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ZUNIL GRAVITY STUDIES

ZUNIL GEOTHERMAL AREA, GUATEMALA

Review Comments

by

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Introduction

Both regional and detailed gravity surveys have been completed by INDE in the Zunil area. A regional survey extends from Quetzaltenango on the north to south of Cerro El Galapago, covering approximately 90 sq km. A more detailed survey of approximately 30 sq km covers the Zunil I geothermal project area (CyM/MKF, 1988). The locations of the gravity survey are not indicated on the available maps with the exception of the main 15 sq km area of the detailed survey. The principal facts of the gravity data (latitute, longitude, station location, station elevation, elevation accuracy, terrain corrections, etc.) were not available for review.

A draft report which describes gravity models of the Zunil I area (Cordon, 1989) and other information refer to a Bouguer gravity anomaly map computed for a density of 2.67 gm/cc. Although this is a commonly used density for igneous, metamorphic and sedimentary terrains, it is almost always too high for young volcanic provinces. Use of an incorrect density in gravity data reduction will lead to false anomalies. U. S. Geological Survey studies on Hawaii (Kinoshita et al, 1963) and by Woollard (1951) on Oahu indicated that a density of 2.30 gm/cc was most appropriate even in this province of basaltic lava flows. Williams and Finn (1982) concluded the bulk densities of most Cascade volcanic edifices fell in the range 2.15 to 2.35 gm/cc in their studies of silic volcanoes of the Cascades. Couch et al. (1982) used a Bouguer density of 2.43 for data reduction in their study of the Western and High Cascades of Oregon. A density of 2.45 is often used for the Tertiary volcanics of the Basin and Range province in the Western United States. The 2.30 gm/cc average density reported by Cordon (1989) for 620 m of volcanic rocks in well Z-11 is in good agreement with both the Cascade and

Hawaii studies.

A quick correlation between the Zunil gravity maps and the topographic maps, using transparent overlays, shows high spatial correlations between gravity lows or negative gradients, and topographic highs or positive gradients. This is additional confirmation that the 2.67 gm/cc used in the Bouguer gravity reduction is too high.

Basic Gravity Formulation

The successful utilization of gravity data is quite dependent upon good field procedures and the careful application of a number of corrections to the observed gravity values. Gravity data reduction has been described in detail by Dobrin (1960), Telford et al (1976), and numerous others. It is appropriate to review some points here.

The value of the earth's gravity field, g, at any point on the earth's reference spheroid is given by the following formula, adopted by the International Association of Geodesy in 1967:

$$g = g_o(1 + \alpha \sin^2 \phi + \beta \sin^2 2\phi) \quad (1)$$

where g = equatorial gravity = 978.0318 gals at sea level, ϕ = latitude, and the constants α and β are α = +0.0053204 and β = -0.0000058 respectively.

Following the notation of Telford et al (1976) the Bouguer gravity g_B is given by,

$$g_B = \text{observed } g + (\text{tidal} + \text{drift corr.}) + \text{latitude corr.} + \text{free air corr.} + \text{Bouguer corr.} + \text{terrain corr.} \quad (2)$$

The reduction of observed gravity data to Bouguer gravity values, in metric units, is given by

$$g_B = g_{obs} + d_{t+d} + 0.8122 \sin 2\phi \text{ mgal/km} + 0.3085\, h \text{ mgal/m} - 0.04188\, h\sigma \text{ mgal/m} + t.c. \quad (3)$$

The latitude correction is positive as one approaches the equator; h is the elevation of the station above the datum plane in meters; σ is the density of the earth slab between the station and the datum plane (often chosen to be 2.67 gm/cc). The free-air correction is positive for stations above the chosen datum plane, while the Bouguer correction is negative for stations above the datum plane. The terrain correction is always positive.

The Bouguer anomaly is

$$G_B = g_B - g_r \quad (4)$$

where g_r is a local reference station value, or g_r = g from eq.1.

The density used for data reduction occurs in eq. 3 in the Bouguer correction and in the terrain correction. Many computer routines for gravity data reduction calculate the Bouguer gravity for several densities simultaneously. In areas of high topographic relief such as the Zunil area the incorrect choice of the density used in the Bouguer and terrain corrections can give rise to misleading gravity maps. The variation in the Bouguer correction for several different densities and station elevations above or below the datum elevation is illustrated in Table 1, below.

Table 1. Bouguer Correction (mgal)

Station Elev. (m)	σ=2.3	σ=2.45	σ=2.55	σ=2.67
1.0	0.0963	0.1026	0.1068	0.1118
10.0	0.9632	1.0261	1.0679	1.1182
100.0	9.6324	10.2606	10.6794	11.1820
200.0	19.2648	20.5212	21.3588	22.3639
400.0	38.5296	41.0424	42.7176	44.7278
600.0	57.7944	61.5636	64.0764	67.0918
800.0	77.0592	82.0848	85.4352	89.4557
1000.0	96.3240	102.6060	106.7940	111.8196

Surface elevations within the area of the detailed gravity survey vary from less than 2000 m near the Samala River to almost 3200 m on Cerro Candelaria. From Table 1 we note that the difference in the magnitude of the Bouguer corrections for an elevation difference of 1000 m and densities of 2.67 and 2.45 gm/cc is 9.21 mgals. Similarily the difference in Bouguer corrections for an elevation difference of 400 m and densities of 2.67 and 2.30 gm/cc is 6.20 mgals. We believe that a substantial portion of the gravity minima occuring over major topographically high areas are due to an improper density (2.67) in the Bouguer correction.

Terrain Corrections

From the data reviewed it is not clear to what degree terrain corrections may have been applied. Survey procedure in areas of extreme topographic variation such as Zunil should include the estimation of near-station corrections (Hammer zones A-D, or 0-170 m) in the field and the application of outer-zone terrain corrections by hand or by computer. An example field sheet for the determination of near-station terrain corrections is included as Figure 1. The quality of older topographic maps may have made terrain corrections for outer zones difficult or impractical. Terrain corrections for many of the Zunil gravity stations could range from 5 to more than 10 mgal, with a high probable error. Since terrain corrections are always positive, incomplete terrain corrections probably contribute to the large gravity minima which correlate with major topographic highs.

Gravity Modeling by M-K

Cordon (1989) reports on the results of preliminary gravity modeling of the graben area within the detailed survey. Because his modeling attempts to match the Bouguer gravity data, which has been reduced with an incorrect density, the models are dominated by low density bodies northwest of the graben. The computed gravity values do not provide a detailed fit to the observed gravity data over the granodiorite body, even though care has been taken to use drill control on the depth to the granodiorite (from ZCQ wells 1-6) and density data for overlying volcanics from well Z-11.

Cordon (1989) recognized the probable effect of an incorrect density in the reduction to the Bouguer gravity, but proceeded with the modeling study as requested by the Advisory Committee. He concludes, correctly, that the graben itself is not responsible for the large negative gravity anomaly. Nevertheless, attempting to match the observed data, and not removing the regional gradient due to the low density volcanic center, yields misleading results. The presence of a 10 km wide, 6 km thick intrusion with a density of 2.0 to 2.1 gm/cc, as he concludes, is highly unlikely. Documented densities for the lightest igneous rocks include (Telford et al, 1976): rhyolite (2.35-2.70); dacite (2.35-2.8); and obsidian (2.2-2.4). Also, a magma body of the size, depth, and density indicated is unlikely, without ongoing, catastrophic eruptive activity.

Alternative Interpretations

In view of the foregoing critical evaluation, it is appropriate to illustrate what might happen using approximately corrected gravity data and an alternative interpretation method. Without exact station locations, elevations, and other principal facts for the gravity data, one cannot complete an accurate reduction of the gravity data. Using adjustments to the gravity data appropriate to a density of 2.3 for the Bouguer correction from Table 1, and rough esimates of station location and elevation from 1:40,000 scale maps, the gravity data along profile A-A' have been adjusted as shown in Figure 2. No adjustment for the effect of changing the density in the terrain correction could be made because we had no information on the magnitude of the terrain corrections. Both regional and residual gravity data along M-K profile A-A' are shown. Where the data overlap, the detailed gravity profile is 8 to 20 mgal higher than the regional gravity indicating reference to a dfferent datum or base station, or additional corrections. Both profiles show an inverse trend to the plot of station elevation taken from the regional scale (1:40,000) topographic map. Profile g_B estimates the change in Bouguer gravity for a density of 2.30 above a datum of 1800 m. The negative anomaly on the northwest is reduced by as much as 17 mgals as compared to the Bouguer gravity for a density of 2.67. Complete terrain corrections might have further reduced this minimum.

Figure 3 illustrates the manual fit of a low frequency curve to the adjusted Bouguer gravity data. This curve simulates a regional gradient probably due to the low density units associated with volcanic centers (Volcan Santa Maria; Cerro Candelaria) below the 1800 m datum plane, and perhaps to incomplete terrain corrections. The residual anomaly results when the regional gradient is removed from the adjusted gravity values. Numerical modeling of this profile, at an expanded vertical scale, would be appropriate only if accurate station locations, elevations, and other data would justify the additional effort. Data processing such as this would result in a more realistic model for the Zunil I area. The approximate position of three faults inferred from the steeper gravity gradients of this residual anomaly profile are shown.

Figure 4 illustrates an alternative (interim) interpretation of fault locations suggested by the detailed gravity data. The positions of three faults interpreted from the residual anomaly of profile A-A' are indicated along this profile. While there is some agreement with structures previously interpreted by INDE, the position of some faults is different and additional northwest-trending structures are indicated. This qualitative interpretation assumes that the existing data are sufficiently accurate as presented (even with a 2.67 density and existing terrain corrections) to support the steep gradients indicated by the contour map. No new numerical modeling has been undertaken to support this interpretation, but some of the northwest trending structures agree with linear features that have been interpreted from topographic expression and aerial photos.

If the interpretaion of three faults just west of ZCQ-6 is correct, this may indicate a zone of considerable fracturing and permeability important to the siting of future production wells. The detailed gravity survey now in progress will provide detailed data with good elevation and location control suitable for in-depth numerical modeling to test this interim interpretation.

Experience in geothermal areas throughout the world indicates that gravity data will not delineate all faults which may be of interest. Detection of faults depends upon the density contrast, the depth to and displacement along the fault, and survey parameters such as station spacing and survey precision. Faults interpreted from the gravity data are often two or more faults which have not been sufficiently resolved by the survey data. Such may well be the case for structures interpreted from the Zunil gravity data.

Recommendations

The granodiorite intersected in Zunil drill holes appears to be well expressed in the gravity data, and major structures which might indicate areas of higher permeability can be inferred from the gravity data. Additional gravity data modeling would be warranted if existing survey data have sufficient accuracy (observed gravity, station location, station elevation, terrain corrections) and the data are reduced using a density of 2.30 g/cc for the Bouguer correction. If there is concern about the level of accuracy of existing data, further modeling should await the completion of the new gravity survey. Care should be taken to complete near-station terrain corrections in the field, and to complete outer zone corrections as well. It may be wise to reduce the data using several densities for the Bouguer correction, such as 2.30, 2.40, and 2.45 g/cc.

References

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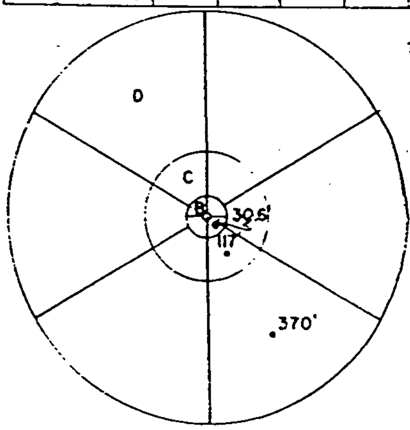
EXPL TION SERVICES – GEOPHYSICS DIVISIO

INNER TERRAIN CORRECTION ONLY

Zone		Compartment	1	2	3	4	5	6	Corr. x0.01 Mg.
6.56' to 54.6'	B	Elev. Diff.							
		Corr.							
54.6' to 175'	C	Elev. Diff.							
		Corr.							
175' to 558'	D	Elev Diff.							
		Corr.							

Total Corr.= ________ Mg.



ROCK . SITY = 2.00
INNER TERRAIN CORRECTION TABLES

ZONE B 4 Compartments 6.56' to 54.6'		ZONE C 6 Compartments 54.6' to 175'		ZONE D 6 Compartments 175' to 558'	
±h, ft.	T	±h, ft.	T	±h, ft.	T
0 - 1.1	0	0 - 4.3	0	0 - 7.7	0
1.1- 1.9	0.1	4.3- 7.5	0.1	7.7-13.4	0.1
1.9- 2.5	0.2	7.5- 9.7	0.2	13.4-17.3	0.2
2.5- 2.9	0.3	9.7-11.5	0.3	17.3-20.5	0.3
2.9- 3.4	0.4	11.5-13.1	0.4	20.5-23.2	0.4
3.4- 3.7	0.5	13.1-14.5	0.5	23.2-25.7	0.5
3.7- 7	1	14.5-24	1	25.7-43	1
7 - 9	2	24 -32	2	43 -56	2
9 -12	3	32 -39	3	56 -66	3
12 -14	4	39 -45	4	66 -76	4
14 -16	5	45 -51	5	76 -84	5
16 -19	6	51 -57	6	84 -92	6
19 -21	7	57 -63	7	92 -100	7
21 -24	8	63 -68	8	100 -107	8
24 -27	9	68 -74	9	107 -114	9
27 -30	10	74 -80	10	114 -120	10
		80 -86	11	120 -127	11
		86 -91	12	127 -133	12
		91 -97	13	133 -140	13
		97 -104	14	140 -146	14
		104 -110	15	146 -152	15

Prospect ____________ Date ____________

Station # ____________

Surveyor ____________ Computed By ____________

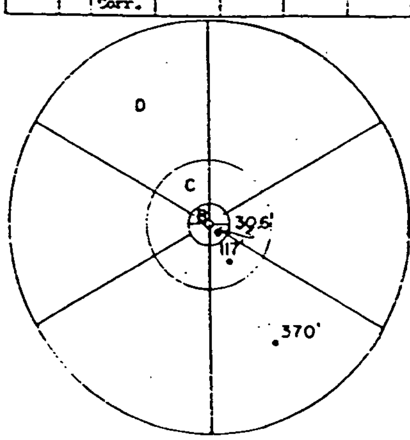
Note: Values are in feet to center of compartment.

EXPL TION SERVICES – GEOPHYSICS DIVISIO

INNER TERRAIN CORRECTION ONLY

Zone		Compartment	1	2	3	4	5	6	Corr. x0.01 Mg.
6.56' to 54.6'	B	Elev. Diff.							
		Corr.							
54.6' to 175'	C	Elev. Diff.							
		Corr.							
175' to 558'	D	Elev Diff.							
		Corr.							

Total Corr.= ________ Mg.



ROCK . SITY = 2.00
INNER TERRAIN CORRECTION TABLES

ZONE B 4 Compartments 6.56' to 54.6'		ZONE C 6 Compartments 54.6' to 175'		ZONE D 6 Compartments 175' to 558'	
±h, ft.	T	±h, ft.	T	±h, ft.	T
0 - 1.1	0	0 - 4.3	0	0 - 7.7	0
1.1- 1.9	0.1	4.3- 7.5	0.1	7.7-13.4	0.1
1.9- 2.5	0.2	7.5- 9.7	0.2	13.4-17.3	0.2
2.5- 2.9	0.3	9.7-11.5	0.3	17.3-20.5	0.3
2.9- 3.4	0.4	11.5-13.1	0.4	20.5-23.2	0.4
3.4- 3.7	0.5	13.1-14.5	0.5	23.2-25.7	0.5
3.7- 7	1	14.5-24	1	25.7-43	1
7 - 9	2	24 -32	2	43 -56	2
9 -12	3	32 -39	3	56 -66	3
12 -14	4	39 -45	4	66 -76	4
14 -16	5	45 -51	5	76 -84	5
16 -19	6	51 -57	6	84 -92	6
19 -21	7	57 -63	7	92 -100	7
21 -24	8	63 -68	8	100 -107	8
24 -27	9	68 -74	9	107 -114	9
27 -30	10	74 -80	10	114 -120	10
		80 -86	11	120 -127	11
		86 -91	12	127 -133	12
		91 -97	13	133 -140	13
		97 -104	14	140 -146	14
		104 -110	15	146 -152	15

Prospect ____________ Date ____________

Station # ____________

Surveyor ____________ Computed By ____________

Note: Values are in feet to center of compartment.

Figure 1. Field computation chart for near-station terrain corrections.

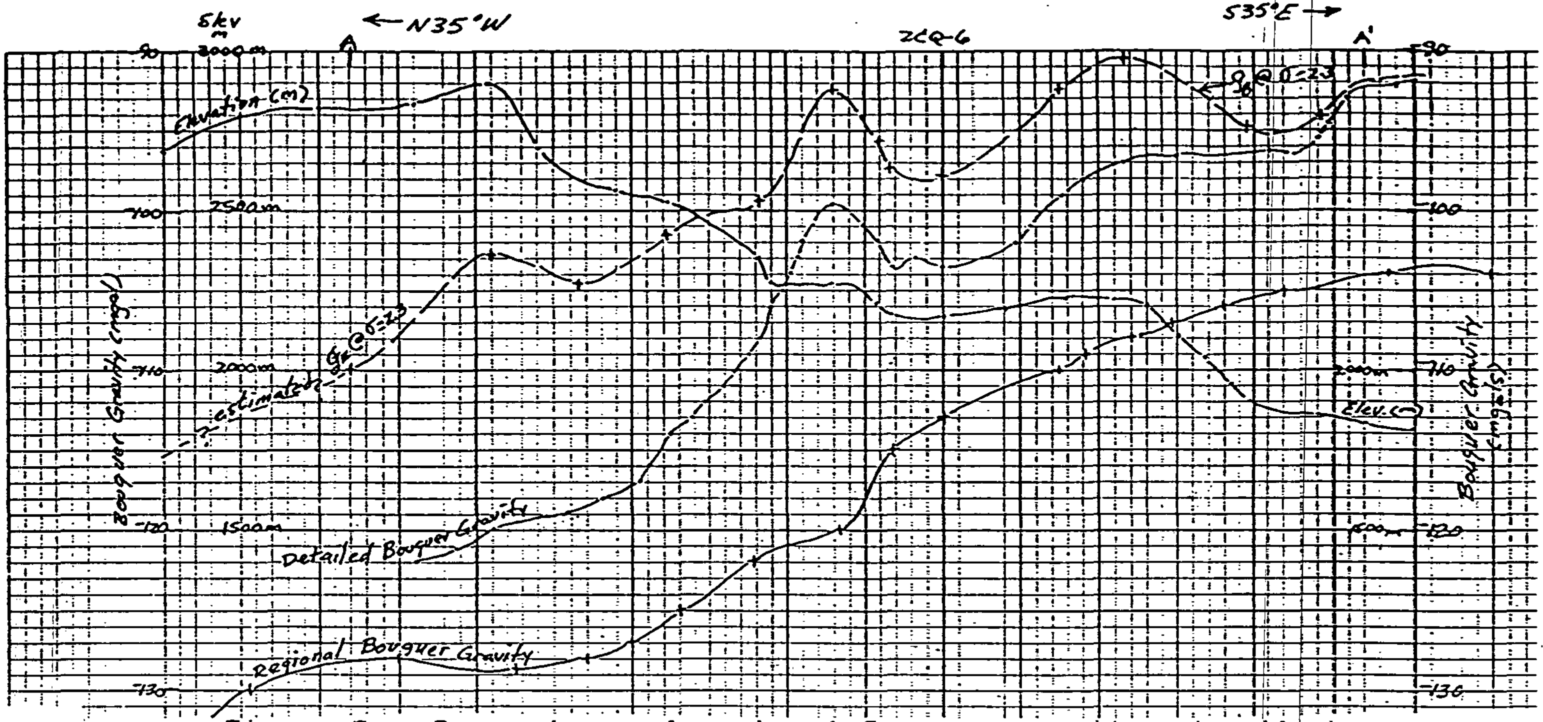


Figure 2. Comparison of regional Bouguer gravity, detailed Bouguer gravity, and surface elevation along profile A-A'. Also shown is the estimatedBouguer gravity for the detailed survey using a density of 2.30 g/cc.

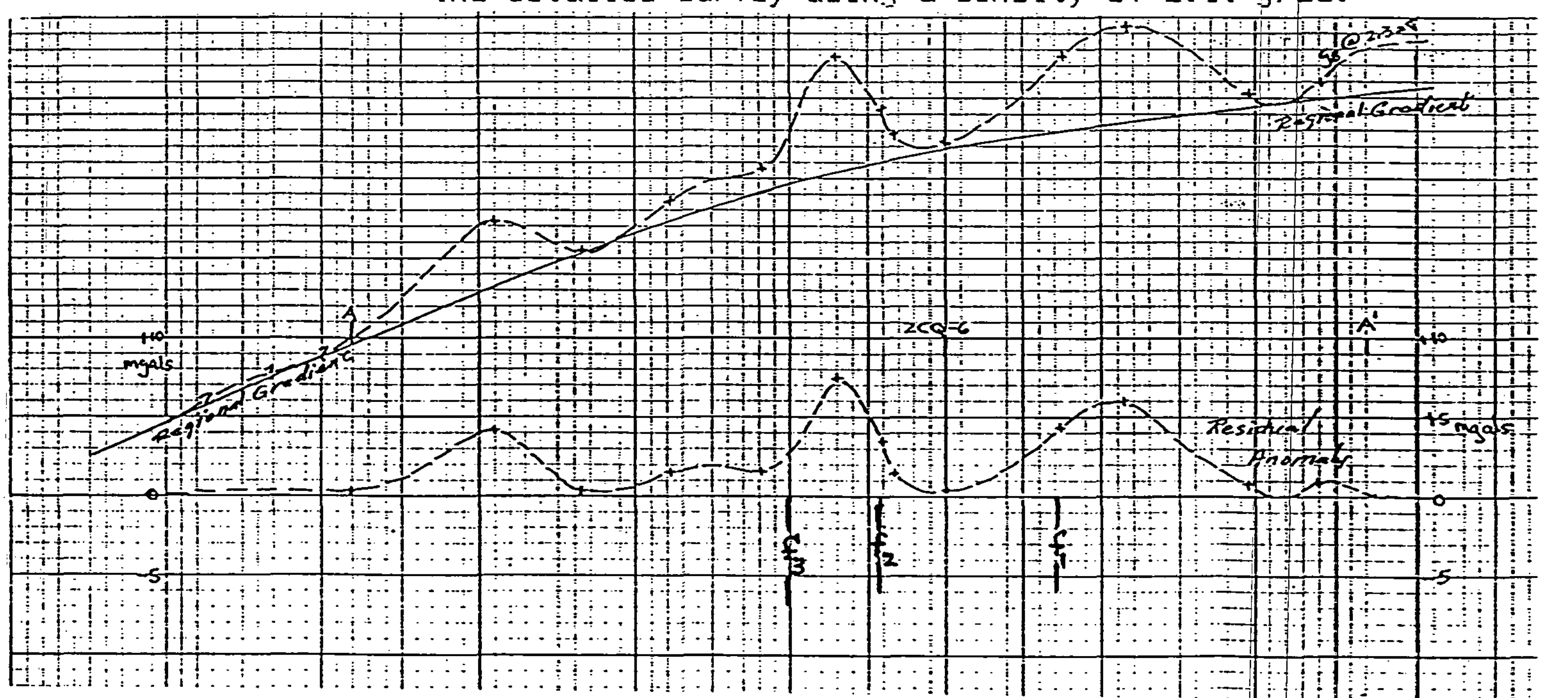


Figure 3. Identification of a regional gradient along profile A-A', and its removal to form a residual anomaly suitable for numerical modeling.

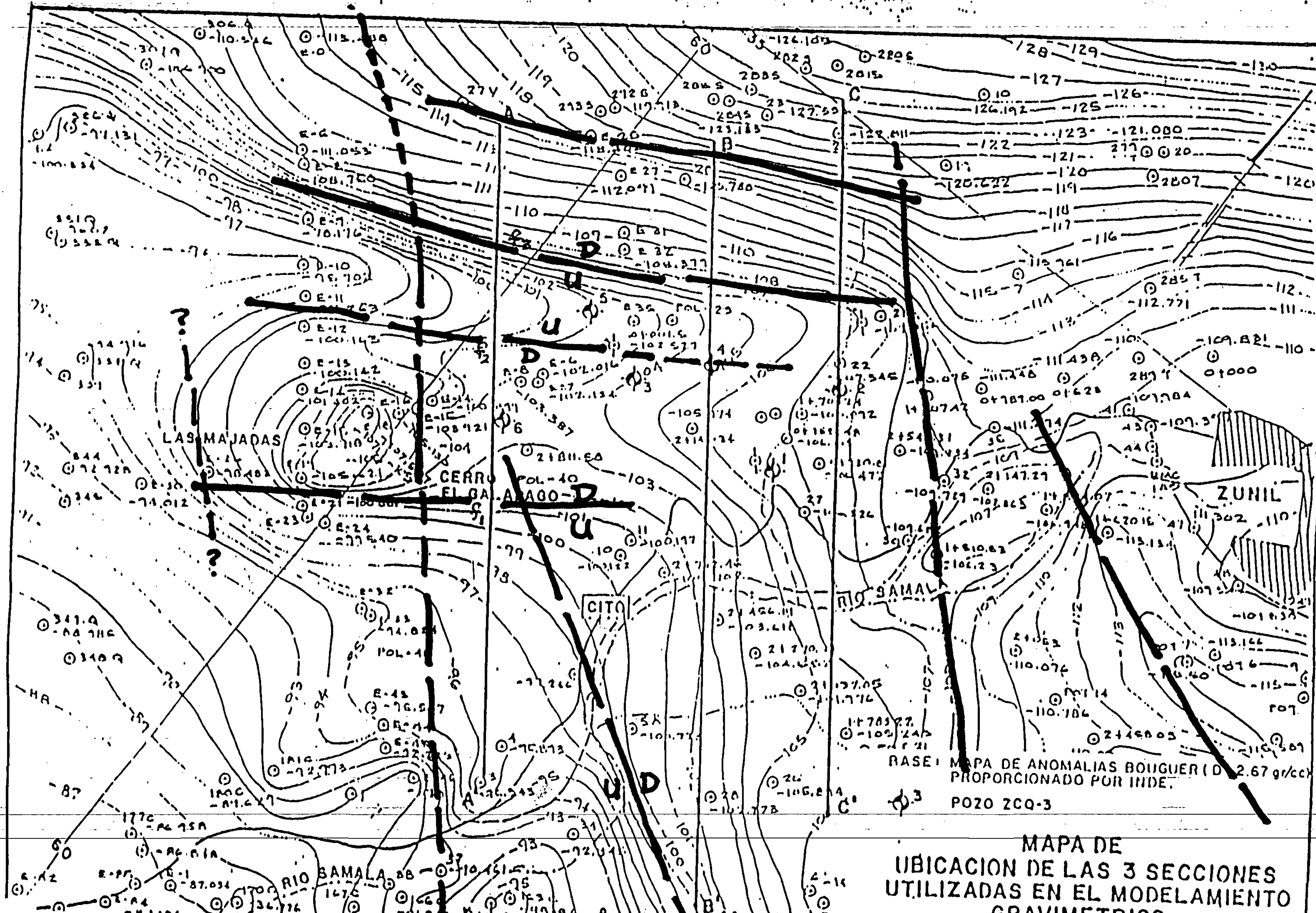


Figure 4. Location of faults in the Zunil 1 area as inferred from the detailed gravity survey. This interpretation has not been supported by numerical modeling.