Using geophysical techniques to trace active faults in the urbanized northern Hueco Bolson, West Texas, USA, and northern Chihuahua, Mexico

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ABSTRACT

The Hueco Bolson serves as one of the primary groundwater sources for the El Paso–Ciudad Juárez metropolitan region of over 2.5 million residents. The bolson lies at the point where the strike of the southern Rio Grande rift changes from north-south to northwest-southeast, likely due to its interaction with preexisting Mesozoic and Paleozoic structures. The region is tectonically active with recent (<750,000 years) movement along basin-bounding faults and low-level (M<4) seismicity. Over the past five years, we have used a combination of microgravity and water well logs to image the complex structure of this basin within an urbanized environment. Our results indicate the East Franklin Mountains fault, the main boundary fault on the west side of the bolson, extends as much as 30 km south of the end of its mapped surficial trace. Two intrabasin faults that have been mapped at the surface in the less developed portions of the city can be traced into central El Paso and Ciudad Juárez. These faults appear to control the boundary between fresh and saline water within the aquifer system beneath El Paso. Gravity modeling also suggests at least two additional concealed intrabasin faults are located beneath the metropolitan area.

INTRODUCTION

The Hueco Bolson, an extensive basin located within the southern Rio Grande rift, consists of two distinct, large (30–50-km-long) subbasins. The northern Hueco Bolson, the focus of this study, trends north-south and extends ~40 km in an east-west direction from the Franklin Mountains on the west to the Hueco Mountains on the east (Fig. 1). The northern Hueco Bolson is separated from the Tularosa Basin to the north by a buried structural high located ~10 km north of the New Mexico–Texas border, although the basins are hydrologically connected (Wilkins, 1986). The northern Hueco Bolson is bounded on the southwest by the Sierra de Juárez and Sierra del Presidio and to the southeast by a bedrock high that separates it from the southern Hueco Bolson (Fig. 1). The southern Hueco Bolson trends northwest-southwest to the Hueco Mountains on the east (Fig. 1). The Rio Grande cuts across the southern portion of the northern bolson where it defines the international border between the United States and Mexico.

The northern Hueco Bolson is a complex, asymmetric graben, typical of many basins within the Rio Grande rift and is deepest on the west near the East Franklin Mountains fault (EFMF) (Fig. 1). The northern bolson contains ~2600 m of Neogene sedimentary fill (Collins and Raney, 1994). An exploratory geothermal well drilled in 2013 in the east-central northern bolson (large diamond, Fig. 2) reached a depth of ~1675 m without encountering the basement (K. Bannister, 2013, written commun.). The northern bolson began to develop at least 10 Ma (Hawley et al., 2009), although it could be as old as 12–15 Ma (Langford et al., 1999). Basin filling slowed or ceased 700,000 years ago with entrenchment of the Rio Grande (Mack et al., 2006).

Keaton and Barnes (1995) and Keaton et al. (1995) have recognized three events along the East Franklin Mountains fault since Middle Pleistocene (<130 ka), although more recent studies by McCalpin (2006) suggest at least four events have occurred along this fault in the past 64 ka. The trace of the fault is difficult to follow along the eastern Franklin Mountains and into Mexico due to extensive urbanization. Hawley et al. (2009) and Keaton et al. (1995) inferred the fault extends 10–15 km southward into Mexico beneath Ciudad Juárez based primarily on water well information.

In addition to the East Franklin Mountains fault, the northern Hueco Bolson is cut by a series of faults that form 2–7-m-high scarps covered by thick eolian sands (Collins and Raney, 1994) (Fig. 1). Scarpas of these faults offset Middle Pleistocene alluvium and soils (Collins and Raney, 1994), but it is unknown if the faults cut younger deposits. The best intrabasin fault exposures lie on lands owned by the U.S. military where access is restricted.

Background seismicity in the region is low. Only one felt event (March 5, 2012; magnitude ~2.5) has occurred within the northern bolson in the past ~40 years (U.S. Geological Survey, 2015). Its location (Fig. 2) and felt reports suggest it occurred along one of the intrabasin faults located near the El Paso International Airport. The occurrence of even a moderate (M~6) earthquake in the study area is likely to produce severe damage due to the high water table of regions near the Rio Grande, the presence of thick sediment in an...
irregularly shaped basin, the common use of unreinforced adobe for building construction in Mexico, and little to no requirement for critical structures to meet seismic design criteria.

The focus of this study has several goals: (1) to delineate how mapped faults extend into the urbanized regions of the northern Hueco Bolson; (2) to determine if other major unmapped faults exist; and (3) to estimate the approximate thickness of basin fill to assist in future studies of expected strong ground motion. The extensive urbanization, lack of access to nonurbanized areas due to military facilities and other land use restrictions, and presence of an international boundary make these goals challenging. We have relied primarily on microgravity studies coupled with water well information to aid in this analysis.
Figure 2. Gravity data used in this study. Green symbols are from the University of Texas at El Paso gravity database. Yellow symbols are data collected by Marrufo (2011); red symbols are data collected by Avila (2011); and blue symbols are data collected by Moncada (2011). Airplane symbols denote the location of the El Paso International (north) and Ciudad Juárez (south) airports. Black diamonds are water wells used in this study. Green diamond is the location of an exploratory geothermal well. Star is the location of the March 5, 2012 magnitude 2.5 earthquake (location from U.S. Geological Survey, 2015).
PREVIOUS STUDIES

Geology

Collins and Raney (1994) presented one of the first comprehensive studies of the geologic structure of the Hueco Bolson that coupled surfacing mapping, seismic-reflection data, and well information. They showed that the southern Hueco Bolson subsided more during the initial stages of basin filling in the Cenozoic, while the northern bolson subsided more in later stages, although the exact timing of these stages is not known (Collins and Raney, 1994). The southern bolson reflects structural trends of older Chihuahua trough (Jurassic)–related extension followed by Laramide compression (80–50 Ma) and thrusting that produced the Sierra de Juárez (Price and Henry, 1985). The red dashed line shown in Figure 1 indicates the northern limit of Laramide thrusting from Collins and Raney (2000).

Extension began in the region by 24 Ma (Henry and Price, 1986). Early extension was oriented ENE–WSW and then changed to NW–SE (Henry and Price, 1986), with extension currently oriented WNW–ESE (Zoback and Zoback, 1989). Several pulses of sediment deposition and faulting occurred in the southern Rio Grande rift, including one lasting from 24 to 17 Ma, one occurring around 10 Ma, and a latest phase that has been active since 7 Ma (Stevens and Stevens, 1985). Seismic data show ~3000 m of Cenozoic basin fill in the southern bolson and ~2600 m of fill in the northern bolson (Collins and Raney, 1994). Collins and Raney (1994) estimated offsets of 800–1000 m across the easternmost intrabasin faults of the northern Hueco Bolson and 100–300 m across the intrabasin faults of the central northern bolson.

Borehole and seismic-reflection data show that the northern bolson and southern bolson are separated by a bedrock high (thick blue lines, Fig. 1) where basin fill is only 150–300 m thick (Collins and Raney, 1994). Collins and Raney (1994) suggested the bedrock high extends into Mexico, but no geophysical or geological data were available to verify its location within Mexico. This uplift is controlled in part by the Laramide-age Clint fault (Uphoff, 1978; Collins and Raney, 1994). Collins and Raney (1994) suggest that the Clint fault was still active during early rift basin deposition (Late Oligocene to Early Miocene); however, Hawley et al. (2009) suggest that most deposition associated with fault movement may have occurred in the Early Tertiary, when the region was still undergoing compression.

Hawley et al. (2009) established a comprehensive hydrostratigraphic framework for the northern bolson based on water well and surficial information. They define three main stratigraphic units—the Upper Santa Fe, Middle Santa Fe, and Lower Santa Fe. The Lower Santa Fe formed prior to uplift of the present-day mountains and consists primarily of playa deposits and eolian sands with coarse-grained material found only at the edges of the basin. The Middle Santa Fe was deposited when uplift of the surrounding mountain ranges began and consists of intertonguing of alluvial and basin-floor materials. The ancestral Rio Grande was present in the region by 2–3 Ma (Hawley et al., 2009) and brought fluvial material from beyond the local basin as observed in sediments of the Upper Santa Fe unit. Sediments in the Upper Santa Fe unit indicate climate shifts from wetter to drier periods and increased fluvial activity. The Rio Grande shifted from the east side of the Franklin Mountains to the west side of the mountains ca. 2 Ma, but did not begin to incise its present course until ~0.7 Ma (Mack et al., 2006). Thus basin fill in the Hueco Bolson alternates both vertically and horizontally between playa and/or alluvial fan deposits, eolian deposits, and fluvial deposits, making it difficult to correlate facies across the basin.

Geophysical Structure

Figuers (1987) determined structure at the northern end of the Hueco Bolson by collecting gravity and seismic-reflection data along a profile extending across the northern end of the Franklin Mountains. He collected gravity data every ~30.5 m with a Worden gravimeter, and surveying was used for elevation control. He estimated a depth to pre-Cenozoic basement of ~3000 m for the northern bolson.

Hadi (1991) compiled ~3600 existing regional and local gravity data for the Hueco Bolson as well as collecting an additional 62 readings to fill gaps in coverage. He used a Worden gravimeter for data collection and topographic maps for elevation control. His results clearly showed the two major subbasins of the Hueco Bolson, the asymmetrical structure of the bolson, and ~3500 m of Cenozoic fill in the northern bolson.

Burgos (1993) extended Hadi’s work by collecting gravity data in Ciudad Juárez. He collected 240 gravity readings with a Worden gravimeter with elevation control obtained by leveling surveys from existing benchmarks. He modeled the combined United States–Mexico data set using water well information from both countries to constrain his results. He estimated the northern bolson had 2000 m of Cenozoic fill and the southern bolson 2600 m of Cenozoic fill. He also found a smaller third basin located north of the southern bolson.

Khatun et al. (2007) conducted a microgravity study of the Mesilla Bolson located west of the Franklin Mountains. They collected gravity data using a Lacoste-Romberg gravimeter with elevation control from differential GPS or leveling surveys from existing benchmarks. They collected ~1200 data points with spacing of 80–200 m. This study identified several new faults within the Mesilla Bolson.

Marrufo (2011) analyzed wireline logs and cuttings from water wells (small diamonds, Fig. 2) to establish facies changes within the upper bolson fill in the central northern bolson. She used these data, in conjunction with results of a microgravity survey (yellow symbols, Fig. 2), to identify faults within the central northern bolson. She collected ~500 new gravity data points with a Lacoste-Romberg gravimeter with elevation control from differential GPS.

Data from the above surveys, as well as several unpublished studies, form part of the gravity database for West Texas and northern Mexico that has been carefully compiled, processed, quality checked, and maintained by the University of Texas at El Paso (UTEP) (green symbols, Fig. 2). We use these data
DATA COLLECTION AND PROCESSING

Gravity Data

We collected gravity data in El Paso using a Lacoste-Romberg Model G gravimeter tied to the absolute gravity base station on the University of Texas at El Paso campus. The data had a spacing of ~150 m. We conducted surveys at night to ensure low levels of traffic noise. Each data loop was completed in less than 5 h. We tied elevations to city monuments located at the edges of most city blocks, with elevations determined through traditional surveying and differential GPS.

In Ciudad Juárez, we collected data using a Scintrex CG-5 gravimeter with elevation control obtained by real-time kinematic (RTK) GPS (~2 mm accuracy). Readings were tied to the gravity base established by Instituto Nacional de Estadística y Geografía. For safety and security, we collected data only during daylight hours. At each location, we automatically took 30 readings and averaged them. Two sets of averages at the same location needed to be repeatable in order to accept the average value. Measurements also needed to have standard deviations of <0.3 mGal. At the base station, we repeated our readings three times, and closure had to be <50 mGal to accept the readings.

We corrected the data for tidal effects, dial constant (only Lacoste-Romberg readings), and drift. We then corrected for latitude, free air, and terrain. Terrain corrections used digital elevation models from the U.S. Geological Survey for U.S. readings and from the Geographic Information Center (CIG) at the University Autónoma de Ciudad Juárez (UACJ) for Mexican readings. We used the NAD 83 datum for these corrections. Finally, we applied the complete Bouguer correction with a reduction density of 2670 kg/m³. Data from the UTEP gravity database were re-processed using the NAD 83 datum to allow merging with the new data. More details of the data reduction may be found in Avila (2011) and Moncada (2011).

Figure 3A shows the complete Bouguer anomaly for the entire northern bolson using all existing gravity data. We used minimum curvature to interpolate the data and a grid size of 2000 m due to poor coverage of data at the regional level (Fig. 2). The closer spacing of readings at the local level (Fig. 2) allows us to interpolate the data at a 500 m grid interval (Fig. 3B).

Water Well Logs

We obtained wireline logs and cuttings from the El Paso Water Utilities to help constrain structure of the upper bolson deposits in El Paso (Fig. 2). In Mexico, we obtained similar data from the Juárez Municipal Water Utilities (JMAS). The geothermal test well drilled to a depth of 1675 m on Fort Bliss that did not encounter the basement is shown by the large green diamond (Fig. 2).

RESULTS

Gravity Anomaly Interpretations

Gravity anomaly lows in Figure 3A clearly outline the extent of the Hueco Bolson system and the change in strike of the Hueco Bolson at ~31°38′N. The map shows several deep (<-165 mGal) gravity anomaly lows in the northern Hueco Bolson.

The first low is located immediately south of the Texas–New Mexico border. The low appears to trend north-south; although mapped basin faults in the region strike northwest-southeast. The low narrows and decreases in value at ~31°54′N and steps over to the west. This step over occurs at the point where intrabasin faults begin to change strike from NW-SE to NS.

The second deep low is located ~3 km north of the U.S.-Mexico border at ~31°47′N in a heavily urbanized region located just south of the El Paso International Airport. The southern edge of this low is poorly constrained due to lack of gravity data in central El Paso (Fig. 3A), and it may merge with a third deep low located in Mexico.

The third low extends between 31°44′ and 31°40′N. The northwest-south-trending low starting at 31°38′ N and extending to the southeast may represent the northernmost portion of the southern Hueco Bolson. Figure 3A suggests the bedrock high mapped in Texas may extend to the northwest at least 10 km west into Mexico. More gravity data should be collected in this region to better resolve the edges of this bedrock high since it could serve to focus strong ground motion during an earthquake.

The red dashed line in Figure 3 indicates the limit of Laramide thrusting as mapped by Collins and Raney (2000). Note that the gravity anomaly low associated with the northern Hueco Bolson extends 5–10 km south of this limit.

Gravity anomaly highs (>~125 mGal) are associated with the Franklin Mountains and Sierra de Juárez (Fig. 3A). To the west, a region of higher relative gravity anomalies (~~145 mGal) is associated with the eastern Mesilla Bolson. The labeled black lines in Figure 3A indicate locations of profiles within the bolson where we constructed two-dimensional (2-D) density models as discussed in a following section. Labeled white lines are intrabasin faults mapped by Collins and Raney (2000) that cross the profiles, and the dashed line labeled M1 is a concealed intrabasin fault inferred by Marrufo (2011) based on gravity and well log information.

The East Franklin Mountains fault can be traced at the surface until ~31°48′N, where it becomes obscured by urbanization. Collins and Raney (1994) have inferred the fault extends to ~31°38′N, although the gravity data suggest it may extend as far south as ~31°34′N (Fig. 3A).
Figure 3 (on this and following page). Complete Bouguer gravity anomaly maps. Solid white lines are mapped surface faults, and dashed lines indicate inferred and/or concealed faults. Small symbols indicate gravity data points in this and subsequent figures. (A) Regional anomaly map. Bold black lines indicate locations of profiles shown in Figure 6. F1 to F7 are faults (mapped by Collins and Raney, 2000) that cross profiles. M1 is a fault inferred by Marrufo (2011). EFMF—East Franklin Mountains fault.
Figure 3 (continued). (B) Urban central El Paso–Ciudad Juárez study area. Bold brown line shows location of freshwater-brackish water boundary from El Paso Water Utilities (2004).
Focusing on the urbanized El Paso–Ciudad Juárez region and primarily using the closely spaced data collected with the Scintrex CG-5 or Lacoste-Romberg Model G gravimeters (Fig. 3B), we note that the Bouguer anomaly low (<−165 mGal) observed just north of the U.S.-Mexico border appears to be controlled on the east by two north-south-striking intrabasin faults (F1 and F2, Fig. 3A). The faults have been mapped as far south as ~31°48′ by Collins and Raney (2000) but cannot be traced farther to the south at the surface due to urbanization. The gravity data (Figs. 3A and 3B) suggest that these faults (F1 and F2) may extend into Mexico. Marrufo (2011) has suggested that these intrabasin faults control the fresh-saline water boundary (brown solid line, Fig. 3B) within the northern Hueco Bolson aquifer. The western side of the central El Paso gravity anomaly low is bounded by an eastward-dipping normal fault inferred by Marrufo (2011) (dashed line labeled M1 in Fig. 3A). Figure 3A suggests fault M1 may extend south to ~31°38′N.

The anomaly high along the U.S.-Mexico border in the western part of the study area (~106°31′W) is likely related to the Mount Cristo Rey andesite body. Recent geological and geophysical studies suggest this body may extend from the southern Mesilla Bolson to the southern Sierra de Juárez (e.g., Baker et al., 2012; Doser et al., 2012).

Residual Bouguer anomaly maps for the larger region and the urban study area (Fig. 4) were obtained by fitting a third-order polynomial to the regional complete Bouguer anomaly map and then subtracting the polynomial to eliminate the deeper-seated regional variations in gravity. The map of the northern bolson (Fig. 4A) still shows two subbasins within Texas with a step over between the basins located at ~31°53′N and a third subbasin located primarily in Mexico. The anomaly high in Mexico located at ~31°38′N, 106°24′W again suggests the bedrock uplift observed on the U.S. side of the region (Fig. 4A) extends into Mexico. Figure 4A also suggests that the bedrock uplift on the U.S. side may extend 7–10 km to the south of where it had been mapped by Collins and Raney (1994). Cross sections published by Hawley et al. (2009) are consistent with the uplift extending farther to the south as suggested by the gravity data.

Figure 4A indicates that faults M1 and F1 may extend southward into Mexico and form the main structures that bound the deepest portion of the basin. Fault F0, required for matching gravity and geologic information along profile D–D′ (Fig. 3A), appears to bound an uplifted block of basement between M1 and the East Franklin Mountains fault.

The residual Bouguer gravity data suggest the deepest portion of the bolson in the urbanized region of central El Paso lies just to the southeast of the El Paso International Airport (Fig. 4B), but this is also in a region with the poor gravity coverage. Within Juárez, the deepest portion of the basin appears to be located northwest of the Juárez airport within a region that is consistently flooded during seasonal rains since it lies at an elevation lower than the present channel of the Río Grande.

The next step in our analysis was to apply the horizontal gradient magnitude (HGM) method to the residual Bouguer anomaly values to help delineate the edges of geological features. We used the method outlined by Grauch and Johnston (2002). The HGM value should be greatest over the edges of a source, although it can be offset from the edge of the source if the body’s edge is not near-vertical or several edges are located close to each other (Grauch and Cordell, 1987). The resulting HGM maps are shown in Figure 5.

Figure 5A shows a broad (5-km-wide) HGM maximum within the northern Hueco Bolson. This could be due to the overlapping effects of the East Franklin Mountains fault and fault M1. The mapped or inferred trace of the East Franklin Mountains fault is located along the western side of the HGM maximum, while fault M1 is located along the eastern side of the maximum. This broad maximum extends to ~31°33′N. Based on this observation, we believe the East Franklin Mountains fault may extend up to 30 km south of the end of its mapped surface trace. South of the U.S.-Mexico border where more gravity data are available, two distinct HGM maxima are observed, and the eastern maximum appears to be associated with fault F0. Although the residual Bouguer anomaly map (Fig. 4A) suggested fault F1 extends into Mexico, it is not observed as a distinct maximum in the regional HGM map.

Figure 5A shows an HGM maximum associated with the inferred bedrock high within Mexico (at ~31°38′N). This maximum does not appear to extend into the United States, but data in the United States are sparse. The HGM analysis also suggests that either the bedrock high does not extend west to the East Franklin Mountains fault and fault M1 or that these faults cut across the high. Fault F1 appears to end at the bedrock high.

The HGM map for the urban study area (Fig. 5B) shows the East Franklin Mountains fault is associated with a maximum that extends across the entire map. The maximum associated with fault F0 extends from the border south to 31°42′N. Fault M1 does not appear to be associated with a maximum. Fault F1, however, occurs at the western edge of a maximum. Again, fault F1 does not appear to cross the bedrock high.

**Forward Modeling of Gravity Profiles**

We modeled the gravity data along four profiles (Fig. 3A) to better determine the structure within the northern bolson. Profile A–A′ was constructed along the seismic-reflection and gravity profile of Figuers (1987). Profile B–B′ was constructed close to the structural cross section of Collins and Raney (2000) and near a gravity profile modeled by Marrufo (2011) that was constrained by water well data (Fig. 2). Profile C–C′ was constructed to trace faults into the more urbanized region of south-central El Paso, and profile D–D′ examines the basin structure within Ciudad Juárez. We used the GM-SYS™ gravity modeling software package based on the forward modeling techniques of Talwani et al. (1959) for our analysis.

The densities used in the modeling are given in Table 1 and are based on the studies of Figuers (1987), Hadi (1991), and Burgos (1993). We differentiate two units in the basin fill based on seismic-reflection data interpreted by Figuers (1987) and Collins and Raney (1994) (Table 1). Tabulations of seismic-refraction velocities, sonic logs, and density logs by Figuers (1987) indicate that the lower basin fill has higher velocities and densities as noted in Table 1.
Figure 4 (on this and following page). (A) Residual Bouguer anomaly map for entire northern Hueco Bolson. White dashed lines are faults inferred from gravity modeling. See text for details. EFMF—East Franklin Mountains fault.
Figure 4 (continued). (B) Residual Bouguer anomaly map for urbanized region of El Paso and Ciudad Juárez.
Figure 5 (on this and following page). (A) Horizontal gradient magnitude map for entire northern Hueco Bolson. EFMF—East Franklin Mountains fault.
Figure 5 (continued). (B) Horizontal gradient magnitude map for urbanized region of El Paso and Ciudad Juárez.
Ruiz (2004) assumed a higher average density of 2350 kg/m³ for all basin fill along profiles with similar locations, this was not necessary for our model. Posed was the mafic root of the Precambrian granites and rhyolites that form body that Figuers (1987) proposed was a Cenozoic dike and Ruiz (2004) proposed was the Precambrian bedrock. There is no geologic evidence for the existence of the mafic basin step over (Fig. 3A). Faults shown on this cross section have been mapped by Collins and Raney (2000). Faults F1 and F2 were also observed in the subsurface by Marrufo (2011) and Hawley et al. (2009). Fault M1 is the concealed fault from Marrufo (2011). The gravity modeling suggests that there is ~1500 m of basin fill just east of the East Franklin Mountains fault and that faults F1 and F2 bound the deepest part of the subbasin. The thickness of basin fill here is 1800 m. Faults F1 and F2 appear to serve as a barrier between saline and fresh water in the shallow aquifer within much of El Paso (Marrufo, 2011; Budhathoki, 2013) (solid brown line, Fig. 4A). Intrabasin faults on this profile have offsets of ~200–300 m.

Profile D–D′ (Fig. 6) is located entirely within Mexico and was constructed to include data from two water wells located only 3 km apart. The first well located 2 km west of the inferred East Franklin Mountains fault encounters bedrock at 60 m depth. This agrees with the gravity data that indicate shallow bedrock for ~3 km along the profile. The second water well, located 2.5 km east of the East Franklin Mountains fault, extends to 250 m depth and does not encounter bedrock. The gravity data, however, indicate the deepest part of the basin lies ~8 km east of this well and is bounded by faults F1 and F2. Unlike profiles B–B′ and C–C′, there appears to be another concealed fault (F0) located between the East Franklin Mountains fault and fault M1. This concealed fault could form the eastern edge of an intrabasin structure suggested by the HGM analysis (Fig. 5B). There appear to be 600 m of offset of bedrock across the East Franklin Mountains fault. The profile suggests the deepest part of the northern Hueco Bolson lies beneath Ciudad Juárez with up to 2500 m of fill within the subbasin. Intrabasin faults offset bedrock by ~200–400 m.

### DISCUSSION

Gravity data collected in the urbanized regions of El Paso and Ciudad Juárez allow us to trace the East Franklin Mountains fault system at least 20 km and possibly up to 30 km south of the end of its mapped surface trace (Fig. 5A). The basin contains between 1800 and 2500 m of fill, in agreement with previous studies by Collins and Raney (1994). These thick sediments would likely enhance strong ground motion in the most heavily urbanized areas of the two cities during earthquakes.

Southward from ~31°48′N, the deepest part of the basin is offset from the East Franklin Mountains fault by a series of east-dipping intrabasin faults that step down into the basin. One of these faults (M1) was inferred by Marrufo (2011) based on gravity and well log information. The faults also appear in the hydrogeologic cross sections of Hawley et al. (2009). Fault M1 appears to extend to the north as far as 31°58′N based on gravity studies of Budhathoki (2013) and to the south into Mexico (Figs. 4 and 5). Two intrabasin faults (F1 and F2) mapped by Collins and Raney (2000) that form a narrow graben appear to define the deepest part of the northern Hueco Bolson between 31°52′N and 31°58′N.

In profiles A–A′ and B–B′, we differentiate Paleozoic from Precambrian bedrock based on the models of Figuers (1987) and Marrufo (2011). In profiles C–C′ and D–D′, the bedrock geometry and composition are less well known, and we assume single density values (Table 1). Our modeling results are shown in Figure 6.

Profile A–A′ (Fig. 6) shows the best fitting density model that matches the seismic-reflection data collected by Figuers (1987). Cenozoic fill lies over the sequence of Paleozoic to Precambrian rocks observed within the Franklin Mountains. The depth to pre-Cenozoic basement is ~1800 m at the eastern edge of the profile. Adjacent to the East Franklin Mountains fault, the upper basin fill is ~300 m thick. Other minor faults are observed on the seismic record sections of Figuers (1987) (Fig. 6) but are not required by the density model.

Although other studies (e.g., Figuers, 1987; Ruiz, 2004) have required a high-density (3000 kg/m³) mafic intrusion to match the gravity high observed along profiles with similar locations, this was not necessary for our model. Ruiz (2004) assumed a higher average density of 2350 kg/m³ for all basin fill and a lower density for Paleozoic and Precambrian rocks that may account for differences between our models. Figuers’ (1987) densities were similar to ours with the exception that he assumed a density of 2670 kg/m³ for the Precambrian bedrock. There is no geologic evidence for the existence of the mafic body that Figuers (1987) proposed was a Cenozoic dike and Ruiz (2004) proposed was the mafic root of the Precambrian granites and rhyolites that form the northern Franklin Mountains.

Profile B–B′ (Fig. 6) shows fault complexity in the region just south of the basin step over (Fig. 3A). Faults shown on this cross section have been mapped at the surface by Collins and Raney (2000) (see Fig. 3A) with the exception of the fault labeled “M1,” which is the concealed fault proposed by Marrufo (2011). Hawley et al. (2009) show a fault located in position similar to M1 on several of their hydrogeologic cross sections. The gravity model indicates that the deepest part of the basin fill is closer to the East Franklin Mountains fault than along A–A′. There is ~1100 m of Cenozoic basin fill just east of the East Franklin Mountains fault, and the thickness of the fill is estimated to be 1800 m within a graben located ~8 km east of the fault. This is comparable to Collins and Raney’s (1994) estimate of 2000 m of Cenozoic fill within this portion of the basin. Mapped intrabasin faults appear to have offsets of 300–500 m. This is similar to Collins and Raney’s (1994) observations.

| Age or formation | Profile       | Density (kg/m³) |
|------------------|---------------|-----------------|
| Upper basin fill | A–A′, B–B′, C–C′, D–D′ | 2100 |
| Lower basin fill | A–A′, B–B′, C–C′, D–D′ | 2300 |
| Upper Paleozoic  | A–A′, B–B′    | 2600 |
| Lower Paleozoic  | A–A′, B–B′    | 2700 |
| Precambrian      | A–A′, B–B′    | 2800 |
| Bedrock          | C–C′, D–D′    | 2670 |
Figure 6 (on this and following page). Two-dimensional gravity models arranged from north (A–A′) to south (D–D′) across the northern Hueco Bolson. Profile locations are shown in Figure 3A. Density constraints are given in Table 1. Solid black lines indicate known faults that extend to the surface; dashed black lines indicate concealed faults. Faults labeled F1 to F7 (mapped by Collins and Raney, 2000) and M1 (mapped by Marrufo, 2011) refer to faults shown in Figure 3A. Seismic section shown in A–A′ is modified from Figuers (1987). Seismic section shown in C–C′ is modified from Collins and Raney (1984). Red dots and green lines show points used to construct geologic bodies from seismic sections. Faults labeled F1 to F7 are faults mapped by Collins and Raney (2000). F0 is a fault suggested by gravity data from this study. Symbols on D–D′ indicate location of water wells within Ciudad Juárez used to constrain model. EFMF—East Franklin Mountains fault.
Figure 6 (continued).
and 31°40′N, possibly extending 15–20 km southward into Mexico. These faults also appear to control the freshwater-saline water boundary of the shallow aquifer within much of El Paso (Marrufo, 2011; Budhathoki, 2013; Thapalia, 2014) (Fig. 4A). Another concealed fault (F0, Figs. 4–6) may be located between the East Franklin Mountains fault and M1 beneath Ciudad Juárez where basin structure appears more complicated. It is not known how these intrabasin faults respond to earthquakes along the East Franklin Mountains fault. The March 5, 2012, earthquake appears to be associated with one of these intrabasin faults, suggesting that the faults can move independently of the East Franklin Mountains fault.

The gravity data suggest the deepest part of the northern Hueco Bolson north of 31°54′N is offset 5–6 km to the east of the deepest parts of the bolson located to the south (Fig. 3A), but sparse data available for the northermmost bolson did not allow modeling of this feature. In 2014, we were granted access to this portion of the study area to collect more gravity data, and we hope to examine this structure in the near future.

The southern end of the north Hueco Bolson appears to extend near 31°38′N, where a gravity high (Figs. 3A and 4A) separates the north-south–trending lows of the northern bolson from the northwest-southeast–trending lows of the southern bolson. This gravity high corresponds well with the bedrock high mapped by Collins and Raney (1994) within Texas. HGM analysis suggests that the East Franklin Mountains fault and M1 fault cut across the bedrock high or form the western boundary of the high. Fault F1 appears to end at the high. These results are in agreement with Hawley et al. (2009), who suggest earliest rift extension (oriented ENE-WSW) was conducive to reactivation of NW-SE–oriented Laramide faults in the southern portion of the Hueco Bolson. When rift extension shifted to the WNW-ESE, more movement occurred on north-south–trending faults, such as the East Franklin Mountains fault and fault M1, and these structures eventually propagated through the older Laramide features. Although the NW-SE–trending faults associated with Laramide and early Rio Grande rift deformation appear to be less active at present, they bound bedrock structures that will influence the focusing of strong ground motion during earthquakes.

## CONCLUSIONS

Gravity data indicate the East Franklin Mountains fault system extends 20–30 km beyond the southern end of its mapped trace. This places the fault system, along with a series of east-dipping, intrabasin faults beneath the most urbanized portion of the El Paso–Ciudad Juárez metropolitan area.

McCalpin (2006) has documented that the East Franklin Mountains fault is capable of magnitude ~7 earthquakes and that at least four earthquakes produced displacements of 0.8–4.45 m within the past 64,000 years. An earthquake that occurred in El Paso in 2012 suggests that intrabasin faults are capable of producing earthquakes that do not involve movement of the East Franklin Mountains fault. Gravity modeling also suggests the presence of several bedrock highs beneath the Juárez region. Our results highlight the need for continued studies of the fault structure, sediment thickness, and soil properties beneath the El Paso–Ciudad Juárez metropolitan area to better predict ground motion that might be expected during a large earthquake.

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