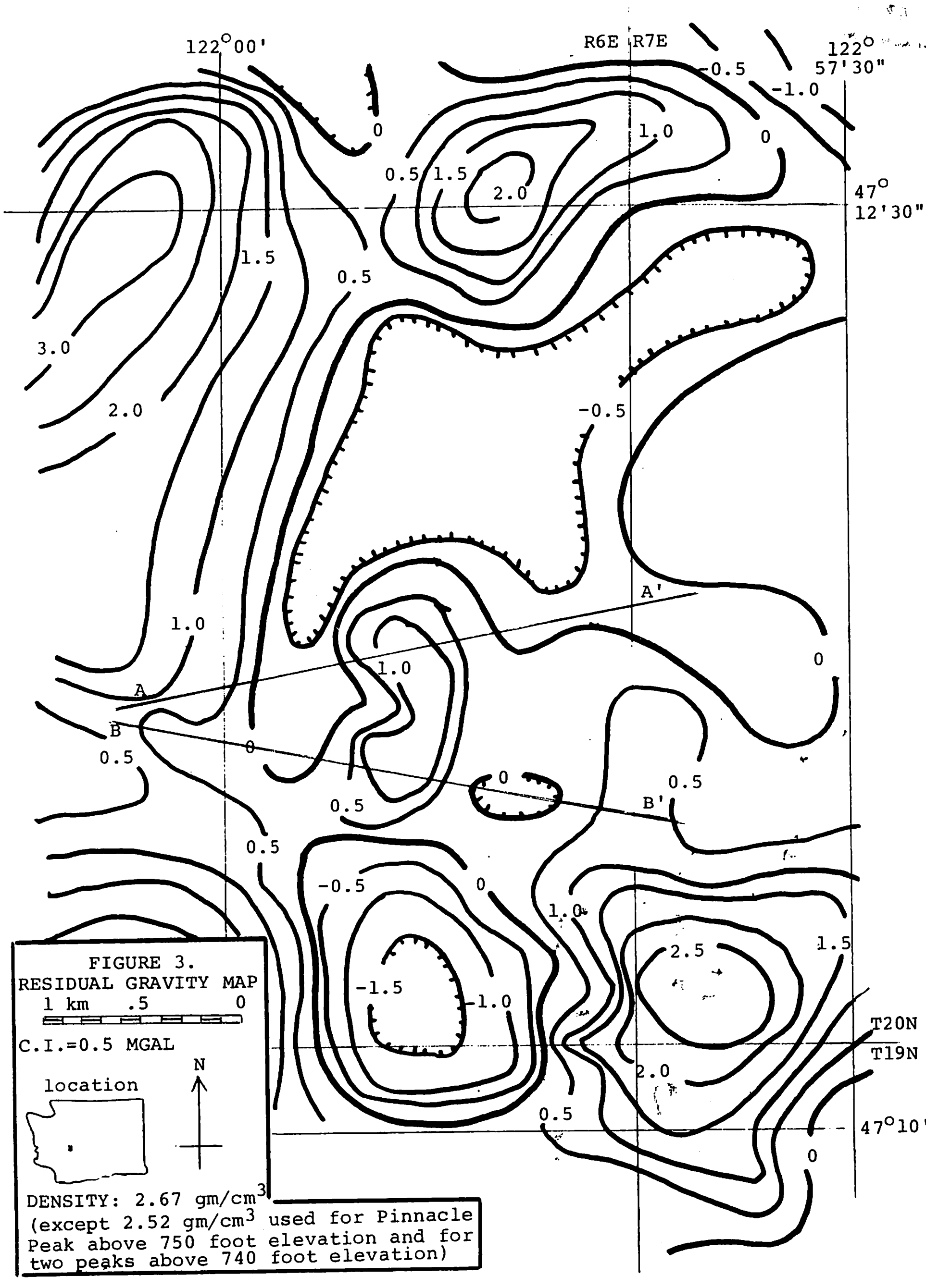


Figure 3. Residual gravity map of study area.

gravitational effect of neighboring masses was estimated and subtracted from these profiles. In this way, the anomaly was isolated and its magnitude was found to be 2.0 mgals.

The half width of an anomaly, $X_{1/2}$, is defined as the distance from the center of the

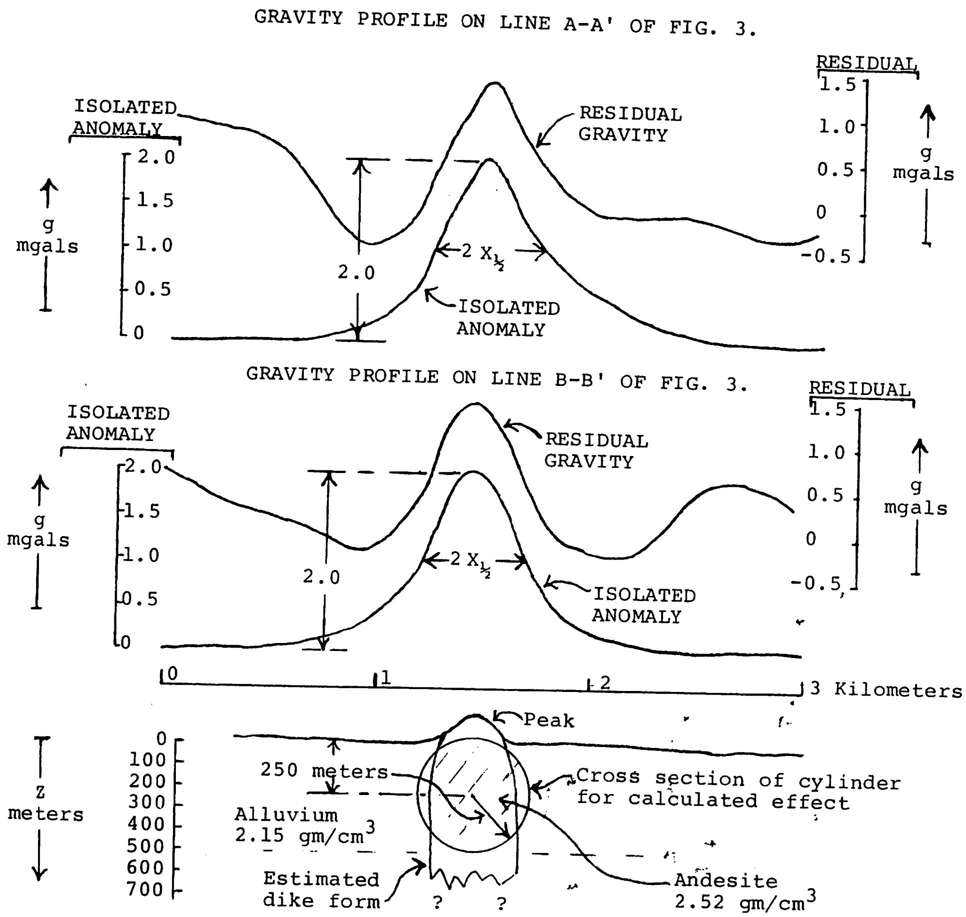


Figure 4. Gravity profiles and interpretation.

anomaly to the point at which the gravity value has fallen off to half of its maximum value, which is equal to the depth to the axis of a horizontal cylinder (Dobrin, 1976; p. 468). In this case, the half width of the anomaly, and thus the depth, is equal to 250 m.

The radius of the cylinder in kilometers is given by Dobrin to be

$$R = \sqrt{\frac{g^2_{max}\, Z}{41.93}} \qquad \text{(eq. 1)}$$

where g_{max} is the maximum gravity value of the profile in mgals, Z is the depth in kilometers, and ρ is the density contrast in gms/cm³. We know, however, that this object is exposed at the surface in the form of the two peaks. Thus, we can assume the radius to be equal to the depth, and we solve for the density contrast by using equation 1, which can be written as

$$\rho = \frac{g^2_{max}\, Z}{41.93\, R^2} \qquad \text{(eq. 2)}$$

In this case, with R and Z equal to 250 m, and g_{max} equal to 2.0 mgals (from Fig. 4), we find that the calculated density contrast is 0.38 gm/cm^3. This calculated density contrast seems reasonable. Based on an assumed density of 2.15 gm/cm^3 for the saturated glacial sediments and 2.52 gm/cm^3 for the andesite of the peaks, we would expect a density contrast of 0.37 gm/cm^3. The agreement between the theoretical model and geological constraints supports the interpretation that these peaks are the surface exposure of a dike.

The geology of this area has not been mapped, so geological information from surrounding areas must be used in order to determine the age of this dike. At a location 7 km to the northwest of the two peaks in sec. 10, T. 20N, R. 6E., a well (McCullock-Krainick #1) was drilled through 453 m (1370 ft) of Pleistocene glacial drift. Below this was found 1297 m (3891 ft) of Eocene sands and shale. Of course, in the area of the two peaks, which is only 1.5 km from the western edge of the Cascade Range, one would expect substantially less Pleistocene fill. With the above information, the authors suspect that these peaks were formed as a result of Eocene or post-Eocene intrusions and were partly covered later by Pleistocene deposits.

The results of this geophysical survey are interesting and deserve further attention. The geology of this region should be mapped, and work should be done to determine its geological history.

A magnetic survey of this area could be of value and might lead to the discovery of similar intrusions which do not crop out. It should be mentioned, however, that a ground based survey would be difficult to carry out due to interference from numerous power lines, fences, railroad tracks, etc., in the area.

Appendix: Computer Program to Model Gravity Field of Isolated Peaks by Method of Prisms

Introduction

This program makes it possible to compute the vertical component of the gravitational attraction of a mass at the center of each grid section of a partitioned area. The system used is similar to that of Danes (1960). By plotting calculated gravitational attraction values on a map and contouring, the gravitational attraction at any given point on the map may be read directly. This method is well suited for isolated hills where the gravitational effects of the nearly flat surrounding topography may be ignored and also for high density surveys where many terrain correction values must be calculated in the same area.

Data Preparation

To use this program, the terrain must be digitized. This procedure is done by subdividing a rectangular topographic map of the area to be digitized into a uniform grid. This program can accommodate up to 50 sections on a side. The numbers of grid divisions in the east-west and north-south directions are recorded. These are labeled "IDIMEA" and "IDIMSO," respectively, in the program. The elevation in ft above the chosen reference level of each grid area is then averaged. The spacing between each grid is measured, converted to centimeters, and recorded. This is labeled "WIDTH" in the program. A data file is constructed for the recording of the elevation values obtained above. In the program this data file is labeled "DIGIT.DAT." Values are listed consecutively in the data file in integer format. The output of this program is a sequential listing of the gravitational attraction of the feature at the centerpoint of each of the same grid divisions used for the input.

Theory

The vertical component of mass attraction of a hill at a point on the surface is calculated by summing the contributions of many subdivisions of that hill. Each subdivision is prismatic in shape with a width equal to the grid spacing and a height equal to the average elevation of the top of the prism minus the elevation of an arbitrary reference level. In most applications, this reference level will be the lowest point of the hill.

The vertical component of mass attraction of each prism can be derived in the following manner:

1. The prism is mathematically subdivided into smaller subdivisions. The gravitational effect of each section is approximated by assuming that its entire mass is concentrated at a point at its

center. We are interested in the vertical component dg of this increment at a point P. This is given by the equation

$$dg = Gdm \frac{Z}{r^3} \qquad \text{(eq. 3)}$$

where G is the gravitational constant and dm is the mass element. Figure 5 shows the relation between the mass element and the point P in terms of lengths Z in the vertical component and r in the radial.

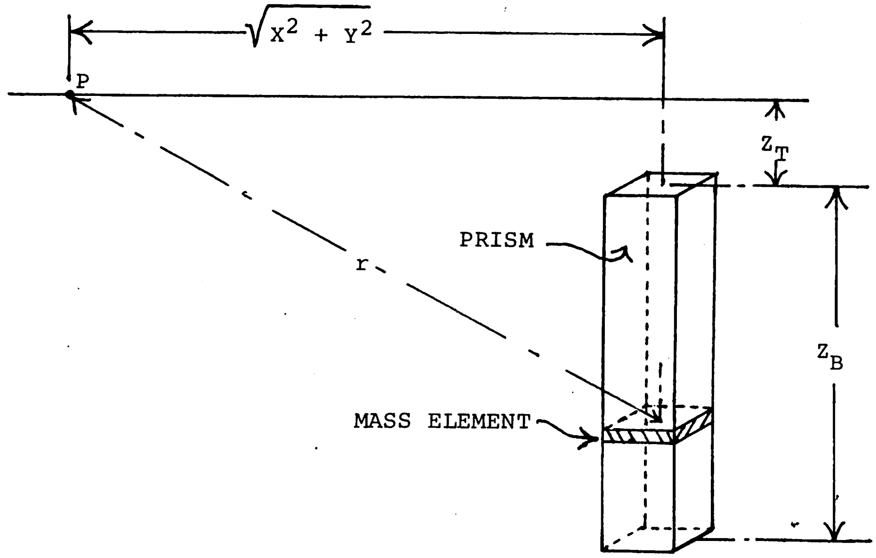


Figure 5. Quantities used in deriving formula for gravitational attraction of a prism.

2. The radius can be expressed in three dimensions by subtracting the equation

$$r = \sqrt{X^2 + Y^2 + Z^2} \qquad \text{(eq. 4)}$$

where X and Y are horizontal components in north-south and east-west orientations, respectively.
3. The mass element may be replaced by the quantity ρdV (eq. 5) where ρ is the density and V is the volume element.
4. The volume element is given by

$$dV = w^2 dZ \qquad \text{(eq. 6)}$$

where w is the width of the prism in the X or Y direction.
5. We now find that the magnitude of attraction of each section of the prism is given by the equation

$$dg = G\rho w^2 \frac{ZdZ}{(X^2 + Y^2 + Z^2)^{3/2}} \qquad \text{(eq. 7)}$$

6. The vertical component of attraction of the prism can be obtained by integrating over the length of the prism.

$$g_{prism} = G\rho w^2 \int_{Z_T}^{Z_B} \frac{ZdZ}{(X^2 + Y^2 + Z^2)^{3/2}} = G\rho w^2 (X^2 + Y^2 + Z^2)^{-1/2} \Big]_{Z_B}^{Z_T} \qquad \text{(eq. 8)}$$

where Z_T and Z_B are the dimensions of the top and bottom of the prism, respectively.
7. This equation can be reduced to the form

$$g_{prism} = G\rho w \left[\frac{1}{\sqrt{m^2 + n^2 + (Z_T/w)^2}} - \frac{1}{\sqrt{m^2 + n^2 + (Z_B/w)^2}} \right] \qquad \text{(eq. 9)}$$

where m and n are the number of grid units east-west and north-south between the prism and the point P.

If we used the above method for that prism on which the point P lies, the gravity field for this prism would become infinite because we have assumed that the mass of the prism is concentrated along the central axis. For this case, the gravitational attraction is determined by the use of a vertical cylinder with a cross-sectional area equal to that of the prism which it replaces.

1. The appropriate radius is given by

$$R = w/\sqrt{\pi} \qquad \text{(eq. 10)}$$

in order that the horizontal cross-section of the cylinder match that of the prism.

2. The equation for the attraction of this central cylinder is given by

$$g_{\substack{\text{central}\\ \text{prism}}} = 2\pi G\rho\,([S_T - Z_T] - [S_B - Z_B]) \qquad \text{(eq. 11)}$$

where S_T, S_B, and Z_B relate to the dimensions indicated in Figure 6.

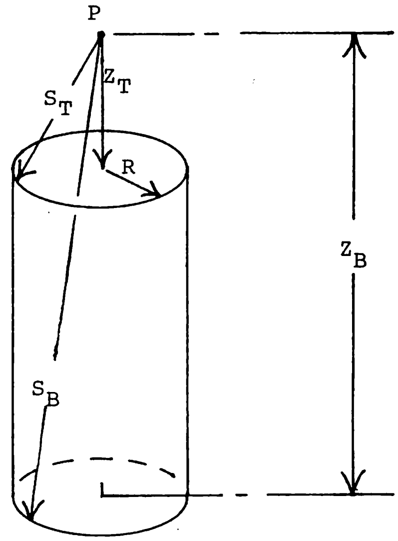


Figure 6. Quantities used in deriving formula for gravitational attraction of the central cylinder.

3. Since, however, point P is in the upper surface of the equivalent cylinder, we have Z_T equal to zero, S_T equal to R and, therefore

$$g_{\substack{\text{central}\\ \text{prism}}} = 2\pi G\rho\,(R - \sqrt{R^2 + Z_B^2}) + Z_B \qquad \text{(eq. 12)}$$

4. Upon substitution of the appropriate value for R given above, this equation becomes

$$g_{\substack{\text{central}\\ \text{prism}}} = 2\pi G\rho \left[\frac{w}{\sqrt{\pi}} + Z_B - \sqrt{\frac{w^2}{\pi} + Z_B^2} \right] \qquad \text{(eq. 13)}$$

and upon factoring, this equation becomes

$$g_{\substack{\text{central}\\ \text{prism}}} = 2\pi G\rho w \left[\frac{1}{\sqrt{\pi}} + \frac{Z_B}{w} - \sqrt{\frac{1}{\pi} + \left(\frac{Z_B}{w}\right)^2} \right] \qquad \text{(eq. 14)}$$

Implementation

Data are prepared as outlined above. The programs are linked and compiled according to the current system commands for FORTRAN-IV. The program will then be executed in the following general steps:

I. Requests
   1. Density of hill.
   2. Width of grid spacing.
   3. Number of grid divisions in east-west direction.
   4. Number of grid divisions in north-south direction.

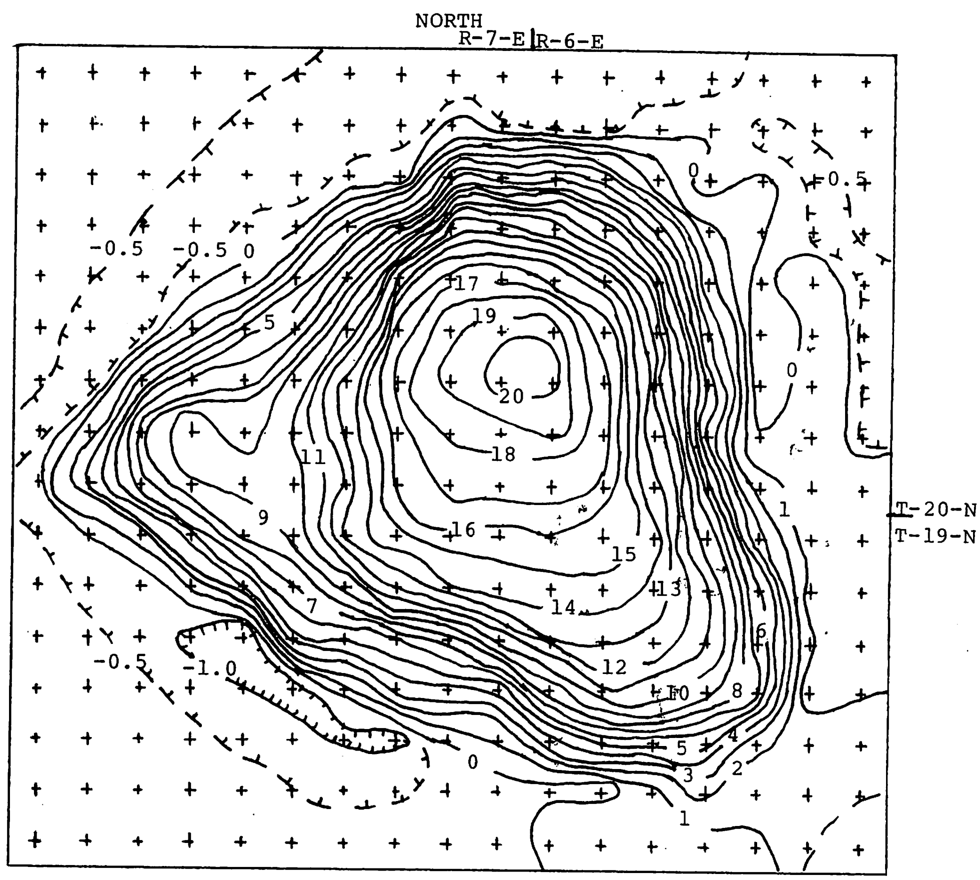
II. Reads the matrix of elevations from the file.

III. Sequentially, for the center point of each grid unit:
   1. Calculates the vertical component of mass attraction of every prism in the matrix except for the central prism using equation 9.
   2. Calculates the vertical component of mass attraction of the central prism using equation 14.
   3. Sums the vertical mass attraction of all prisms and the central prism.
   4. Prints the sum after converting to mgals.

Example

This program was used to obtain terrain corrections for gravity measurements on Pinnacle Peak. Only the mass of Pinnacle Peak above the 750 ft elevation of the surrounding flat plain was modeled. In this case, the density of the peak was assumed to be 2.52 gm/cm³ as measured for several rock samples taken from the peak. The area of Pinnacle Peak was partitioned into a grid system with dimensions of 17 by 16 grid spaces east and south, respectively. Each grid section had a width of 12,000 centimeters. The area covered by this grid system is indicated in Figure 1.

After running the program, the output was plotted on the same grid system used for the input and the values contoured. The resulting map of the gravity field of Pinnacle Peak is shown in Figure 7. The center point of each grid section has been indicated by a "+" symbol.



+ indicates centerpoint of grid unit

Grid spacing: 1,200 cm. Contour interval: 1 mgal

Area of this map indicated in Figure 1.

Calculations based on attraction of mass above 750 foot elevation and density of 2.52 gm/cm³.

Figure 7. Gravity field of Pinnacle Peak.

Figure 8. Fortran Program to model gravitational mass attraction of isolated peaks by method of prisms.

```
        DIMENSION MATRIX (50,50)
        OPEN(UNIT=1,NAME='DIGIT.DOT',TYPE='OLD')
      WRITE(7,10)
10    FORMAT(1X,'ENTER DENSITY,GRID WIDTH,DIM. EAST, DIM. SOUTH')
      READ(5,11) DENSE, WIDTH, DIMSO, DIMEA
11    FORMAT(1X,2F,21)
        DO 2,I=1,IDIMSO
        DO 2,J=1,IDIMEA
2     READ(1,5,END=1) MATRIX(J,I)
1     DO 37,K=1,IDIMSO
      DO 37,L=1,IDIMEA
7     SUMG=O.
5       FORMAT(I)
      SOUTH=FLOAT(K)
      EAST=FLOAT(L)
      HEIGHT=FLOAT(MATRIX(L,K))*30.48
        DO 30,I=1,IDIMSO
        DO 30,J=1,IDIMEA
      A=FLOAT(J)
      B='FLOAT(I)
      ATRIX=MATRIX(J,I)*30.48
17      IF (I.EQ.SOUTH)GO TO 20
        GO TO 25
20        IF (J.EQ.EAST) GO TO 35
25    C=.666667E-7*DENSE*WIDTH
      D1=(ABS(EAST-A))**2.
      D2=(ABS(SOUTH-B))**2.
      D3=(ABS(HEIGHT-ATRIX)/WIDTH)**2.
      E=1./SQRT((ABS(EAST-A))**2.+(ABS(SOUTH-B))**2.+
    1(HEIGHT/WIDTH)**2.)
      PRISM=C*(1./SQRT(D1+D2+D3)-E)
30      SUMG=SUMG + PRISM
      SUMG=SUMG*1000.
        GO TO 37
35      PRISM=.418879*10.**(-6.)*DENSE*WIDTH*(.56419
      1+HEIGHT/WIDTH—SQRT(1./3.14159+(HEIGHT/WIDTH)**2))
        GO TO 30
37    WRITE(7,40) SUMG
40    FORMAT(F7.2)
      REWIND 1
45      END
```

Acknowledgments

Our thanks are expressed to our thesis advisor, Dr. Z. F. Danes, for his help and direction. We wish to thank the University of Puget Sound Geology Department for the use of the gravity meter and the Computer Sciences Department for computer time.

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Received May 20, 1981
Accepted for publication December 4, 1981