ZUNIL GRAVITY STUDIES

ZUNIL GEOTHERMAL AREA, GUATEMALA

REVIEW COMMENTS

BY

Howard P. Ross

June 1, 1989

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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:

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

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 = observed g + (tidal + drift corr.) + latitude corr. (2)
+ free air corr. + Bouguer corr. + terrain corr.

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

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

R1

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

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

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.

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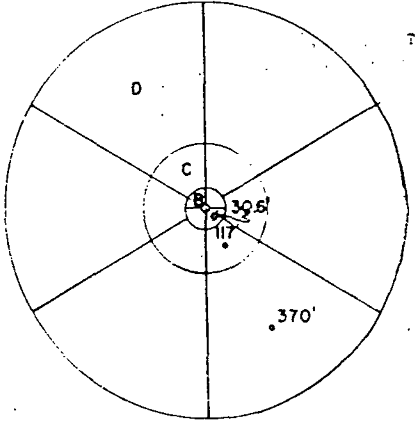
EXPL TION SERVICES – GEOPHYSICS DIVISIO

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 DENSITY = 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 ____________

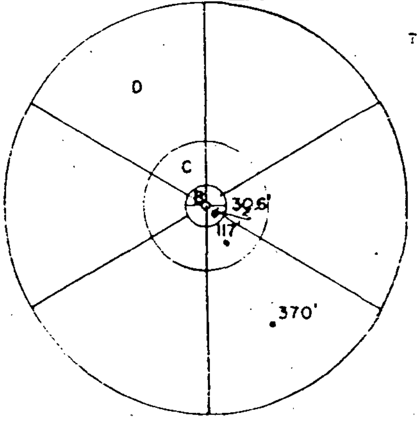
Note: Values are in feet to center of compartment.

EXPL ATION 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 DENSITY = 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.

complex regional gradient with a strong northeast component of -15 mg/3 km (-5mg/km) to the northeast. A simple linear gradient of -5mg/km to N 45 E was judged to be the most certain and least biased regional gradient in the Zunil I area, and this regional gradient was then removed from the 2.30 g/cc detailed survey data. This resulted in a Residual Gravity Anomaly map, Plate II.

The residual gravity anomaly map has been interpreted qualitatively to identify probable structures, and these are compared to structures interpreted earlier. The residual map shows a weak 2 mg positive anomaly which trends N 60 E adjacent to a similar low, suggesting a horst-graben geometry. Northwest trending structures including one near ZCQ-6 can also be inferred.

Numerical Modeling

Numerical modeling of the residual gravity map is now in progress. Most portions of the map show three-dimensional anomaly patterns rather than two-dimensional anomalies. This is especially true in the main area of intrest, near wells ZCQ- 3, -5, -6. The UURI three-dimensional gravity modeling program GME was judged to be most appropriate for modeling these data.

Results to date indicate that most of the anomaly patterns, particularly the higher frequency features, can be attributed to density contrasts between the surface and the granodiorite, i.e. above depths of 800 m. This does not mean that structures are not present in the granodiorite, just that the density contrasts in the overlying volcanics and closer to the gravity meter, are dominant in the gravity data. Preliminary gravity model results are presented here to support these observations.

g/cc. This corresponds to a maximum correction of 11.8 mg for a density of 2.0 g/cc and 13.6 g/cc for a density of 2.30 g/cc. The difference in terrain corrections excedes 3.0 mg (at p=2.30 g/cc) for adjacent stations at several locations. An error of 10 to 30 percent is common in estimating terrain corrections for cases of severe topography, suggesting a possible error level of 1.4 to 4.1 mg from inaccuracies in terrain corrections alone. The contoured data suggest an error level somewhat less than this, perhaps indicating a diligent effort in terrain corrections by INDE.

UURI determined Bouguer corrections and topographic corrections for all stations for densities of 2.20 and 2.30 g/cc, plotted Bouguer anomaly maps, and contoured these maps at 0.5 mg.

Qualitative Interpretation

Bouguer anomaly maps for densities of 2.00, 2.20, and 2.30 g/cc were superimposd over topographic maps at a scale of 1:10,000 and evaluated for topographic correlation. All three maps showed less correlation with topography than the 2.67 g/cc Bouguer Anomaly map, with the 2.00 and 2.20 g/cc maps showing the least correlation.

Geologic structures were interpreted from the steep gradient areas of all three maps. These gradients are thought to arise from subsurface density contrasts along linear features, most probably faults. The high frequency content (i.e. steep gradient and short extent normal to the trend) of most gradients suggest many of the density contrasts occur within 500 m of the surface (and hence above the granodiorite) or result from: a) other near surface density variations, or b) inaccuracies in the data collection and/or reduction.

Structures interpreted from the data are compared for the three Bouguer anomaly maps and summarized on Plate I. The agreeement of structures qualitatively interpreted is rather good. A structure which trends northwest near ZCQ-6 is the most consistantly interpreted structure, and is most likely to extend to considerable depth. Several northeast-trending structures are also indicated on multiple maps. The agreement is best for structures interpreted form the 2.20 and 2.30 g/cc maps. A direction of fault movement is suggested for several faults, assuming that the density contrast results from movement on top of the more dense granodiorite. This sense may disagree with fault directions observed at the surface in volcnic rocks.

Quantitative Interpretation

Inspection of regional Bouguer Gravity maps (at p = 2.00, 2.50, and 2.67 g/cc), and the new detailed data indicate the presence of strong regional gradients in the Zunil I area. The most important northwest-trending gradient on the 2.67 g/cc map is due to the incorrect density reduction. All maps indicate a

Aug '89

PRELIMINARY INTERPRETATION

DETAILED GRAVITY SURVEY, ZUNIL I AREA

Introduction

The UURI study of the 1989 Zunil I detailed gravity data has included several elements including review of INDE Bouguer Gravity maps and principal facts, measurement of densities, computation of the Bouguer Gravity anomaly for densities of 2.20 and 2.30 g/cc, contouring, qualitative interpretation, and numerical modeling. A brief review of the results to date follows.

Density Studies for Bouguer Gravity Data Reduction

Density determinations were completed for Zunil I drill core available at UURI. Saturated densities for seven volcanic rock core samples from drill holes Z-2, Z-11, and ZCQ-2 averaged 2.25 g/cc. The saturated density for a granodiorite (altered) core sample from ZCQ-4 was found to be 2.58 g/cc. These few density values are in good agreement with density values reported by Cordon (1989) in a more extensive density study of core samples from well Z-11.

Also in support of the density study, Bouguer anomaly profiles were calculated for lines 2, 3, 7, and 8 using eight density values ranging from 1.7 to 2.67 g/cc. These profiles were compared to elevation along the profiles following the density determination method of Nettleton. These profiles suggest that densities of 2.1 and 2.2 g/cc result in Bouguer gravity profiles which have the least correlation with topography, and are therefore most appropriate for the densities used in Bouguer and topographic corrections. The Nettleton method is somewhat limited because of three-dimensional effects near the profiles and by subsurface density variations. Regional Bouguer gravity maps for densities of 2.00, 2.50, and 2.67 g/cc were also correlated with topography. The 2.00 and 2.50 density maps showed much less correlation with topography than the 2.67 density map. We conclude, on the basis of this evidence, density measurements, and experience in other volcanic areas, that densities of 2.20 and 2.30 g/cc are most appropriate for Bouguer and topographic corrections for depths to 1000 m in the Zunil I area. A density of 2.0 to 2.1 may be most appropriate for depths of 0 to 300 m.

Bouguer Map Preparation

UURI contoured Bouguer Gravity maps reduced at densities of 2.00 and 2.67 g/cc which were telefaxed to UURI from CyM/MKE. Contouring the maps at 0.5 milligals (mg) allowed identification of questionable data values and provided one indication of the noise level of the data. Review of principal facts provided by INDE reveals numerous topographic corrections exceding 12 mg, and a maximum topographic correction of 15.8 mg for a density of 2.67

serie de perfiles (con una sola densidad, 2.2 por ejemplo) sobre el campo de Zunil I.

Se podría empezar con un modelo de 4 capas :

1. Capa superficial (volcanitas)
2. Capa representativa de las formaciones alteradas (capa conductora de los sondeos eléctricos)
3. Capa andesitica que representa el reservorio
4. Basamento

Siendo la geometría del campo bastante bien conocida se podría intentar (fijando los datos cuantitativos) estudiar las posibilidades de variaciones de las densidades en el interior de cada capa y en modo particular en el basamento.

Este conjunto de perfiles tendría que permitir localizar con más precisión las principales discontinuidades (zonas de mayor fracturación probable) y contribuir a un mejor conocimiento de la estructura de el campo de Zunil I.

3.6 Pruebas de Pozo (P.E. Liguori)

3.6.1 Pruebas de corta duración

Estas pruebas consistieron en poner en producción uno a la vez, durante una semana más o menos, los tres pozos ZCQ-3, 5 y 6 dejándoles descargar libremente el silenciador con posición de válvula fija. Durante la producción se midieron caudales de agua y vapor, se sacaron unos perfiles de presión, temperatura y "spinner" y se tomaron muestras químicas. Antes de terminar la producción se bajó en el pozo un elemento de presión

3.5 Geofísica (A. Duprat)

3.5.1 Gravimetría

En el año 1989 MKF efectuó un estudio gravimétrico de detalle en el campo de Zunil I. Los resultados de este estudio han sido presentados: Anomalía de Bouguer con más densidades, residuales (anomalía regional escogida = plano inclinado) que permitieron trazar las discontinuidades gravimétricas principales para cada una de las densidades. El perfil de Nettleton muestra que la densidad de corrección más conveniente está comprendida entre 1.9 y 2.2.

Un mapa con d = 2.3 ha sido escogido para la interpretación, MKF modeló solamente un perfil con parámetros demasiados sencillos (2 capas con densidad del basamento de 2.6).

3.5.2 Eléctrica

Para lo que concierne el estudio eléctrico, solo se efectuó una diferenciación cualitativa entre sondeos eléctricos: los que han alcanzado un substrato resistivo y los que han alncanzado un substrato conductor.

Se puede sugerir a MKF :

- De establecer cortes eléctricos cuantitativos en los datos de inversión de los sondeos eléctricos. Para cada sondeo que ha alcanzado el substrato resistivo efectuar una prueba de equivalencia para la capa conductora que sobre yace el substrato.
- Utilizando estos datos eléctricos completados, con las informaciones litológicas y cuantitativas de los pozos profundos, de realizar una

This could be started with a model of four layers:

1. Superficial layer (vulcanites)
2. A layer representative of the altered formations (conductive layer of the electrical probes
3. Andesitic layer which represents the reservoir
4. Basement.

Since the geometry of the field is fairly well known, an attempt could be made (fixing the quantitative data) to study the possibilities of variations in the densities on the interior of each layer and particularly in the basement.

This set of profiles would have to make it possible to locate more precisely the main discontinuities (zones of greater probably fracture) and contribute to better knowledge of the structure of the field of Zunil I.

3.6 Well Tests (P. E. Liguori)

3.6.1 Short Duration Tests

These tests consisted in placing into production, one at a time, for one week more or less, the three wells ZCQ-3, 5 and 6, allowing them to discharge the muffler freely with fixed valve position. During production, the rate of flow of water and steam was measured, and profiles of pressure, temperature and "spinner" were made and chemical samples were taken. Before production was shut down, a pressure element was lowered into the well and, when the well was closed, a limited build-up test was performed on wells ZCQ 3 and 5. The data were presented in a well organized fashioned and are sufficiently clear to interpret the results of the tests even if these are not amply described.

Results of 2nd Panel meeting

IDEM JOB NO. 89-10-123

3.5 Geophysics (A. Duprat)

3.5.1 Gravimetrics

In 1989, MKF carried out a detailed gravimetric study in the field of Zunil I. The results of this study were presented: Bouguer Anomaly with greater densities, residuals (regional selected anomaly - inclined plane) which made it possible to trade the main gravimetric discontinuities for each of the densities. The Nettleton Profile shows that the correction density most appropriate is between 1.9 and 2.2

A map with d = 2.3 was chosen for the interpretation; MFK modeled only one profile with parameters which were too simple (2 layers with a basement density of 2.6).

3.5.2 Electric

With respect to the electric study, only a qualitative differentiation was made between electrical probes; those which reached a resistant substratum and those which reached a conducting substratum.

The following can be suggested to MKF:

- To establish quantitative electrical cuts in the inversion data of the electrical probes. For each probe which reached a resistant substratum, carry out an equivalence test for the conducting layer which rests upon the substratum.

- Using these complete electrical data, with lithological and quantitative data of the deep wells, to carry out a series of profiles (with one single density, 2.2, for example) on the field of Zunil I.

With the help of the models, considering the geometry of the geological sections and the various densities elected, it is possible to calculate a theoretical curve identical as the measured curve.

If this happened, it will mean that the graben effect is enough to explain the anomaly. If this does not happen, it will be necessary to identify which modifications give the densities (without modifying the geometry) to reproduce the measured curve. This is a short term job, that can be done with a microprocessor and an interactive program.

c) Electrical Resistivity

The information indicated in the Mision de Enfoque report are purely qualitative. The conductive anomalies are enhanced, considered as the representatives of the most favorable zones. The cause of these anomalies is not univocal. These are caused by the seal cap behavior: relatively developed alteration, clay presence, temperature, salted fluid. The resistivity of the granodiorites, even though they are fractured and with a hotter fluid, it will always be higher than the sealed cap altered, this is the reason why the analysis of these anomalies does not give any information about the basement nature. Therefore it seems very important to make a quantitative interpretation of all the electrical soundings with the objective of giving a structural outline of the studied zone. This interpretation appears in the INDE

- Or if, to the contrary, considering that the density of the recent formations is constant, there will be no need to identify another cause for this anomaly, like: density variation in the covering or in the basement, producing a little decrease, that could be explained by a fissure a little more developed in some part of the basement.

It is clear that these are hypothesis that can be proved by a series of modelings; three perpendicular profiles to the graben could be drawn that cut it in the ZCQ-6 and ZCQ-4 well zones. The height of the coverages and the tectonics of the granodiorite ceilings will be deduced from the wells.

Therefore three geological sections, assigning densities to the different formations evidenced by the wells (and the electrical soundings) could be done. This can be scheduled as follows:

- Upper level with high density (e.x. d=2.6)
- Intermediate level, with lower density (e.x., d=2.4)
- Granodioritic basement (e.x., d=2.65)

This density values are indicative. Measurement on samples taken from the wells will permit its better definition.

- Two discontinuities in the NE-SW that bound the positive sector where ZCQ-5 is located.
- One discontinuity parallel to the above mentioned passing to the E of Cerro El Galapago.
- Between this discontinuities develops the little negative anomaly ending to the SW beyond Cerro El Galapago. This last shows as a negative circular anomaly strongly pronounced and that can be disassociated from the general anomaly. The reason of this anomaly is probably that Cerro El Galapago represents a high fractured block with a possible high water content (surface infiltrations). The existence of a discontinuity in the E-W could be imagined that goes through between the ZCQ-6 well and Cerro El Galapago.

From the qualitative point of view, the information given by the gravimetry in the deep well sector is very good according to the structural geology as it can be deducted from the wells. This enhances a fault between wells ZCQ-5 and ZCQ-3, 4 marked by a little gravimetric gradient.

However the terciary and cuaternary covering is practically the same for ZCQ-3, 4, 5 (920 - 950 m.) wells, therefore we can question:

- If the negative anomaly that goes through ZCQ-6 well to ZCQ-1 is totally caused by the graben effect.

Jan 17, 90

ZUNIL

~~MK - SOW with INDE~~ re Results of 1st Panel meeting

It could be possible to think that re-elaborating the seismical data will allow obtaining better quality sections, clean of all noises and with better continuity in the seismical levels. At the actual state of the development of the Zunil I studies and considering the location of the seismic profiles (none of them is important in the deep soundings ZCQ-3,-4-5-6), it seems that re-elaborating these data is not justified. In fact the zone actually considered interesting is in the ZCQ-3 and ZCQ-6 sector. On the other hand, this task could be useful in the Zunil II study.

b) Gravimetry: Various maps present the Bouger anomaly (d=2.0, 2.5, 2.67 and 3.0); this maps cover a bigger extension of the zone actually considered of interest for Zunil I. The map with more contrasts is the one with 2.67 density where the deeper soundings is particularly characterized. This zone is presented as a little negative anomaly oriented SW-NE, limited in the NW and SE by a small positive gradient. Towards the NW a high negative gradient is enhanced by the density value elected. The gradient is notably lower in the map with d=2.5.

Limiting to the interest zone, particularly represented by the deep sounding sector, the map with d=2.67 evidences:

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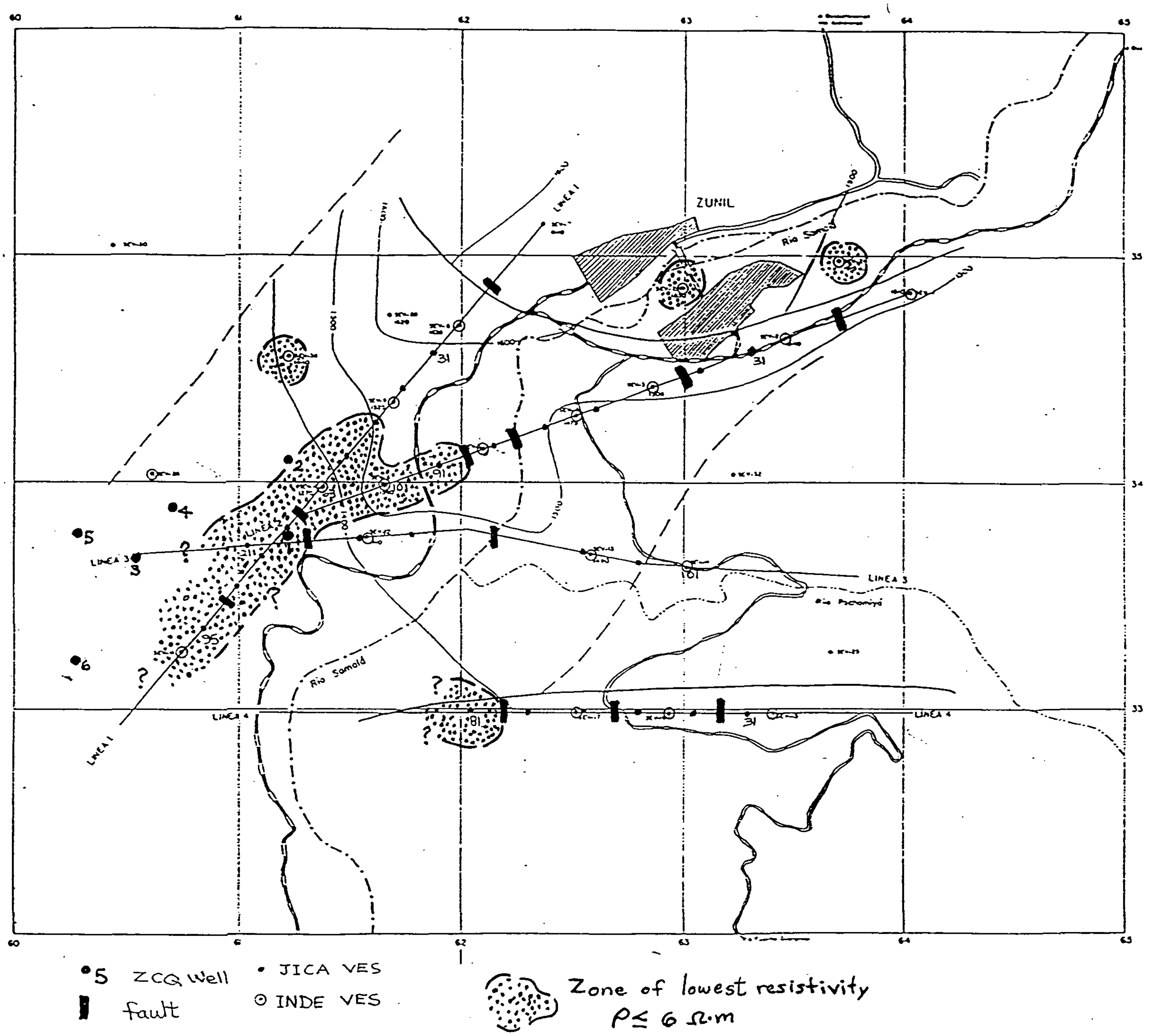

Figure 4. Summary of INDE and JICA electrical resistivity results, Zunil area.

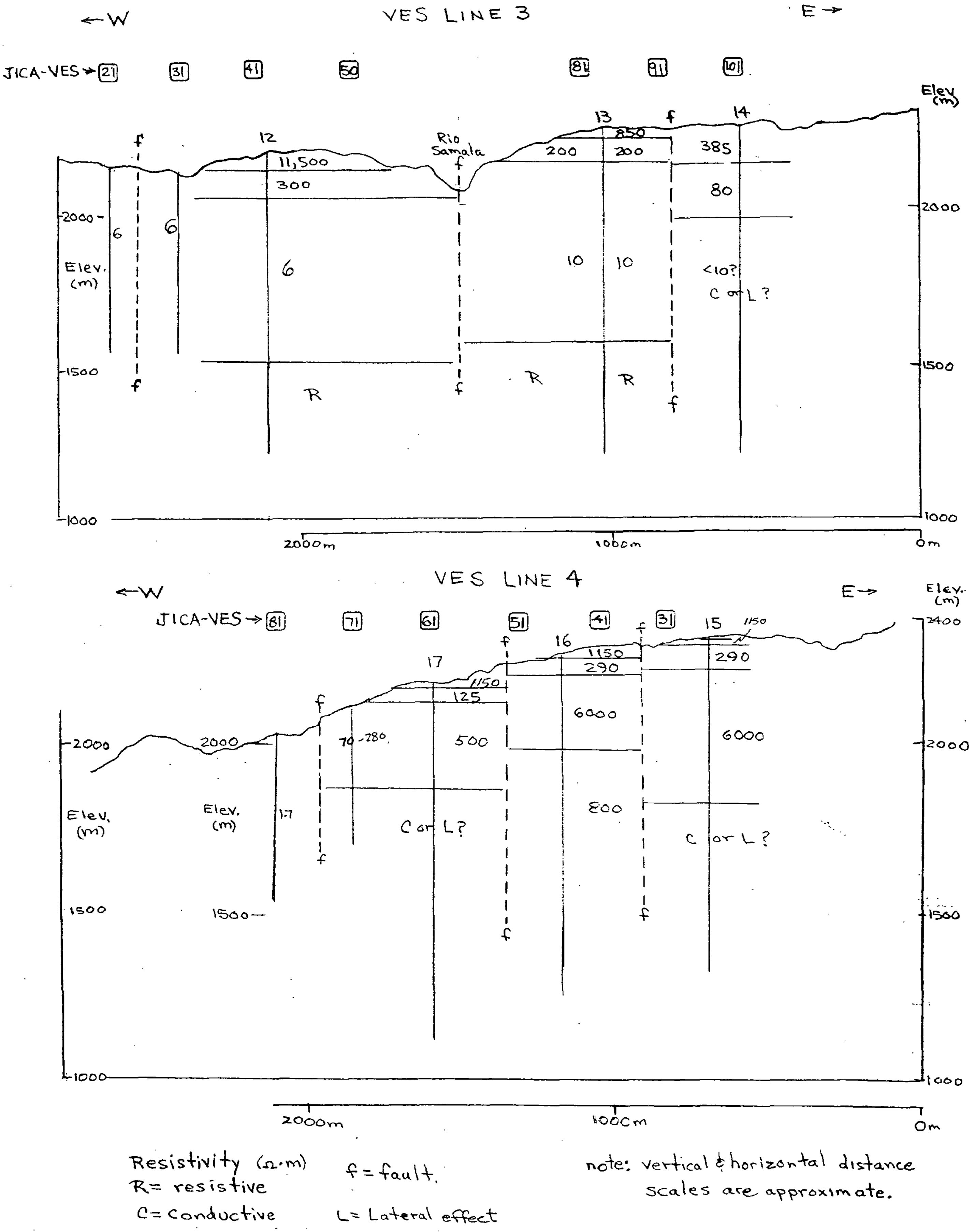

Figure 3. Electrical resistivity cross sections for INDE VES Lines 3 and 4. Corresponding JICA VES sounding locations are indicated.

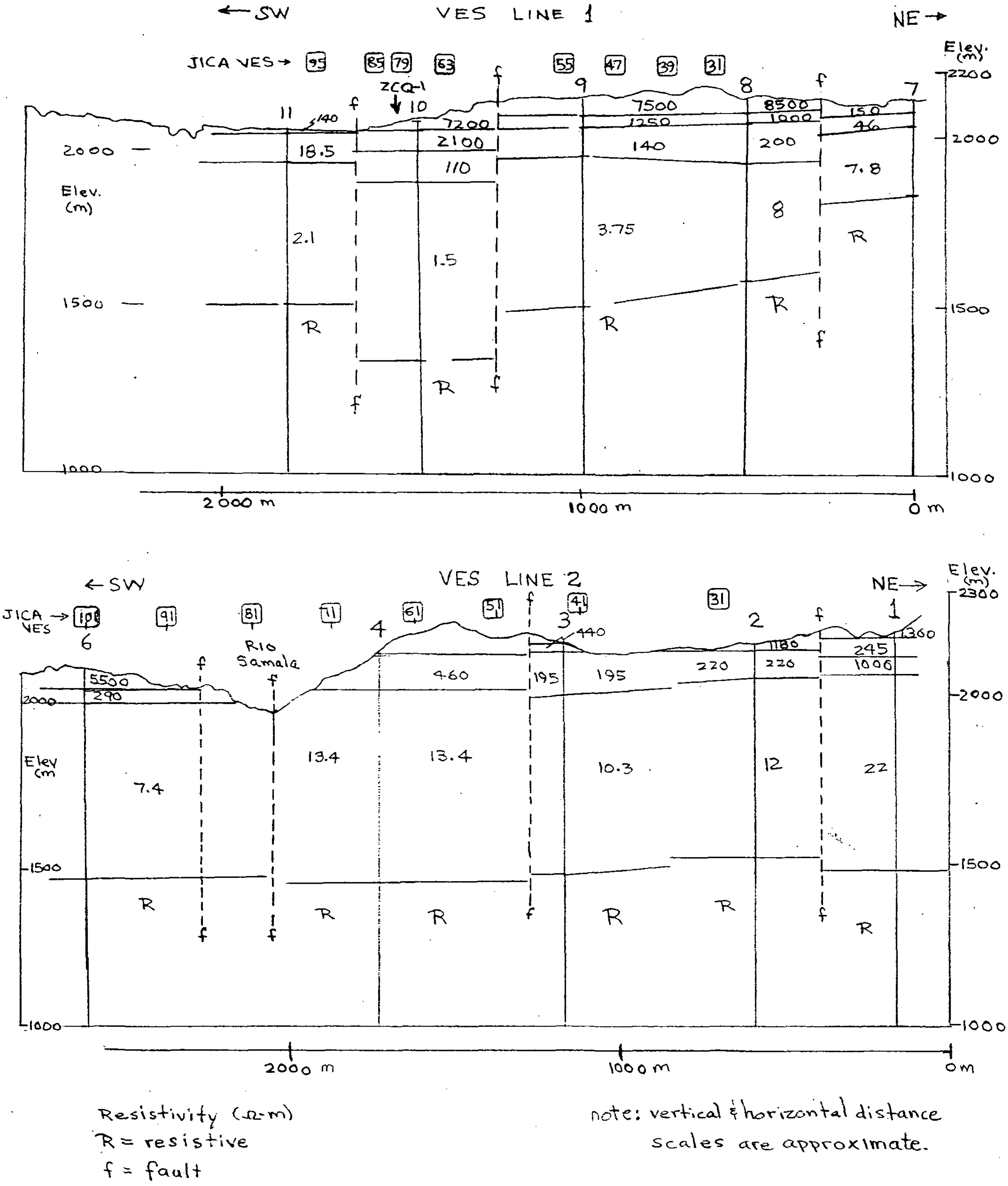

Figure 2. Electrical resistivity cross sections for INDE VES Lines 1 and 2. Corresponding JICA VES sounding locations are indicated.

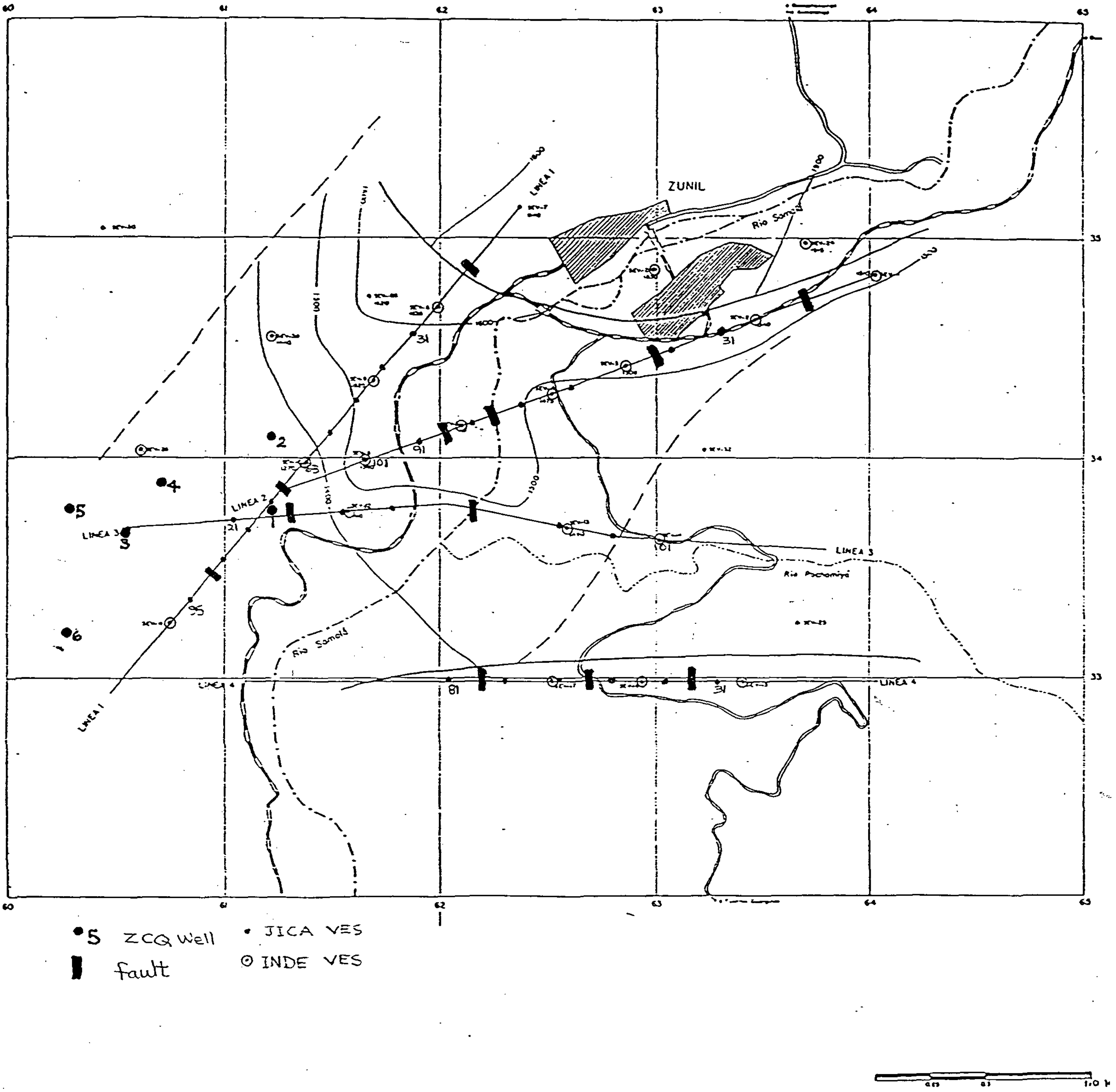

Figure 1. Location of JICA and INDE Schlumberger vertical electric soundings (VES).

This review has not yielded new data or interpretative results, but does provide familiarity with and confidence in the JICA and INDE work completed several years ago. The resistivity data suggest that the least-diluted thermal fluids are transmitted along structures near the western limit of the survey area, near the ZCQ wells. The locations of faults inferred from the data should be integrated with other information to improve the understanding of faulting and permeability in the area.

It is possible that additional electrical resistivity work would aid in better delineation of fractures in the area of the ZCQ wells. Two or three dipole-dipole lines which trend roughly northeast parallel to Line 1, using an electrode separation of 200 m, would map resistivity structure to depths of 400-500 m and would probably detect major fault offsets and zones of upwelling thermal fluids. The dipole-dipole array would be compatible with the terrain northeast of ZCQ-6 and most topographic effects could be accounted for in the numerical model interpretation of the data.

References

CyM/MKF, 1988, Summary of Zunil exploration data and results (title unknown), CyM/MKF Tech. rept. to INDE.

Palma Ayala, J. C., 1977, Proyecto Zunil estudio de factibilidad preliminar - informe geoelectrico, Septiembre, 39 p.

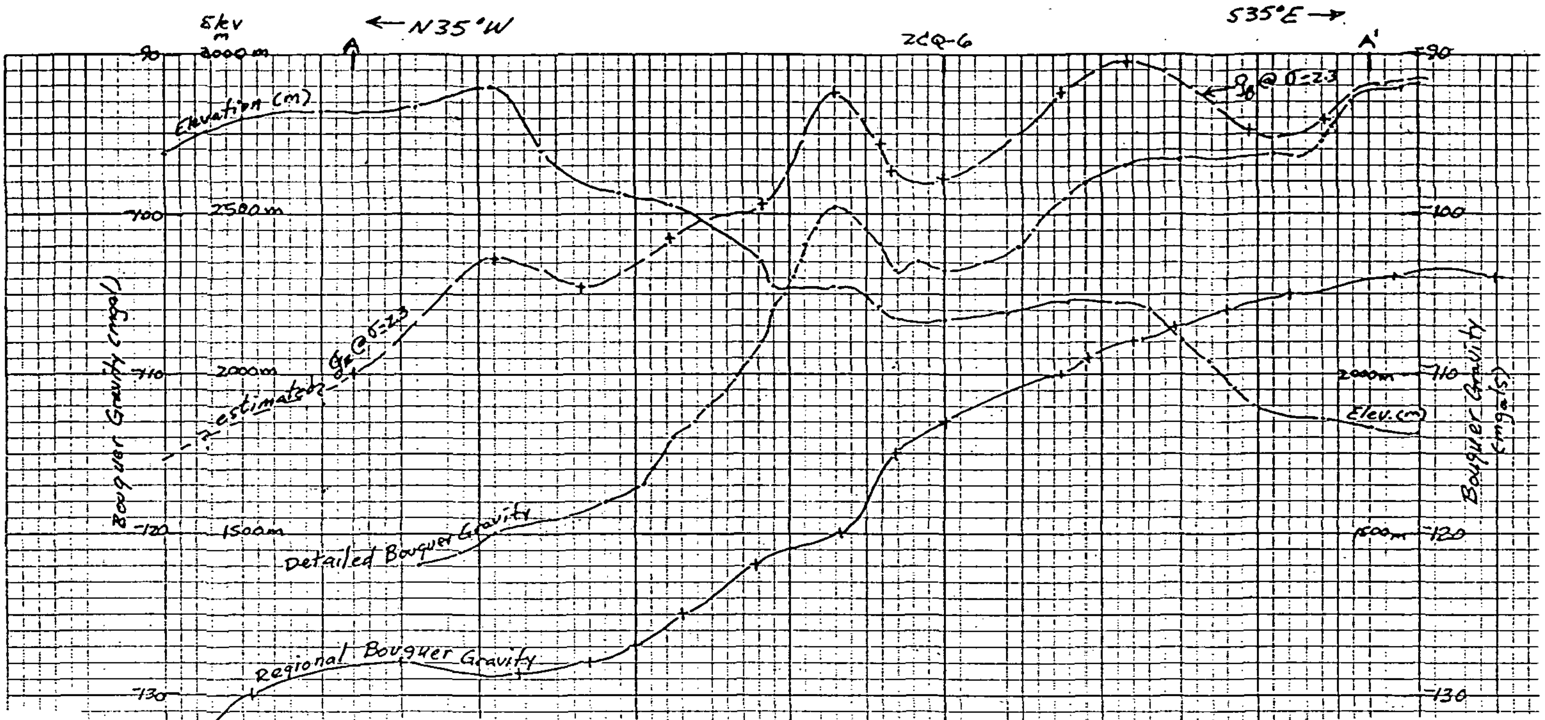

Figure **2**. Comparison of regional Bouguer gravity, detailed Bouguer gravity, and surface elevation along profile A-A'. Also shown is the estimatedBouguer gravity for the detailed survey using a density of 2.30 g/cc.

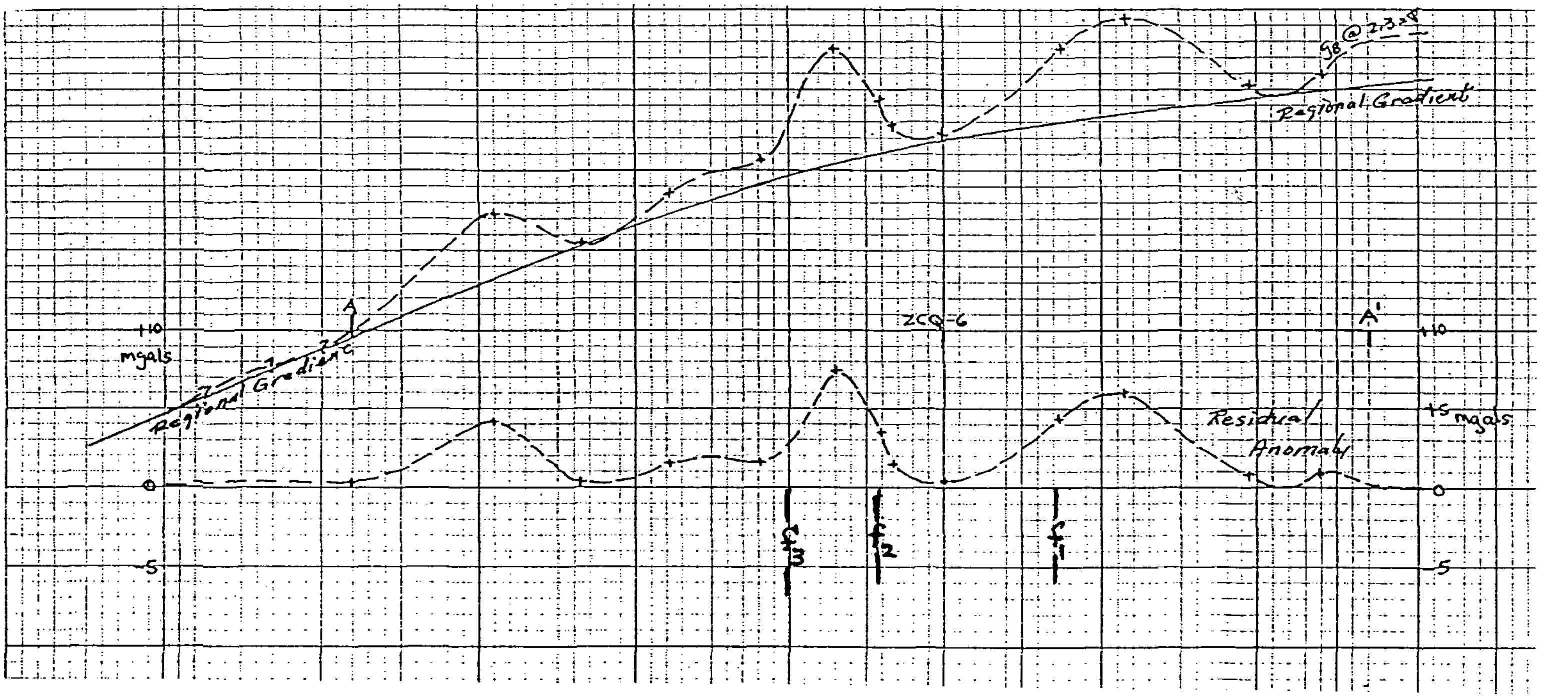

Figure **3**. Identification of a regional gradient along profile A-A', and its removal to form a residual anomaly suitable for numerical modeling.

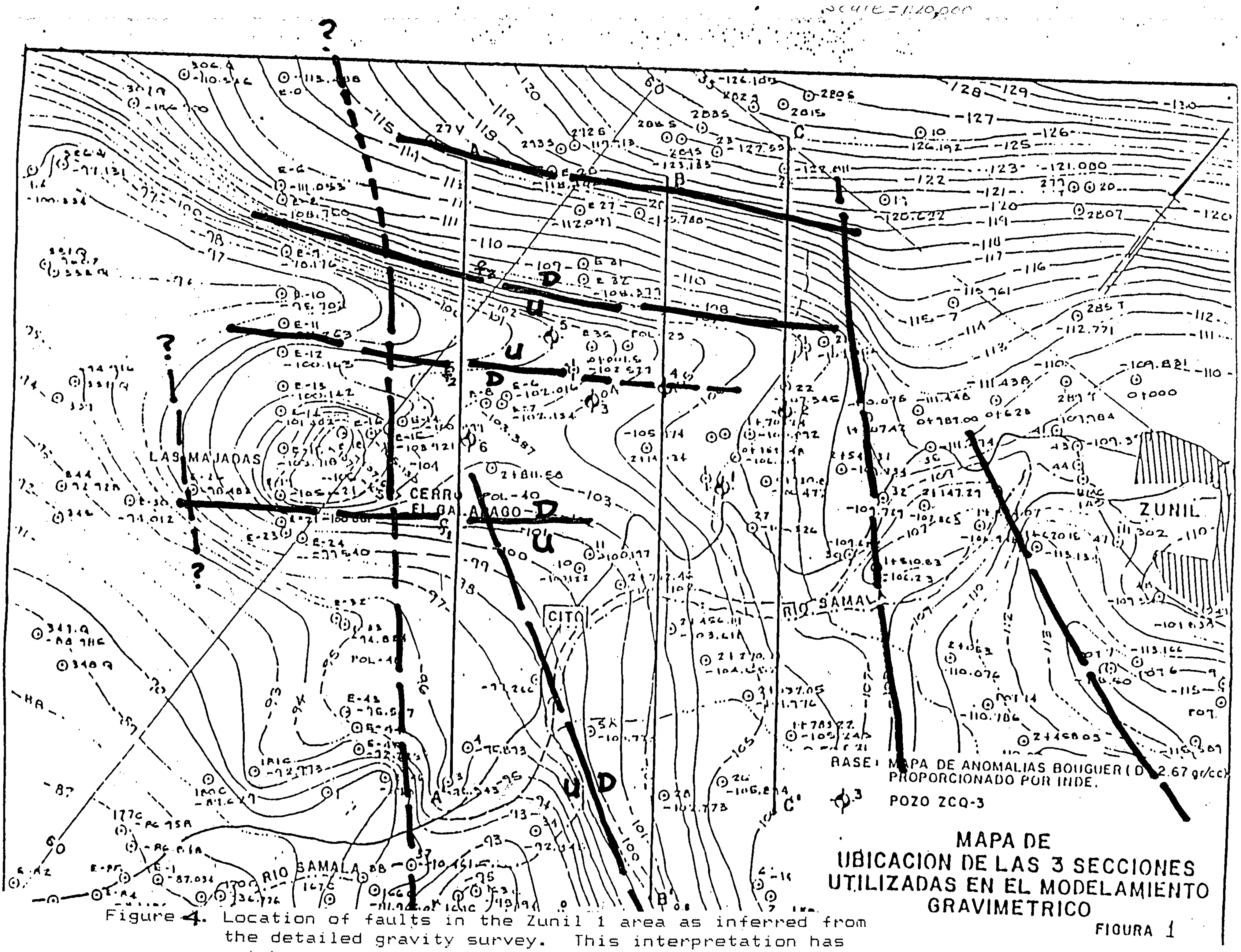

Figure 4. Location of faults in the Zunil 1 area as inferred from the detailed gravity survey. This interpretation has not been supported by numerical modeling.

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ZUNIL ELECTRICAL RESISTIVITY STUDIES
ZUNIL GEOTHERMAL AREA, GUATEMALA

REVIEW COMMENTS

by

Howard P. Ross

June 1, 1989

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ZUNIL ELECTRICAL RESISTIVITY STUDIES
ZUNIL GEOTHERMAL AREA, GUATEMALA

Review Comments

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June 1, 1989

ZUNIL ELECTRICAL RESISTIVITY STUDIES

Introduction

Electrical resistivity surveys completed earlier have been reviewed in support of the CyM/MKF Zunil I project. It appears that two electrical resistivity surveys have been completed in the Zunil I area, both of which employed the Schlumberger array to complete vertical electric soundings (VES). The first survey was completed by Japanese scientists (JICA) in 1976-77 and the second survey by INDE in 1977.

JICA Survey

The JICA data were obtained as a series of VES stations with centers at intervals between 150 m and 250 m along Lines 1, 2, 3 and 4. All of these station centers are located north and east of the area which includes wells ZCQ-3, -4, -5, -6 and are generally south and west of the town of Zunil (CyM/MKF, 1988). Difficult terrain conditions precluded the extension of the VES soundings to the southwest. The maximum depth probed by the JICA soundings was limited by the AB/2 distance of 750 m. The data were presented in map and block diagram form (CyM/MKF Figs. 3.3-20, 3.3-21) but individual VES plots were not available for review. The locations of JICA and INDE VES station centers are shown on Figure 1.

INDE Survey

The INDE survey (Palma A., 1977) included 17 soundings along Lines 1, 2, 3, and 4 and approximately 18 additional soundings, using AB separations of 1,000 m, 1,600 m, and 2,000 m. A notable result of this work was the delineation of a low resistivity zone at depths approaching 100 m in the area of wells ZCQ-1 and ZCQ-2, which extends to the southwest. The INDE data are reported in much more detail by Palma A.,(1977) who includes VES plots of resistivity versus AB/2 as well as final interpretative results.

INDE Resistivity Interpretation

Most of the INDE VES plots indicate good data and a reasonably layered resistivity structure which is important to the correct interpretation of the VES data. INDE completed both qualitative and quantitative interpretations. The quantitative interpretation of individual soundings appears to have been completed using graphical and curve matching techniques. The interpretations appear valid and no attempt was made to verify or reinterpret these sounding plots. This could be done using the UURI Schlumberger inversion computer program if the additional effort was justified. Using the INDE resistivity-thickness solutions, resistivity cross sections were plotted for Profiles 1, 2, 3, and 4. These sections are similar to those completed by INDE (which were not readable in the copied document).

The resistivity cross sections are shown in Figures 2 and 3, with the positions of JICA stations incicated for reference. While these stations are in general agreement with the resistivity-depth diagram from the JICA data (CyM/MKF Fig 3.3-21) some differences were noted. The INDE data with the larger AB/2 respond to a resistive layer not seen by JICA on Line 1. The depth to the top of the conductive layer and it's interpreted resistivity often differ between the two surveys. On Line 1, JICA resistivities of 6.5, 5.6, and 8-14 ohm-m contrast with INDE values of 2.1, 1.5, and 3.75 ohm-m for VES 11, 10, and 9 respectively. On Line 2, JICA data show resistivity values of 5-6 ohm-m compared to 7.4 and 13.6 ohm-m interpreted by INDE. The shorter distances between stations of the JICA data provide some additional detail and therefore more indications of faulting. Without the detailed resistivity versus depth plots of the JICA soundings they cannot be evaluated in detail. The JICA VES results are used to supplement the interpretation of the INDE data.

Figure 4 summarizes the principal results of the INDE and JICA resistivity data. Discontinuities betwen resistivity layers are interpreted as faults on Figures 2 and 3, and these have been transfered to Figure 4. Unfortunately most of this information is east of the portions of the reservoir tested by ZCQ-3, -4, -5, and -6, due to the steep topography in the area which has been drilled. Projection of the interpreted faults to the northwest is of current exploration interest however. Since the position of the discontinuity can only be estimated between adjacent VES centers, the trend and continuity of the structures must be inferred from geologic and topographic information.

Several soundings indicate very low resistivities (1-6 ohm-m) in the conductive layer. These include VES 11, 10, and 9 on Line 1; the area between VES 6 and 4 on Line 2; west of VES 12 on Line 3, from JICA stations 21 and 31; and JICA station 81 on the west end of Line 4. These areas are important because the low resistivities may indicate hot, relatively undiluted reservoir fluids circulating near faults, and/or increased clay alteration resulting from geothermal fluids. These areas are shown on Figure 4.

Summary

Experience in geothermal areas throughout the world indicates that electrical resistivity surveys will not delineate all faults and fractures which may be of interest. The detection of these structures requires a significant physical property contrast, perhaps in the form of a vertical offset along a fault. The survey type and resolution are also important factors. Discontinuities which are interpreted as faults are often major structures important as structural controls to the geothermal system, or as fluid conduits. Discontinuities interpreted as faults are often several structures which cannot be resolved by the observed data.

MEMORANDUM

TO: Joe Moore

FROM: Howard Ross

DATE: July 21, 1989

SUBJECT: Zunil Gravity Interpretation

This week I received from Luis Merida Bouguer Gravity data for the new gravity survey at Zunil. One map was reduced with a density of p = 2.00 g/cc for the Bouguer correction, the other with a density of p = 2.67 g/cc. Both data sets had been corrected for topography, but the density used for the terrain corrections was not indicated.

I have contoured both data sets in an approximate (quick interpolation) manner, and then recontoured the 2.00 g/cc data at 0.5 mg using careful interpolation. For the most part the data contour quite smoothly, suggesting an excellant job of data acquisition, survey elevation and terrain corrections. One value (-104.314 mg, middle of Line 6) could be incorrect and the corrections should be checked. The same station appears normal on the 2.00 g/cc map however.

BOuguer Gravity at 2.67 g/cc

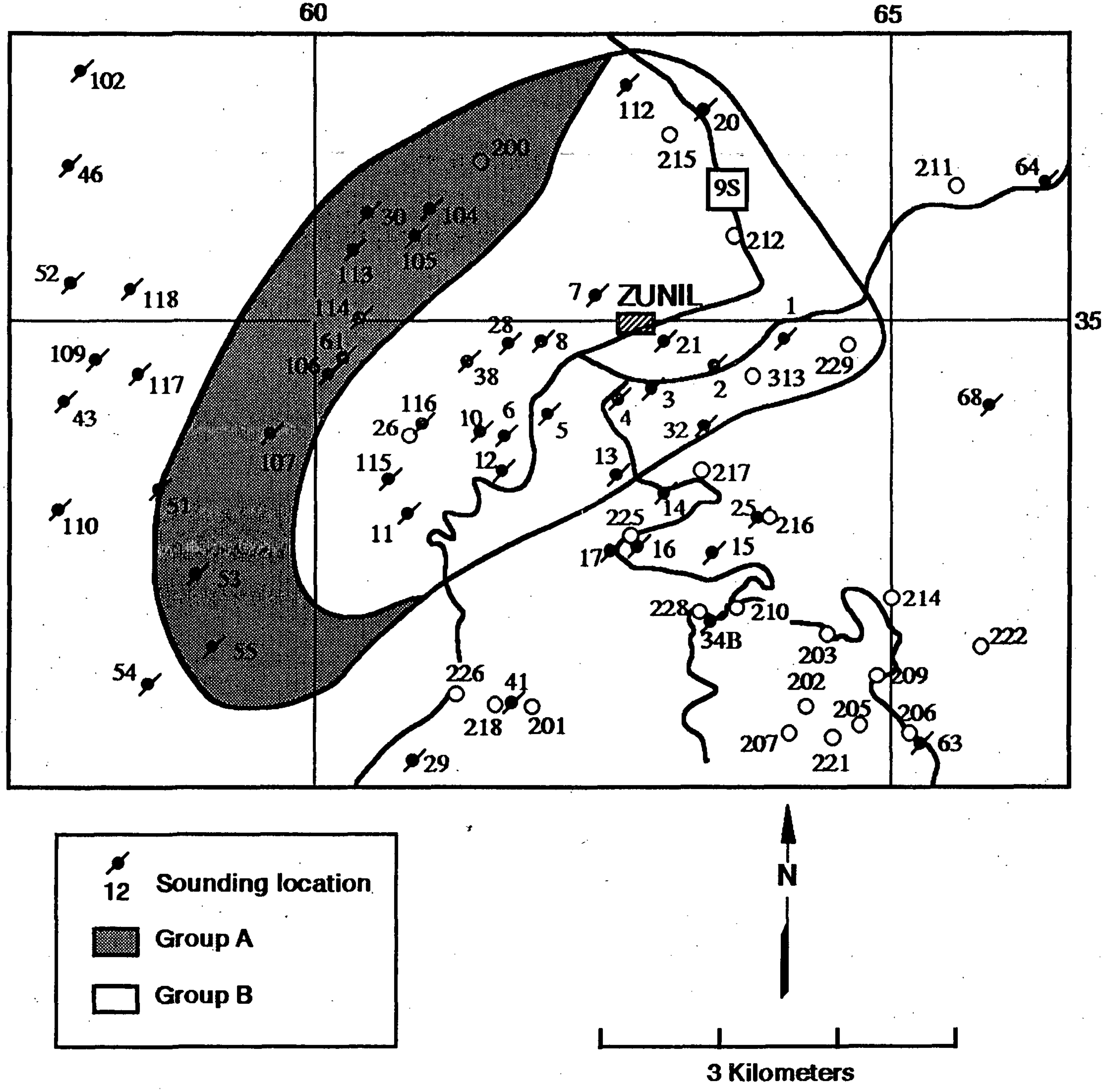
This map shows a strong correlation between higher topographic elevation and increasingly negative gravity values, and an elongate gravity high corresponding to the low topography of the Rio Samala valley. The close correspondence of the contours indicate too high a density (at 2.67 g/cc) was used in the Bouguer (and topographic ?) corrections. This correspondence dominates the map and obscures the gravity indications of buried structures. A few indications of structure may be present when the gravity contours cut across topography (see map). Note that these features are only a few milligals and are nearly lost in the regional trends.

Bouguer Gravity at 2.00 g/cc

The Bouguer Gravity values for this reduction differ by about 55 mg from the 2.67g/cc map, clearly illustrating the importnce of using the correct density in Bouguer and terrain corrections. The correlation between gravity and topographic contours is much weaker than for the 2.67 g/cc map, but a positive correlation (topo high, gravity high) is present in the west, northwest, and southeast portions of the survey. This suggests that the 2.00 g/cc is too low a density, but this map is much more meaningful than the 2.67 g/cc map. Gravity indications of a northeast trending graben-horst structure are very weak, if present at all. This agrees with preliminary numerical modeling which suggests only 1-3 mg anomaly for a Zunil graben structure, using drill hole depths as control. A northwest-trending structure may be indicated along Line 6, but this gravity gradient is due in part to the 2.00 g/cc density used. There is only a weak suggestion (0-1 mg) of northeast-trending structures, in marked contrast to the earlier data presented by INDE and modeled by Cordon.

Discussion

The gravity expression of northeast-trending structures is very weak, 0-3 mg, and previous interpretations should be disregarded unless the older data can somehow be verified. I still believe that a density of 2.30 may be optimum for Bouguer and terrain corrections, and recommend that the data be reduced with this density for comparison with the 2.00 and 2.67 g/cc maps. The corrections should be checked for all gravity values which result in major pertubations of the contours, for the gravity expression of most structures is weak. Numerical modeling of these data is not warranted until we are certain that we have the best possible Bouguer Gravity map. It may be that the gravity data will offer little new structural information for use in drill hole siting.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4.4 Stable Isotope Studies

Stable isotope studies (oxigen-18, deuterium) will be carried out on selected samples of fluids and rocks. The primary objective of the fluid analyses is to determine the location of the recharge zones. Samples of the production fluids, thermal and non-thermal springs will be obtained. (See Geohydrology - Geochemical Sampling Plan). Data from the non-thermal springs (or local precipitation) will be used to construct a local meteoric water line. The thermal waters will be compared to the meteoric oxygen-deuterium relationships to establish the elevation of the recharge zones, the relative extent of interaction with the reservoir rocks, and the importance of boiling, mixing, based on the results of the alteration studies. Rock samples will be selected for stable isotope analysis. If appropriate, samples of unaltered and altered rocks produced by the geothermal fluids will also be selected. From these data, the isotopic composition of the fluids, and data on the temperatures of alteration the integrated fluid flux through the system will be estimated.

4.5 Geophysical Studies

4.5.1 Electrical Resistivity

4.5.1.1 Methods

Electrical surveys by JICA and INDE, (1976-77) consisted of Schulumberger arrays and were conducted in the area of Zunil I southwest of the village of Zunil. Several resistivity anomalies were observed. These could be due to clay alteration, the presence of saline fluids differences in rock lithologies. As a result a quantitative interpretation of the existing electrical soundings has been recommended. The objective of this interpretation will be to provide a better structural outline of the area covered by the electrical resistivity surveys.

4.5.1.2 Result

The quantitative interpretation of the existing electrical data will be designed towards producing a resistive substrate ceiling map. The map should show the substrate ceiling near the granodiorite ceiling and may indicate more exact information on the location of principal discontinuities which relate to the granodiorite basement.

4.5.2 Gravity Modeling

4.5.2.1 Methods

Modeling of the Zunil I area using existing data has been recommended by the Advisory Panel to better define the subsurface structure beneath the Zunil ZCQ well field. The modeling will use formation densities as represented from the different formations. The densities recommended are as follows:

- upper level with and high density (d=2.6) 2.2-2.3?
- intermediate level with a lower density (d=2.4)
- Granodiorite basement (d=2.65)

The above density values are indicative of typical volcanic granodiorite rocks. Measurements of densities from borehole samples should be used to refine the above suggested values. The modeling should use actual densities taken from borehole samples. The model selected to be used is the MAGIX gravity forward and inverse model for personal computers. The model is a real time interactive interpretation program which uses an interactive graphically oriented earth model editor in conjunction with the real-time calculation and display of the forward response curve. As the earth model is varied on the screen, the forward response curve for the new model is calculated and displayed on the screen automatically. Forward modeling the MAGIX model provides a synthetic gravity curve up to 9 bodies with a total of 80 vertices spread among the bodies. Each body is calculated from published Talwani-style polygon algorithms with the density specified in terms of density contrast. MAGIX will provide inverse solutions from a starting model within the same parameters as mentioned above. The user can fix parameters of the body he wishes to remain unchanged. The Imman style inversion routine contained in the program will vary the other parameters to obtain the least squares fit. The parameters of a body that are variable include its vertices and physical property.

In normal operation the best fit to the observed data would be obtained using the interactive forward model then optimize the model parameters using the inverse solution features. Output is in the form of graphics with the operator setting the dimensions of the plot. The screen display is generally used for review prior to plotting the output.

4.5.2.2 Result

With the modeling, considering the geometry of the sections and densities used, a theoretical curve will be calculated which can be compared to the measured curve. This will allow a better interpretation of the anomaly which is presently interpreted as the Zunil Graben.

These cross sections will be generated as a result of the modeling. These cross sections will be perpendicular to the Zunil Graben and go through the ZCQ-4 and ZCQ-6 well zones. The granodiorite contact, amount of overlying volcanics and tectonic nature of the top of the granodiorite will be deduced from the existing ZCQ well data for input into the interpretation.

4.5.3 Detailed Gravity Survey

The following information provides overall guidelines for a detailed gravity survey within the Zunil I geothermal field. The suggested field exploration program (survey lines, station density, field procedures) may be modified to obtain a better resolution of the objective. The area considered for the gravity study encompasses approximately four square kilometers centered on the Zunil I well field.

Field procedures as these should follow general standards applicable to gravity field measurements. It should be noted, however, that the rugged topography in the Zunil area may require special consideration both during field measurements and later during data reduction. The area being investigated consists of 75% moderately sloping ground and 25% steeper slopes and rugged terrain.

of a Worden or LaCoste-Romberg gravimeter with a sensitivity of .01 s recommended. Once the final field exploration program is selected the gravity stations located on a topographic map, a survey crew will ke out the survey lines and obtain accurate station coordinates and evations. It is conceivable that barometric leveling may be required for some selected locations.

4.5.3.1 Field Exploration

The currently proposed investigation program consists of a detailed gravity survey of approximately 130 to 150 stations spaced every 100m along 7 survey lines (lines 1,2,3,4,6,8,9) and every 200m along 2 lines (lines 5 and 7). Refer to Figure 4-1 for the approximate location of the survey lines and station density. The survey is oriented to obtain maximum coverage of the inferred Zunil Graben and associated faults depicted in Figures 3-7 and 4-1. A greater number of stations are located along the southwest part of the Zunil I area in order to assist in the interpretation of a previously detected gravity low in the vicinity of Cerro El Galapago.

4.5.3.2 Data Reduction and Results

Standard correction factors (drift, latitude, free-air, Bouguer, terrain) will be applied to all gravity field measurements during data reduction procedures, with special consideration to terrain correction. The corrected station values will be plotted on a topographic map along with station identification and location. The end result will produce a Bouguer anomaly map of the area investigated and the accompanying interpretation with appropriate profiles. A report, accompanying this map should include all data (raw and corrected) including a clear description of the data reduction path followed to obtain the final station value. A description of computer data-reduction programs used will also be included.

4.6 Mercury Soil Surveys

Mercury (Hg) is a common and highly mobile trace element in geothermal systems. Because Hg is then supported as a vapor, it can be deposited in soils above fault zones that are connected to the geothermal reservoir. Mercury surveys have proven to be a cost effective means of locating the surface traces of permeable fault zones, and have been utilized successfully in a range of geologic environments. They are particularly useful in areas where there is evidence of boiling within the reservoir and transfer of steam and gas to the surface. This is the case at Zunil, where the surface manifestations of the geothermal system consist entirely of fumaroles.

Soil samples will be collected along a series of traverses where faults are known or suspected to occur. The samples will be analyzed for Hg by gold film detector which has a detection limit of five parts per billion (ppb). The results of the analyzes will be contoured on large scale maps to delineate zones of high permeability.

HPR

original
revisions sent
DHL to
Guatemala
03/03/89

DRAFT!

REVIEWED
by
H. P. Ross
report of June 1, '89

GRAVITY MODELS OF THE ZUNIL I GEOTHERMAL FIELD, QUETZALTENANGO, GUATEMALA

Ulrich J. Cordón
M-K Engineers, Inc.

February 1, 1989

CONTENTS

(attachment α)

1. Executive Summary

Three gravity sections across the Zunil I geothermal field were modeled using a forward response gravity modeling program labeled Magic. The three sections pass through ZCQ wells (ZCQ-2, 3 and 6) in order to maintain some control of the subsurface structure, i.e. thickness of volcanics and depth to top of granodiorite. In addition, the Z-series wells provided data on density values of the volcanics. The variable parameters included the small variation in density values, the number of bodies, and some flexibility on the geometry of these. Results indicate that the gravity anomaly is dominated by the presence of a less dense body (than the granodiorite) lying at a depth of 3 to 4 km. and extending laterally from under Cerro Quemado. Numerous modifications to the variable parameters served only to refine the theoretical-to-observed curve matching process. This less dense body could be of rhyodacitic composition and its presence is supported by vulcanologic studies

1. Executive Summary

see attachment α (include here)

α ~~1~~. INTRODUCTION

Gravity measurements in the Zunil area (Bouguer anomaly map, d=2.67 gr/cc by INDE) depict a small, elongated negative anomaly with a NE-SW orientation within the Zunil I geothermal field. The maximum gravity low occurs in the area between Cerro El Galapago and Las Majadas with the anomaly decreasing toward the northeast and terminating approximately 1km southwest of the town of Zunil. Refer to Figure 1. The presence of this anomaly enhanced the concept of a graben structure in the subsurface, possibly in the granodiorite bedrock, with a similar orientation and boundaries as the gravity anomaly, (Mision de Enfoque Report, 1988). The existence of a graben is supported by drillhole data (ZCQ wells) which show a displacement of approximately ~~[illegible]~~ 95m in the bedrock along the NW boundary (wells ZCQ6 an ZCQ5) and a shallower basement to the SE (well ZCQ1). This is further supported by electrical resistivity surveys (INDE, Geoelectric Report, 1977) which indicate a deepening of the resistive strata (bedrock) toward Cerro El Galapago. The gravity anomaly may be a reflection of this subsurface structure or the result of other factors such as density changes or other structures/bodies.　①

3 ~~2~~. OBJECTIVE

The objective of the gravity model is to resolve whether the negative anomaly is (a.) caused by the graben effect, or (b.) the result of density variations in the (volcanics) covering or in the basement. The graben would tend to decrease the gravity measurements as the basement deepens, provided the upper volcanics maintain a fairly constant density. The amount of displacement of the graben however, may not be sufficient to alter the measurements. If this is the case then another cause of the anomaly has to be found: this may be a less denser body in the granodiorite or considerable density variations in the volcanics above the granodiorite.　②

Three (passes) perpendicular profiles to the graben in the geothermal field were chosen: line A-A' extends 2.9 km through well ZCQ-6, and shows a variation from -115 mgals to -96mgals; line B-B' extends 2.78 km crosses through well ZCQ-3, and varies from -120 to -101 mgals; line C-C' extends 2.82km through well ZCQ-2 and varies from -125 to -106 mgals. The large decrease in the gravity measurements to the northwest (Figure 1) is somewhat enhanced by the density value selected (2.67gr./cc).

4 ~~3~~. PROGRAM DESCRIPTION

The gravity program used for this study is labeled Magix, a forward modeling program for personal computers. It was developed by Interpex Ltd. of Golden Colorado. Magix is designed to run on IBM and compatible machines with 512 kilobytes of RAM, one 5¼" floppy disk drive, an IBM color graphics card and a monochrome monitor. The program provides report-ready graphical output via pen plotters. Magix provides a synthetic (theoretical) curve for up to 9 bodies with a total of 80 vertices spread among the bodies. The program requires that each body contains at least three vertices. Each body is calculated from industry accepted, published, Talwani-style polygon algorithms. The density of the gravity model is specified in terms of density contrasts. Data is entered into the program files and a graphically oriented earth model editor allows for changes to the bodies on the screen; the forward response curve for the new model is subsequently calculated and displayed on the screen. The [illegible] that are variable include its vertices and its physical properties. Refinement of the synthetic curve is therefore possible through a series of editing and iterations until a close fit with the observed curve is obtained. For purposes of this study refinement iterations ceased after a better than 95% fit was obtained. Magic was selected over other programs because it provides a fast, interactive, and accurate method of computing the forward response of a two dimensional earth requiring no additional program to enter, edit, interpret, and make a hard copy, graphical output from most pen plotters.

5A. MODEL PARAMETERS

Some geologic control was available from drillhole data (ZCQ and Z wells) and electrical resistivity studies in order to elaborate the model. Hard data from wells ZCQ-1 through ZCQ-6 provided the depth to the granodiorite basement and the thickness of the overlying strata (Tertiary and Almolonga volcanics). Table 1 summarizes the geologic control at these points.

TABLE 1

Well	Depth to Granodiorite	Total Well Depth
ZCQ-1	690 m	1310 m
ZCQ-2	780	812
ZCQ-3	990	1041
ZCQ-4	975	1025
ZCQ-5	940 (altered to 1050)	1080
ZCQ-6	1035	1142

Density values from the Z (or ZP) wells were also available and used. Values from well Z-11, located next to ZCQ-3, provided the most accurate density values within the upper 620m of the geothermal field. The average density value for each 100m of depth is demonstrated in the following table.

TABLE 2

Well Z-11

Depth (m.)	Avg. Density (gm/cc)
0 - 100	2.21
100 - 200	2.21
200 - 300	2.27
300 - 400	2.29
400 - 500	2.32
500 - 600	2.46
600 - 620	2.61

~~Upper~~ Volcanic~~s~~ Rocks

It remains clear from this well and from wells Z-7 and Z-2 that the upper volcanics have an average density generally less than 2.3 gm/cc. Although these are volcanic rocks that usually exhibit densities of 2.3 to 2.6 gm/cc in their natural state, the lower densities in this area my reflect their ~~altered and~~ slightly fractured condition. No values were available for the Tertiary volcanics but the density may vary between 2.1 - 2.4 gm/cc for the andesitic and dacitic rocks to possibly less than 2.1 gm/cc for the breccias and pyroclastics that are encountered throughout this section. Density values for granodiorite are quoted in textbook tables (Telford, W.M., et.al., 1976) to range between 2.67 and 2.79 gm/cc. This range seems appropriate for the basement rocks at Zunil. ~~[illegible]~~ It appears that the densities of the rocks increase with depth in this area.

(6)

6 ~~5~~. GEOLOGIC AND VULCANOLOGIC CONSIDERATIONS

The basic rock sequence within the general area of Zunil consists of volcanic rocks of various compositions, ranging from basalts and basaltic andesites to dacites, rhyodacites, and andesitas over a granodioritic basement. Within these volcanics, pyroclastic beds and breccias are interbedded throughout the lithologic column, so the density value will vary throughout the site. The presence of dacites and rhyodacites (with a lower density than the granodiorites) both in the near surface and at depth is corroborated by numerous vulcanological and petrological studies, (Rose, 1987; INDE. Informe Preliminar Geologico y Vulcanológico, 1977; Stoiber, 1980). These also point out to the possible existence of magma chambers at shallow depths which may have partly solidified. ~~The occurrence of~~ Records of historic eruptions throughout the area and the presence of various active volcanoes within 8 km of the Zunil field support the existence of these shallow magma chambers, which may quite possibly be connected in view of the close spacing among the volcanoes. Within the 8 km radius of the geothermal field lie among the most notable: Volcán Santa María, Santiaguito, Volcán Siete Orejas, Volcán Cerro Quemado, Volcán Santo Tomás Pecul, Cerro de Zunil, Tzanjuyub, Cerro El Galapago, and Las Majadas caldera. The once active crater at Las Majadas caldera for example may have ceased to erupt but the chamber in the subsurface, although solidified, is still there. Las Majadas lies within 1 km of the geothermal field. The occurrence of the "lighter" rocks (dacites and rhyodacites) at shallow depths is therefore quite plausible.

7 ~~6~~. GRAVITY MODEL RESULTS

The three modeled gravity sections are shown in Figures 2, 3 and 4. Both the observed and synthetic curves are drawn in the upper section of each figure; the geometric model and density contrasts (with the host rock) are shown in the lower half. Density values for the upper volcanics (Almolonga Fm.) varied from -.45 to -.47 mgals with respect to the granodiorite. Since the gravity program deals only with density contrasts, the value for the basement rock was the host rock value to which the remaining bodies are compared. So if a value of 2.67 gm/cc is chosen for the granodiorite, then the upper (Almolonga) volcanics would have ~~has~~ a density of 2.20 to 2.22 gm/cc. The thickness of the Almolonga volcanics is close to 600 m in all three sections within the field, a value taken from ~~most~~ the ZCQ drillholes. (Refer to Figures 2, 3 and 4).

The Tertiary volcanics extend to the basement rocks in all holes and similarly in all gravity sections. The three sections were ~~This section was~~ assigned a density contrast of -.37 mgals thus exhibiting a slightly denser mass than the surface

overlying Almolonga formation. The thickness of the Tertiary volcanics varied with the bedrock surface topography and thinned out near the town of Zunil where bedrock was detected at a depth of 425 m in well Z-5. This ~~section~~ unit of Tertiary rocks is possibly most susceptible to changes in density throughout the area as it contains the breccias and pyroclastic beds within the fractured andesites. Both of these lithologic formations (Almolonga and Tertiary volcanics) increase in thickness toward the northwest. But as previously noted, the large negative anomaly decrease toward this area may be the result of the density value selected for the Bouguer map (2.67 gm/cc). It should be mentioned that this area ~~approaches~~ adjacent to Cerro Quemado and the less denser rocks associated with this volcanic complex. The ~~influence~~ existence of the Quetzaltenango valley pyroclastic and pumice deposits may also influence the area within Cerro Quemado and Llano del Pinal, an area only 1.5 km from the field. ~~So,~~ Therefore the representation on the model depicting considerably thick volcanics and a deeper basement in this area may only be partly accurate.

(4) Yes This gradient is lower in the area map with a density of 2.5 gm/cc

enter here

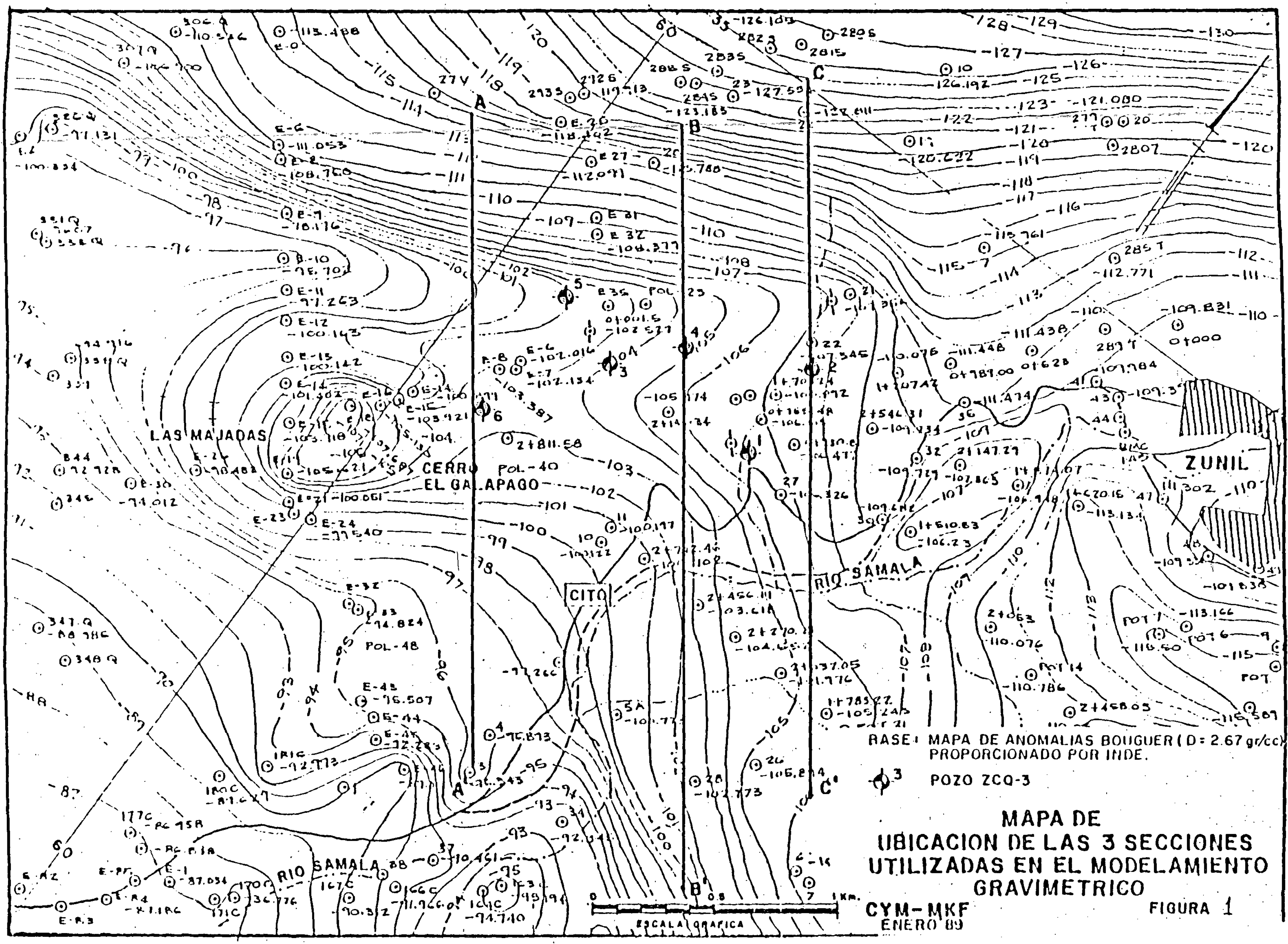
~~Maintaining~~ the geometry of the bedrock fairly constant and the density values of the volcanics to vary only slightly from known and acceptable values the synthetic curve results in ~~an~~ 50% to 82% error with the measured curve. This answers the question of whether the graben is responsible for producing the negative gravity anomaly. It is not because its structure does not cause a [illegible] in the gravity [illegible]. Apparently the depth and width of the graben and the variation of density contrasts between the granodiorite and the overlying rocks do not exhibit a sufficiently large contrast to produce such a negative anomaly. Varying the densities of the volcanics to minimum acceptable values only improve the fit to a 50% ~~error~~ match.

The synthetic curve produced by these aforementioned parameters has a contrast of approximately +60 to +80 mgals with the observed curve. Therefore a less denser body than the granodiorite must be introduced at depth in order to lower the synthetic curve to the -120 to -96 mgal range of measured values. This body could well consist of a dacite or rhyodacite with a density of 2.1 to 2.22 gm/cc at a depth of 3 to 4 km. This dacitic intrusion may therefore be related to the known "lighter" rocks in the area and ~~corroborates well with~~ [illegible] the vulcanologic concepts and petrologic investigations. The body would originate from a depth of approximately 10 km in the vicinity of Cerro Quemado and extend laterally under the field. This correlates with the existence of a solidified magma chamber at depth under Las Majadas Caldera and connected to the chamber from Cerro Quemado and Santa Maria volcanoes. The resultant synthetic curve under these assumptions has a 95% or better fit with the observed curve. The results are demonstrated in Figures 2, 3 and 4. Figure 5 represents a conceptual configuration of this lighter intrusion.

It should remain clear that some variations in the model will produce the same fit; for example, the density of the dacitic intrusion may be decreased in order to diminish the size of the body. These variations are nevertheless subject to geologic, vulcanologic, petrologic, and structural controls. ~~It could well be the case that a hot magmatic body~~ It could well be the case that a hot magmatic body at depth (with a density of less than 2 gm/cc) produces the same result as the models in Figures 2, 3 and 4. The configurations may vary and other hypotheses can be formulated but the current gravity modeling [illegible] demonstrated ~~fact~~ that a less dense body is present within the granodiorite under the field, ~~[illegible] the gravity modeling attempt~~

(attachment β)

Various models were developed in the initial stage in order to produce a basic model which could be modified or refined. One of the first attempts in modeling included the Panel's suggestion of using three different densities (2.6, 2.4 2.65 gm/cc) for the volcanics and the granodiorite and modifying the geometry of these bodies, especially the graben structure. The resulting synthetic curve yielded only a 20% to 40% approximation with the observed curve. Various geometries and variations in densities did not improve this model. Geologic control from the ZCQ and Z wells could not be modified and the model had to remain within credible parameters. In addition density values from well Z-11 also provided a slight control in this parameter for the Almolonga volcanics (Refer to Table 2) Therefore by maintaining . . . ! (sigue en el texto)



BASE: MAPA DE ANOMALIAS BOUGUER (D= 2.67 gr/cc) PROPORCIONADO POR INDE.

ϕ3 POZO ZCQ-3

MAPA DE UBICACION DE LAS 3 SECCIONES UTILIZADAS EN EL MODELAMIENTO GRAVIMETRICO

CYM-MKF
ENERO 89

FIGURA 1

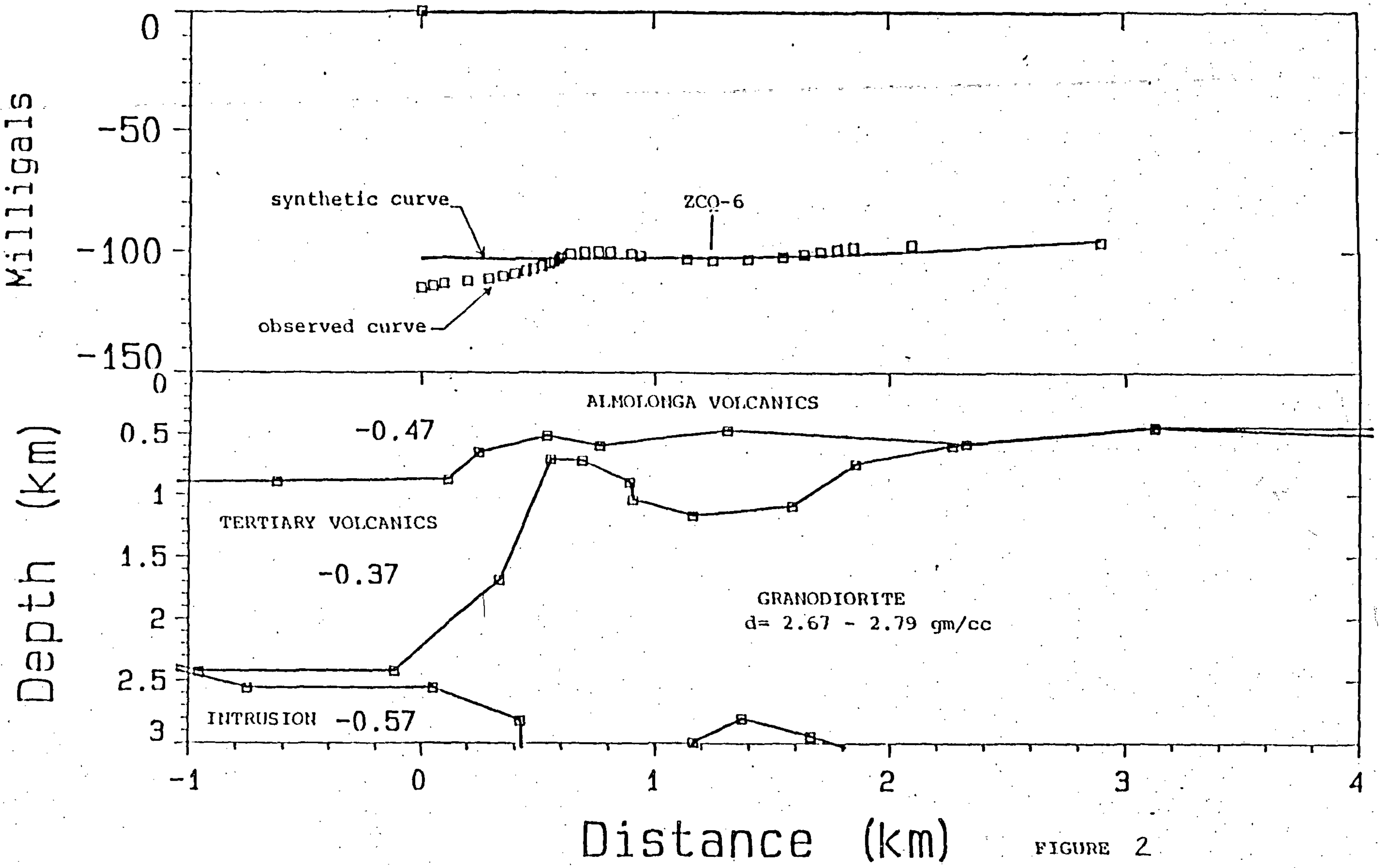


FIGURE 2

for: INDE

by: Morrison-Knudsen Engineers, Inc.

Data Set: GRAV17	Date: 12-JAN-89
Scale: 1:24918	Profile: A-A'

QUEZALTENANGO, GUATEMALA

ZUNIL I
GEOTHERMAL FIELD

Vertical

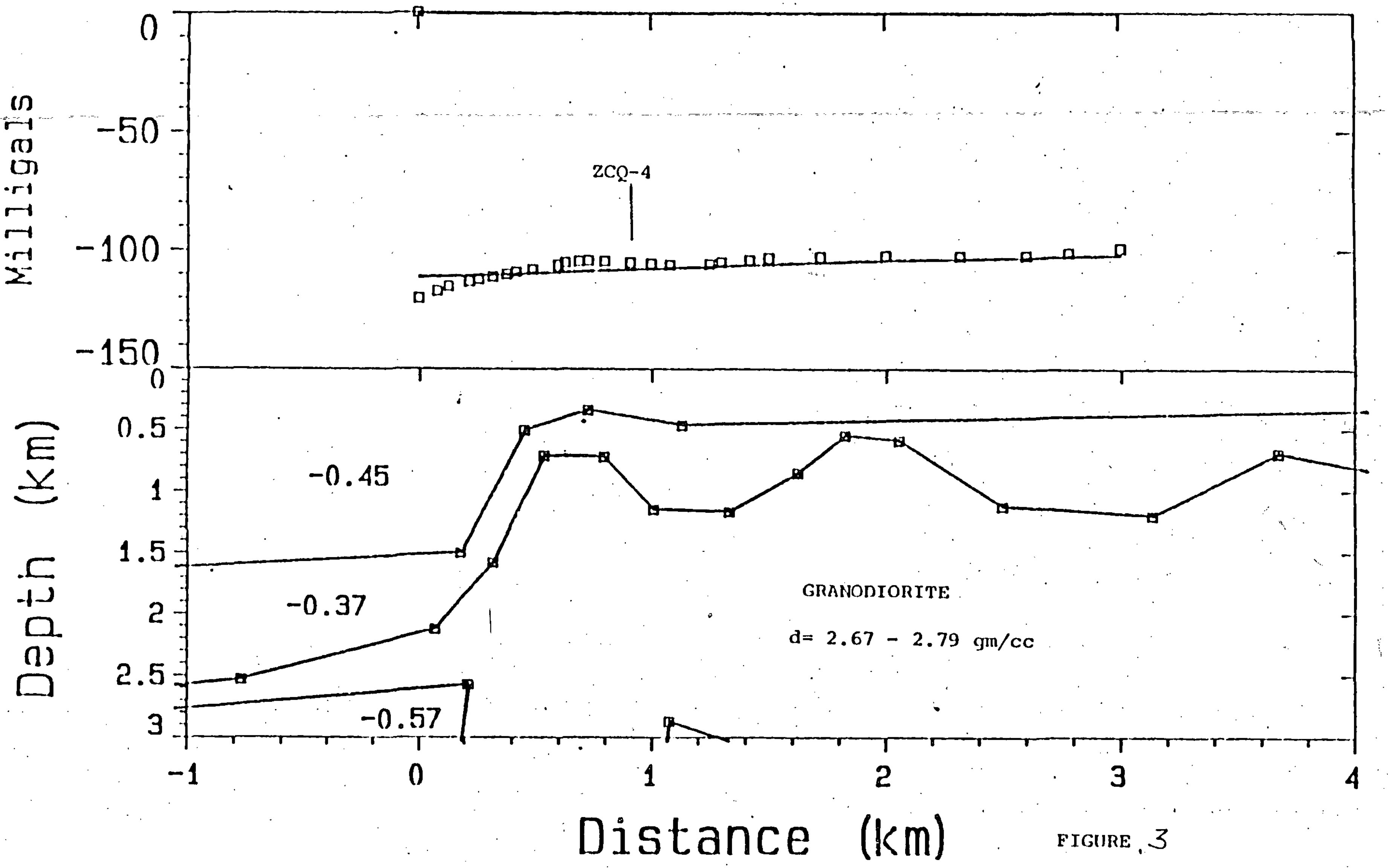


FIGURE 3

for: INDE

by: Morrison-Knudsen Engineers, Inc.

Data Set: GRAV23	Date: 29-JAN-89
Scale: 1:24918	Profile: B-B'

Quezaltenango, Guatemala

ZUNIL I
GEOTHERMAL FIELD

Vertical Exaggeration: 0.53 : 1

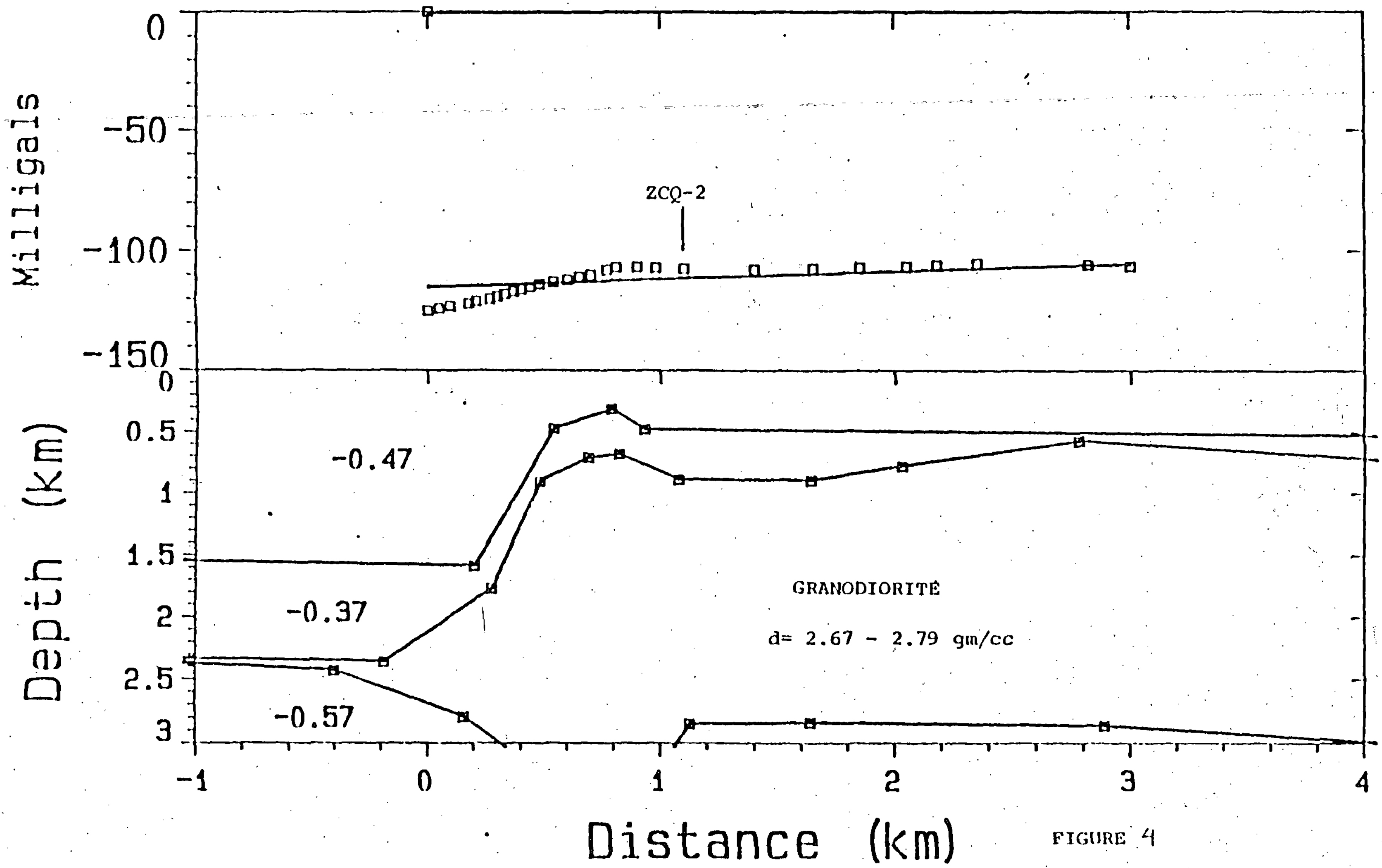


FIGURE 4

for: INDE

by: Morrison-Knudsen Engineers, Inc.

Data Set: GRAV33	Date: 24-JAN-89
Scale: 1: 24918	Profile: C-C'

QUEZALTENANGO, GUATEMALA

ZUNIL I
GEOTHERMAL PROJECT

Vertical Exaggeration: 0.53 : 1

Example of one possible configuration of the less dense intrusive body. Fit=97%

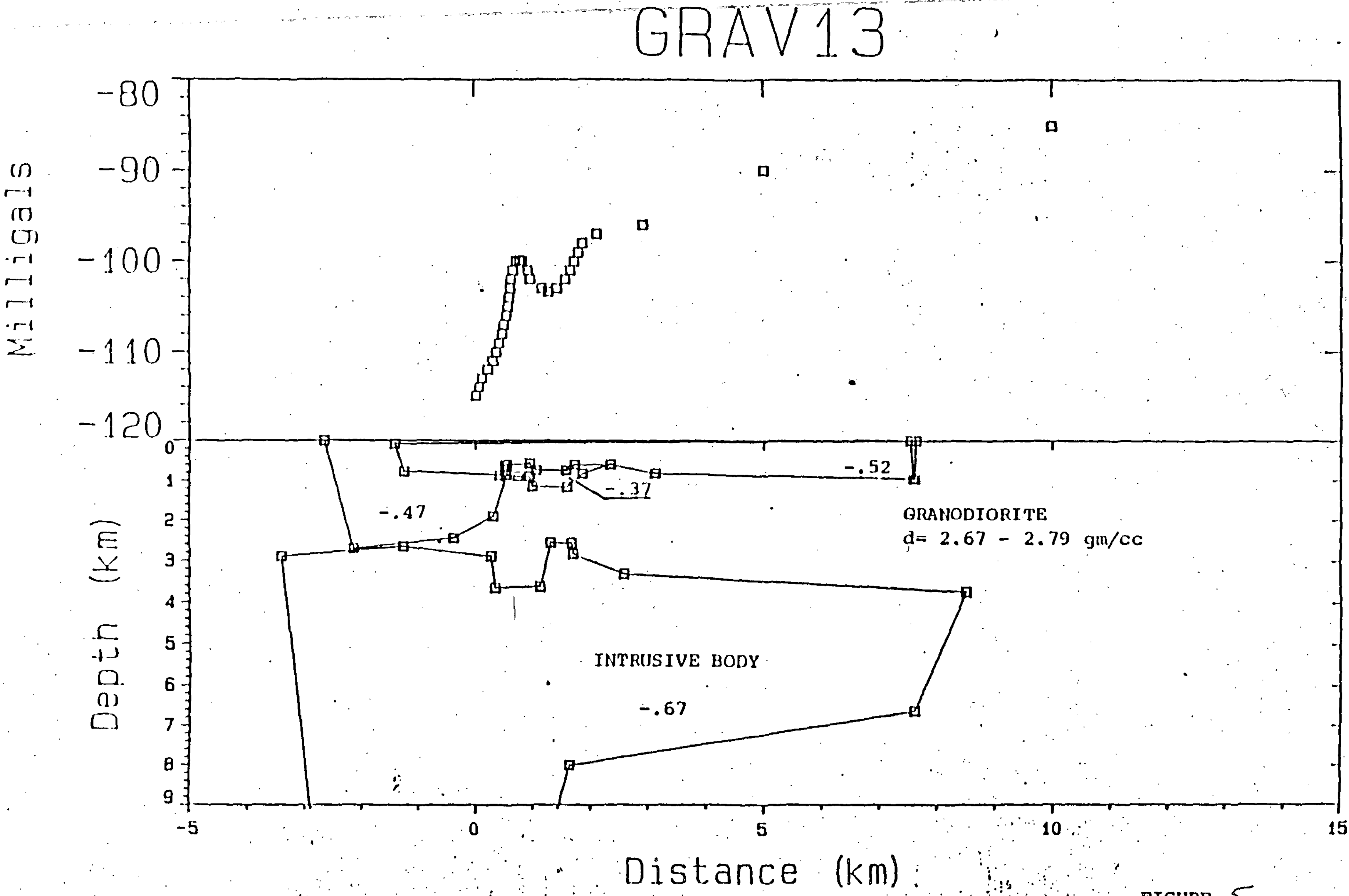


FIGURE 5

87. CONCLUSIONS

insert attachment 8 here

In summary gravity models of three sections across the Zunil geothermal field show that the gravity anomaly is dominated by a deep intrusion with a density less than the basement rock. It is conceivable this instrusion is a large dacitic or rhyodacitic body lying at a depth of 3 to 4 km and extending from under Cerro Quemado. This result is supported both by vulcanologic and petrologic studies. It may be that this body is in a solid state, such as a solidified magma chamber (as presented in this investigation), or in a semisolid to molten state and thus of smaller dimensions or deeper than the solid state dacitic intrusion.

In terms of field development, the results of this study suggest that the presence of the "lighter" intrusion provides a heat source if a quasi-molten state exists. The intrusion may also be a (or various) magma chambers at shallow depths (3-5 km) that have solidified (say under Las Majadas) and the heat source is latent heat that is released on crystallization or solidification of molten rock. In either case the presence of a heat source is established. Production of the field through deep wells would therefore concentrate on intersecting faults and large fractures where thermal fluids are channeled at exploitation depths.

(attachment 8)

The gravity modeling investigations attempted to respond the concerns on the effect of the basement graben, the density variations in the volcanics, and the cause of the elongated gravity anomaly in the geothermal field. Of primary concern was the Panel's query of whether the graben was sufficient to produce the anomaly or to consider density/geometry changes. One of the first models considered the Panel's suggestions of a fixed geometry and densities of 2.6, 2.4 and 2.65 gm/cc for the Almolonga Formation, the Tertiary volcanics and the granodiorite respectively. The results of this model (3 sections across the field) produced a matching error of 60 to 80%. Several other densities were considered and the basement structure was slightly modified (keeping the ZCQ and Z well control) but the curves only produced a less than 50% match with the ~~observed~~ synthetic curve. The result of over a dozen conceptual models relying solely on geometric modifications and variations in density in the volcanics did not produce a close match with the existing gravity data.

Relying on volcanological and petrological data and reports, as well as the need to produce a conceptual and accurate solution to the gravity anomaly, a body with a density less than the granodiorite was introduced at a depth of 3 to 4 km. The result was a better than 95% fit with the observed curve. The supporting parameters consist of: a density of 2.2 to 2.32 gm/cc for the Almolonga Formation, a density of 2.3 to 2.42 gm/cc for the tertiary volcanics, a value of 2.67 to 2.79 gm/cc for the granodiorite, and 2.1 to 2.22 gm/cc for the less dense intrusion. The range in density is used because the values for all bodies are given in contrast to the host rock: the basement granodiorite which may have a range of 2.67 to 2.79 gm/cc. The "lighter" intrusion may consist of dacitic or rhyodacitic composition as suggested by volcanological/petrological studies; it extends laterally from under Cerro Quemado depicting a solidified magma chamber. If the density of this body is further reduced to represent a quasi-molten state, then the size of the body will decrease or its depth will increase in order to justify approximation, maintain the accurate match between the curves.

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EXPL TION SERVICES – GEOPHYSICS DIVISIO

ROCK SITY = 2.00

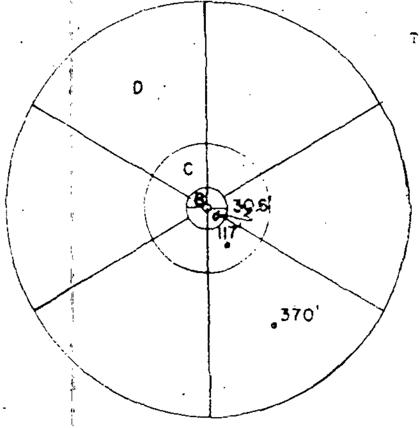
INNER TERRAIN CORRECTION ONLY

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.

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

ROCK SITY = 2.00

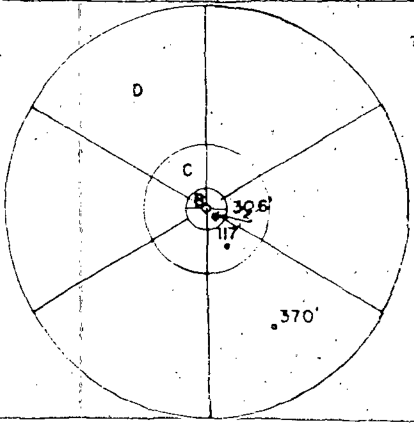
INNER TERRAIN CORRECTION ONLY

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.

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.

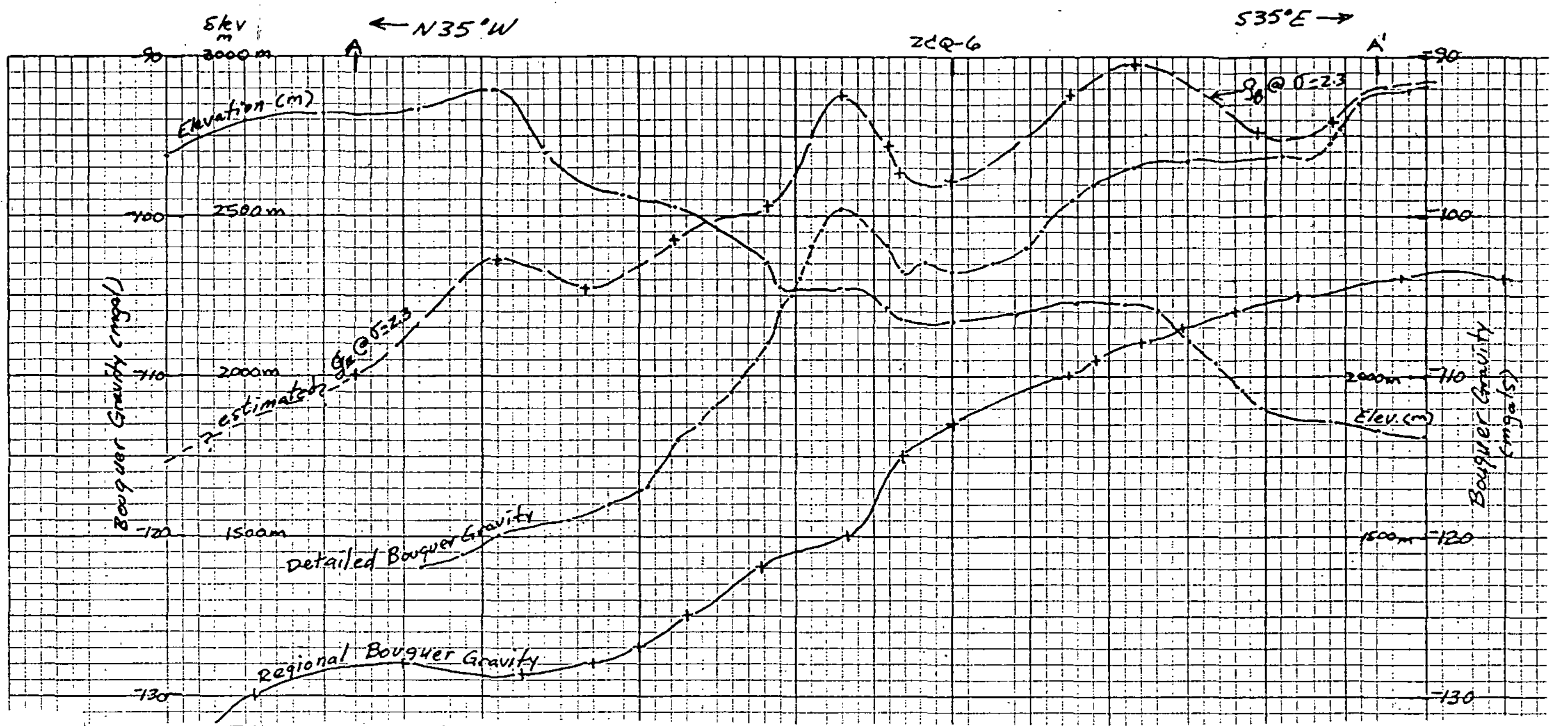


Figure **2**. Comparison of regional Bouguer gravity, detailed Bouguer gravity, and surface elevation along profile A-A'. Also shown is the estimatedBouguer gravity for the detailed survey using a density of 2.30 g/cc.

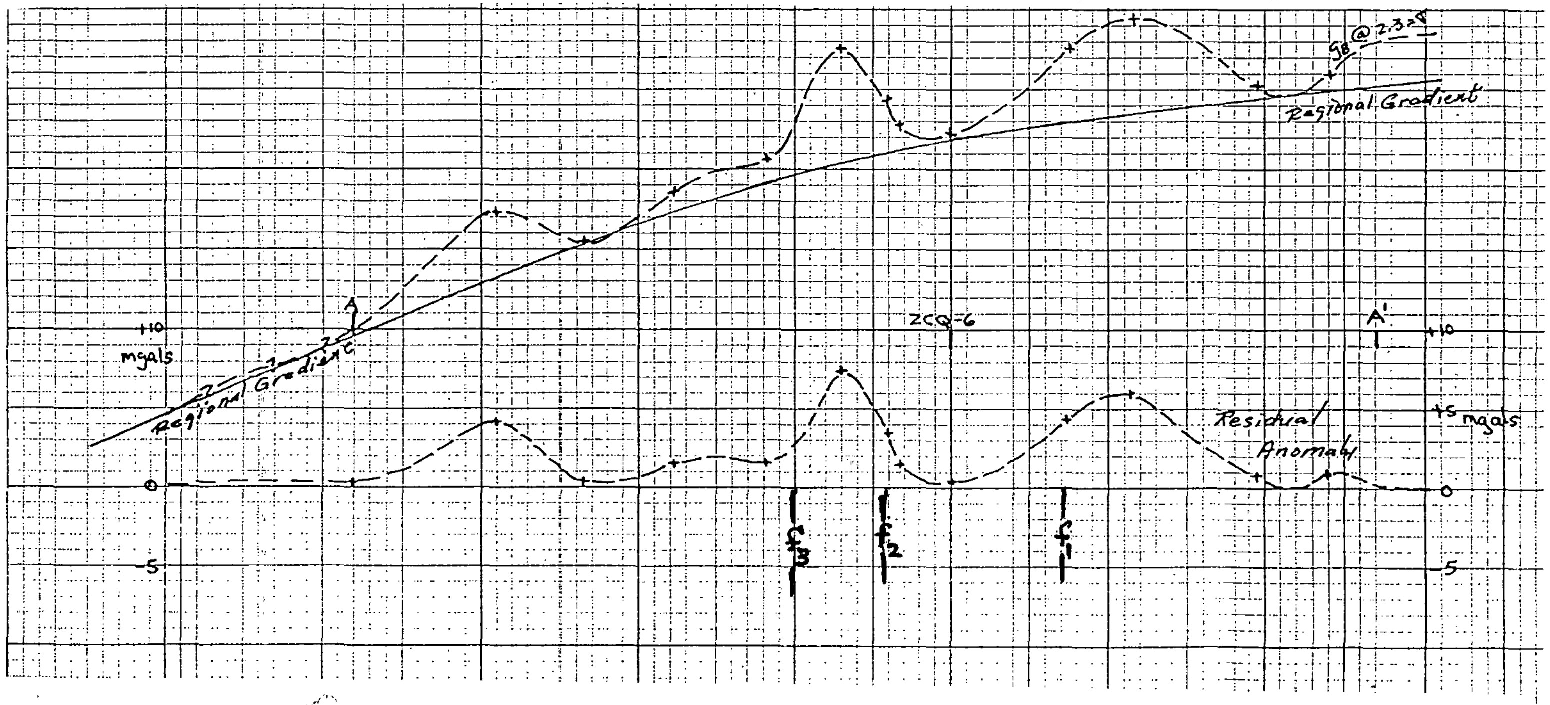


Figure **3**. Identification of a regional gradient along profile A-A', and its removal to form a residual anomaly suitable for numerical modeling.

scale = 1:20,000 x .80 = 1:25,000

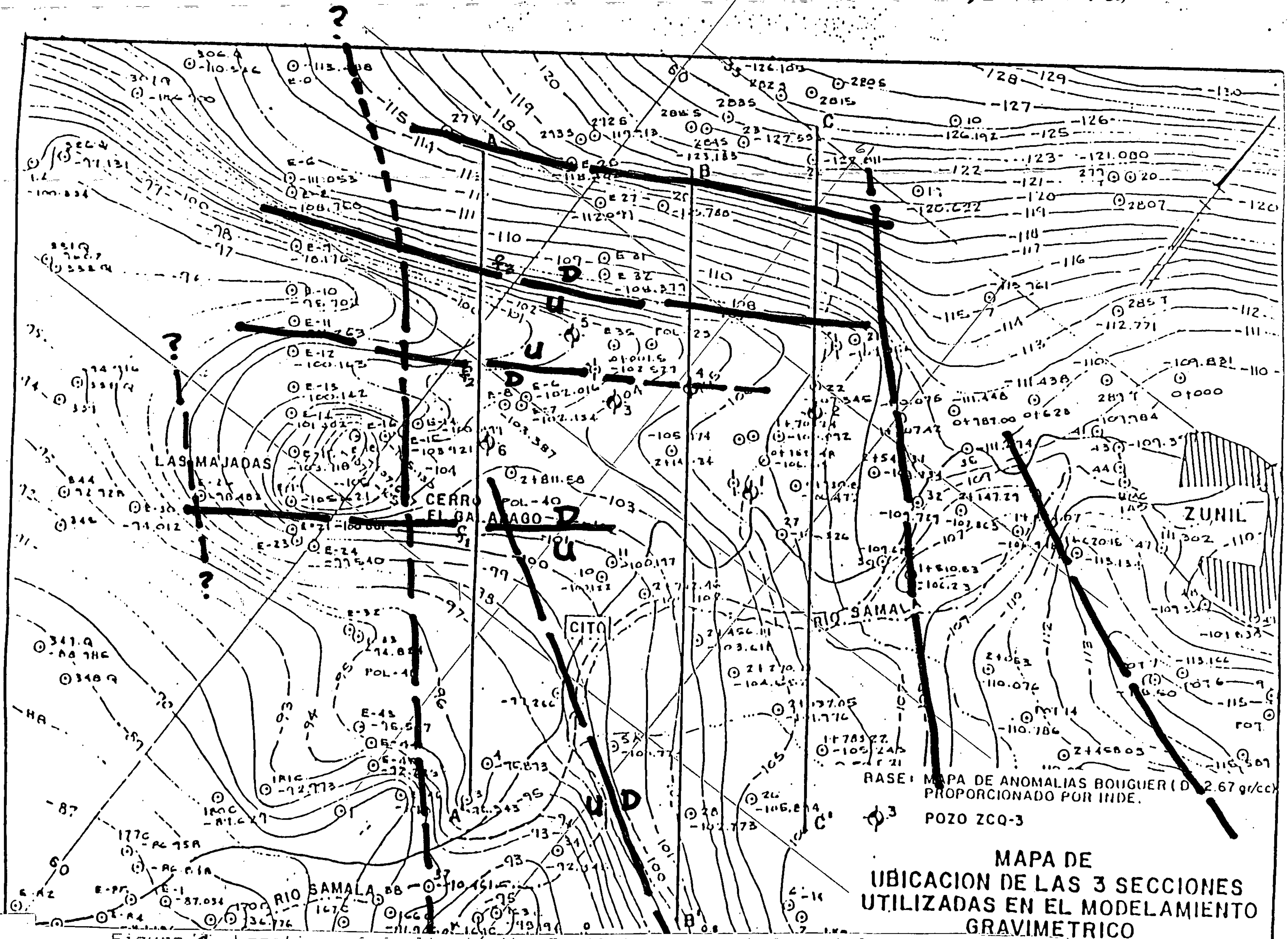


Figure 4. Location of faults in the Zunil 1 area as inferred from the detailed gravity survey. This interpretation has not been supported by numerical modeling.