# TELLURIC, SELF-POTENTIAL, AND SURFACE TEMPERATURE PROFILES ON LOS HUMEROS CALDERA

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## RESUMEN

Se hicieron levantamientos geofísicos en dos líneas (16.5 y 17 Km) de la caldera de Los Humeros, la cual se encuentra situada en la parte centro-oriental de México, con el propósito de delinear preliminarmente áreas de interés geotérmico. El método telúrico de cociente de campo eléctrico E, que consiste en dipolos colineales y medidas a frecuencias .05 y 8 Hz, se usó como método de reconocimiento para tener una idea de los cambios relativos en conductividad eléctrica a través de la caldera; se hicieron asimismo mediciones de autopotencial y temperatura superficial a lo largo de dichas líneas. Las respuestas telúricas sugieren marcados contrastes de conductividad en la parte occidental de ambas líneas y en ambas frecuencias; además, la línea más al norte parece definir con gran exactitud la porción colapsada (que está cubierta de piroclásticos) de la caldera a lo largo del perfil. Los datos telúricos y gravimétricos coinciden muy bien en delinear los rasgos estructurales más importantes de la caldera. El autopotencial muestra que el borde occidental de la caldera está aproximadamente 800 mV más alto que el potencial del borde oriental. Las temperaturas superficiales (i.e., 0.5 a 1 m de profundidad) en la parte occidental de la caldera están de 3° a 6°C más elevadas que las temperaturas en el lado oriental. Con base en estas evidencias proponemos que el flanco occidental de la caldera es un blanco primario de exploración para propósitos geotérmicos.

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## ABSTRACT

Two geophysical lines of 16.5 and 17 Km in length have been surveyed in Los Humeros Caldera, in central-eastern Mexico, in order to delineate preliminary areas of geothermal interest. The E-field ratio telluric method, which consist of collinear dipoles and measurements at frequencies of .05 and 8 Hz, was used as a reconnaissance tool to get an idea of the relative changes in electrical conductivity across the caldera; self potential and surface temperature data were also collected along the lines. Tellurics suggests sharp conductivity contrast on the west side of both lines and at both frequencies; in addition, the northern line appears to define quite well the collapsed portion of the caldera along the profile, the topography of which is oblitarated by pyroclastics. Telluric and gravity data agree quite well in delineating the major structural features. Self-potential responses show that the western caldera rim is approximately 800 mV above the electric potential of the eastern rim. The average surface temperatures (i.e., 0.5 to 1 m depth) on the western caldera portion are from $3^{\circ}$ to $6^{\circ}C$ above the temperatures on the eastern portion. On the basis of this evidence the western flank of the caldera is proposed as the primary exploration target for geothermal purposes.

## INTRODUCTION

Surface geothermal activity is necessarily linked to underground heat sources. Although surface activity is easily detected, location of the main reservoir or of the primary heating source is often a complicated task that requires correlation of geological features and various geophysical responses. In selecting possible geophysical methods to be applied in geothermal exploration one must bear in mind that most heat sources of economic relevance are likely to be located at depths ranging from 2 to 20 Km (Stanley, 1977; Ward, 1977). Thus, if the exploration target is the primary heat source of a geothermal system and not only its shallower manifestations, it is imperative to have high penetration capabilities.

No single method has been established as the best for locating geothermal targets. However, tellurics and magnetotellurics often appear associated with other exploration methods, owing to their high penetration capability that allows target detection down to 20 Km, and to the large, often undetermined electrical conductivity contrast between a hot mass of rock and its surrounding (e. g., West and Shankland, 1977). in fact, magnetotelluric or audiomagnetotelluric determinations have already revealed the presence of many zones with electrical conductivities larger than 1 $(ohm\text{-}m)^{-1}$ within 10 Km from the surface (Hoover *et al.*, 1976; Ward, 1977). Both methods yield apparent resistivities; although the telluric method cannot determine apparent resistivity values it can yield resistivity ratios between a given location and a reference base.

Los Humeros caldera is being used as a test area for deciding which geophysical methods, and which exploration strategies, are best suited for surveying extensive volcanic areas in search of geothermal sources and, possibly, in the evaluation of their energies. Morphologically Los Humeros is probably the best developed example of a caldera in Mexico. It is of Quaternary age and there is yet no detailed mapping of the geologic structures within the caldera. A photogeologic map, as well as

some petrographic analyses have recently been reported (Pérez-Reyno-so, 1978).

Figure 1 shows the photogeologic map of the caldera as well as the two geophysical lines. Close to station 0 on Line 1 one finds the only geothermal manifestation in the caldera: 6 to 10 steam fumaroles appearing on the downthrown block of a normal fault (Los Humeros fault) and scattered in an area of approximately 1 Km². The ground temperature at the fumaroles exhaust ranges from 60° to 90°C.

## TELLURIC METHOD

The particular version of the telluric method used in the present case is shown schematically in Figure 2 and was originally proposed by H. F. Morrison (Beyer *et al.*, 1976) and developed by Beyer (1977); it has been used in conjunction with other geophysical techniques in the Grass Valley area of Nevada. The method consists of two contiguous intervals (X and Y) of 500 m each in which the electric field is determined ($E_X$ and $E_Y$) simultaneously at one of two frequencies (.05 or 8 Hz); frequency selection is made at a system of filters whose output is plotted on an X-Y recorder, in such a way that the ratio $E_Y/E_X$ is directly obtained. The E-ratio is related to the resistivity ratio through

$$E_Y/E_X = (\rho_Y/\rho_X)^{1/2} \tag{1}$$

(e.g., Keller and Frischknecht, 1966), where $\rho_X$ and $\rho_Y$ are the apparent resistivities of the media excited by the electromagnetic wave under intervals X and Y respectively. If the two intervals have the same electrical resistivity the slope of the $E_Y/E_X$ plot will be 45°; higher resistivities under Y will result in slopes greater than 45° in such plots, while slopes of less than 45° denote that the X-interval is more resistive than the Y-interval. Equation (1) holds in uniform media; if a contact between two media of different resistivities is found, such a relation

becomes

$$E_y/E_x = \rho_y/\rho_x \qquad (2)$$

in the vicinity of the contact (Beyer, 1977), owing to the requirement of continuity of the normal component of the current across the contact (i.e., $J_n = \frac{1}{\rho} F_n$ continuous at contact).

Since no absolute value determinations of the apparent resistivities can be made, an arbitrary reference value is established; the electric field at the reference interval is 1 by definition and, consequently, all other values are expressed as multiples of this unit. If by other means (e.g., by magnetotelluric measurements) one could subsequently determine the apparent resistivity at the reference interval, one could immediately obtain the apparent resistivities at all other intervals along the surveyed lines. This possibility represents indeed a great advantage for the utilization of the telluric method in reconnaissance studies of large areas; magnetotelluric determinations are considerably more involved and time consuming and could in principle be made only at a few key locations, while the bulk of the effort would be dedicated to covering the area with the telluric method. Two additional assets can be found in this method with respect to its applicability in geothermal exploration: (1) its great penetration capability and (2) its relatively inexpensive instrumentation and operation. Penetration is of course controlled by the electrical resistivity of the media under each interval (i.e., the impedance or the media at a given frequency); in the way of an example consider two media with apparent resistivities of 1 ohm-m and 100 ohm-m. The wave of frequency .05 Hz would penetrate 2.3 Km and 26 Km respectively in the media with the above resistivities, while the 8 Hz wave would penetrate 0.2 Km and 2.3 Km in the same media.

## TELLURIC RESPONSES

Preliminary results of the telluric and self-potential (SP) responses on

Los Humeros caldera were reported by Alvarez and Morrison (1976). Since the time of that report Line 1 has been extended 9 Km and Line 2 extended 6 Km, both to the West, so that the western caldera rim has been crossed twice. Figure 3a shows the telluric (i.e., electric field ratio) response along Line 1. The 8 Hz response shows gentle variations in the stations interval 6W-16E and abrupt changes West of station 6W. There is a resistivity low, at such a frequency, occurring in the interval between stations 0 (i.e., where the fumarolic activity is located) and 6W; between stations 4E and 5E occurs a resistivity high suggesting, together with the .05 Hz response, the existence of a shallow, resistive body. Such a body may be a block of material belonging to the central body inferred from the aeromagnetic (Flores *et al.*, this issue) and the gravity (Mena and González-Morán, this issue) results, and according to these telluric data it may extend from stations 3E to 6E. Between stations 12W and 15W the response of the two frequencies clearly indicate the existence of a vertical contact, probably the caldera rim, with the more resistive material located West of the contact. The most conductive area occurs in the interval between stations 11W and 13W for both frequencies.

In addition to the above observations, the .05 Hz response indicates a series of contacts at depth, between sections that become more conductive toward the West (e.g., contacts at intervals 3E-4E, 0-1W, and at stations 6W and 13W). This response may correspond to a geologic situation in which a series of collapsing blocks reach greater depths toward the West. In the section of Line 1 West of station 15W, the 8 Hz response suggests a shallow resistive body while the .05 Hz response suggests the opposite. Such an ambiguity should be resolved by extending the line to the West. Between station 6W and 10W the 8 Hz response suggests the presence of another shallow resistive body; the .05 Hz response, however, shows only a small increase in the resistivity.

Figure 4a shows the telluric response along the 16.5 Km covered by Line 2; the responses can be described in terms of three major portions: the eastern (1E-7W), the central (8W-28W), and the western (29W-32W) portions. The former shows a rather flat response both at .05 Hz and at 8 Hz, reflecting structural uniformity along the eastern section. The

central portion shows a strong decrease around station 8W indicating that resistivity of the central portion is considerably smaller than the resisitivity of the eastern section. In fact, station 8W is actually the eastern caldera rim (e.e., the place where blocks begin to collapse on the eastern side of the caldera), as confirmed by the gravity model that will be shown subsequently (see Figure 6). The western portion starts at a contact between conductive and resistive media, which define the western caldera rim between 29W and 30W at the 8Hz frequency and between 27W-28W at the .05 Hz. From West to East the .05 Hz telluric response suggests that after the first collapsed block inside the western caldera rim, there are a series of blocks falling en échelon toward the western caldera rim. The 8 Hz response shows that the shallow, most conductive area of the line is located close to the western rim.

Summarizing these results we have that while the telluric responses along Line 2 clearly define the caldera limits (see Figures 4a and 6), the responses along Line 1 intersect only the western caldera rim; such a result is in agreement with the gravity model (see Figure 5), which shows the caldera limit approximately 2 Km East of station 16E. Thus, the eastern caldera rim along the continuation of Line 1, is that shown in the photogeologic map of Pérez-Reynoso (Figure 1); however, the eastern limit shown for Line 2 in the photogeologic map cannot be reconciled with telluric or gravity data. Such data indicate that the eastern caldera rim is intersected at station 8W on Line 2, coinciding with a fault in the photogeologic map, that we had previously designated as Monte Nuevo fault. The pyroclastics thickness is indicated by the gravity models as ranging between 1.0 to 1.5 Km on the central portions of Lines 1 and 2.

## SELF-POTENTIAL AND SURFACE TEMPERATURE

The self-potential data along Line 1 and Line 2 (Figures 3b and 4b) show that the western caldera rim is at a higher potential than the eastern portio i. Potential differences as large as 1300 mV are observed on each ine across the caldera; these potential differences are

slightly larger than those observed by Anderson and Johnson (1976) across the Long Valley caldera.

Line 1 shows a gradient of approximately 37 mV/Km with a well defined anomaly of 550 mV between stations 7W and 14W. The anomaly correlates quite well with the conductivity anomaly detected with tellurics. The self-potential along Line 2 experiences a steady climb to the West of station 11W, but no clearly defined anomaly appeared as in the case of Line 1. Extending the Line 4 Km to the West should provide enough data to define the self-potential behavior away from the rim. The surface temperature profile along Line 1 (Figure 3c) shows that there is a temperature increase from an average of 11°C on the eastern section (i.e., between stations 0 and 13E) to an average of 16°C on the western portion of the line (i.e., between 1W and 17W). Figure 4c shows the temperature data for Line 2; an average temperature of 11°C is obtained for the section between 1E and 26W while an average value close to 14°C is observed between 25W to 31W. Thus, is appears that the average value of 11°C observed on the eastern portions of the line may represent normal surface temperatures in thermally unaltered sections of the caldera.

## CONCLUSIONS

The E-field ratio telluric method was tested in Los Humeros caldera and it was found to be a valuable tool in delineating structural features within it. The applicability of such a method in volcanic areas is considered to be of high value on the basis of its penetration capabilities and its economy. Gravity data correlated quite well with telluric data. The self-potential profiles indicated that the western portion of the caldera is at approximately 800 mV above the potential of the eastern portion, and surface temperature data showed higher temperatures on the western caldera rim. On the basis of this information the western caldera portion is suggested to be a primary target for detailed geothermal exploration.

## ACKNOWLEDGEMENTS

PHOTOGEOLOGIC INTERPRETATION BY J. PEREZ-REYNOSO (1978)

Figure 1. Photogeologic map of Los Humeros caldera after Pérez-Reynoso, 1978, showing the two geophysical lines.
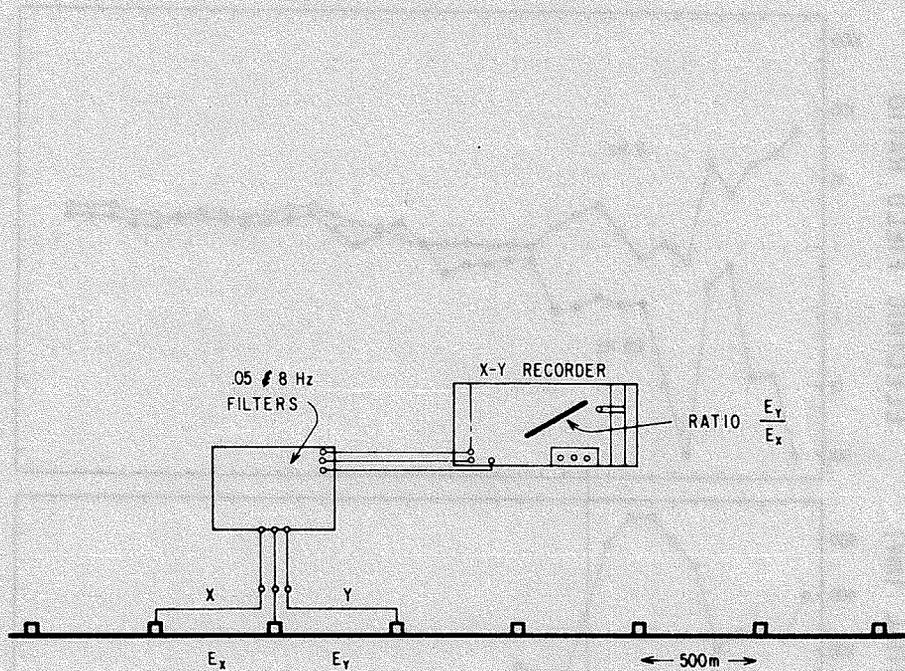
Figure 2. Schematics of the E-field ratio telluric method as used in the present surveys. Electromagnetic waves of .05 or 8 Hz are detected and filtered; the ratio $E_y/E_x$ of the contiguous intervals is fed into an X-Y recorder that displays lines or ellipses, whose inclination depends on the ratio of the fields.
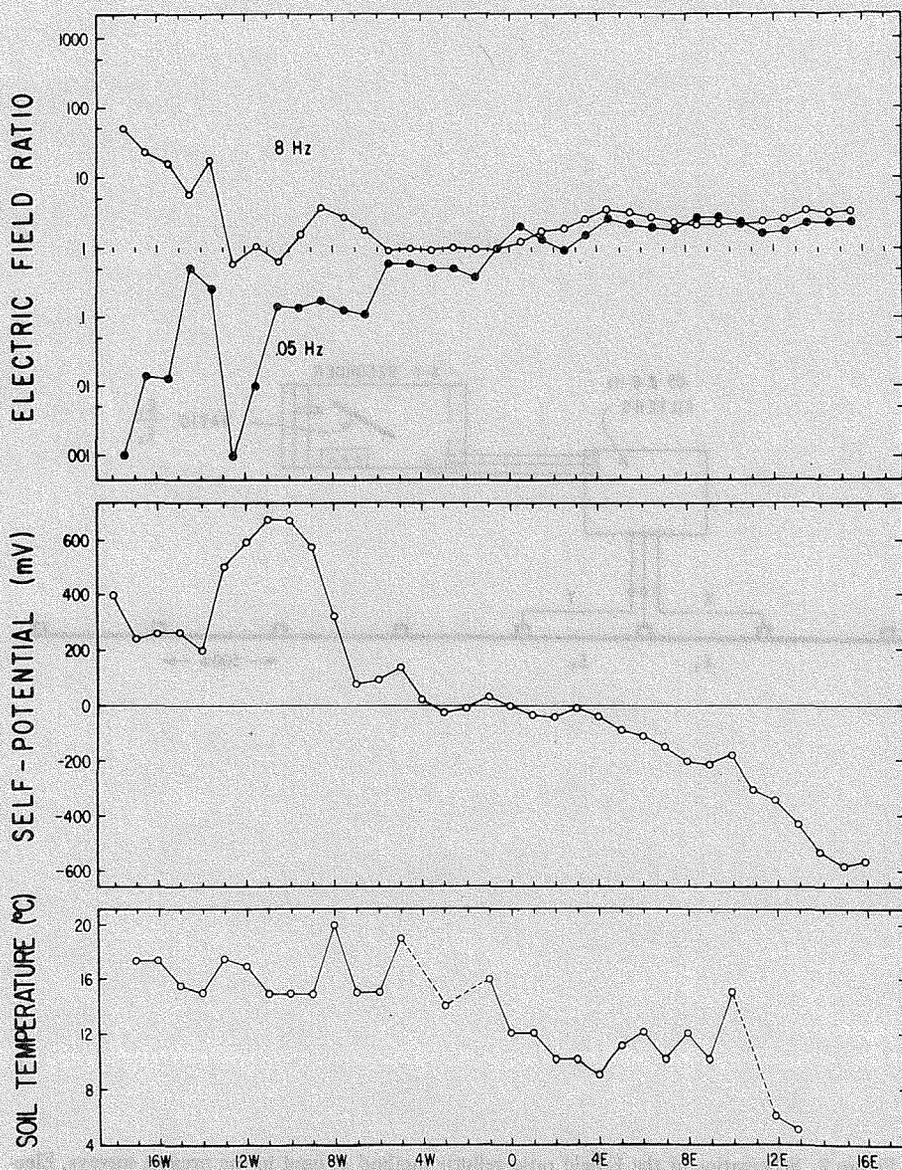
Figure 3. Line 1.   a) Telluric responses at .05 and 8 Hz,   b) Self-potential, and   c) Surface temperature.

LINE 2
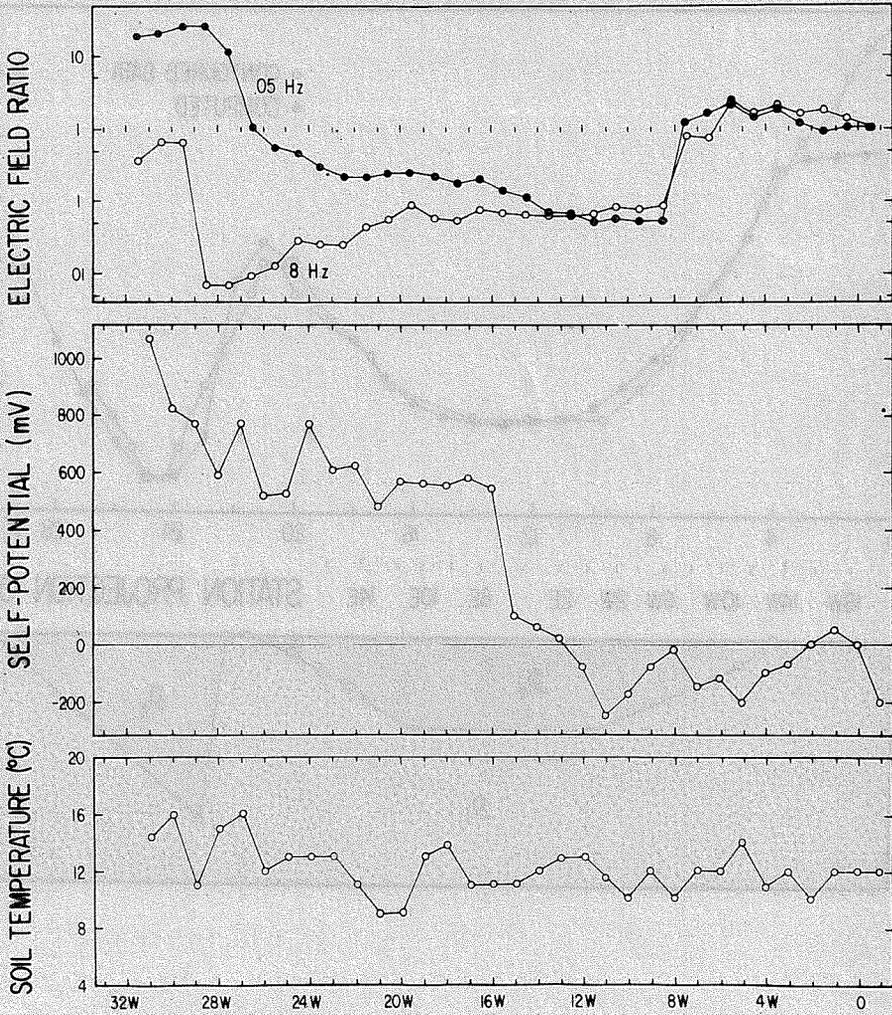


Figure 4. Line 2.   a) Telluric responses at .05 and 8 Hz,   b) Self-potential, and   c) Surface temperature.
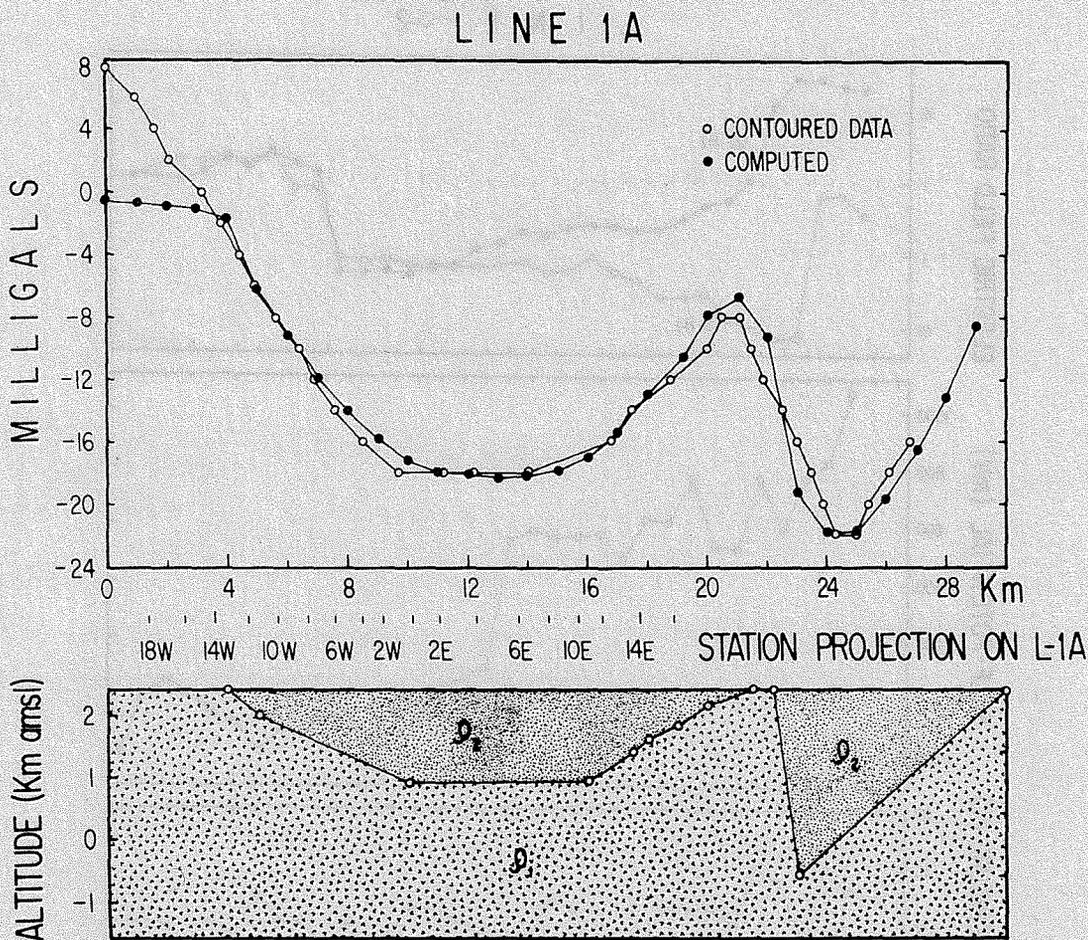
Figure 5. a) Observed and computed gravity profiles along Line 1A. The former were obtained from the contoured data of Mena and González-Morán (This issue). The computed data were obtained by the same procedure as described in their paper. Line 1A is a straight line that cuts Line 1 at stations 12W and 12E.

b) Gravity model corresponding to the computed data above. The density values are $\rho_1 = 2.67$ and $\rho_2 = 2.35$ g/cm$^3$; calculations were made considering a flat surface at 2400 m above mean sea level (amsl).
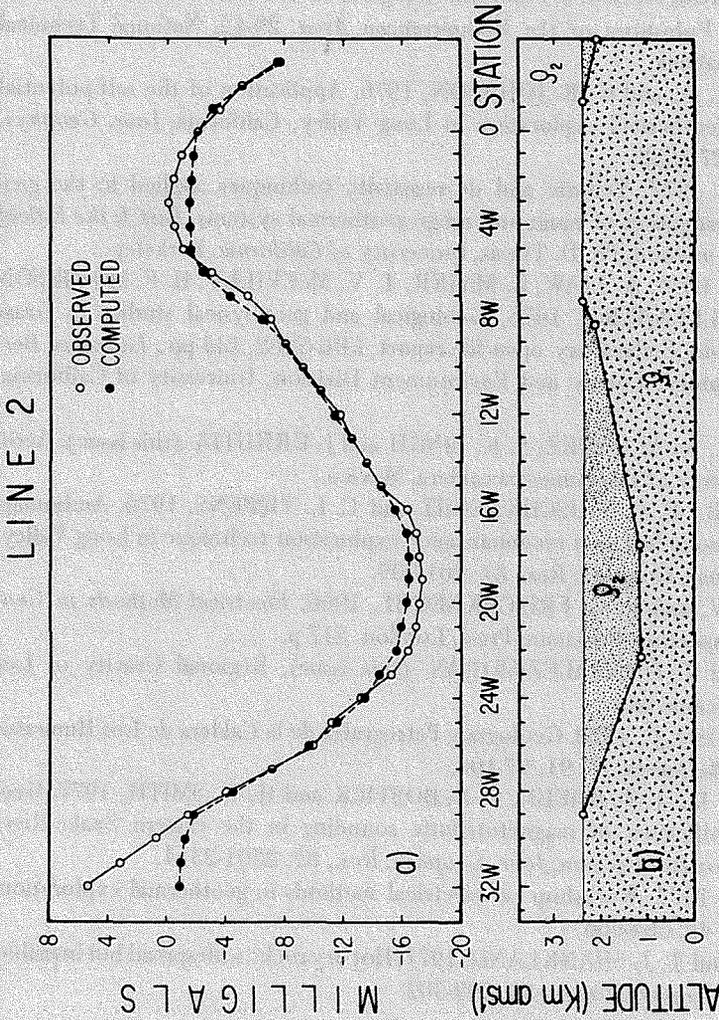
Figure 6. a) Observed and computed gravity profiles along Line 2. The former were obtained from the contoured data of Mena and González-Morán (this issue). The computed data were obtained by the same authors following the same procedure as described in their paper.

b) Gravity model corresponding to the computed data above. The density values are $\rho_1 = 2.67$ g/cm$^3$ and $\rho_2 = 2.35$ g/cm$^3$; calculations were made considering a flat surface at 2400 m amsl.

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