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Free-Air Gradient Observations
in Yucca Flat, Nye County, Nevada

by

Philip S. Powers and Don L. Healey

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1985

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FREE-AIR GRADIENT OBSERVATIONS IN YUCCA FLAT,
NYE COUNTY, NEVADA

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ABSTRACT

In Yucca Flat, Nevada Test Site, the free-air gradient (F) has been calculated from international formulas and from surface gravity data. It has also been determined from measurements on, or near, the ground surface and at an elevated position vertically above. The latter (measured), has been the principal method of determining F at Yucca Flat.

The free-air gradient is used to reduce borehole gravity meter (BHGM) data to the interval bulk density. Any error in F translates directly to an error in the interval bulk density. Therefore, the value for F must be determined as accurately as possible.

Errors in F affect the interval gravity value (Δg) and can occur from operator reading error, vibrations, and incorrect terrain corrections. Measurement inaccuracies when determining the interval height (Δh) can also influence F. Each of these factors and the magnitude of these possible errors are discussed.

76 measured free-air gradient values in Yucca Flat are studied in this report. The measured F values range from a low of 0.089 to a high of 0.096 mGal/ft. These values range from -5.38 percent to +2.02 percent of the theoretical value of 0.09406 mGal/ft (0.3086 mGal/m). The mean value is 0.092015 mGal/ft, and the estimated standard deviation is 0.001266 mGal/ft.

A contour map of the Yucca Flat F values was produced after the random spaced were converted to a regular spaced grid by use of the computer program MINC.

INTRODUCTION

Borehole gravity meter (BHGM) surveys at the Nevada Test Site (NTS) (fig. 1) began in 1967 when the U.S. Geological Survey (USGS) logged three holes (Healey, 1970). The BHGM used was the USGS prototype instrument developed jointly by the USGS and LaCoste Romberg, Inc. (McCulloh and others, 1967). Subsequently a BHGM contractor, Gravilog Corp., Houston, Texas, logged numerous holes and more recently, Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) have begun BHGM logging.

The USGS, in cooperation with LLNL and LANL, also logged additional holes at Yucca Flat (Schmoker and Kososki, 1978; Robbins and others, 1982; and Robbins and Clutson, 1983).

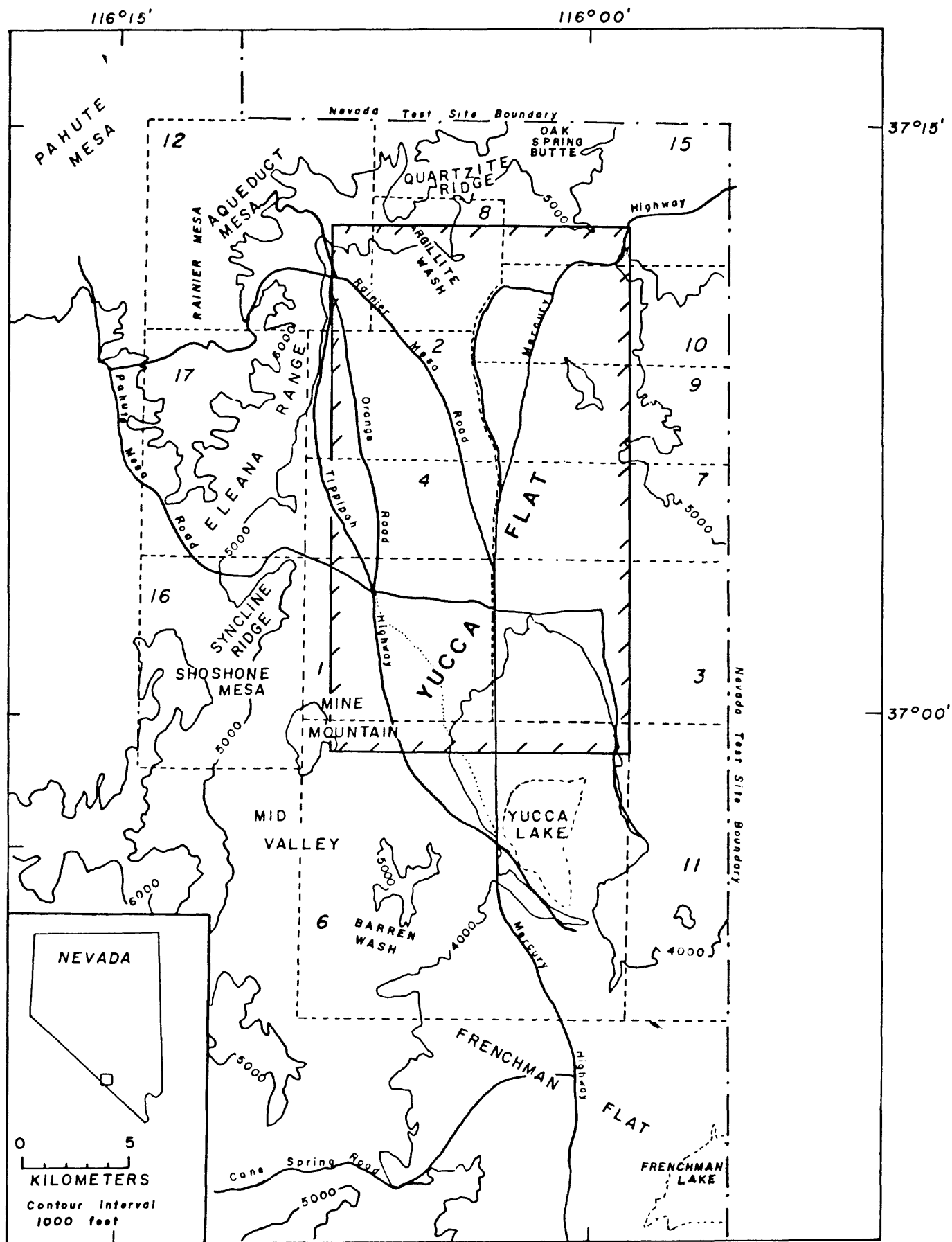


Figure 1.--Index map of Yucca Flat and contiguous areas, Nevada Test Site, Nye County, Nevada. Area of this report is hachured.

Numerous references concerning the fundamentals of BHGM logging and data reduction have been published. A selected listing from this group includes the following: McCulloh, 1966; Healey, 1970; Robbins, 1981; and Robbins and others, 1982.

The BHGM data, after corrections for instrument drift, Earth tides, and adjacent terrain are reduced to the in situ bulk density. The in situ bulk density (ρ_b), in megagrams per cubic meter (mg/m^3), between two points vertically separated in a drill hole, is given by Robbins (1981) as

$$\rho_b = (F - \Delta g / \Delta z) / 4\pi k \quad (1)$$

where F is the free-air gradient of gravity in mGals/ft; Δg is the measured difference in gravity, as corrected; Δz is the vertical distance separating the two points in the drill hole; and k is the Universal gravitational constant.

Equation 1 shows that the reduction of the BHGM data to the in situ bulk density (ρ_b) requires a free-air gradient (F). This free-air gradient can be either measured or calculated. Throughout this report the term "measured" is defined to mean a value of F that was determined by physical measurement of gravity values on, or near, the ground surface and vertically above on a structure of some sort (tower, drill rig, etc.). The term "calculated" is defined to mean a value of F determined from one of the international formulas (Heiskanen and Moritz, 1967; International Association of Geodesy, 1971) or from surface gravity data (Beyer, 1971; A. H. Cogbill, Los Alamos National Laboratory, 1985, oral commun.).

Gravilog Corp. calculated the F values used in the reduction of the BHGM data obtained under their contract at NTS. After evaluating the calculated F values obtained by Gravilog Corp., the USGS decided to measure F on elevated structures. This practice has remained the standard to date. S. L. Robbins (USGS) has attempted to calculate F from the surface gravity surveys with only partial success. A. H. Cogbill (LANL) has recently developed a rapid and accurate method for calculating F from surface gravity (1985, oral commun.).

Beginning in 1967 and continuing to date, approximately 80 measurements of F have been made in Yucca Flat. Most of these data are shown in this report in tabular form, three-dimensional perspective, and as a contoured map. Because of the on-going nature of the testing program in Yucca Flat, it is thought that new measured values of F will be obtained in the future. Any additional data obtained can be used to check the accuracy of the contour map presented herein.

Acknowledgments

F. E. Currey (deceased) made most of the early F measurements at NTS. These data were obtained on the "monkey board" of drill rigs, on an open steel framework, on headframes, or any other elevated structures available. C.H. Miller (USGS) and G. R. Terry (deceased) also assisted in this work. The majority of the F measurements reported herein have been made by personnel of LANL and LLNL. A special thanks is extended to our colleagues from these laboratories for permission to use these data.

THE FREE-AIR GRADIENT

The "free-air" effect is due to the vertical gradient of gravity, i.e., the decrease with elevation as the point of measurement is moved farther away from the center of the Earth. This effect is, to a close approximation, linear and independent of latitude. It is called "free-air" because the attraction of the material between the measuring station and sea level (Bouguer effect) is ignored as if the gravity meter were suspended free in the air (Nettleton, 1971, p. 65). The theoretical magnitude of this effect is +0.09406 mGal/ft (+0.3086 mGal/m).

Measured Free-Air Gradient

Equation 1 indicates the direct role of F in the calculation of the interval in situ densities from BHGM data. The measured free-air gradient (F) is determined from the formula

$$F = (\Delta g + \Delta Tc) / \Delta h \quad (2)$$

where F is the measured free-air gradient; Δg is the difference in gravity, in mGals, measured on, or near, the ground surface and at some point vertically above; ΔTc is the difference in the terrain correction between the two points and; Δh is the vertical distance (above the ground) separating the two points. McCulloh (1966, p. 2-3) indicated that the local and regional geologic effects can cause F to vary by more than ± 10 percent from the theoretical value. At the Nevada Test Site measured variations in F of -9.76 and +6.22 percent have been recorded on Rainier and Pahute Mesas (fig. 1). In Yucca Flat, however, all the measured values, except one, fall below the theoretical value. This one value is thought to be erroneous and will be discussed later. Ignoring this one high value, the range is from -5.38 to -0.06 percent. Including this value the range becomes -5.38 to +2.02 percent of the theoretical value.

Calculated Free-Air Gradient

The free-air gradient can also be calculated from several widely recognized formulas. Gravilog Corporation had the option of calculating F using either of the following formulas:

$$\begin{aligned} \text{Heiskanen} = & 0.09411 - 0.00013 \times \text{SIN}(\text{lat.} \times 0.01745329) ** 2 \\ & - 0.000000022 \times \text{Elevation} \end{aligned} \quad (3)$$

or

$$\begin{aligned} \text{Gutenberg} = & 0.09405 + 0.00007 \times \text{COS}(2.0 \times \text{lat.} \times 0.01745329) \\ & - 0.000000004 \times \text{Elevation} \end{aligned} \quad (4)$$

However, they used the Gutenberg equation exclusively, (B. R. Jones, Gravilog Corp., 1973, written commun.).

Utilizing the surface gravity survey data in the area around a hole logged with the BHGM is yet another method of calculating F. Beyer (1971)

describes an extensive study wherein he compared values of F calculated from a detailed surface gravity survey and F as measured on a portable tower. He describes in detail the field procedures used and the mathematical formulas employed. Using data from the extensive surface gravity survey in Yucca Flat, S. L. Robbins (USGS, oral commun., 1984) calculated F at several places as part of a very limited study. The accuracy of these calculated values was apparently only marginal.

After a long-term study of this problem, A. H. Cogbill (LANL, oral commun., 1985) has developed a rapid, and apparently accurate, method of calculating F from surface gravity data. Cogbill's results will be published in a forthcoming Los Alamos National Laboratory report.

Lawrence Livermore National Laboratory has also developed a method to calculate F from surface gravity data. However, they have elected to continue measuring F (S. R. Clark, EG&G, oral commun., 1985).

GRAVITY OBSERVATIONS

Field Work

Over the years, gravity observations from which the F is determined, have been attempted on various types of elevated structure available in Yucca Flat.

Drill Rigs

The derrick on drill rigs was utilized during the first attempts to measure F . The "monkey board" on these large rigs provided more than adequate height at 90 ft (27.4 m), but there were other problems. The gravity observations had to be made during standby periods when all compressors, generators, etc., could be shut down to minimize vibrations. Any vibration in the derrick would cause the reading beam in the gravity meter to fluctuate. However, due to the sensitivity of the gravity meter, observations were still difficult to obtain. There had to be very little or no wind, no nearby vehicular traffic, and the operator had to be very careful about shifting his body weight. When all the above conditions were met, acceptable gravity observations were obtained.

Assembly Buildings

Assembly buildings are stackable, semi-portable, wooden structures utilized for the final assembly of nuclear devices and the attendant cable bundles before the devices are lowered into the drill hole. These structures, although strongly constructed, are still subject to wind induced vibrations. Under favorable conditions, these buildings permitted the acquisition of very good gravity observations. Unfortunately, these buildings were usually brought on site just prior to the planned experiment. Unfortunately, the F measurement was usually required for the containment calculations long before the building was available. Also, it proved to be too costly to have an assembly building moved on site for the specific purpose of obtaining an F value. These two factors have somewhat restricted the use of these buildings as measuring sites.

Borehole Gravity Meter

In a recent discussion with Mel Millett (LLNL, oral commun., 1984), he indicated that LLNL had been attempting to measure F by suspending the BHGM on the end of a boom. They had experienced some trouble with hydraulic bleed-off that allowed creep in the supporting boom. This movement slowly lowered the height of the BHGM and negated any observations obtained. This problem has since been resolved and their system may become a viable method of measuring F .

Bureau of Land Management Truck

In April 1984, the USGS borrowed from the Bureau of Land Management (BLM) a hydraulically hoisted, truck-mounted survey tower (Beyer, 1971, p.41; Healey and others, 1984, p. 6). This truck is temporarily located at the NTS. To date, free-air gradients have been measured at seven sites on or near Yucca Mountain and one site at Yucca Flat.

The tower is designed as a tower within a tower (Loving and Sappington, 1966). The inner tower is independent of the outer tower and has a raised optical plummet upon which the gravity meter may be set. The operator stands on the outer tower, which nearly eliminates his/her movement from being transmitted to the inner tower. During periods of little or no wind, gravity observations can be obtained on top of the inner tower. As presently configured, the measurement height is 34.80 ft (10.61 m). Repeated observations are made (usually four on the ground and three on the tower) to insure that acceptable data are obtained.

Terrain Corrections

Terrain corrections (T_c) are applied to free-air gradient measurements (above the ground) for the same reason they are applied to surface gravity surveys and borehole gravity measurements. The explanation for this correction can be found in geophysical text books such as Nettleton (1976).

The purpose of the terrain correction is to remove from the gravity observation the effect of irregular topography. Much has been written on this subject (Hammer, 1939; Hearst, 1968; Beyer, 1971; Beyer, 1979, a, b; and Hearst and others, 1980).

In Yucca Flat, the natural topography varies smoothly which minimizes the terrain effect. Topographic disruptions (mud pits, collapse sinks, etc.) do require careful correction. The first terrain correction scheme used at NTS was the method of Hammer (1939). Compartment elevations through zone L, a radial distance of 14.742 km, were determined from surveyed elevations, sketch maps of the site, and topographic maps. Computer programs are now used to calculate the terrain correction. Usually the inner zone compartments (through zone G or H) are still determined by hand. Digitized topography is used to calculate the outer zone correction.

The terrain correction sensitivity to near surface features (known or unknown) can be minimized by elevating the bottom observation (Beyer, 1971, p. 40). Beginning in 1977, the bottom measurement of F was elevated above the ground surface from 4 to 27 ft (1.22 to 8.23 m) by LLNL and LANL. The bottom observation at 4AF, a recent measurement by the USGS, was measured on the

ground surface. The authors only have limited data on the calculated terrain corrections for the F measurements in their files, and therefore, will not pursue this subject any further. However, much thought and care have gone into the terrain corrections applied to the measured F in Yucca Flat.

Error in the measured free-air gradient

Error in the measured values for Δg and Δh translate directly to error in the measured F and consequently into errors in the calculated interval densities from the BHGM data.

Errors in Δg arise from gravity meter reading errors, gravity meter calibration inaccuracies, and incomplete or incorrect terrain corrections. An error in Δh would occur from any mis-measurement of the vertical distance separating the gravity observations.

The repeatability of gravity observations on top of a vibrating tower (structure) may be the largest contributor to error. Because Δg is a relatively small member (approx. 2.5-15.0 mGals, depending on Δh), gravity meter calibration is not usually a factor. Incomplete or inaccurate terrain corrections may contribute to Δg error, however, the magnitude of Tc in Yucca Flat is low.

At six representative sites (lowest to highest Δh) in Yucca Flat, the measured ΔTc , Δh and Δg values were allowed to vary by ± 10.0 percent, ± 0.1 foot, and ± 0.02 and 0.1 mGal, respectively. These ranges are thought to bracket any errors in the actual data. The results of this study are shown on figure 2 as the percent change in F introduced by these assumed errors.

The greatest Tc effect occurs at the intermediate heights (68.5 and 83 ft or 20.9 and 25.3 m). The larger Δh and Δg effects occur at the lower heights and become linear with increased height. Figure 2 illustrates the need to measure F as high as possible (see also Kuo and others, 1969). For this reason the minimum height desirable is taken to be 30.0 ft (9.14 m).

In this paper we are not discussing the results of down-hole BHGM surveys. We do, however, discuss the effect of F on the BHGM surveys.

From equation 1 it is evident that changes in F will also change the calculated interval density ρ . This relationship is shown on Figure 3. Changing F by 1.0 percent changes ρ by 0.037 mg/m^3 . A 2.0 percent change varies ρ by 0.074 mg/m^3 , etc. The magnitude of the combined errors in F are unknown, but hopefully are no greater than 2.0 percent for most sites.

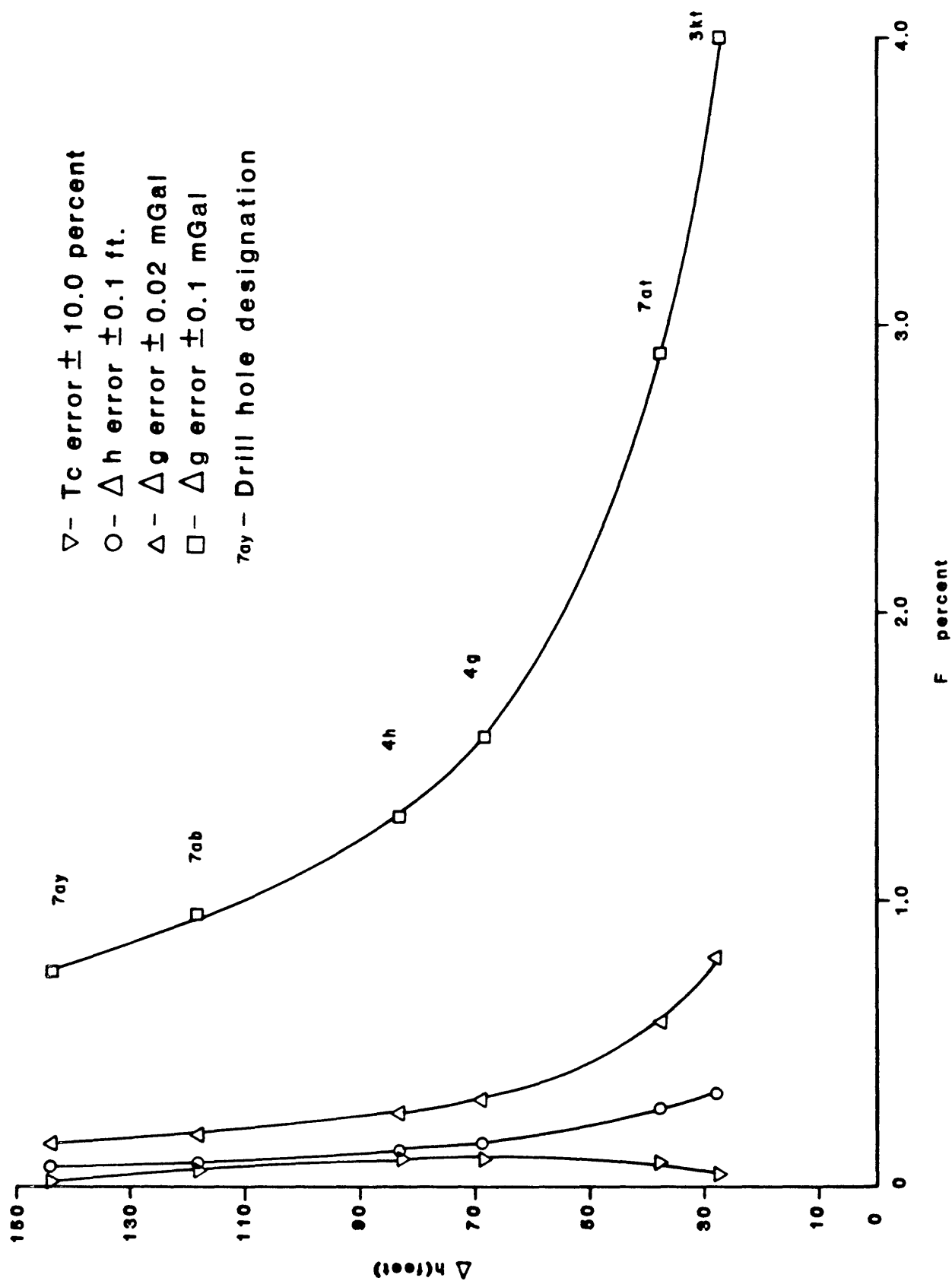


Figure 2.--Graph showing percent error in measured F caused by assuming errors in the measured parameters at six sites in Yucca Flat (lowest to highest Δh elevations).

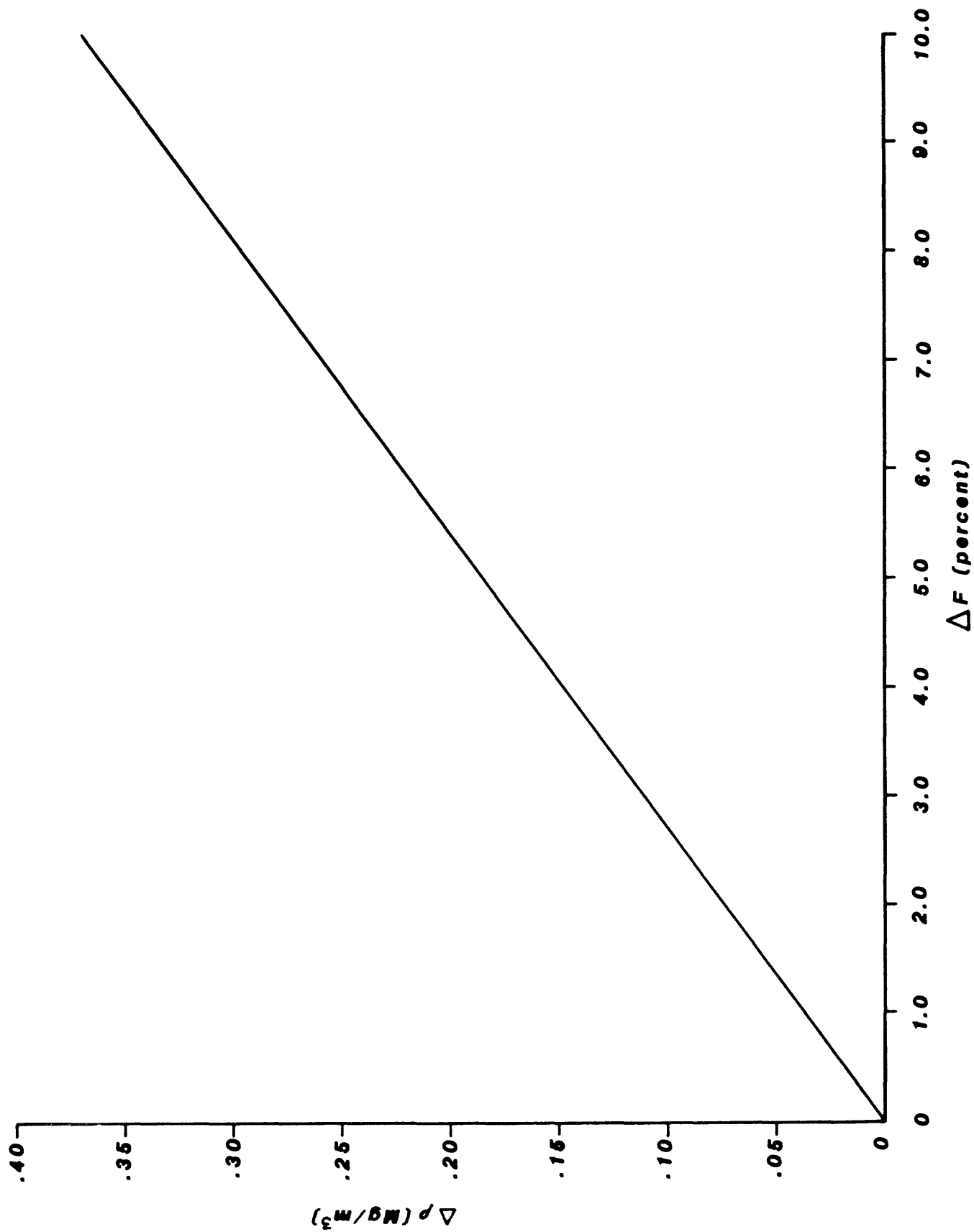


Figure 3.--Graph showing the percent change in the free-air gradient (F) versus the change in the calculated in situ bulk density ($\Delta\rho$) (after Robbins, 1981).

DATA BASE

History

A total of 76 selected F measurements, obtained between 1967 and 1984, are utilized in the compilation of the contour maps presented in this report. The authors have field data sheets for 31 measurements in their files and the remainder were obtained from either LANL or LLNL. The principal facts necessary to plot, contour, and label the free-air gradients (F) measured in Yucca Flat are listed in table 1. Excluded from this listing is the date measured, by whom, and the ground-surface elevation. The location of each measurement and the drill-hole identifier are shown on figure 4 (in pocket). Measurement heights ranged from a minimum of 27.7 ft (8.44 m) to a maximum of 143.8 ft (43.83 m).

Conversion of Random Spaced F Values into a Regular Spaced Data Grid

The original data, which is randomly spaced, was changed into a regular spaced grid by a program named MINC (Webring, 1981). This program performs grid interpolation from randomly located data using the principle of minimum curvature. The size of grid that was generated by MINC, based upon preselected parameters in a command file, was 55 columns by 85 rows. This represents a ratio of 62 generated grid points to each original data point. Even though this ratio is greater than recommended (Webring, 1981), because of the spacing of F values within Yucca Flat, this ratio proved to provide the best contours. Too coarse an interval results in the loss of information, while too fine an interval results in isolated anomalies and an obscure regional picture (Webring, 1981). A distance weighing parameter slope, equal to 5, was used in the program command file. A slope equal to 5 gives a 5:1 weight for data near the mesh location when compared to one grid interval away. The purpose of the parameter slope is to provide a way to reduce high-frequency aliasing caused by use of too coarse of a grid interval (Webring, 1981). This parameter causes all data within one grid unit to be combined into one weighted location and z-value.

Values generated by the gridding program farther than 10,000 ft (3048 m) from a real observation were flagged by the radius parameter in the command file to suppress contour generation. Due to the high frequency nature of the free-air gradient, generation of contours at greater than 10,000 ft were not of any value. The continuity of the contour map would have been disrupted if a smaller radius parameter had been used.

Data Analysis by Inspection of 3-D Perspective Mesh Plots

A preliminary three-dimensional (3-D) perspective mesh plot was produced to visually portray the data. To exaggerate the small differences between the F readings, the z-axis (F) was set to be .4 times the length of the base of the 3-D perspective plot. The preliminary 3-D mesh plot showed one very conspicuous peak (F value of 0.09787 mGal/ft (0.3211 mGal/m) measured at location 4AF).

Table 1.--Principal Facts for F measurements in Yucca Flat

(To convert from English to metric units multiply feet by 0.3048 to obtain meters; divide mGal/ft by 0.3048 to obtain mGal/m; leaders (--) indicate no data; stations are ordered by Easting coordinate)

INDEX	STATION ID	EASTING (ft)	NORTHING (ft)	DELTA HEIGHT (ft)		F (mGal/ft)
				LOWER	TOP	
1	2CO	657374.0	861900.0	5	50	0.09199
2	2CR	657800.0	871800.0	9	50	0.08900
3	2CQ	658901.0	860450.0	5	50	0.09200
4	E4AF	662900.0	846300.0	0	64	0.09234
5	E8I	665390.0	882139.0	0	65	0.09293
6	4AC	667250.0	853150.0	9	50	0.09000
7	8N	667500.0	883300.0	5	50	0.08900
8	4AF	667900.0	855000.0	0	35	0.09089
9	2EU	668270.0	876860.0	9	50	0.09200
10	8J	668300.0	885000.0	5	50	0.09000
11	2FE	668301.0	872502.0	7	50	0.09200
12	2FF	668450.0	862800.0	9	50	0.09400
13	2FD	668550.0	865551.0	7	49	0.09100
14	E8E	668700.0	881600.0	0	105	0.09015
15	2FC	668801.0	871601.0	4	40	0.09088
16	2DY	668901.0	861600.0	0	105	0.09209
17	2FA	669251.0	868949.0	0	44	0.09118
18	8K	669531.0	884049.0	8	49	0.09070
19	8L	669667.0	885709.0	8	49	0.09150
20	2EV	669801.0	872800.0	9	50	0.09100
21	2FB	669900.0	865675.0	20	90	0.09180
22	8C	670003.0	885003.0	10	49	0.09190
23	E10J	670453.0	887033.0	0	43	0.09121
24	4AH	670653.0	850502.0	0	68	0.09240
25	E4AB	672450.0	856750.0	0	65	0.09078
26	E4AL	672570.0	848700.0	--	--	0.09350
27	2EX	673310.0	870640.0	9	50	0.09200
28	2EO	673353.0	874852.0	20	90	0.09290
29	4AL	673500.0	848700.0	9	50	0.09250
30	2ES	673650.0	873550.0	9	50	0.09200
31	4AI	674075.0	850075.0	4	42	0.09205
32	4AK	674500.0	847300.0	8	50	0.09100
33	2EI	674602.0	874552.0	0	29	0.09340
34	2ER	674882.0	877923.0	8	49	0.09400
35	2EP	674953.0	863652.0	14	84	0.09270
36	E1H	675000.0	820000.0	--	--	0.09270
37	E2Y	675249.0	873100.0	0	41	0.09324
38	2EQ	675554.0	861705.0	20	90	0.09300
39	2EN	675750.0	864550.0	0	48	0.09182
40	2ET	675800.0	878800.0	9	50	0.09600
41	2EL	676200.0	863300.0	0	43	0.09149
42	E1Q	677500.0	841500.0	--	--	0.09070
43	9CT	677550.0	869601.0	9	50	0.09200
44	4E-1	677550.0	858200.0	0	64.5	0.09115

45	2EW	678160.0	863720.0	13	51	0.09300
46	4L	678420.0	856850.0	0	37.5	0.0922
47	4H	678500.0	859600.0	0	83	0.09317
48	4F	679100.0	851500.0	0	32	0.09238
49	4G	679500.0	856600.0	0	68.5	0.09320
50	7AQ	679900.0	845850.0	0	68	0.09108
51	10BH	680100.0	885500.0	8	50	0.08900
52	10BF	680302.0	888652.0	0	70	0.09071
53	7AP	681350.0	853900.0	0	31.4	0.09381
54	7AV	681700.0	848200.0	0	32.5	0.09311
55	3KT	681999.0	831498.0	0	28	0.09014
56	3KQ	683000.0	829700.0	0	37.6	0.09121
57	10BD	683212.0	876001.0	0	55	0.09232
58	10BG	684062.0	875551.0	8	43	0.09300
59	10CA	684267.0	889822.0	14	53	0.09300
60	9CR	684501.0	866401.0	8	49	0.09400
61	9CP	685102.0	865502.0	0	48	0.09403
62	7AM	686300.0	854100.0	0	144	0.09261
63	3KM	686300.0	824500.0	0	69	0.09060
64	3KO	686600.0	843700.0	0	31	0.09225
65	3KF	687250.0	839600.0	0	118	0.09284
66	9CS	687850.0	860200.0	8	50	0.09300
67	9CL	688250.0	861151.0	0	105	0.09305
68	7AY	688700.0	855600.0	0	144	0.09181
69	9CQ	688950.0	860203.0	9	58	0.09270
70	3KW	689500.0	818950.0	0	37.5	0.09121
71	9CN	689551.0	861201.0	8	50	0.09310
72	3JB	689778.0	822381.0	0	144	0.09212
73	7AT	690000.0	858800.0	0	37.5	0.09195
74	7AE	692450.0	851150.0	0	69	0.09143
75	E7NS	693701.0	855600.0	0	48	0.09301
76	7AB	693999.0	848501.0	0	118	0.09117

After viewing the preliminary 3-D plot, it was determined that as many suspicious values would be remeasured as time and conditions permitted. Also, as conditions permitted, new F values at selected locations would be measured. However, field conditions permitted only the remeasurement of the anomalous high at location 4AF. The remeasured value of 0.09089 mGal/ft (0.2982 mGal/m) was more in agreement with adjacent stations, and now fit into a low trend (fig. 5). A low value at location 9CG (0.0890 mGal/ft, 0.2920 mGal/m) did not appear to fit with any surrounding trends, and was discarded as a suspicious value.

A 3-D mesh plot of the final data set is shown on figure 5. Figure 5 is dominated by the high value (0.096 mGal/ft) at 2ET. This high was measured three times by LLNL and may or may not be a valid point.

The data set was thinned to remove closely adjacent stations before the F values were contoured. The value at E4AH was removed because it was in close proximity to 4AI and had nearly the same reading. The value at 10BC was removed because it was near the location of 10BG, and was not in close agreement with 10BG or the other adjacent value at 10BD. See Table 1 for the Nevada State Coordinates (Central Zone) for each measurement.

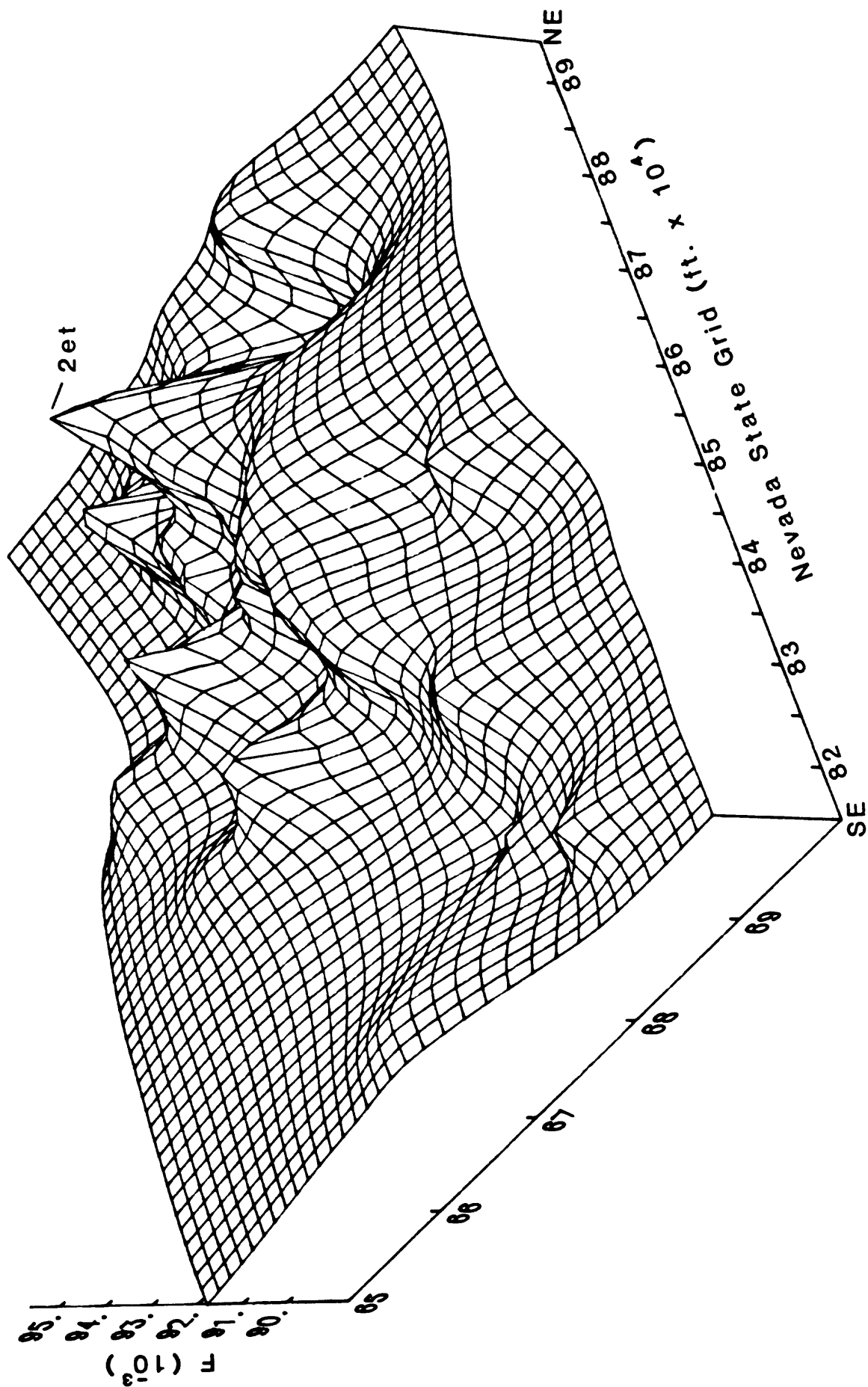


Figure 5.--3-D mesh plot of measured Free-air gradient (F) data
in Yucca Flat, Nevada Test Site.

CONTOUR MAP

The final data set includes 76 F observations in Yucca Flat. This data set includes 5 stations not included on the previous data transmissions from LLNL, but were published by Robbins, Schmoker, and Hestor (1982), and Robbins and Clutsom (1983) in connection with borehole gravity-meter (BHGM) surveys for LANL and LLNL. These stations will be discussed in detail later in this report.

The contoured free-air gradient map (fig 6., in pocket) was produced from the regular grid created by the MINC program from the edited F values. The program used to produce the contour map is named CONTSG.FOR and is located at the U.S. Geological Survey, Branch of Geophysics, P.O. Box 25046, Mail Stop 964, Denver, Colorado, 80225.

Every fifth line is labelled with the appropriate contour value and drawn in bold for emphasis. The lows that have five or more closed contours are hachured. Contour lines are not drawn when more than 10,000 ft (3048 m) from a measured F value.

STATISTICS

The 76 utilized F values within Yucca Flat have an average value of 0.09199 mGal/ft (0.3018 mGal/m). The population estimated standard deviation is 0.001208 mGal/ft (0.00396 mGal/m). Assuming a normal distribution of F values within Yucca Flat, 95.45 percent of the F values will fall between 0.0896 and 0.0944 mGal/ft (Till, 1974). This percentage is a range from minus two standard deviations to plus two standard deviations. This makes it highly unlikely (4.55 percent or less) that values less than 0.0896 and greater than 0.0944 mGal/ft belong to the sample population mean (0.09199 mGal/ft, 0.3018 mGal/m).

To test the capability of predicting F values from the contoured data set, a preliminary contour map was generated. This preliminary map was based on 69 measured values and did not include the five published values mentioned above nor the high (2 ET) and low (9 CG) values. This provided a rigorous test of the gridding and contour computer programs as the extremes (high and low values) of the data set occur within 8,000 ft (2,438 m) of each other.

Values at these seven sites were then interpolated from the contours on the preliminary map and compared with the measured values. Table 2 shows the resulting information derived from this comparison.

Table 2 shows the comparative statistics between the measured F values and the contour predicted F values.

Table 2.--Comparison of measured F values to contour predicted F values.

Index No.	Location ID	Measured F mGal/ft	Contour F mGal/ft	ΔR mGal/ft
1	3KW	0.09121	0.0925	+0.00129
2	3KQ	0.09103	0.0901	-0.00093
3	7AT	0.09195	0.0923	+0.00035
4	4L	0.09220	0.0923	+0.00010
5	4H	0.09317	0.0920	-0.00117
6	2ET*	0.09600	0.0936	-0.00240
7	9CG**	0.08933	0.0927	+0.00337

*High value.

**Low value.

The sum of the error terms for the data from table 2 is +0.00061 mGal/ft (.00200 mGal/m). The sum of the error terms excluding the extreme values (locations 2 ET and 9 CG) is -0.00036 mGal/ft (.00118 mGal/m). The average error with the extreme values used in the calculations is +0.00120 mGal/ft (.00394 mGal/m). The average error without the extreme values used in the calculations is 0.00064 mGal/ft (.00210 mGal/m).

To further test the accuracy of the contour map (fig. 6, in pocket), a test sample of 10 locations were randomly chosen from the sample population of F values at Yucca Flat. The points were selected by blindly moving a pencil about the area of the map and selecting the location closest to the pencil point as the random point. F values were then interpreted from the contour map and recorded along with the actual field measured values, and the residuals calculated.

The following table shows the randomly selected locations, measured F values, contour map interpreted F value, and the calculated residuals:

Table 3.--Contouring accuracy of random F values

Index No.	Location ID	Contour F mGal/ft	Measured F mGal/ft	Residual mGal/ft
1	2ES	0.09235	0.09200	+0.00035
2	2EP	0.09242	0.09270	-0.00028
3	4AC	0.09018	0.09000	+0.00018
4	8I	0.09270	0.09293	-0.00023
5	7AV	0.09290	0.09311	-0.00021
6	9CN	0.09300	0.09310	-0.00010
7	4AH	0.09237	0.09240	-0.00003
8	2ER	0.09410	0.09400	-0.00010
9	3KO	0.09230	0.09225	+0.00005
10	9CT	0.09215	0.09200	+0.00015

The sum of the residuals (from table 3) is -0.00002, which indicates a random dispersion about the average of the residuals (+0.000168). A random dispersion of the residuals indicates that the contour map predicts the F values in a manner such that there is nearly an equal probability of a high prediction, as a low prediction. The average of the residuals is the average error of the predicted (contour) F values from the measured F values. The sum of the residuals squared is 3.762 E-07. The standard error of estimate is 0.000194.

The standard error of estimate is:

$$((\text{sum} ((\text{Observed F} - \text{Predicted F}))^2)/\text{number of samples})^{0.5} \quad (5)$$

CONCLUSIONS

The contoured free-air gradient (F) map of Yucca Flat (fig. 6) defines a series of short-wavelength anomalies scattered over the flat. These anomalies can change markedly over short horizontal distances. These changes are emphasized by the contour interval of 0.002 mGal/ft (0.007 mGal/m). Although these changes appear large, one must keep in mind that we are dealing with very small numbers (0.089 to 0.096 mGal/ft or 0.292 to 0.315 mGal/m). However, even minor changes in these values are important and translate to significant differences in bulk densities calculated from BHGM data using the measured F values. For this reason it is necessary that the F values be precisely and accurately determined.

With these standards in mind, we felt obligated to discard the data base value of 0.08933 at 9CG. This decision was based on the following arguments: First, the measurement height of 29 ft (8.84 m) was minimal (one of the shortest); second, statistically, the value lies beyond two standard deviations of the data mean; and third, intuitively perhaps, the value does not appear to fit in this part of Yucca Flat. Figure 6 is contoured without this value. By the same line of reasoning applied to 9CG, we believe the value of 0.096 mGal/ft (0.029 mGal/m) measured at 2ET (see fig. 5) is suspect. This F value is also statistically beyond two standard deviations of the data mean. However, this station was measured three times and the same value was determined from each set of data. Because of these replicate values we did not remove 2ET from the data file.

The contoured free-air gradient map (fig. 6) should prove to be a worthwhile addition to the literature on the geology and geophysics of Yucca Flat. Future F values should provide the opportunity to check the predictive capabilities of the contour map. Additional field work is necessary to improve and upgrade this map. The F values at 9CG and 2ET should be re-measured. It would be worthwhile to remeasure the F values from Yucca Flat, in particular these at locations 2CR, 8N, and 10BH, which are below two standard deviations from the sample mean.

New measurements at selected fill-in sites would improve the accuracy of the contours in areas where the measurements are widely separated.

Because of the on-going nature of the BHGM work in Yucca Flat, it is presumed that F measurements will also continue. As new measurements are obtained, the contour map of F values can be updated. The predictive qualities of the contour map (table 2) for the determination of the F value at Yucca Flat can be used as an early warning indicator of a potentially poor reading in the field. To insure that the accuracy of the prediction is good, the F value to be determined should be within 10,000 ft (3,048 m) of a measured F value. If a set of F field readings do not fall within the contour map predicted range, the data should be re-checked, and possibly new readings taken.

Based on the random test sample (table 3), the contour map accurately reproduces the F value with a standard error of estimate of 0.000194 mGal/ft (0.000636 mGal/m), or a simple average error of 0.000168 mGal/ft (0.000551 mGal/m).

It will be interesting to compare future F values which have been derived by the calculated method, with the F values produced by the contour map, and see which more closely matches the actual measured F values.

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