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Geometry of the El Fresnal basin, northern Chihuahua, Mexico, as inferred from three-dimensional gravity modeling

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RESUMEN

Desde 1998, se iniciaron los trabajos multidisciplinarios de la cuenca que ocupa en la actualidad el lago-playa El Fresnal, norte del estado de Chihuahua, para determinar las relaciones que existen entre la estructura, la geomorfología, los suelos, la distribución de la vegetación y la evolución paleoambiental cuaternaria. Como parte de este estudio, se obtuvieron 221 nuevos datos de gravimetría registrados dentro y en los alrededores de la cuenca, mismos que combinados con 506 datos preexistentes, son la base para la determinación de la geometría y la profundidad de los rellenos sedimentarios de la cuenca. Estos datos, a partir de un modelo de basamento-profundidad , indican que la cuenca El Fresnal consiste en dos subcuencas separadas por un pilar, actualmente enterrado y cubierto por alrededor de 500 metros de sedimentos. La subcuenca meridional carece de un lago-playa axial y se extiende a lo largo de 20 km en dirección N21ºW y contiene 800 metros de sedimentos. La geometría de la subcuenca sugiere un mediograben con un falla normal localizada en el flanco oeste. La subcuenca septentrional, dentro de la que se encuentra actualmente el lago-playa denominado localmente como laguna El Fresnal, se extiende a lo largo de 20 km con una orientación N10ºE y contiene 1500 metros de sedimentos. Similarmente a la subcuenca sur, su geometría sugiere un medio-graben; sin embargo, a diferencia de ésta, la falla normal principal se localiza en la parte este. Las orientaciones de las dos subcuencas sugieren que la de la parte sur es más antigua y se formó durante el Oligoceno tardío y el Mioceno temprano, seguida por la formación de la subcuenca norte posterior al Mioceno temprano, cuando la orientación y los esfuerzos tensionales cambiaron de orientación de WNW-ESE a E-W. Desde que el lago-playa ha sido confinado a la subcuenca septentrional, la subsidencia ocurre únicamente en ésta.

PALABRAS CLAVE: Anomalías gravimétricas, cuencas sedimentarias, México, Río Grande rift, Chihuahua.

ABSTRACT

A multidisciplinary study of the El Fresnal basin, Chihuahua, Mexico is being conducted to investigate the relationships between the structure, vegetation and geomorphology and the Quaternary paleoenvironment. As part of this study, 221 new gravity measurements were collected within the basin and combined with 506 preexisting measurements from the surrounding area to determine the basin geometry and the depth of the sediment infill. A basement-depth model calculated from these data indicates that the El Fresnal basin consists of two sub-basins separated by a basement high, which is presently buried by about 500 meters of sediments. The southern sub-basin, which lacks an axial playa lake, extends for 20 km in a N21ºW direction and contains 800 meters of sediments. The geometry of the sub-basin is suggestive of a half-graben with the major normal fault located to the west. The northern sub-basin, within which lies the playa lake Laguna El Fresnal, extends for 20 km in a N10ºE direction and contains 1500 meters of sediments. Like the southern sub-basin, its geometry is suggestive of a half-graben; however, unlike the southern sub-basin, the major normal fault is located to the east. In conjunction with previous studies of other rift basins comprising the Río Grande rift, the orientations of the two sub-basins suggest that the southern sub-basin formed first, during the late Oligocene to early Miocene, followed by the formation of the northern sub-basin sometime after the early Miocene when the orientation of the tensional stresses within the rift changed from WNW-ESE to E-W. Since the playa lake is now confined to the northern sub-basin, it appears that subsidence is presently occurring only in the northern sub-basin.

KEY WORDS: Gravity anomalies, sedimentary basins, Mexico, Río Grande rift, Chihuahua .

INTRODUCTION

The El Fresnal basin lies in the northwest part of the state of Chihuahua, Mexico (Figure 1), within the Chihuahua desert. The basin is one of several asymmetric grabens comprising the southern Río Grande rift (e.g. Seager and Morgan, 1979; Keller *et al*., 1989; Morrison, 1991), which formed by crustal extension since late Oligocene. It is roughly

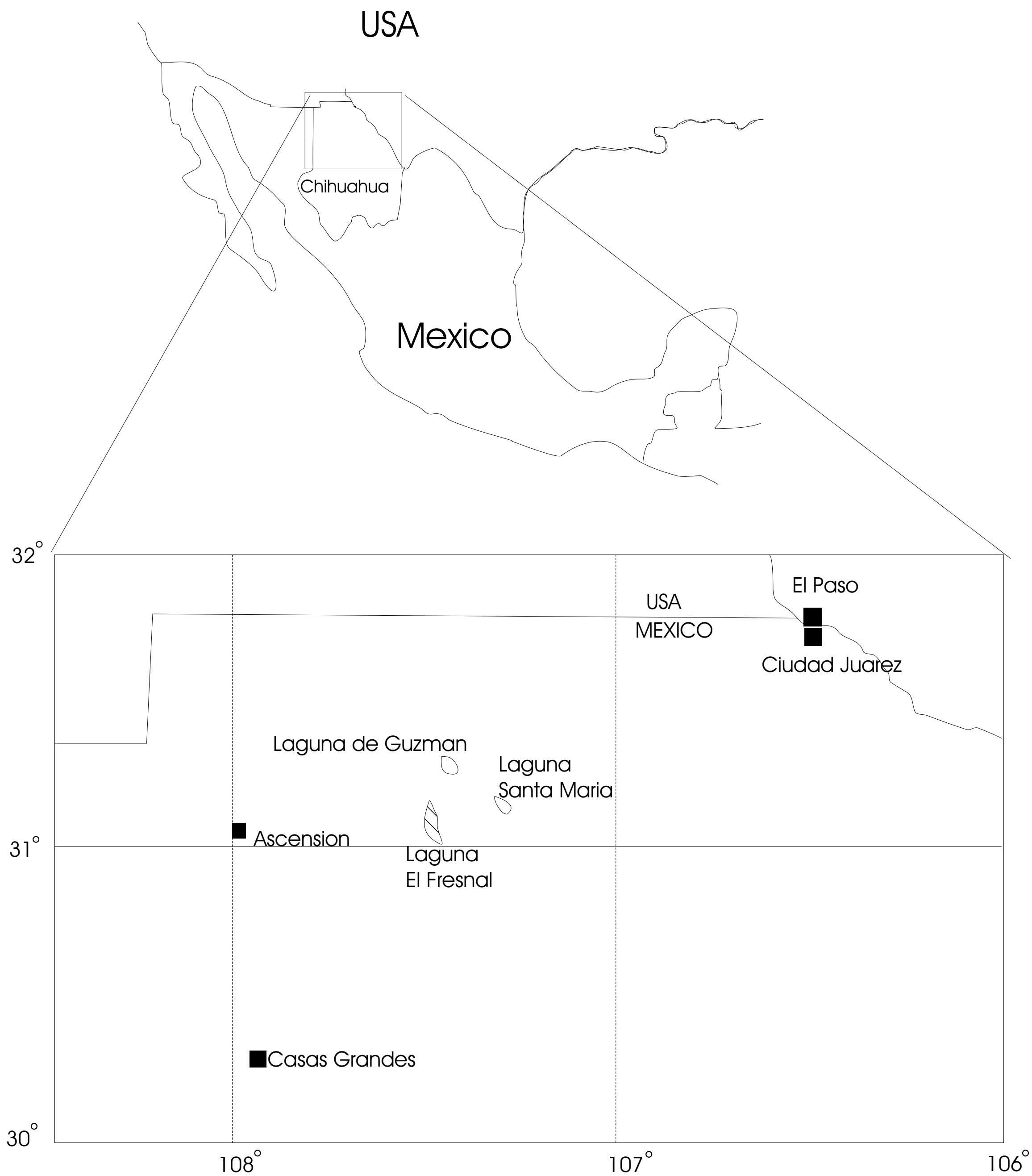

Fig. 1. Location map of study area.

40 km long and contains a playa lake, Laguna El Fresnal, in its northern sector (Figure 2).

In 1998, a multidisciplinary study (Campos-Enríquez *et al*., 1999; Maillol *et al*., 2000a, b; Ortega-Ramírez *et al*., 2001) of the basin was initiated to determine the relationship between the structure, vegetation and geomorphology and the Quaternary paleoenvironment. As a first attempt to investigate the structure of the basin, gravity data (Campos-Enríquez *et al*., 1999) were collected along an east-west oriented, 2-dimensional, profile crossing the center of the basin (Figure 3). The results indicate that the basin is a half-graben structure with the major bounding fault located in its western sector.

The purpose of the present study is to refine the study of Campos-Enríquez *et al*. (1999) by determining the 3-dimensional structure of the basin from gravity data employing

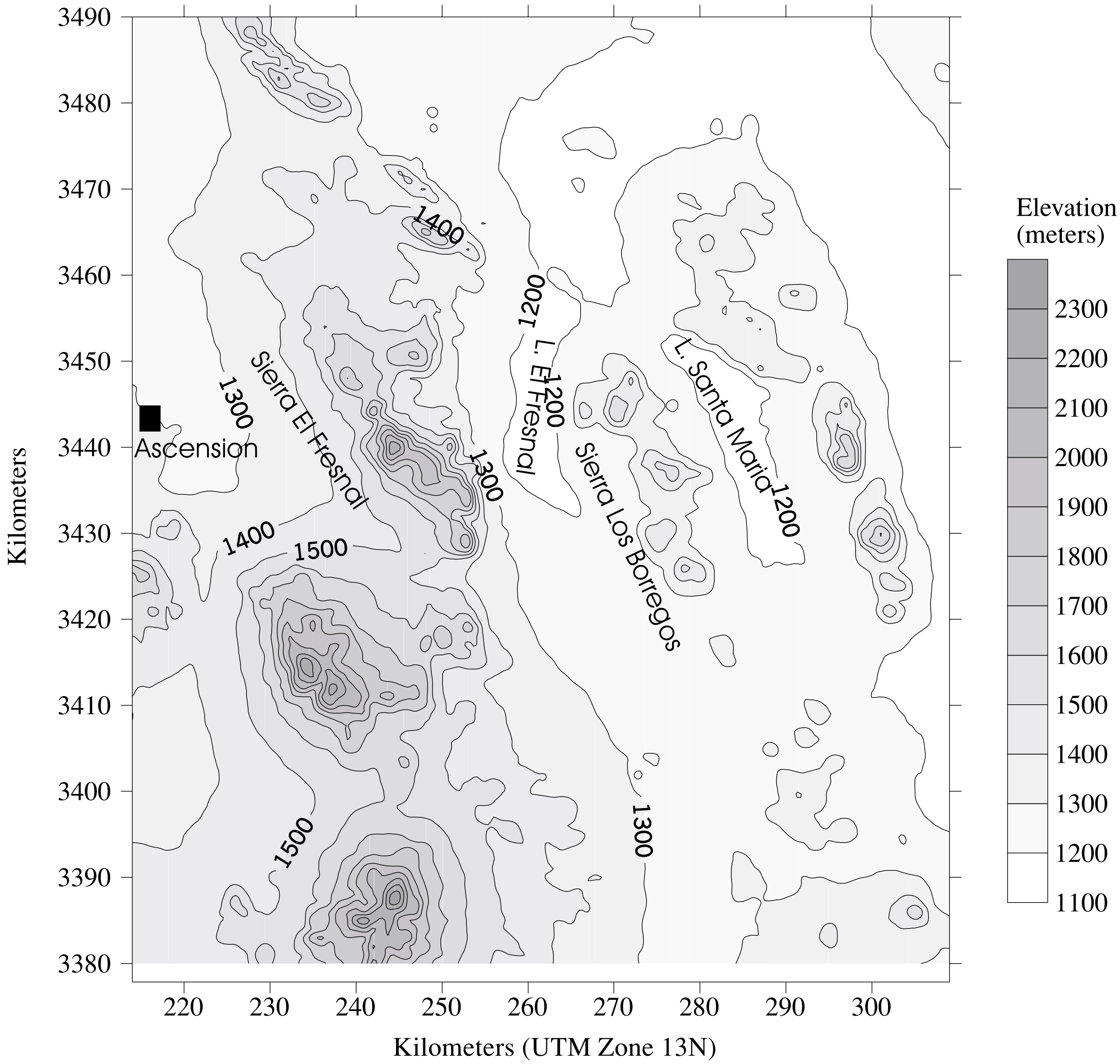

Fig. 2. Topographic map of the study area (GTOPO30 digital terrain data base). Contour interval = 100 meters.

the 3-D, gravity modeling algorithm of Bhaskara Rao and Ramesh Babu (1991). The results indicate that the El Fresnal basin consists of two sub-basins separated by a basement high, which is now buried by roughly 500 meters of sediments. The southern sub-basin contains 800 meters of sediments, with the main graben-forming fault located to the west. The northern sub-basin, in which is located the Laguna El Fresnal, contains 1500 meters of sediments, with the main graben-forming fault located to the east. The lack of an axial playa lake in the southern sub-basin suggests that the majority of subsidence/tectonic activity is presently occurring in the northern sub-basin.

GEOLOGIC SETTING

The El Fresnal basin is, arguably, located in the southernmost part of the Río Grande Rift system (Keller *et al.*, 1989; Seager and Morgan, 1979). As such, the basin most likely initially formed during the late Oligocene to middle Miocene as a result of ENE-WSW extension (Chapin and Seager, 1975; Bachman and Mehnert, 1978; Muehlberger *et al.*, 1978; Seager *et al.*, 1984; Gustavson, 1991; King and Ellis, 1990; Morrison, 1991; Mack *et al.*, 1994; Perez-Arlucea *et al.*, 2000). During the latest Miocene, the orientation of the extensional stresses changed to an east-west direction,

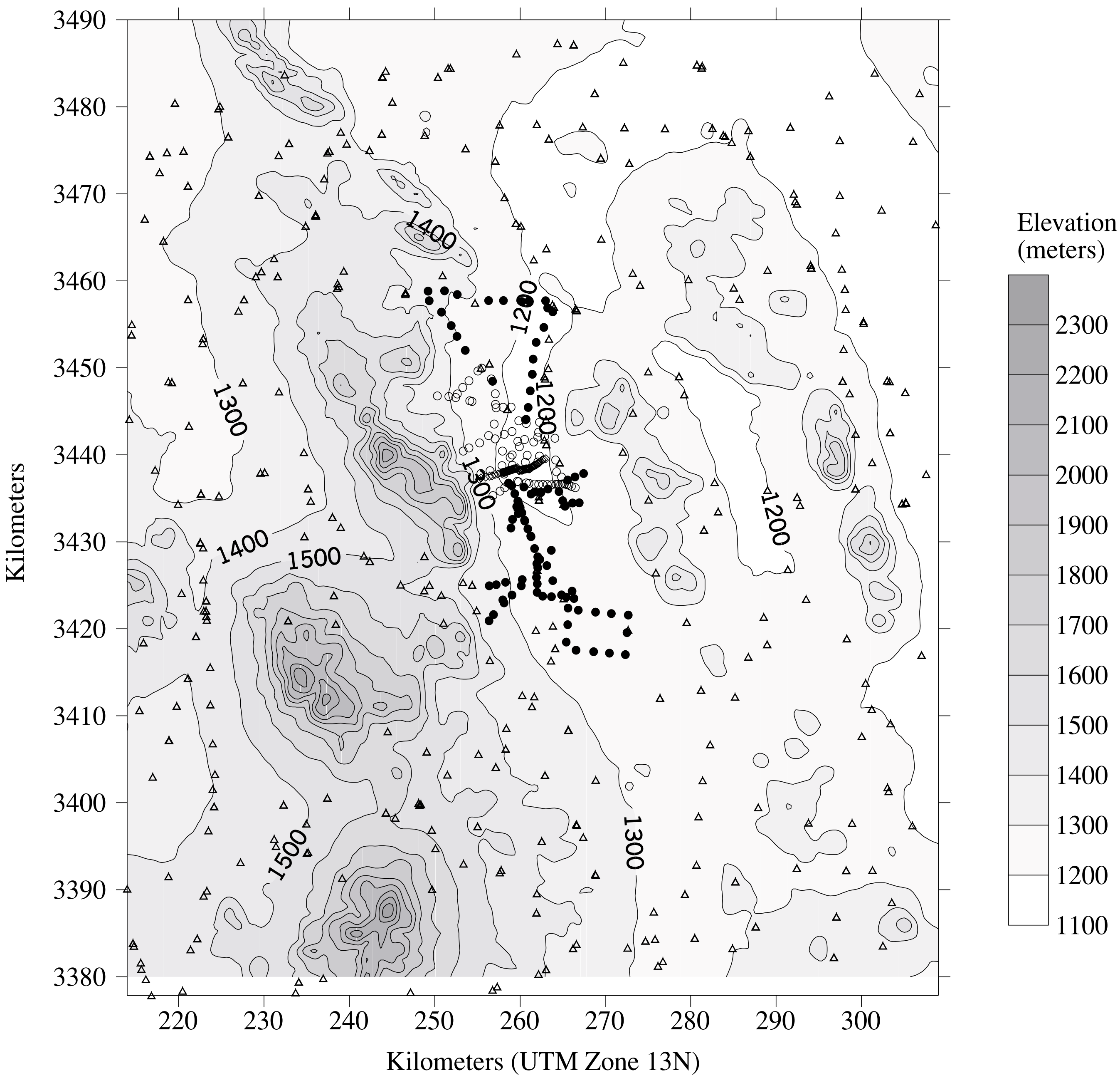

Fig. 3. Location of gravity stations. Stations marked by open triangles are those of PEMEX, open diamonds are those of Campos-Enríquez *et al*. (1999), open circles are those of the May 1998 survey, and the solid circles are those of the June 2000 survey.

and the structure of the basin was most likely affected by this change. These stresses have continued to act during the Quaternary within the Río Grande Rift (Seager and Morgan, 1979).

The El Fresnal basin is bounded on the west by the mountain ranges of Sierra El Fresnal. The sierra exhibits an overall north-south orientation, however, adjacent to the basin it consists of two NW-SE oriented, *en echelon* mountain ranges (Figure 2). The Sierra El Fresnal is comprised of Tertiary acidic volcanic rocks at its base, capped by Quaternary basalts and andesites (Campos-Enríquez, *et al*., 1999). The basin is bounded on the east by the Sierra Los Borregos. This range consists of mid to upper Tertiary rhyolites and acidic tuffs at its base, capped by Pliocene/Pleistocene plateau-type basalts (Seager *et al*., 1984). Gravity data (Campos-Enríquez *et al*., 1999) suggests that the basin is formed by a half-graben with the major bounding fault located on the west side of the basin, and that it contains about 1 km of sediment.

No subsurface information is presently available from which to determine directly the nature of the sediments infilling the basin. However, studies (Strain, 1966, 1969; Tedford, 1981; Seager *et al.*, 1984; Stuart and Willingham, 1984) conducted within other basins located close to the El Fresnal basin suggest that the lower sediment section is most likely comprised, in part, of Tertiary to lower Quaternary fluvial and lacustrine sediments correlative with the Santa Fe supergroup found throughout much of West Texas, New Mexico and northern Chihuahua. Active depositional environments within the basin include clastic gravel alluvial fans along the basin margins, and axial playa sediments in the northern part (Ortega-Ramírez *et al*., 2001).

DATA

A total of 727 gravity measurements (Figure 3) were used in this study. Of these measurements, 506 are proprietary data from Petróleos Mexicanos (PEMEX), 56 are from the 2-D study of Campos-Enríquez *et al.* (1999) conducted across the central part of the Laguna El Fresnal employing a SCINTREX microGal gravity meter, and 165 are new measurements collected within the Laguna El Fresnal during May, 1998 and June, 2000. A LaCoste & Romberg model G gravity meter from the University of Texas El Paso was employed during the May 1998 survey. Two SCINTREX microGal gravity meters (one provided by the Instituto Mexicano del Petróleo, and one by the Facultad de Ingenería, UNAM) were employed during the June 2000 survey.

Topographic control was obtained by first-order levelling during the survey of Campos-Enríquez *et al.* (1999), by differential GPS measurements during the May 1998 survey and from 1:50,000 scale topography maps during the June, 2000 survey. The topography illustrated on the various figures of this article is constructed from the GTOPO30 global digital elevation model obtained from the United States Geological Survey, EROS Data Center, Sioux Falls, South Dakota. The digital terrain elevation data for Mexico was provided to the EROS Data Center by INEGI.

All gravity measurements, with the exception of the proprietary data, were tied to the International Gravity Standardization Net 1971 (IGSN71) gravity base located at the Ciudad Juárez international airport, Chihuahua, Mexico (31°44'N, 106°28'W; absolute gravity = 979055.26 ± 0.2 mGals). These data were corrected for instrument drift and the effects of Earth-tides, and reduced to simple Bouguer anomaly values employing the World Geodetic System 1984 (WGS84) ellipsoidal gravity formula and a reference density of 2.67 g/cm^3.

The proprietary data consists of widely spaced measurements located within and adjacent to the Laguna El Fresnal. These data were primarily used in the construction of a regional Bouguer Anomaly map for the area surrounding the Laguna El Fresnal. These data include both simple and complete Bouguer anomalies. Information as to the reference density, the absolute datum, the reference spheroid and the terrain correction method used to calculate the anomalies was not provided to the authors. However, a comparison between these data and newly collected data indicates that these data were most certainly tied to the International Gravity Standardization Net 1971 (IGSN71) and that the reference density used in the Bouguer reduction was 2.67 g/cm^3. As these data were collected during the 1970's, the theoretical gravity was most likely calculated using the 1967 Geodetic Reference System (GRS67) or perhaps the World Geodetic System 1972 (WGS72). The uncertainty as to which theoretical reference system was used poses no major problem to the present study as the differences between the WGS84 and the WGS72 and GRS67 at the latitude of the study area is about 0.59 mGals and 0.85 mGals, respectively.

METHODS

The 3-D, rectangular prism, iterative modeling algorithm of Bhaskara Rao and Ramesh Babu (1991) was employed to ascertain the geometry of and the thickness of sediments infilling the El Fresnal basin from the gravity data. The algorithm determines the thickness of sediments within a sedimentary basin from a grid of residual gravity values. The residual gravity is determined by subtracting a regional field from the Bouguer anomalies. In the algorithm, a quadratic density function can be used to approximate the decrease of the density contrast between the sediments and the surrounding rock with depth. One disadvantage of the method is that it assumes a flat basin surface and that all gravity stations lie on this surface.

In the present study, the grid of the residual gravity was constructed as follows. First, an analysis was done to determine if terrain corrections for the new data were necessary. The analysis, the details of which are presented in the following section, indicated that the terrain corrections are most likely small and, thus, could be ignored. This allowed us to combine the complete Bouguer anomaly values of the proprietary data with the simple Bouguer anomaly values of the remaining data. A krigging method was then used to grid the Bouguer anomaly data into a 1 km x 1 km grid. This grid was then smoothed using a running, 2 grid point x 2 grid point, smoothing, matrix in which the center point was given a weight of 10 and all other points a weight of 1; the final smoothed value being the weighted average of the values contained in the smoothing matrix

Next, a regional trend for the study area was determined by best-fitting (in the least squares sense) a first-order polynomial surface to the Bouguer anomaly grid. This best-fit surface was then shifted by a constant amount. The optimal shift was selected to be the one that produced a rough match between the boundaries (the zero-depth contour) of the basin model obtained from the modeling algorithm and the actual basin margin as defined from surface observations. A similar approach for determining the residual field was used by El-Batroukh and Zentani (1980) in their study of the Raguba oil field, Libya. The residual anomaly grid is thus the Bouguer anomaly grid minus this shifted, best-fit surface.

This residual anomaly grid was then input into the modeling algorithm to produce a map of the depth of sediments contained within the Laguna El Fresnal basin. As no subsurface density information is available for this area, the variation with depth (z) of the density contrast ($\Delta\rho$) between the sediments contained within the basin and the surrounding rock was assumed to follow the relation, $\Delta\rho(g/cm^3) = -0.56 + 0.18z(km)$. This density function approximates a sedimentary section consisting of unconsolidated alluvium at the surface and consolidated sandstones at a depth of 2 kilometers.

The algorithm also allows the user to specify the number of iterations used in the inversion. To speed up the algorithm, it also allows the user to specify a distance from a grid node beyond which an approximate equation for the attraction of the prisms is used. A separate distance can be specified for three stages of the iteration process. In the present study, 10 iterations were used to produce mis-fits of less than 0.5 mGals between the gravitational attraction of the model and residual gravity within the basin. During iterations 1 to 2, 3 to 8, and 9 to 10, the distance beyond which the approximate equation is used was set to 1, 3, and 5 km, respectively.

RESULTS

Terrain Corrections

Correcting the data for the effects of topography is a time consuming process. Thus, it is worth spot-checking the data to determine if the terrain effects can safely be ignored in the analysis. The proprietary data, which contains both simple and complete Bouguer anomalies, allows for the construction of a general terrain correction map (Figure 4a), from which one can obtain a rough idea of the expected magnitudes of the terrain corrections in the study area. This map suggests that the terrain corrections at the locations of the new stations (Figure 4b) are all less than 1 mGal. As will become apparent later, a 1 mGal error does not affect our conclusions about the geometry of the El Fresnal basin. Thus, in the present study, we can safely ignore the effects of topography, and treat the simple Bouguer anomaly values for the new data as being equivalent to complete Bouguer anomaly values. The resulting Bouguer Anomaly and smoothed Bouguer Anomaly maps are shown in Figures 5a, and 5b, respectively.

Regional Determination

The first-order polynomial surface (Figure 6) which best fit the Bouguer Anomaly grid is:

$$z(x,y) = -746.747 + 0.203295x + 0.157076y,$$

where the units of z are mGals, and the units of x and y are kilometers.

The appropriate shift of this surface was determined to be –4 mGals by comparing the zero depth contour of the model basin with the edge of the sedimentary fill of the basin as defined from surface observations. The determination of the desired shift is illustrated in Figure 7. Figure 7a illustrates the modeled basement depth in which no shift to the best-fit regional was applied; the topographic map of the area is superimposed on the basement depths. The 1300 and 1400 meter contours approximate the limit of sedimentary fill within the southern half of the basin to the east and west, respectively. As illustrated, the zero depth contour of the resulting basement-depth model does not coincide with either of these contours. Also, the cluster of 5 stations (marked ‘A’ on Figure 7a) located at the northeast margin of the basin lie over the sediment infill of the basin, whereas, they lie outside the basin as defined by the model. Figures 7b, 7c, and 7d illustrate the basement-depth models calculated by shifting the best-fit surface by –2, -4, and –6 mGals, respectively. The zero depth contour of the basement-depth model produced using a –4 mGal shift of the regional most closely coincides with the actual eastern edge of the basin, and the cluster of five stations lies over the sediment infill of the model. The zero depth contour of the basement-depth model produced using a –6 mGal shift better fit the western margin of the basin, however, it overshot the eastern margin. Therefore, we feel that the –4 mGal shift is the most appropriate shift.

Residual Gravity and Model Residuals

The residual gravity map obtained by subtracting the -4 mGal shifted, best-fit surface from the grid of smoothed, Bouguer anomaly values is illustrated in Figure 8. The gravity signature of the El Fresnal basin extends for about 40 km in an overall NNW-SSE direction, however, in the northernmost part of the basin, its orientation changes to N-S. The residual gravity exhibits two isolated, closed gravity lows. The southernmost, located south of the Laguna El Fresnal, exhibits

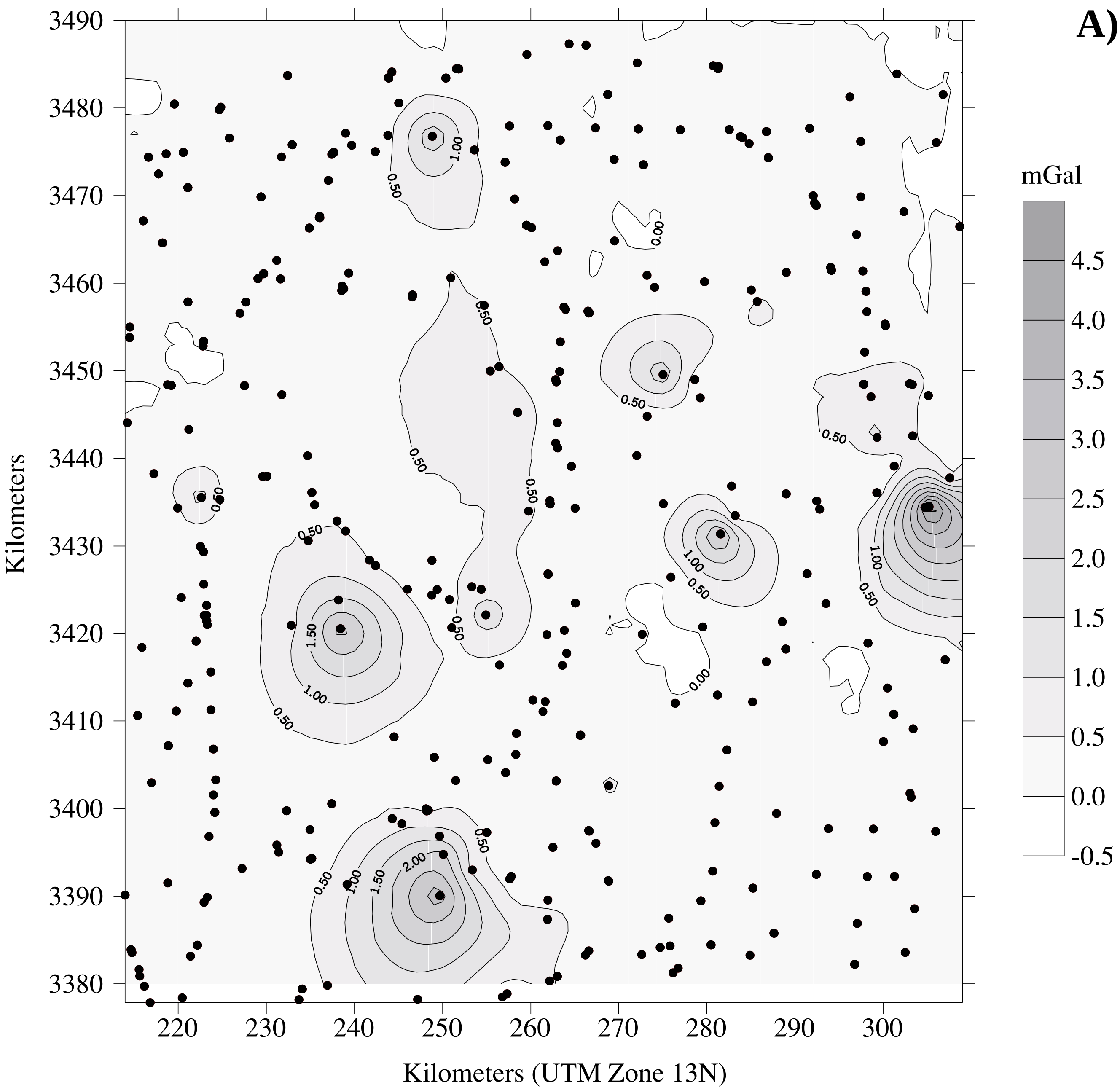

Fig. 4. A) Terrain correction map constructed from the PEMEX gravity data (solid circles).

a minimum of –14 mGals. The northernmost exhibits a minimum of –20 mGals. The closed gravity low associated with the Santa María basin exhibits a minimum of –14 mGals. Positive residual anomalies are associated with the mountain ranges, perhaps indicating that the reference density of 2.67 g/cm^3 used in the Bouguer reduction was somewhat low.

The fit between the residual gravity and the calculated gravity is illustrated in Figure 9. The fit is better than ±0.5 mGal within the El Fresnal and Santa María basins. The areas of large misfits correspond to the areas of positive residual gravity values, i.e. the mountain areas. The large misfits are the result of the fact that, since a negative density contrast is used, positive anomalies cannot be modeled using the algorithm.

Basin Geometry and Depth of Sediment Infill

The basement-depth model (Figure 10) indicates that the El Fresnal basin consists of two sub-basins. The southern basin extends for 20 km in a N21°W direction and contains approximately 800 meters of sediment. Although more data

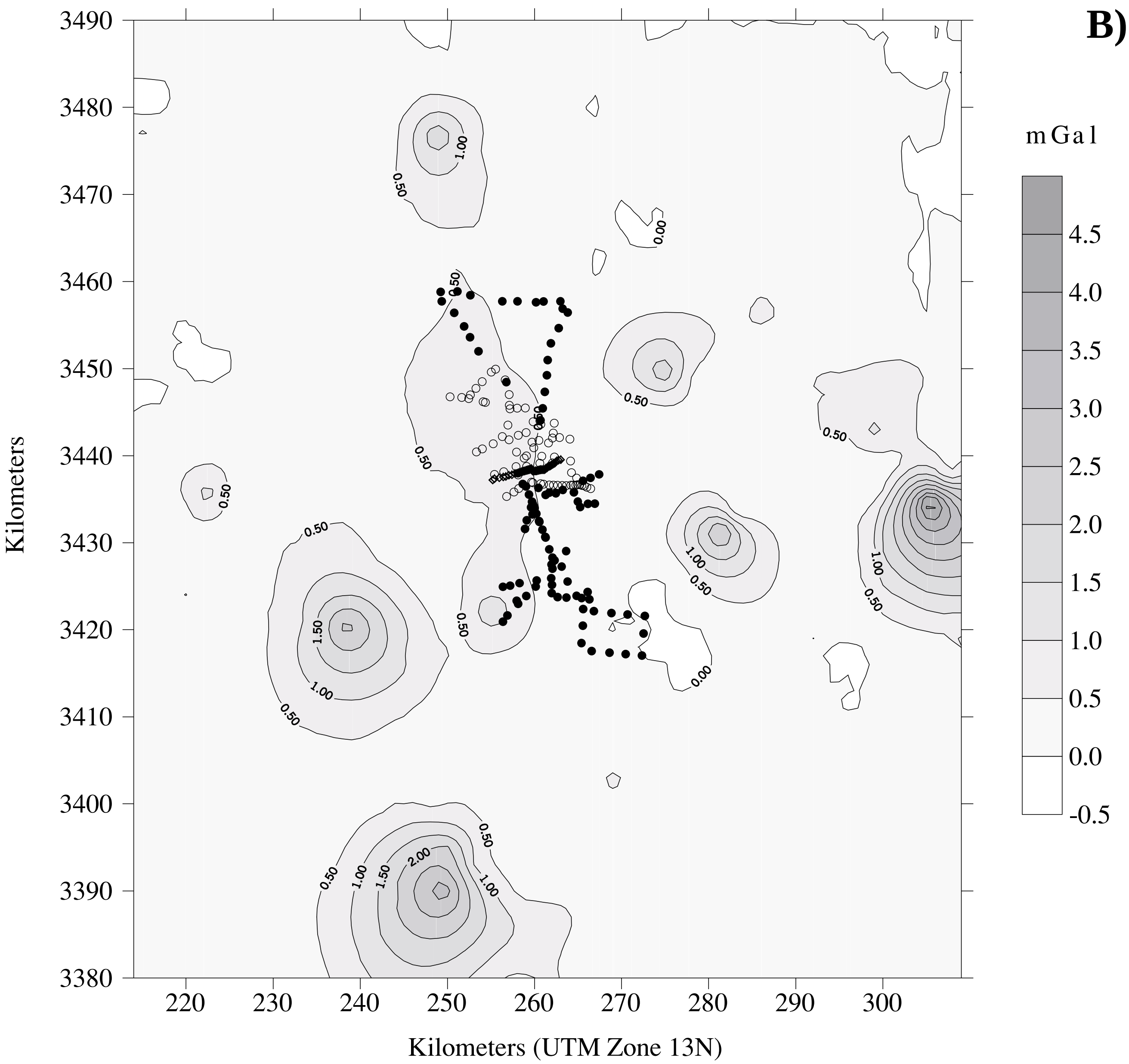

Fig. 4. B) More recent gravity stations superimposed on the terrain correction map. See caption of Fig. 4 for symbol definitions.

needs to be collected on the eastern flank, the available data suggests that this sub-basin is asymmetric, with a steeper slope to the west, suggesting that it is a half-graben structure with the main normal fault being located along the western margin of the basin. Campos-Enríquez *et al.* (1999) obtained similar results in the area between the two sub-basins. Also, the model indicates an eastward shift of the depocenter. Specifically, the area of maximum sediment thickness lies west of the present day basin axis (Figure 7c).

The northern basin, which contains the Laguna El Fresnal, extends for 20 km in a N10 °E direction and contains approximately 1500 meters of sediments. In contrast to the southern sub-basin, the basement is steeper on its eastern margin, suggesting that the main normal fault lies along the eastern margin of the basin. Like the southern sub-basin, the model indicates an eastward shift of the depocenter; the area of maximum sediment thickness lies west of the Laguna El Fresnal, which we assume is the area of maximum present-day subsidence.

A side result of this study is that the Santa María Basin, located east of and parallel to the southern sub-basin, contains up to 1 km of sediments. However, more data is needed in that area to better define the geometry of this basin.

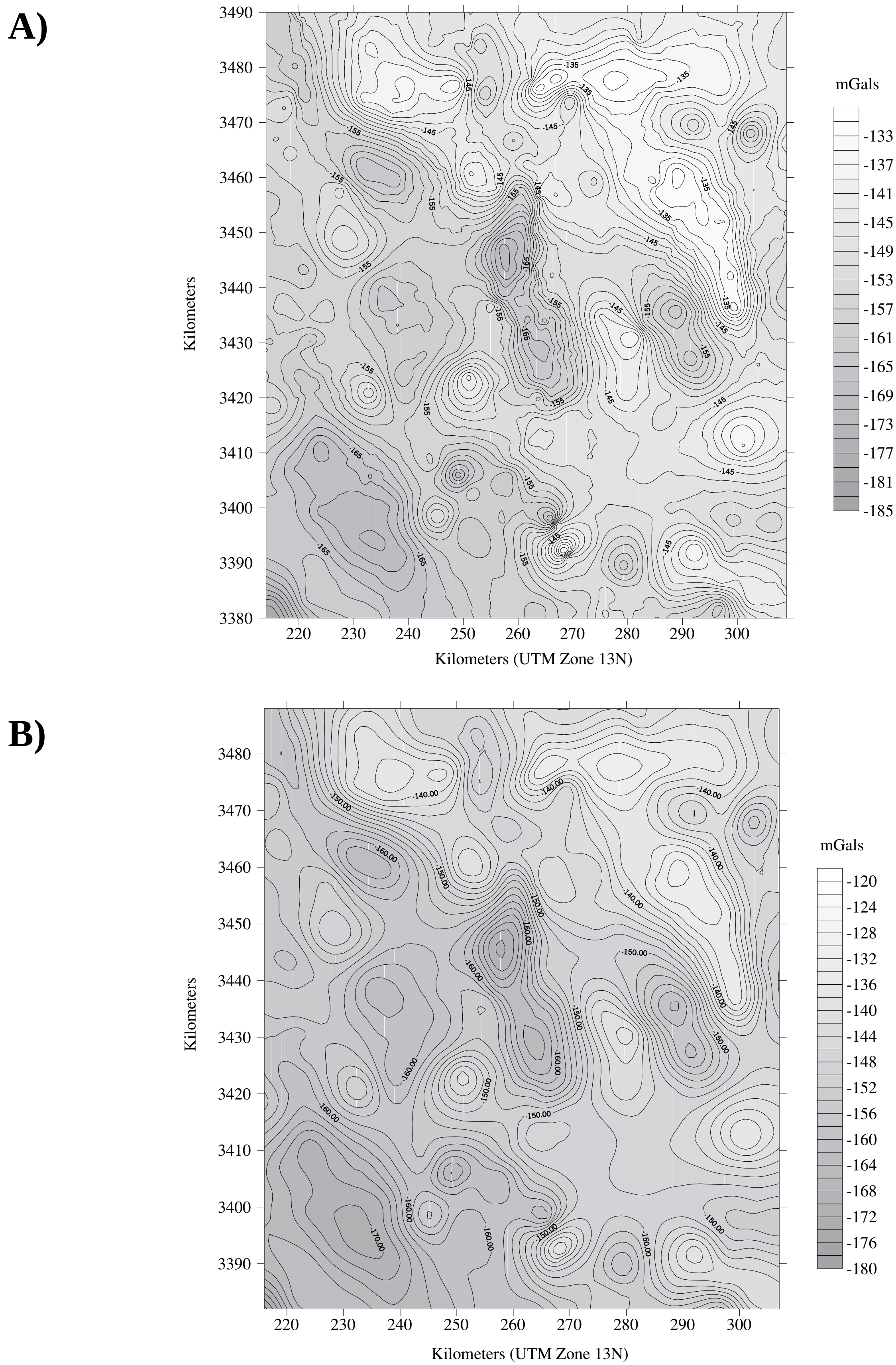

Fig. 5. Bouguer Anomaly map. A) unsmoothed.; B) smoothed. Contour interval = 2 mGals.

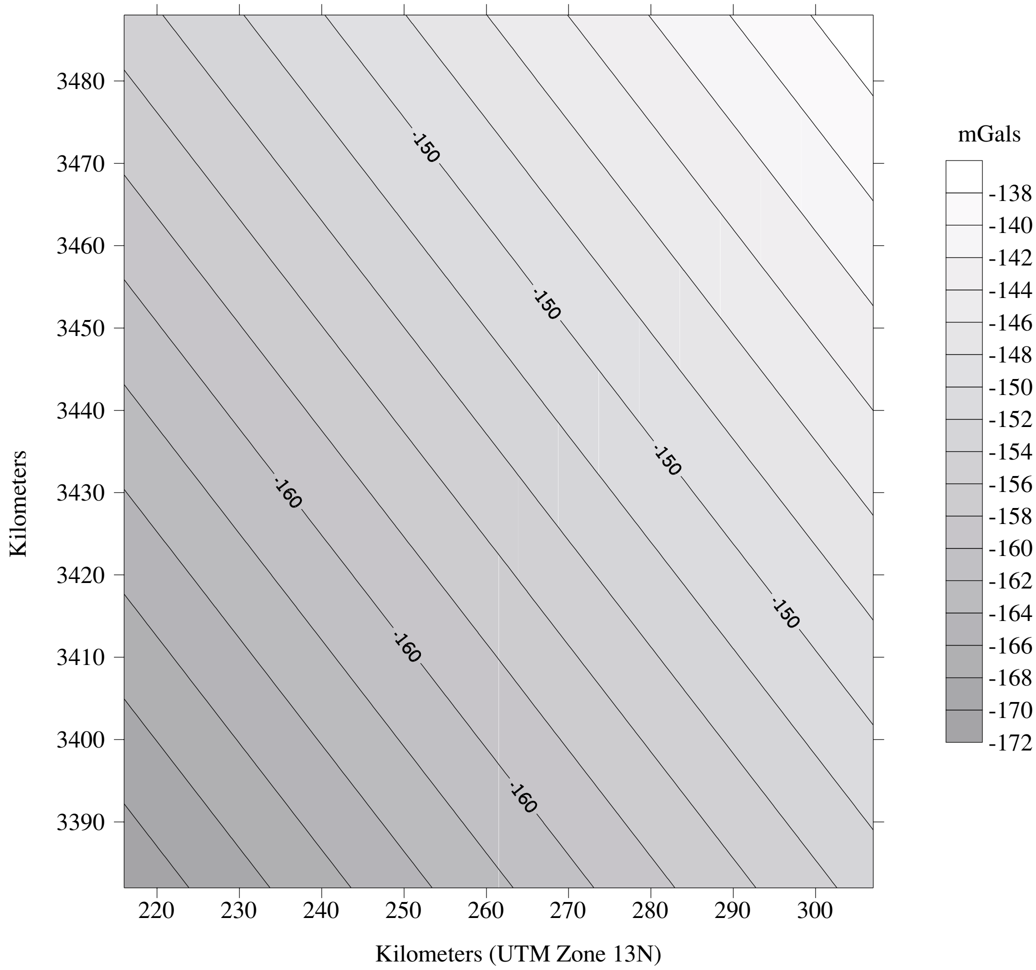

Fig. 6. Planar surface which best fits the smoothed Bouguer Anomaly grid.

DISCUSSION

Extension within the Río Grande rift has been active since the late Oligocene. Prior to early Miocene, these stresses were oriented ENE-WSW, whereas since that time, they have been oriented east-west. The results of the present study indicate that the southern part of the El Fresnal basin, which arguably lies within the southern part of the Río Grande rift, is oriented N21°W, whereas the northern part of the basin exhibits a N10°E orientation. The orientation of the southern sub-basin is consistent with its formation during the time when the extensional stresses were oriented ENE-WSW. The orientation of the northern sub-basin is consistent with its formation during the time when the extensional stresses were oriented east-west. These observations suggest that the basin may have formed in two stages as follows.

During the late Oligocene to Early Miocene, the southern-sub-basin formed as a result of the ENE-WSW oriented extension, most likely by the simple shear mechanism proposed by Wernicke (1985). During this time the basin probably existed as a single basin formed by a single half-graben system. From the geometry (Figure 10) of the western margin of the northern sub-basin, the basin at this time most likely extended northward from 3 418 000 m to 3 447 000 m (UTM coordinates, zone 13N).

The major normal fault bounding the northern sub-basin to the east next formed as a result of the reorientation of the extensional stress to an east-west orientation. Its formation resulted in the present day, paired half-graben system. It is not known if the formation of the new fault deactivated the older fault, or if both faults were active at the same time. However, given the substantial overlap of the two faults, and the lack of an expected uplift within this overlap zone (which encompasses most of the present day area of the northern sub-basin), it seems likely that the western fault was deactivated north of 3 440 000 m.

If the western fault remained active south of 3 440 000 m then the basement high separating the two sub-basins could

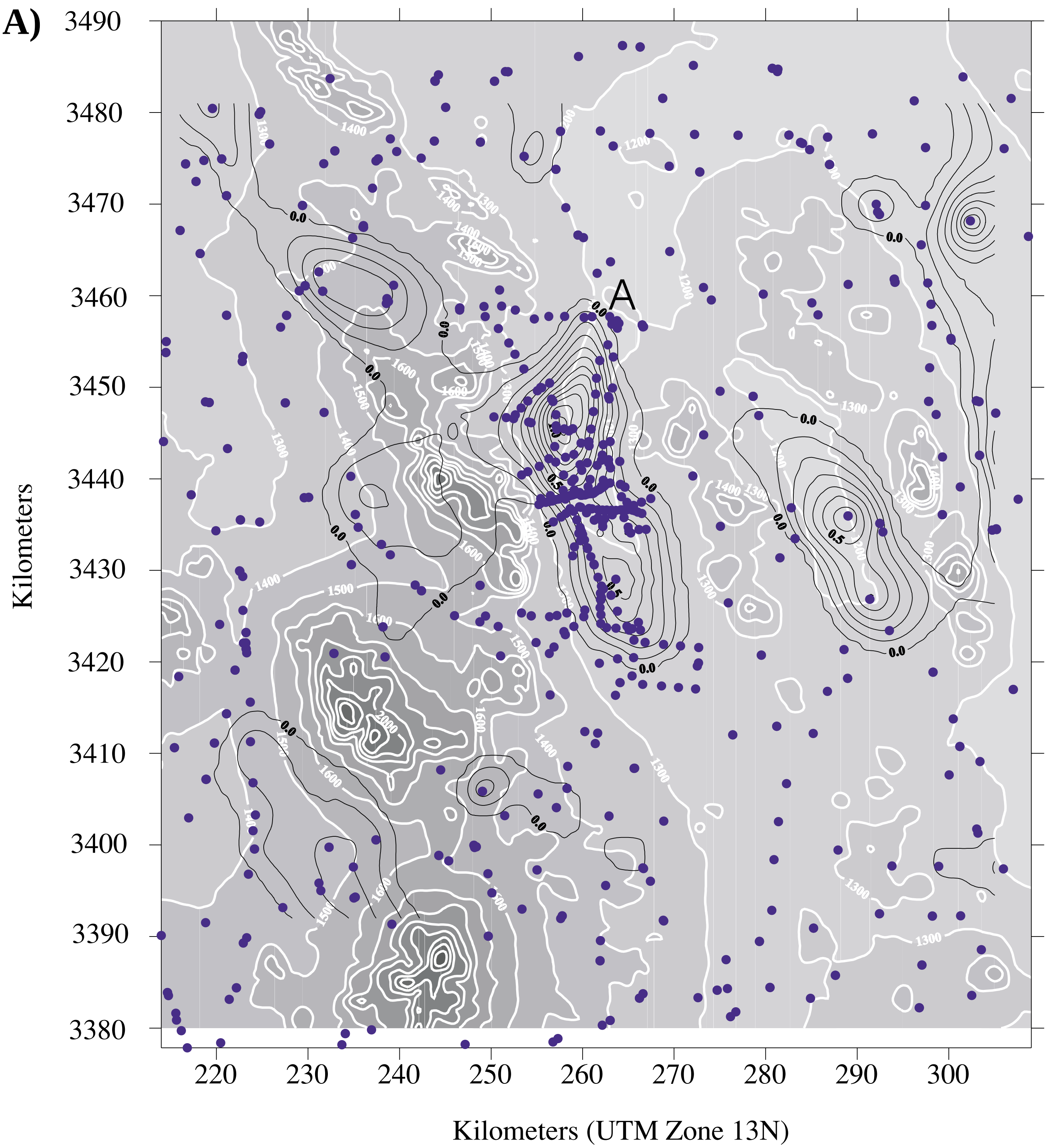

Fig. 7. Basement-depth models superimposed on the topographic map. Basement-depth model calculated by shifting the best-fit planar surface by A) zero, B) –2 mGals, C) –4 mGals, and D) –6 mGals.

have conceivably formed within an accommodation zone of an active, paired, half-graben system, similar to those observed in the East African Rift (e.g., Bosworth, 1987). If so, the 'basement' high may consist, in part, of uplifted and folded sediments originally deposited within the old basin. If the western fault was completely deactivated, the origin of the basement high becomes more difficult to explain. Perhaps it reflects the geometry of the original basin.

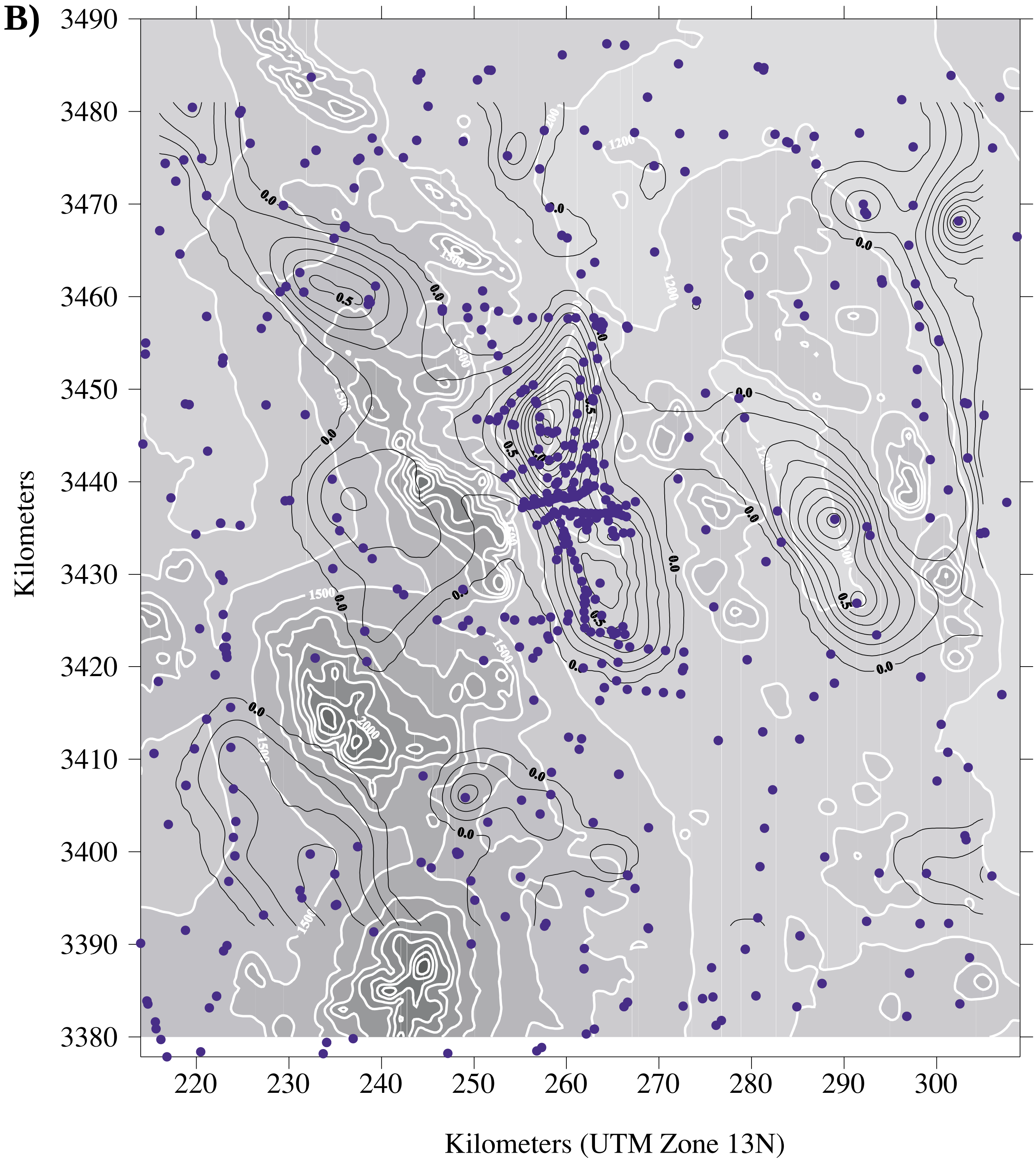

Fig. 7. Continued.

It is not known if the western fault is presently active. However, the playa lake is now confined to the northern sub-basin, suggesting that the majority of subsidence and tectonism is presently occurring in the northern sub-basin. This suggests that the western boundary fault may be inactive at present. However, a microseismicity survey is needed to resolve this uncertainty.

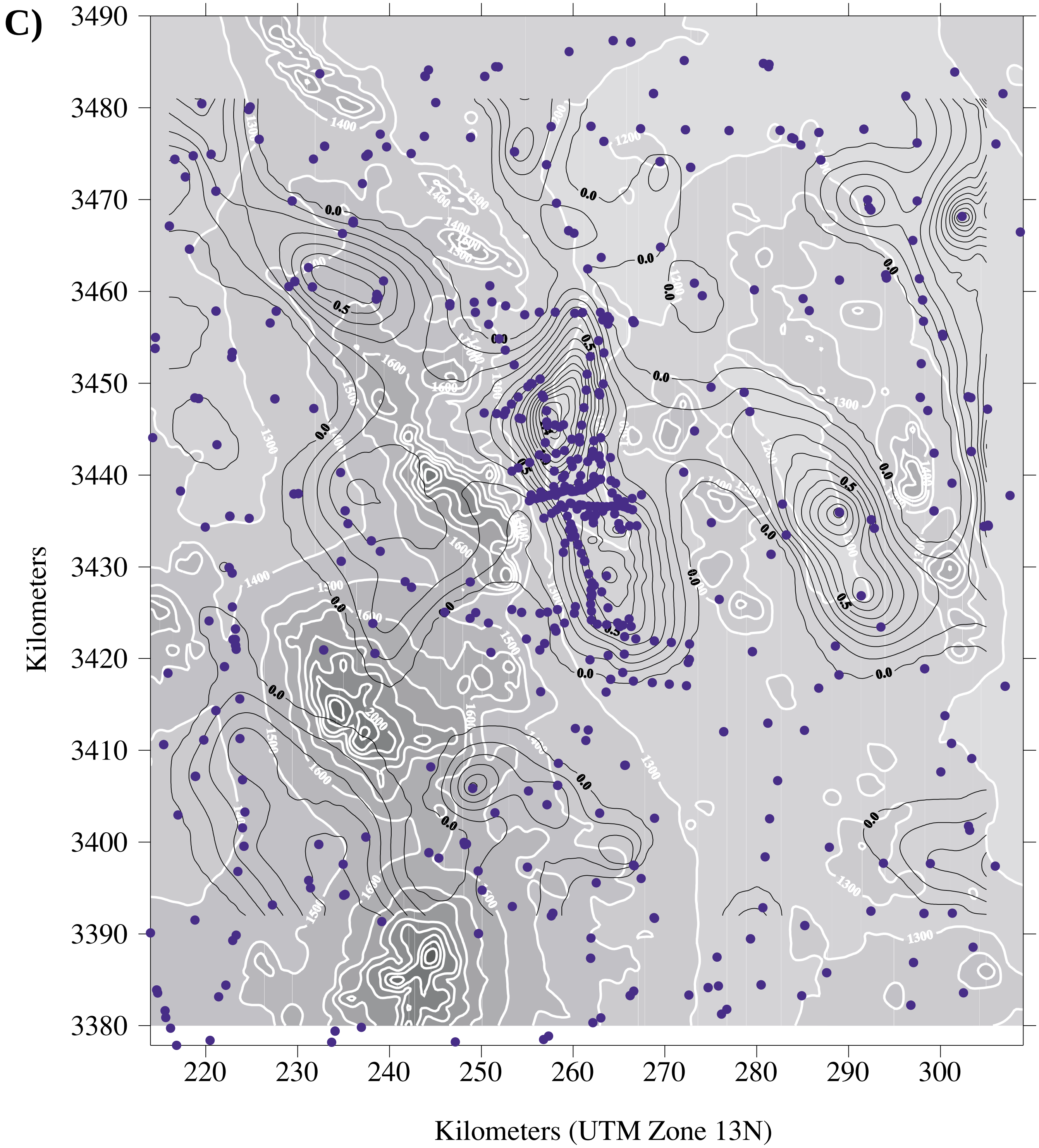

Fig. 7. Continued.

CONCLUSIONS

Results of the three-dimensional gravity modeling and integration of geomorphologic and tectonic data indicate the following:

(1) The El Fresnal basin consists of two sub-basins separated by a basement high, which is presently buried by about 500 meters of sediments.

(2) The southern sub-basin, which lacks an axial playa lake,

D)

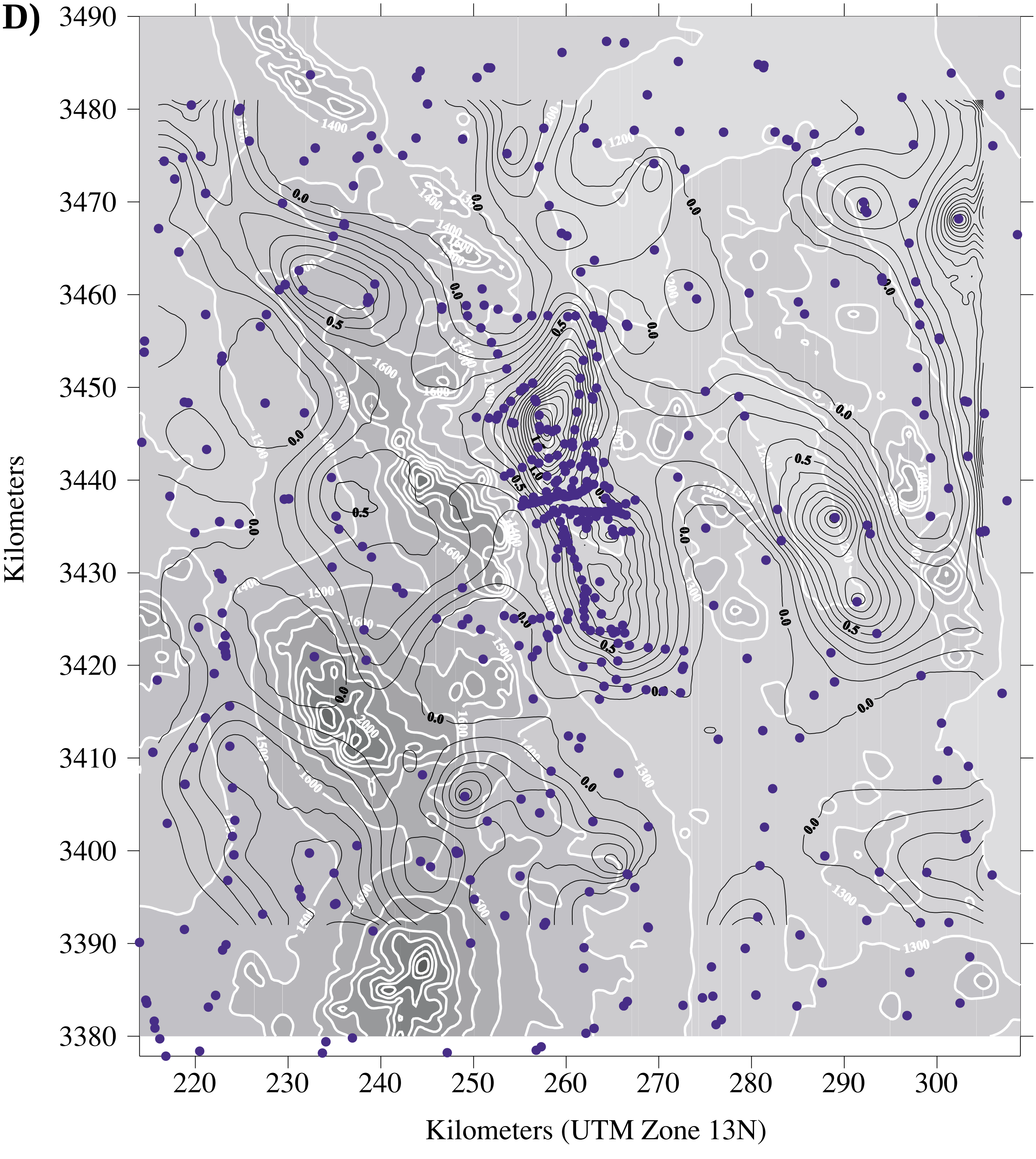

Fig. 7. Continued.

extends for 20 km in a N21°W direction and contains 800 meters of sediments. The geometry of the sub-basin is suggestive of a half-graben with the major normal fault located to the west.

(3) The northern sub-basin, within which lies the Laguna El Fresnal, extends for 20 km in a N10°E direction and contains 1500 meters of sediments. Like the southern sub-basin, its geometry is suggestive of a half-graben,

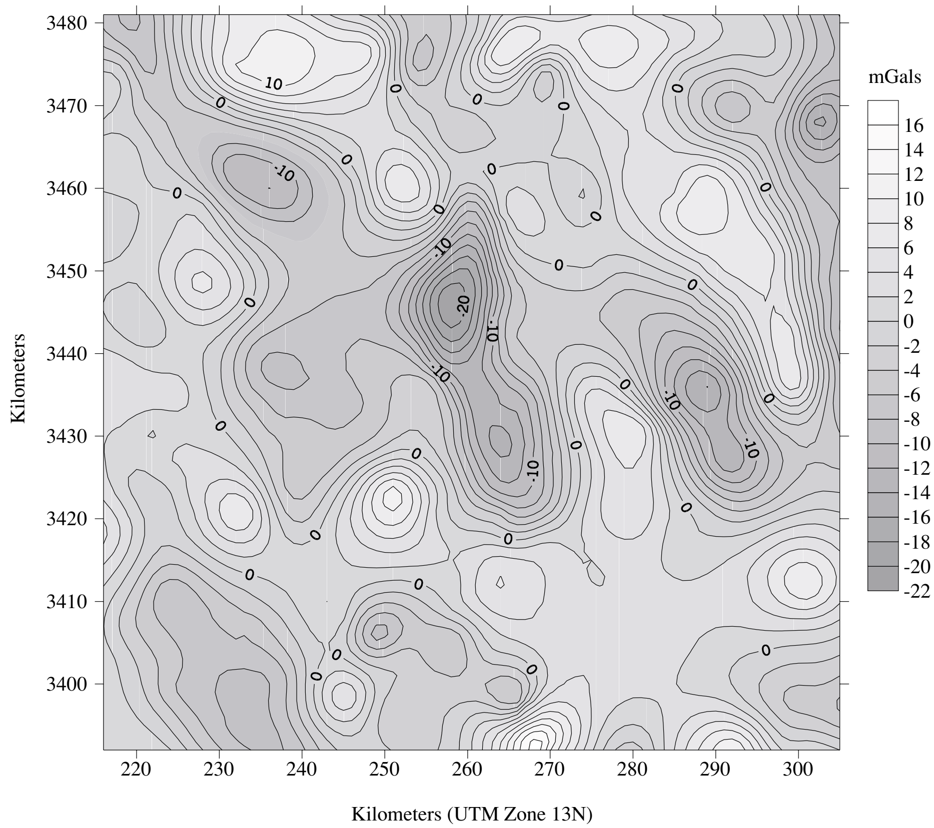

Fig. 8. Residual gravity map. Contour interval = 2 mGals.

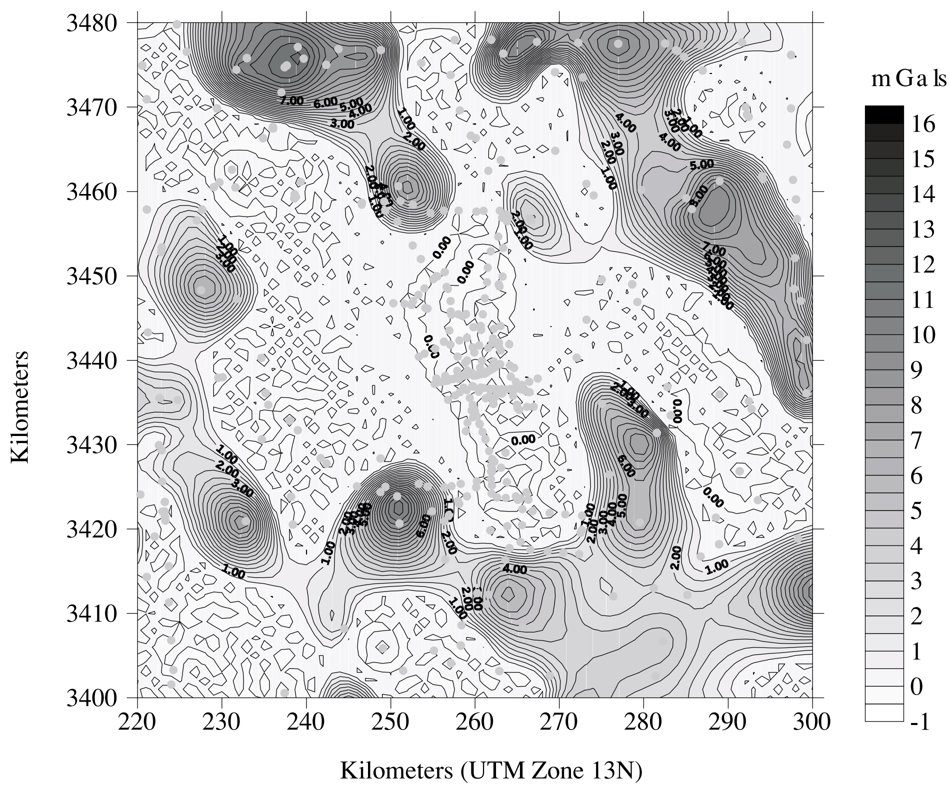

Fig. 9. Contour map of the difference between the residual gravity and the gravitational attraction calculated for the –4 mGal-shifted, basement-depth model.

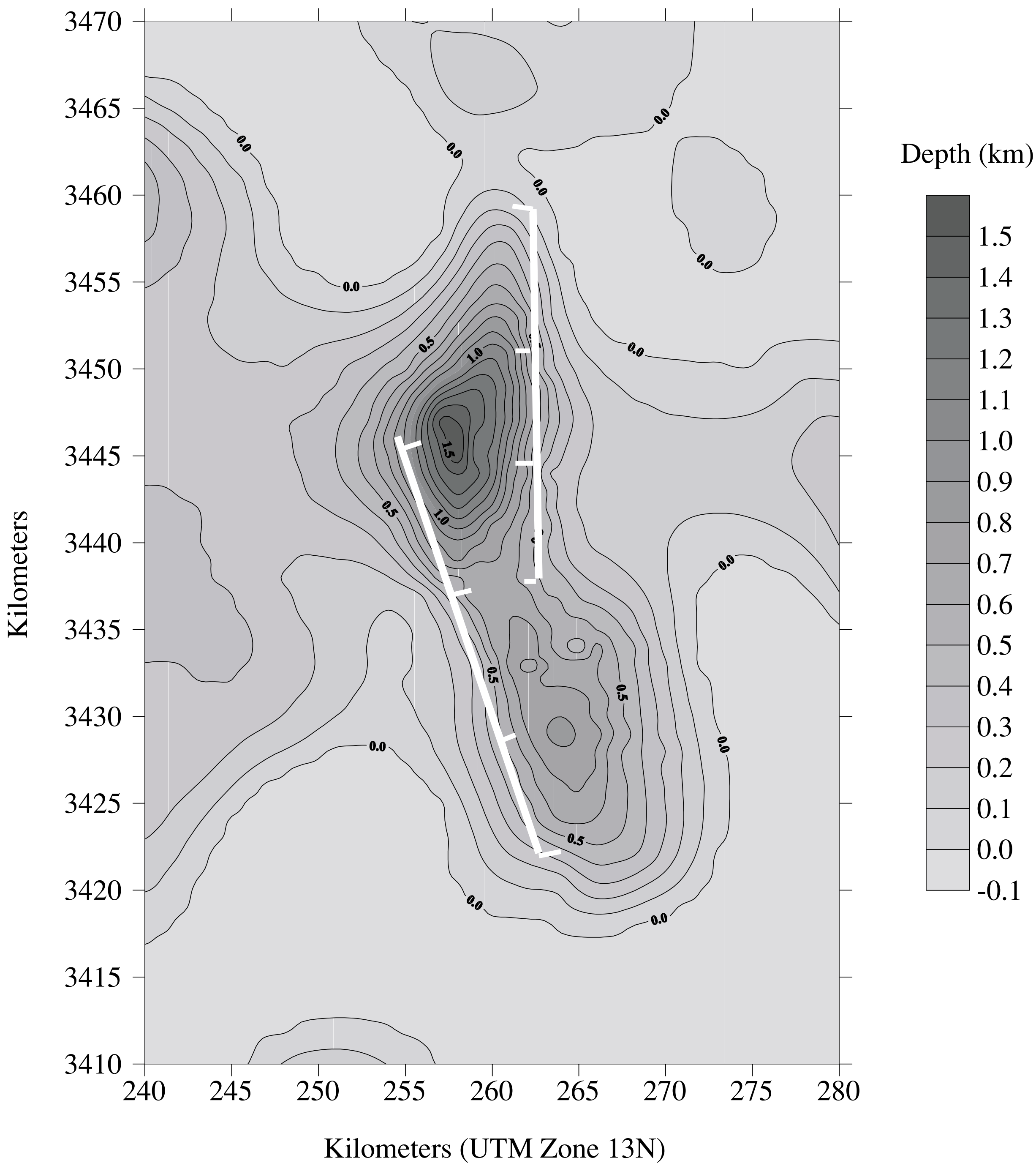

Fig. 10. Final basement-depth model for the El Fresnal basin. Contour interval = 100 meters. White lines mark the approximate location of the major basin forming, normal faults.

however, unlike the southern sub-basin, the major normal fault is located to the east.

(4) The El Fresnal basin appears to form a paired half-graben system similar to those comprising the East African Rift, and that, like the East African Rift system, the basement high separating the two sub-basins may define the accommodation zone between the two half-grabens.

(5) The orientations of two sub-basins, and their location within the Río Grande rift, suggest that the southern sub-basin formed first, during the late Oligocene to early

Miocene, followed by the formation of the northern sub-basin, sometime after the early Miocene when the orientation of the tensional stresses within the rift changed to an east-west direction.

(6) The lack of a playa lake in the area of the southern sub-basin suggests that recent subsidence appears to be presently confined to the northern sub-basin which contains the Playa El Fresnal.

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