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SHALLOW GEOPHYSICAL STUDY OF THE GRAPEVINE CANYON AREA, EASTERN TULAROSA BASIN: IMPLICATIONS FOR GROUNDWATER RESOURCES

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ABSTRACT.— For the residents of the Tularosa Basin, fresh water is a scarce resource. Water is obtained either from stream diversions in the mountains or from rapidly depleting aquifers in the basin. Here we report on results from geophysical surveys undertaken in 1997 to help locate new potable groundwater supplies in the eastern Tularosa Basin, near Grapevine Canyon. This area is considered a good candidate for the location of potable water because groundwater is thought to be diverted into the basin along fault systems and surface canyons of the Sacramento Mountains during snowmelt in the winter and during rainfall in the summer. The geophysical surveys included a 2-km-long seismic profile, and nearly 600 gravity readings, taken primarily along three east-west profiles. Interpretation of the data suggests that the bedrock contact slopes northward from depths of 250 to as much as 1000 m and that a previously unrecognized graben system occurs in the subsurface immediately adjacent to the Sacramento Uplift. Basin fill within the graben system is probably comprised primarily of fine-grained lacustrine deposits. The presence of these deposits reduces the likelihood of finding permeable zones with freshwater, but may be indicative of ongoing tectonic uplift of the Sacramento Mountains.

INTRODUCTION

The Tularosa Basin (Fig. 1) is an intermontane basin of the Rio Grande rift that lies in the arid to semi-arid desert southwest. Average rainfall in the region ranges from 15 cm/yr in the basin to ~ 80 cm/year in the highlands of the adjacent Sacramento Mountains (TWDB, 1997). Residents of the region obtain water primarily from the Sacramento Mountains. Secondary sources are the scarce and rapidly depleting aquifers of the Tertiary basin fill (TWDB, 1997). Here we report on results from geophysical surveys undertaken in 1997 to help locate new potable groundwater supplies in the eastern Tularosa Basin, near Grapevine Canyon at the foot of the Sacramento Mountains (Figs. 1, 2). The surveys were conducted for the 49th Civil Engineering Squadron, Holloman Air Force Base that was interested in finding potable water in order to supply the airbase. The mouth of Grapevine Canyon was considered to be a good candidate for the location of a potable water because seasonal groundwater may be diverted into the basin along fault systems in the Sacramento Mountains during snowmelt and rainfall in the warmer seasons (ETC, 1987). Since the subsurface geology of this region is not well known at present, analysis of new geophysical data should give better constraints on the stratigraphy and structure of the eastern Tularosa Basin that may influence water flow.

To achieve these goals, both gravity and seismic data were collected in the region. Gravity data were collected along three east-west profiles extending from the edge of the Sacramento Mountains into the Eastern Tularosa Basin (Fig. 2). In addition, a 2-km-long seismic reflection profile was collected.

BACKGROUND GEOLOGY AND HYDROLOGY

At the latitude of Grapevine Canyon, gravity modeling shows that the eastern Tularosa basin is comprised of an eastward tilting half graben that is filled with up to ~ 700 m of Tertiary fill that is underlain by Paleozoic sedimentary rocks (King and Harder, 1986; Lanka, 1995). The half graben is bound on the east by a normal fault zone along which the Sacramento Mountains fault block has been uplifted in Late Cenozoic time (Pray, 1961). Precambrian igneous and metamorphic rocks as well as Paleozoic and Mesozoic sedimentary rocks, are exposed in the Sacramento Mountains in the eastern part of the study area (Pray, 1961).

The Tertiary basin fill is comprised primarily of Miocene to Middle Pleistocene Santa Fe Group sediments (Seager and others, 1987). In the study area, the fill consists of weakly consolidated alluvial fan material that interfingers with lacustrine deposits. The alluvial fans have high permeability and are thought to allow the runoff from the mountains to percolate down to the bedrock (ETC, 1987). By contrast, lacustrine deposits are low permeability and probably do not permit much downward migration of surface water.

Basin fill sediments respond as a leaky confined aquifer in the deeper zones and as a water table aquifer in the shallow zones (Basablivazo and others, 1994). Aquifer recharge in the area is from intermittent streamflow from the Sacramento Mountains through the alluvial fans (Burns and Hart, 1988). Springs drain the west slopes of the mountains and recharge coarse-grained materials at the canyon mouths (Garza and McLean, 1977). Recharge occurs primarily at two times during the year, during snowmelt in the spring and heavy rainfall in the summer (Burns and Hart, 1988). Little recharge occurs through the basin floor due to the high rate of evapotranspiration and because infiltration into the basin from the basin floor is impeded by clay and caliche layers (TWDB, 1997). Within the study area, recharge occurs primarily from Grapevine Canyon as well as some contribution from Black Ed Canyon and several other small steep canyons along the escarpment (TWDB, 1997). Throughout the basin, water quality deteriorates westward from the Sacramento Mountains (Orr and Myers, 1986). Fresh groundwater is thought to be confined to an area within 10 to 15 km of the mountains (Burns and Hart, 1988). Depth to ground water along the flanks of the Sacramento Mountains is between 6 and 45 m and groundwater moves south from the Tularosa Basin into the Hueco Basin (TWDB, 1997).

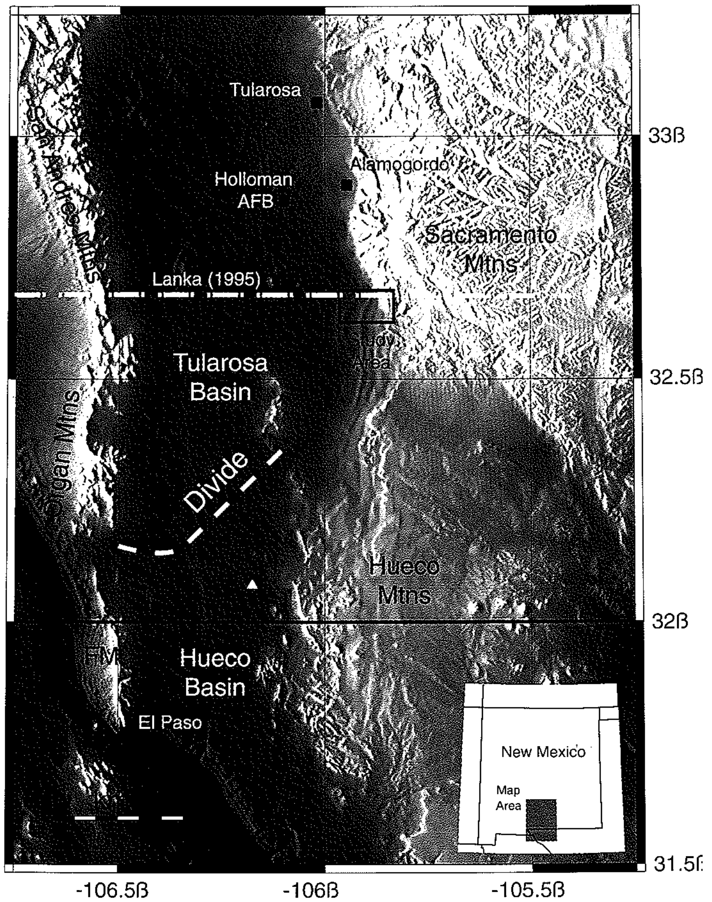

FIGURE 1. Shaded relief map illuminated from the west. Dark grays are lower elevations, lighter grays are high elevations. The Tularosa and Hueco Basins are connected structural basins of Tertiary age that are separated at the surface by a topographic divide (dashed white line). Area of Figure 2 is shown with the black rectangular outline. Dot-dashed line is the location of the portion of the gravity model of Lanka (1995) that crosses this map. White triangle is the location of the similar seismic survey of O'Donnell et al. (2001) in the Hueco Basin.

Preliminary groundwater studies near Grapevine Canyon were conducted by and for the U. S. Geological Survey in the mid-1980's. Interpretation of resistivity soundings along the road to Grapevine Canyon found the water table to be at 60 m and freshwater to occur to depths of 180 m adjacent to the mountains (Orr and Myers, 1986). On the basis of these results, two wells were drilled in an unsuccessful search for fresh water (ETC, 1987). Well GCOW-1 (Fig. 2) encountered 157 m of interbedded alluvial gravels, sands, and clays typical of distal alluvial fan deposits, above 40 m of dense lacustrine clays (ETC, 1987). Interpretation of log data suggested that the water table was at 76 m and that the freshwater zone persisted to 128 m in the well. However, attempts to recover water from the well were unsuccessful, possibly because low permeability clays are the dominant lithology below the water table. Well GCAO-1 (Fig. 2) was then drilled closer to Grapevine Canyon, updip of a fault mapped by Pray (1961), in an effort to find water in high-permeability, coarse-grained deposits of the proximal portion of the fan. This well encountered 100 m of coarse alluvial deposits before entering alternating shales and carbonates of Pennsylvanian-age bedrock. Drilling was terminated in bedrock at 127 m depth without encountering the water table (ETC, 1987). In summary, the drilling results showed that the distal portions of the fan deposits are too impermeable for water production and that the bedrock contact is above the water table in the more proximal portion of the fan.

GEOPHYSICAL SURVEYS

The new geophysical data collected for this study included a 2-km-long seismic profile, and nearly 600 gravity readings, taken primarily along three east-west profiles. Analysis of the seismic data provides an estimate of the depth to bedrock beneath the Tertiary fill that is a key constraint in interpretation of the gravity data.

Seismic Profile

The seismic profile location was chosen based on an initial gravity interpretation and the accessibility of the terrain near gravity profile B-B' The seismic survey was comprised of 180 shots fired at 11.2-m intervals into a 48-channel geophone spread with a group interval of 33.6 m. In an effort to increase the maximum offset in the data to obtain better velocity information, 20 shots were fired off each end of the spread. The source consisted of a 0.15-kg explosive charge. After acquisition, the data were processed to obtain a stacked record (Belzer, 1999) and interpreted (Fig. 3).

The stacked record is characterized throughout by subhorizontal layering. We interpret the first coherent reflection in the data near 0.08 s to represent the water table. This corresponds to a depth of ~ 50 m and is consistent with an estimate of depth to water table at Langford Windmill (Bruce Call, personal communication, 1999). We interpret the prominent reflector just below 0.5 s to be the top of bedrock. This event occurs as a very strong coherent arrival in shot gathers. The apparent decrease in frequency content below this event is also suggestive of a major change in lithology. Above this event reflections in the basin fill are horizontal, whereas below it the data suggest east dip. These dipping events probably represent Paleozoic strata within a gently east-tilted fault block at the foot of the Sacramento Mountains. We interpret reflectivity in the basin fill to represent lacustrine deposits similar to those encountered in well GCOW-1. This basin fill is markedly more reflective than that in the eastern Hueco Basin (Fig. 1; O'Donnell et al., 2001), where alluvial fan and fluvial deposits dominate.

A velocity model (Fig. 4) was also constructed from first arrival times picked on a subset of shot gathers using the forward modeling program MacRay (Luetgert, 1992). Modeling of first arrivals (Belzer, 1999) revealed three layers in the near surface. The boundary between layers 1 and 2 is interpreted to represent the water table and is consistent with the interpreted arrival time on the stacked seismic record (Fig. 3). The boundary between layers 2 and 3 steps up from 400 m to 250 m toward the west. Since the reflection data lack a corresponding reflection, we interpret this step up to represent a lateral change in the lithology of

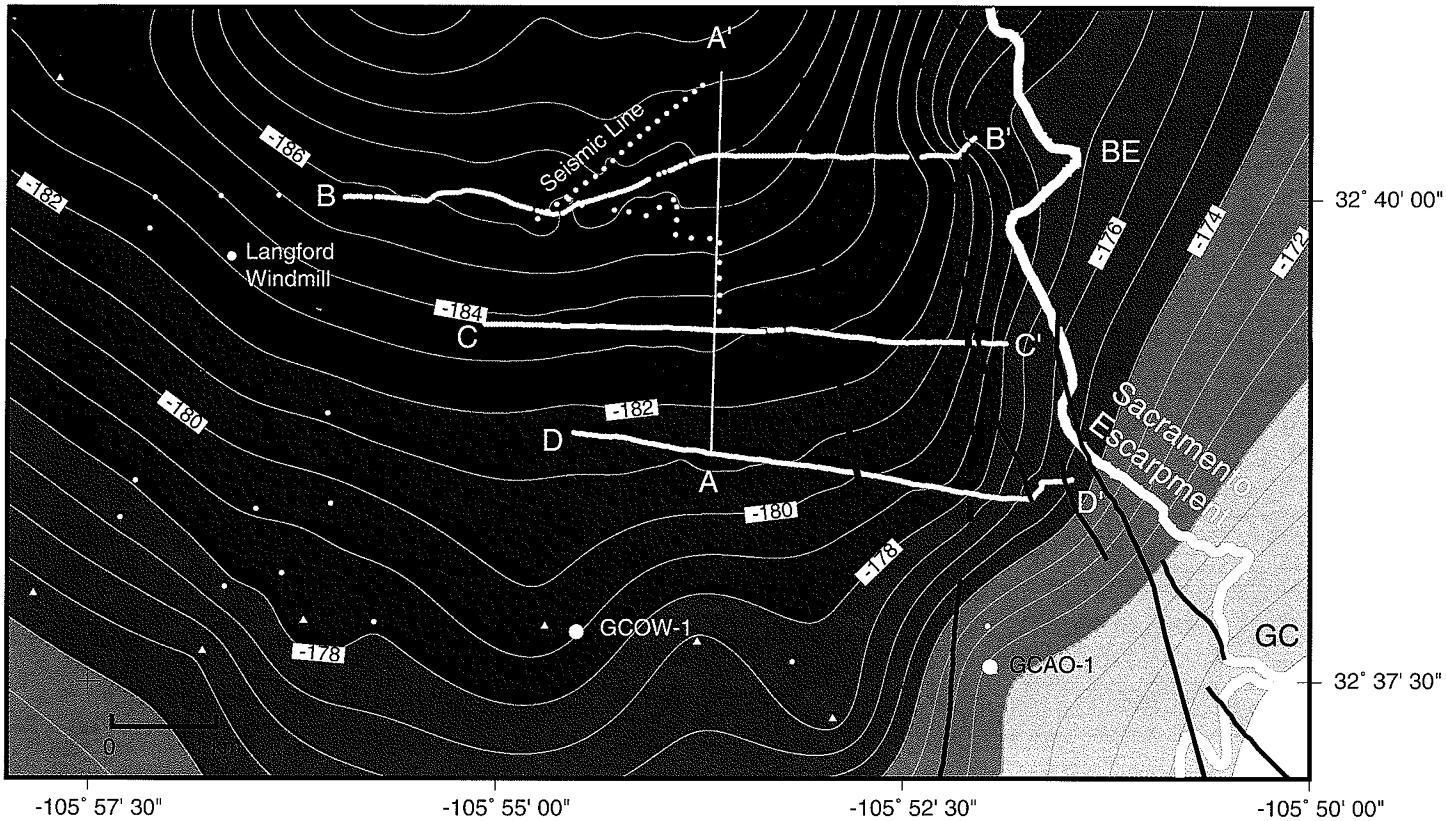

FIGURE 2. Bouguer gravity map of study area in the eastern Tularosa Basin. Gravity contour interval is 1 mGal. Small white circles are locations of new gravity readings taken for this study. Small triangles are data points from the regional database. A-A', B-B', C-C', and D-D' are gravity profiles collected for the study. Thick white line marks the location of the Sacramento Mountains Escarpment. Black lines mark the location of faults mapped by Pray (1961). These faults are part of the normal fault zone along which the Sacramento Mountains were uplifted. Dashed black lines are new faults inferred through gravity modeling in this study. Large white circles are location of wells GCAO-1 and GCOW-1 drilled by ETC. BE - Black Ed Canyon; GC - Grapevine Canyon.

the fill. One possibility is that this boundary represents the juxtaposition of alluvial fan deposits and lake sediments. The depth to the base of layer 3 was modeled using reflected arrival times from the top of bedrock. The velocity model shows that the top of bedrock lies at ~ 550 m.

Gravity Data Analysis

Nearly 600 new gravity readings were collected for the study. Most of the new readings were acquired along three east-west profiles separated by ~ 1.8 km. Additional readings were taken along the seismic profile and to fill in gaps in the regional gravity coverage (Fig. 2). The Bouguer gravity map (Fig. 2) shows that gravity decreases northward, suggesting that basin fill thickens to the north. A strong gradient in the gravity field near the Sacramento Escarpment marks the position of the uplifted, higher density Paleozoic strata.

Gravity models were constructed along four profiles: a north-south profile, A-A', that ties the seismic line and three east-west profiles, B-B', C-C', and D-D' (Fig. 5). Modeling was conducted with a 2.5D program based on the algorithm of Cady (1980). The goal of the modeling was to determine the geometry of the bedrock-basin fill interface. A model was first constructed along profile A-A' using the depth to bedrock determined from the seismic data as a constraint on the north end. Iterative forward modeling along this profile showed that the best match to the observed data was obtained with a north-dipping bedrock surface and a density contrast of 1000 kg/m^3 (Fig. 5A). The other 3 profiles were then constructed using depth to bedrock on A-A' as a constraint.

All three of the east-west models show that basin fill must thicken above down-dropped bedrock blocks adjacent to the Sacramento Uplift. The northernmost model, B-B' (Fig. 5B), contains two down-dropped bedrock blocks that cause the basin fill to thicken to as much as 1000 m. Without this increase in basin fill adjacent to the uplift, the sharp gradient in the observed gravity near km 5 could not be modeled (Fig. 5B). The eastern basin-bounding fault nearest the uplift was modeled with a dip of ~ 75 degrees. This geometry fits the observed gravity well and is consistent with the ~ 70 degree slope on the face of the Sacramento escarpment east of the study area. The other two faults were modeled as vertical, but need only have dips of 75 degrees or greater to adequately fit the observed gravity. Profiles C-C' and D-D' (Figs. 5C, D) contain only one down-dropped block and a shallower graben with a maximum depth of ~ 600 m. A graben that is smaller both in depth and width is required to match the observed gravity that climbs more gradually to the east than on profile B-B'.

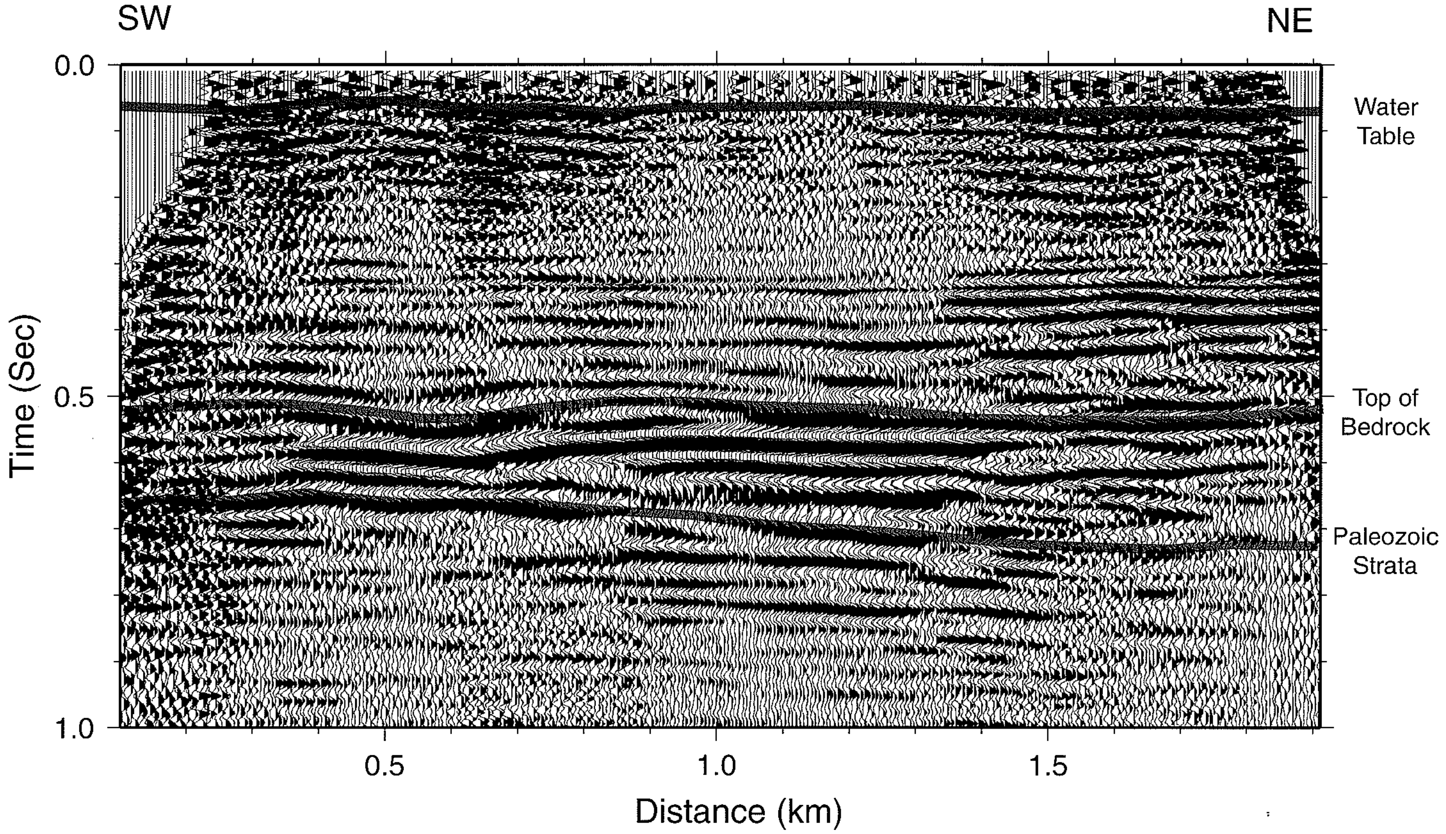

FIGURE 3. Interpreted stacked seismic record from data collected in this study. Major features are a water table reflection at ~ 90 ms, a top of bedrock reflection just below 500 ms, and east-dipping reflections interpreted to be tilted Paleozoic strata of the bedrock. The record has no vertical exaggeration assuming an average velocity of approximately 2.5 km/s.

Two potential sources of error in our gravity models are the choice of density contrast and the effect of regional scale density anomalies. At 1000 kg/m^3, the density contrast between bedrock and basin fill is higher than might normally be expected. The consequence for the gravity models of a lower density contrast would be an increase in the thickness of the basin fill in the grabens adjacent to the uplift. We view this possibility as unlikely since the seismic refraction analysis constrains the top of bedrock to be only slightly deeper than ~ 450 m, the depth to the base of layer 2 (Fig. 4).

To check the possible effects of regional-scale density anomalies, we inserted our gravity readings along profile B-B' into a more regional gravity model that crosses the Tularosa Basin on the north-side of our study area (Lanka, 1995; Fig. 1). We were able to obtain a good fit to the calculated gravity in this model (Belzer, 1999) by adjusting Lanka's model only for the new information on depth to bedrock and the location of the boundary fault that we obtained in this study. This result suggests that regional scale anomalies do not affect our models.

DISCUSSION AND CONCLUSIONS

Analysis of new geophysical data in the Grapevine Canyon area has led to new information on near-surface structure and stratigraphy that can be related to both the interaction between tectonics and sedimentation during uplift of the Sacramento

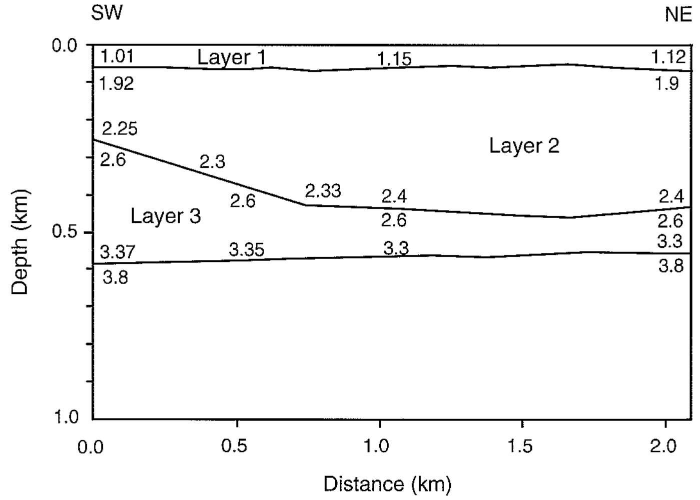

FIGURE 4. Velocity model derived from modeling of first arrivals and the bedrock reflection in selected shot gathers from the seismic survey. First arrivals constrain the velocity and geometry of layers 1, 2, and 3. The depth to the base of layer 3 is constrained by modeling bedrock reflections. Vertical exaggeration is 1.5:1.

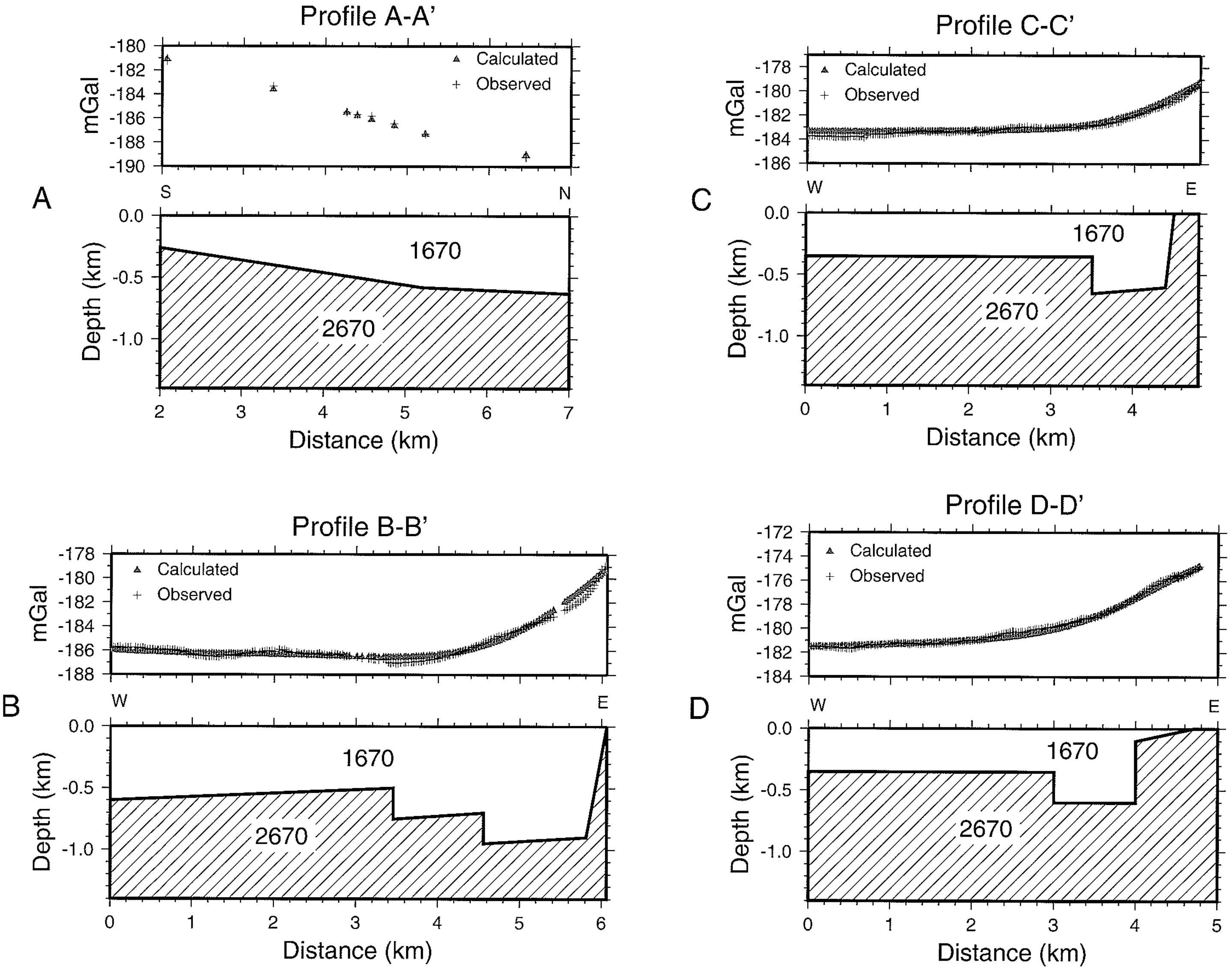

FIGURE 5. Gravity models along the four profiles shown in Fig. 2. The models show that depth to bedrock increases to the north and that a one to two km wide graben occurs adjacent to the range front. The graben and the faults that it bound it to the west have not been previously recognized. Vertical exaggeration is 1.5:1. Density values are in kg/m^3.

Mountains in Late Cenozoic time and regional hydrology. The delineation of local grabens adjacent to the mountains provides new evidence for subsurface antithetic faults that have accommodated subsidence near the eastern boundary of the basin. These additional faults and associated fracturing may provide conduits for groundwater recharge from the mountains.

The data also indicate that the graben is more likely to be filled with fine-grained lacustrine sediments than coarse-grained alluvial fan deposits. Deposition of fine-grained material adjacent to an uplift is considered to be an indicator of renewed tectonic activity as the rate of subsidence and lake sedimentation outstrips the rate of fan sedimentation (Blair and Bilodeau, 1988). Thus, the observed depositional patterns in the basin fill may provide additional evidence for the long-standing inference that uplift of the Sacramento Mountains has been recent and continues to the present time (Pray, 1961). If fine-grained deposits are the dominant lithology in the subsurface west of the basin-bounding fault zone, then the prospects for finding permeable zones in the basin fill below the water table are diminished. Permeable zones may be limited to thin layers of coarse-grained material deposited when streams develop in the canyons of the Sacramento Mountains during flood events.

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