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Gravitational Analysis And Fault Identification Within An Active Rift Basin: The Mesilla Valley Bolson In Western Texas - Southern New Mexico

Jose Pablo Cervantes
University of Texas at El Paso, cervantes.josepablo@outlook.com

GRAVITATIONAL ANALYSIS AND FAULT IDENTIFICATION WITHIN AN ACTIVE RIFT BASIN: THE MESILLA VALLEY BOLSON IN WESTERN TEXAS – SOUTHERN NEW MEXICO

JOSE PABLO CERVANTES

Master's Program in Geophysics

APPROVED:

Diane I. Doser, Ph.D., Chair

Laura Serpa, Ph.D.

Oscar Dena, Ph.D.

Charles Ambler, Ph.D.
Dean of the Graduate School

Dedication

This thesis is dedicated to my mother, Lidia Alcázar and Ana Paula Quevedo for all their support and sacrifices endured throughout my academic career. For always being strong role models and encouraging me to complete my graduate degree.

Thank you.

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By

JOSÈ PABLO CERVANTES, B.S.

THESIS

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Abstract

The metropolitan region of El Paso Texas and Ciudad Juárez, Chihuahua, located within the northern Chihuahua Desert, contains approximately two million inhabitants. The two main aquifers that supply groundwater to this region are the Mesilla and Hueco Bolsons. Both bolsons have been tapped for decades without sustainable recharge. This study's purpose is to use geophysical methods coupled with published geochemical analyses to determine the structural and stratigraphic controls on the quality and quantity of groundwater in the southern Mesilla Bolson.

The Mesilla Bolson is one of many fault-controlled basins within the Rio Grande Rift – southern Basin and Range. Faults control major aspects of the bolson, serving as barriers or conduits to the movement of fluids within the bolson. The main focus of this study is the Mesilla Valley fault, which appears to be the major fault controlling the geometry of the eastern side of bolson. Although other geophysical research projects have been conducted in the region, none have focused on the structure of the Mesilla Valley fault and the western margin of the Mesilla Valley. Over 250 data points were collected in a region specifically designed to cross the inferred position of the Mesilla Valley fault in several places.

The additional data have updated the UTEP database and have established more confidence in the location of various faults in the Mesilla Bolson. An updated location for the Mesilla Valley fault was established as well as recognizing that some gravity anomalies that were previously mapped faults may represent the edges of igneous intrusions. My updated residual Bouguer anomaly map correlates well with surface Quaternary faults previously mapped in other studies. The updated Horizontal Gradient Magnitude map (HGM) confirmed the structural complexity of the basin due to various extensional and compressional tectonism.

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1. Introduction

The Chihuahua desert region of El Paso, Texas and Ciudad Juárez, Mexico depend greatly on subsurface water from two main aquifers. With the large cities growing at a rapid rate, water consumption has increased drastically in the past decades. The regional precipitation averages approximately 20 cm/yr. This precipitation is inadequate to refill the aquifers. Drought conditions have also led to decreased flow from the Rio Grande which supplements the domestic water supply during the summer months, creating even more demands for groundwater. There is a great need to conserve and carefully extend the lifetime of the remaining water within the basins. By having a more detailed insight into the local geological structures that control remaining water, we can further understand how these structures control the movement of water within the bolson.

This study focuses on locating the major faults within the western Mesilla Valley and analyzing the crucial role they play in both water mobility and recharge of the aquifer. I used gravity studies, stratigraphic analysis, water well logs, and water well geochemistry to help identify faults within the western Mesilla Valley and constrain the geometry of the faults. My specific focus was the Mesilla Valley fault. Previous studies suggest this fault contains one or more strands, and the spacing of water wells is not adequate to pinpoint its location to less than several kilometers.

Precision gravity data were collected at 500 m spacing across the suspected location of the fault. The use of differential GPS and precision gravity data is an effective method to identify major geological features in an urban area (Avila, 2016), where cultural features make it difficult for data collection of seismic, magnetic or electrical methods. In order to further constrain the fault system, additional data were collected to fill in data gaps from previous studies. A series of

corrections were applied to the data in order to obtain maps of the complete Bouguer and residual Bouguer anomalies, and the horizontal gradient magnitude. I also modeled the density along two east-west and one north-south profile.

2. Location

My study area is located in the northwestern portion of the southern Mesilla Valley, Doña Ana County, New Mexico and El Paso County, Texas (Figure 1). The study area extends north-south approximately 16 km between the Texas-New Mexico border to the Texas-Chihuahua, Mexico international border (Santa Teresa). The Franklin Mountains form the easternmost boundary of the study area and the westernmost boundary is at ~ -106.7° W along the La Mesa surface. The area encompasses the Mesilla Valley fault and other regions to the east where gravity data were collected by previous researchers. The region contains a mix of highly urbanized areas in the east and south and agricultural lands in the north and west.

In this thesis I will refer to the Mesilla Valley as the present-day river valley, a topographically low region, but not the deepest part of the Mesilla Bolson (basin). The southern Mesilla Bolson covers a larger region and is constrained by the Franklin Mountains - Potrillo Mountains – Mount Cristo Rey (Figure 1). The deepest part of the basin is not beneath the present course of the Rio Grande River; it is actually beneath the topographically high area of the La Mesa surface west of the river. Its deepest point is 810 located near 32.32 °N

The new gravity data I collected supplements past work completed by Avila (2016) and Hiebing (2016) and the UTEP regional gravity database (C. Montana, personal communication, 2018). Previous hydrogeologic studies conducted by Hawley and Kennedy (2004) and Hawley and Swanson 2017 used water wells to try to locate the position of the Mesilla Valley fault, but the wells used were located 3 to 10 kilometers apart. With such large distances between wells, it is difficult to obtain an accurate location of the Mesilla Valley fault. Previous gravity studies have not been successful in identifying the Mesilla Valley fault due to a lack of data coverage in the area.

The work of Hiebing (2016) and Hiebing et al., 2018 indicates that the Mesilla Valley fault has a major impact on the geochemistry of the study area. These studies identified that a potential source of high water salinity in the southern Mesilla Valley was from the dissolution of evaporite layers in the upper and middle Santa Fe units that then upwell along the Mesilla Valley fault and other faults to the east. The addition of more gravity readings will verify if a gravity anomaly is associated with the Mesilla Valley fault and better identify other structures within the region.

2.2 Geology of Area

2.2.1 Franklin Mountains

The present Franklin Mountains (Figure1) were shaped by extensional forces related to the crustal extension of the Cenozoic Rio Grande Rift. Faults within the mountains show signs of previous deformation caused by the Laramide Orogeny (70 - 40 Ma) (Hudson and Grauch, 2013) although the current topography is a result of the extensional forces of the Rio Grande Rift. The Franklin Mountains are a Basin and Range type fault system with the main boundary fault on the east side of the range (East Franklin fault) causing rocks to dip in a westward direction (Phillips et al., 2011). The East Franklin fault shows a larger amount of movement compared to the other faults in the area, which leads to a deeper basin, the Hueco Bolson, on the east side of the mountains. The Franklin Mountains are composed of mainly sedimentary and igneous intrusive rocks.

2.2.2 East Potrillo Mountains

The East Potrillo Mountains (Figure 1) are located about 36 km west of the study area and are part of a north-northwest trending mountain chain that extends into Mexico (Carciamuru, 2006). They consist of Permian and Cretaceous rocks from the northern margin of the Chihuahua

Trough. The Chihuahua Trough is a Jurassic aged rift basin with an east-west orientation that paralleled what is now the U.S.A – Mexico border region (e.g., Lawton, 2004). The Permian age rocks consist of slightly arkosic clastics and limestones while the conglomerate beds contain rocks from the early Cretaceous carbonates (Broderick, 1984). The East Potrillo Fault, found on the eastern side of the East Potrillo Mountains, strikes north-south with a dip of 75° to the east. It was caused by the extensional deformation related to the formation of the southern Basin and Range and Rio Grande Rift. In the region of the Potrillo Mountains we find a variety of volcanic features which include volcanic features such as Aden Crater and the maar formations of Kilbourne and Hunts Hole.

2.2.3 Mount Cristo Rey

Mount Cristo Rey (Figure 1), a trachyandesite pluton, is another major geological feature of the southern Mesilla Valley basin. Gravity studies indicate the intrusions are more extensive than seen at surface (Hiebing, 2016). The Cristo Rey pluton forms the southern boundary of the Mesilla basin and channels groundwater flow to the southeast out of the Mesilla basin into the Hueco Bolson (Figure 2). The Cristo Rey pluton caused intense deformation of the surrounding pre-existing Cretaceous aged sedimentary rocks.

2.2.4 Sierra de Juárez Mountains

The Sierra de Juárez Mountains in Ciudad Juárez, Mexico (Figure 1) are a direct result of compressional forces caused by the subduction of the Farallon Plate approximately 50 Ma (Seager and Mack, 1986; Seager 1987). The mountains act as the southwestern boundary of the Mesilla Bolson. The Cierra de Juárez Mountains are underlain by strongly folded and thrust faulted Cretaceous sedimentary rocks that trend northwest, consisting almost entirely of marine deposits.

2.2.5 Mesilla Bolson

The Mesilla Bolson extends from ~50 km north of Las Cruces to northern Mexico (Figure 2). It ranges in depth between 460 to 810 m. The basin is the narrowest in the north (8 km), thickening towards the center (40 km) and narrowing again in its southern section (Hiebing, 2016). High angle normal faulting is present throughout the bolson. The hydro-geologic framework of the bolson is directly constrained by the bedrock and the tectonic activity that formed the boundaries of the basin. The Rio Grande flood plain is believed to be controlled by the Mesilla Valley fault (Lovejoy, 1976b), although recent studies suggest the presence of other faults near the present channels of the river (Hiebing, 2016; Hiebing et al, 2018).

These faults impact the groundwater flow of the basin which tends to flow southeast, as well as groundwater quality. Previous studies conducted by Hiebing (2016) and Hiebing et al. (2018) suggest that increased groundwater salinity in the southern Mesilla Bolson (as observed by Hibbs and Merino, 2007; Gelhar and McLin, 1979) is due to up-flow along these faults.

Most of the water from the Texas portion of the Mesilla Bolson is extracted from the Canutillo well field located in the northwest part of the study area (Figure 1). The Mesilla Bolson's yearly extraction rate for the City of El Paso varies from normal conditions (full river water allocation) at 25,000 acre-ft/yr (3.1 x 10^7 m^3/yr) to drought conditions of 35,000 acre-ft/yr (4.3 x 10^7 m^3/yr) ("El Paso Water Utilities – Public Service Board | El Paso's Water Resources," 2007).

One of the main methods of aquifer recharge within the Mesilla Valley basin is through tributary recharge (Kernodle, 1992; Nickerson and Myers, 1993). The tributary recharge is estimated to be less than 1.23 x 10^7 m^3/yr (10,000 acre-ft/yr) (Frenzel and Kaehler, 1992). Additional recharge also occurs around the basin's boundaries. Frenzel and Kaehler (1992)

estimate that about 1.19 x 10^7 m^3/yr (9700 ac-ft/yr) is recharged into the Mesilla Valley basin from mountain fronts, with two thirds of this originating from the Franklin and Organ Mountains fronts, and approximately 2.71 x 10^7 m^3/yr (2,200 ac-ft/yr) is recharged from the Potrillo Mountains. These amounts are alarming due to the excessive extraction rate (Hawley and Kennedy, 2004).

2.2.6 Bolson Stratigraphy

The Mesilla Bolson is composed of two major hydrogeologic units, the upper Tertiary to Quaternary Santa Fe Group and the Pleistocene to Holocene Rio Grande Alluvium (Hibbs et al., 1997) (Figure 1). These units cover an area of approximately 2850 km^2, with 200 km^2 belonging to Chihuahua, Mexico. The Rio Grande Alluvium is thin (46 m) in comparison to the Santa Fe Group which ranges in thickness between 460 to 760 meters (Hawley and Kennedy, 2004). The valley fill is underlain by Cretaceous and older bedrock (Uphoff, 1978). The Santa Fe Group can be subdivided into three main unites; Upper, Middle, and Lower (Hawley and Lozinsky, 1992). Both the Santa Fe and Rio Grande Group consist of clays, silt, sand, gravel, and caliche (Hawley and Kennedy, 2004).

The Lower Santa Fe unit is made up of mainly medium to fine grained silt, and is the most uniform layer of the three units (King et al. 1971; Nickerson and Mexico, 1989). Hydraulic conductivities are highest in the Upper Santa Fe unit (Hawley and Kennedy, 2004). The Middle and Lower Santa Fe units contain playa-lacustrine and evaporite deposits, which include calcium sulfates (gypsum selenite) and sodium sulfates (mirabilite – thenardite) (Hawley and Kennedy, 2004). The Upper Santa Fe unit lacks these evaporite lacustrine deposits (Sellepack, 2003).

The majority of the sediments in the Mesilla Valley originated from the ancient Rio Grande or from lake deposits that occasionally formed in the Mesilla or adjacent basins (Strain,

1973; Gates et al., 1978). A percentage of sediments in the Mesilla Valley are thought to have originated from the northern Rio Grande Rift basin and its tectonically uplifted flanks.

2.2.7 Groundwater

Groundwater from the Mesilla Bolson is pumped for a variety of purposes. Agricultural lands that use river water for irrigation sometimes also use ground water during drought years or winter months (November to February) when water from the Rio Grande is restricted. Most of the water pumped from the bolson is taken from the Santa Fe units, while the shallow wells, primarily for agriculture, are fed from the Rio Grande alluvium (Cliett, 1969). The middle Santa Fe unit produces the most water for industrial and drinking-water use (Wilson and White, 1984). The water in the Rio Grande alluvium mainly consists of seepage from the Rio Grande but is also fed by its tributaries and irrigation water (Sheng, 2013).

2.2.8 Mesilla Valley Bolson Fault System

Multiple studies have concluded that the southern Mesilla Valley Bolson is interlaced by a variety of north-south trending faults (Hawley and Lozinsky, 1992; Arunshankar, 1993; Imana, 2002; Sellepack, 2003; Hawley and Kennedy, 2004; Khatun et al., 2007). The major faults between the Franklin Mountains and the La Mesa surface include the I-10, River (east and west branches), Three Sisters, Western and the Mesilla Valley faults (Figures 3 and 4). These faults appear to play a major role in ground water mobility.

Two other major north-south trending faults in the Mesilla Bolson are found between the La Mesa surface and the East Potrillo Mountains (Figure 1). The westernmost fault is the Robledo fault, forming the eastern boundary of the East Potrillo Mountains (Bowers, 1960). The central fault, the Fitzgerald fault, is located in the vicinity of Kilbourne and Hunts Hole and may have controlled the occurrence of these volcanic features.

Faulting within the Mesilla Valley Bolson began in the Quaternary (Seager and Morgan, 1997). The region has stayed active to present time, but we observe a decrease in activity within the past two to three million years (Seager at al., 1984). The faulting observed in the Mesilla Valley Bolson is caused by two periods of extensional forces during development of the Rio Grande Rift. The initial rifting phase began approximately 29 Ma (Chapin 1979, Seager et al., 1984) with extension oriented northeast–southwest oriented extension. This rifting created northwest-trending grabens that are evident in the southern Hueco Bolson and other regions. The second rifting phase began 12-15 Ma (Keller and Cather, 1994; Langford et al., 1999) with east-west oriented extension. This rifting created asymmetrical closed basins split up by intra-rift uplifts which produced north-south trending basin patterns seen today. The main easternmost fault in the Mesilla Bolson is the Mesilla Valley fault, but it lacks surface exposure due to agricultural and urban development. Figure 1 shows these faults, and the inferred location of Mesilla Valley fault.

3. Previous Geophysical Studies

A variety of geophysical studies have been conducted in the Mesilla Bolson, which include gravity, magnetics, seismic and wells log interpretations by multiple UTEP researchers. Figuers (1987) completed a gravity survey in the northeastern part of the study area, along the Pipeline Road. The study was able to identify the orientation and location of the eastern and western boundary fault systems of the Franklin Mountains (Avila, 2016). Figure 3 shows the previously mapped out faults conducted from multiple past studies (Imana, 2002; Sellepack, 2003; Hawley and Kennedy, 2004; Khatun, 2004; Witcher et al., 2004, and Hiebing, 2016)

Imana (1994) analyzed the similarities and differences between the Rio Grande Rift and the East Africa Rift within a focus on the overall structure of the Mesilla Bolson, especially for groundwater analysis of the region. Imana (2002) continued his research in the area by collecting additional gravity data in the southern Mesilla Valley and analyzing various other geophysical data. He determined that the southern Mesilla Valley was shallower than the Hueco Bolson and appeared to be cut by a number of faults.

Another major study in the region was conducted by Khatun (2003) to analyze faulting within the southern Mesilla Valley. She completed three individual north-south trending surveys with station spacings of ~200 m, resulting in better resolution of three faults originally identified by Imana (2002). Khatun also identified an additional fault located just north of Mount Cristo Rey that appears to truncate the north-south trending faults.

Hawley and Kennedy (2004) created a detailed hydrogeologic-framework model for the Mesilla Valley Bolson and southern Jornada del Muerto basin. All major hydrogeologic structures currently in place were formed by the late Miocene to early Pliocene. With the dominant topographic structures oriented north-south (Franklin, Organ, Potrillo Mountains),

these structures play a large role in separating the region into various hydro-geologically linked basins such as the Mesilla and Hueco Bolsons (Hawley and Swanson, 2017).

The Mesilla Valley fault is believed to create the observed offsets of the Upper Santa Fe units in water wells in the western Mesilla Valley as well as changes in the course of the Rio Grande (Lovejoy, 1976b). The fault is theorized to have raised the eastern Mesilla Valley approximately 70 m, with 30 m of movement occurring since the initial development of the La Mesa surface (Khatun, 2003). Hawley and Kennedy (2004) interpreted the Mesilla Valley fault as a high angle normal fault that dips to the west.

4. Methodology and Data Processing

4.1 Gravity Processing

Gravitational analysis has been proven to be an immensely effective tool for determining fault locations in urbanized regions (Avila, 2016; Hiebing, 2016). Figure 5 displays the locations of previous collected gravity readings (Imana, 2002; Khatun, 2003; UTEP gravity data base, 2018). My study was conducted to fill in a gap in the previously collected data (Figure 5). The survey covered an area of 8 km^2 just north of the Santa Teresa airport and was specifically designed to cross the inferred Mesilla Valley fault zone in several places. The spacing for the gravity survey was ~ 500 m. I constructed two east-west striking density profile and one northwest-southeast profile to determine the fault structure and its control on local stratigraphy.

The western two thirds of my survey were conducted in an arid desert environment with little to no cultural interference. The other one third of the survey was conducted mainly on agricultural lands and around some new housing developments currently under construction. This region was exposed to a higher level of vibration noise interference due to large amounts of tractor and large construction vehicle movement. I also experienced some minor noise from the private Cielo Dorado Airport. This was mitigated by pausing data collection during airplane movement.

In order to eliminate the effects of noise in the data, each reading was collected twice and had to be within a margin of error of 0.1 mGal prior to accepting the data value. Once all the gravity data had been collected, standard corrections were applied including drift, tide, free-air, terrain and Bouguer corrections using *Microsoft Excel*. The data were quality checked by comparing to surrounding gravity data and then incorporated into the UTEP database (C. Montana, personal communication, 2018). The main software tools used to process the gravity

data were ESRI's *ArcGIS*, and *Oasis Montaj* ™.

A *Lacoste-Romberg model G-115* gravity meter was used for the study. The observed gravity readings were in Decimal Dials (DD) units, which were later converted to mGals. This survey required a new base to be established because the base used for past surveys (Hiebing, 2016) was destroyed. To avoid destruction of the base site, the new base was established on private property. The new established base, called DDHBase was located about 100 m from the Rio Grande along Strahan Road in El Paso, Texas. Its proximity to the study area was essential to minimize the length of time it took to tie in data collection loops from the study area.

4.1.1 Drift Correction

The Lacoste and Romberg gravity meter utilized in this study is influenced by drift, caused by changes in temperature, pressure and Earth tides. A correction for this drift is applied by completing a series of loops throughout each field day. For this survey, a loop would be completed by returning to DDHBase every 2 to 3 hours and taking a reading. There usually was an appreciable change in gravitational acceleration of the base, typically higher after returning to complete the loop later in the day.

4.1.2 Free Air Correction

Due to the nature of how gravity readings differ inversely with the square of distance from the center of two masses, it is necessary to correct the readings for changes in elevation between individual stations and reduce the readings to a common datum surface. This correction does not consider the density of the material between the stations and the datum plane (Telford et al., 1990); although this correction does take into account the vertical decrease of gravity with the increase of elevation (Khatun, 2003).

4.1.3 Bouguer Correction

The Bouguer correction corrects for the attraction of material between the station and the datum plane which was previously ignored in the Free-air correction (Telford et al., 1990). This correction essentially assumes a slab of constant density that is horizontally infinite (Khatun, 2003).

4.1.4 Terrain Correction

Terrain corrections where applied to the data in order to remove the effects of near topographic features. A Digital Elevation Model (DEM) was used to remove these effects. Local elevation data was supplied by the GPS survey conducted for tis research. The terrain correction was completed in order to produce the Complete Bouguer Anomaly map (Figure 6 and 7).

4.2 GPS Processing

The GPS data collected for the study were acquired using a *Topcon GB-1000* differential GPS, which has 1 cm vertical accuracy. For this study, a static mode survey mode was implemented, which used a fixed location (base) and a mobile unit (rover) for the survey. The fixed receiver was placed at the same position as the DDHBase. The base used a static survey mode due to its highly precise location. Kinematic mode was used for the actual survey grid because of the changes in location throughout the study area between each gravity reading. When beginning the survey, the first GPS reading collected on each field day was based on the data collected for 10 minutes in order to achieve excellent pairing of the base and rover units. The subsequent data points were collected with 3 to 5 minutes' worth of GPS data. Although the kinematic survey mode is not as precise as static, it is adequate for the goals of this study.

After each survey was completed, the data were transferred from the *Topcon GB-1000* base and rover to an external storage device for further processing. A solution to the receiver was

completed using Online Positioning User Service (OPUS) in order to obtain the most accurate data processing. The raw data were then corrected using the solution supplied by OPUS using *Topcon Tools* software. This process modifies the location of the base and rover GPS locations.

The new data were then added the existing UTEP dataset in order to create various maps (Complete Bouguer Anomaly, Residual Bouguer Anomaly, Free-Air Anomaly, Horizontal Gradient Magnitude). Two east-west geology-density profiles were created at different latitudes across the Mesilla Valley fault. Water well information (e.g., Hawley and Kennedy, 2004; Hawley and Swanson, 2017) were used to help constrain the geology.

5. Results and Discussion

5.1 Gravity Data Processing

The main method for data interpolation used in this study is minimum curvature. Minimum curvature interpolation was applied in order to achieve the smoothest surface possible without altering the surrounding measured gravity data. In order to maintain data accuracy, the newly collected data were compared to past studies in order to merge the two datasets together. Various points throughout the survey matched previously collected nearby data points by 0.02 to 1.14 mGal. The raw gravity data were corrected for the meter dial constant and converted to absolute gravity by comparing values from KIDD Station (on the UTEP campus) after tidal and drift corrections had been applied. Then latitude, Bouguer and free air effects were applied. The Bouguer correction used a reduction density of 2670 kg/m^3.

The next step was to apply a terrain correction in order to produce the complete Bouguer anomaly maps (Figure 8 and 9). Terrain corrections used a digital elevation model DEM of the study area in order to correct for the effects of the surrounding topography. The complete Bouguer anomaly map shows the effects produced by local and regional features which have densities that deviate from the original Bouguer reduction density (Hiebing, 2016). A third order polynomial surface was removed from the complete Bouguer Anomaly map in order to produce the residual Bouguer anomaly maps (Figure 8 and 9).

5.2 Gravity Interpretation

5.2.1 Complete Bouguer Anomaly

The additional 255 gravity points have greatly improved our ability to detect changes in the geology of the western Mesilla valley (Figure 6 and 7) (Imana, 2002; Khatun, 2003; Sellepack, 2003; Hawley and Kennedy, 2004; Witcher et al., 2004; Avila, 2011 and 2016;

Hiebing 2016; Hiebing et al., 2018). The map indicates the deepest part of the bolson (lowest anomaly) is located in the northwestern portion of the study area. Gravity anomaly value increases towards the Franklin Mountains and to the south.

The complete Bouguer anomaly map for a smaller portion of the study area that focuses specifically on the Mesilla Valley fault zone (Figure 7) shows that the southern end of the basin is located near 31.832° N. The inferred location of the Mesilla Valley fault zone is east of the main anomaly low (-160 to -162 mGal), and there is no evidence that either the Mesilla Valley fault or Western fault extend south of 31.872° N. The most rapid change in gravity (~7 mGal over <2km) appears to occur east of the inferred trace of the Mesilla Valley fault.

5.2.2 Residual Bouguer Anomaly

The residual Bouguer anomaly map (Figure 8 and 9) shows features that are well correlated to known geological structures in the region, including the Three Sisters, Mount Cristo Rey, and the Franklin Mountains. The same general north-south trend of the basin is still observed with additional data, but there appears to be a narrowing of the basin south of 31.888° N with a marked increase in anomaly values near the international border. Several anomaly highs also appear to radiate to the north from Mount Cristo Rey.

The regional residual Bouguer anomaly map shows a transition from high to low anomaly values at -106.725° W near an un-named fault with known Quaternary surface offset that is shown in maps by USGS Quaternary Fault and Fold Database (2018), Hawley and Kennedy (2004) and Hawley and Swanson (2017. In this study I will refer to this fault as the Eastern La Mesa (ELM) fault. This fault forms the eastern boundary of a horst interpreted by Hawley and Kennedy, (2004) (their cross -section J-J') with about 140 m offset. Hawley and Kennedy (2004) shows a fault with 80 m of offset on the western edge of the horst. Although

less gravity data are available to the west, the data are consistent with Hawley and Kennedy's (2004) interpretation and suggest the western boundary of the horst lies near -106.762 °W (Figure 8)

The Bouguer anomaly map shows several northwest – southeast striking features near the international border that may be related to mapped Quaternary faults (USGS Quaternary Fault and Fold Database, 2018) that also strike in this direction. It appears that the anomaly lows within the southernmost basin also begin to trend northwest-southeast with an eastward step-over into the Hueco Bolson at the extreme southeastern edge of the map.

The previously inferred Western (Witcher et al., 2004) and Mesilla Valley (Hawley and Kennedy, 2004) faults do not appear to align gravity anomalies that cross the entire study area. The southernmost part of the Western fault does align with the edge of a 1-2 mGal anomaly high from -106.627 °W to -106.595 °W, but the inferred trace of the Mesilla Valley fault does not appear to separate any distinctive anomalies. Hawley and Kennedy (2004) originally showed a 140 m offset of sediment along the Mesilla Valley fault that would be expected to produce a similar anomaly to that observed across the Eastern La Mesa fault at -106.722 °W / 31.8898 °N. However more recent studies by Hawley and Swanson (2017) now indicate a smaller offset of 50 m along the Mesilla Valley fault, giving a more subtle change in gravity across the feature. This smaller offset would produce a smaller anomaly that could be difficult to detect with the ~500 , station spacing of my survey.

A more localized residual Bouguer anomaly map was created to further investigate the position of the Mesilla Valley fault (Figure 9). This map shows a total anomaly change of less than 3 mGal. Neither the inferred Western or Mesilla Valley faults appear to separate distinct regions of highs from lows. The map suggests there may be several smaller sub-basins within

the main basin (see circles, Figure 9) that may be reflections of variations in the topography of the underlying bedrock or changes in bedrock lithology due to igneous intrusions. The eastern fault of the horsts (ELM fault) is well correlated to the regional residual Bouguer while the western boundary of the horst lacks data coverage but is still apparent in Figure 8. This area needs further gravity data to accurately locate the fault and estimate its offset.

A local residual Bouguer anomaly map was created to further constrain the location of the Mesilla Valley fault (Figure 9). Strong anomalies appeared in the local interpolation, such as the same gravity low anomaly we see in the complete Bouguer data located at 31.915 °N / -106.666 °W. Various north-south trending density contrast trends exist which indicates the Mesilla Valley fault may have splayed into various smaller faults due to suspected igneous intrusions in the southern area (31.886 °N / -106.663 °W).

5.2.3 Horizontal Gradient Magnitude

In order to identifying near vertical structures, a Horizontal Gradient Magnitude (HGM) map was created using derivative filters supplied by the USGS and applied to the residual map using *Oasis Montaj* ^{TM} *software.* This is an efficient technique to highlight shallow basement structures with high angle edges including faults and abrupt changes in density such as intrusions (Hiebing, 2016; Hiebing et al., 2018). The greater the change in gravity across a feature, the greater the HGM.

The HGM map (Figure 10) shows that the 3 faults (white) with known Quaternary offsets in the western portion of the study area align with the edges of HGM highs. The inferred traces of the Western or Mesilla Valley fault do not align well with transitions between HGM lows and highs.

The HGM map for the smaller region of the study (Figure 11) also does not indicate a good correlation between the inferred faults and the locations of anomalies. This could suggest that there is not sufficient offset along the faults to produce strong HGM anomalies, that the faults do not dip steeply or that other features, such as pre-existing bedrock topography or igneous intrusions, are obscuring the signatures of the faults.

5.3 Data Modeling

The final step in processing the gravity data was the construction of various density cross-sections profiles across key features identified within the area to better understand the basement rocks of the Mesilla Bolson. Several previous studies (Hiebing, 2016; Hawley and Swanson 2017; and Hiebing et al., 2018) helped constrain the density models. Two east-west profiles were selected to cross the inferred Western and Mesilla Valley faults (Figure 12). One profile was constructed to match the hydrogeological cross section J-J' of Hawley and Kennedy, (2004) and Hawley and Swanson (2017). The other (profile A-A') crosses just north of the profile Q-Q' from Hiebing et al., (2018). The north-south profile was selected to match the hydrogeological cross section, NW-SE of Hawley and Kennedy (2004) and O-O' of Hawley and Swanson (2017) (Figure 12). The density profiles incorporated data from petroleum well logs and water well logs based on Hawley and Swanson (2017). Note that most profiles from Hawley and Swanson (2017) only extend to a maximum depth of 1,200 m below the La Mesa surface. Thus I have few geologic constraints below this depth.

The density profiles were constructed using GM-SYS™ forward modeling software which works in conjunction with Oasis Montaj™. The forward modeling technique is based on the Talwani 2.5 D (1959;1964) which work by assigning a hypothetical density value to the polygons within a model and then calculates a gravity response that the user can then manipulate

to fit the geology (Hiebing, 2016). The anomalies from the observed and calculated gravity values are then compared and adjusted to a certain degree of error. Density values for bolson fill were based on Avila (2016) and Hiebing et al., (2018). These previous studies did not extend into the Tertiary volcanics of the western study area, so a density value from Figuers, (1987) was used for this unit. Density values used in this study are shown in Table 1.

Table 1

Body Code	Stratigraphic Unit (Hawley and Swanson, 2017)	Density (kg/cm^3)
RGA	Quaternary Rio Grande Alluvium	2,100
USF	Pliocene Upper Santa Fe Group	2,300
MSF	Pliocene Middle Santa Fe Group	2,300
LSF	Pliocene Lower Santa Fe Group	2,300
TV	Tertiary Volcanics	2,400
C	Cretaceous Bedrock	2,500
UPZ	Upper Paleozoic Bedrock	2,600
LPZ	Lower Paleozoic Bedrock	2,700
T	Tertiary Intrusion	2,800

5.3.1 Profile J-J’

Profile J–J’ (Figure 13) follows the Hawley and Swanson (2017) cross section line J–J’ in order to use their hydrogeologic model to help constrain the subsurface geology. Faults in this profile are from the USGS Quaternary Fault and Fold Database (2018) as well as iterations of the inferred location of the Mesilla Valley fault. The Mesilla Valley fault is inferred to be located between previously suggested locations, i.e., east of Mesilla Valley fault (Hawley and Kennedy, 2017) and west of the River fault (Hiebing et al., 2018). This profile shows a gravity high on the eastern edge which can also be seen in the complete Bouguer anomaly map that is associated with the Franklin Mountains. The profile also shows a gravity low on the central western side followed by a gravity high at its westernmost edge corresponding to the horst originally

interpreted by Hawley and Kennedy (2004). The Eastern La Mesa fault forms the eastern boundary of the horst, which Hawley and Kennedy theorized to be offset by 140 m, while this density profile suggests an offset of approximately 350 m. The Mesilla Valley fault is estimated to offset the surrounding by about 50 m by Hawley and Swanson (2017), while this study suggests a slightly increased offset of 60 m.

To match the gravity high at the eastern end of the profile I added an intrusion, consistent with the presence of andesitic bodies observed within the region, but its existence has not been confirmed by other geologic or geophysical information. Intrusions this far north were not shown by Hawley and Kennedy, (2004). Well north of the study area (~ 15 km) we find the Vado igneous outcrop which is believed to have formed from the same parent reservoir (Garcia, 1970; Barnes et al., 1991). Previously mapped faults east of the Mesilla Valley Fault (I-10 fault, Three Sisters fault) may be related to the intrusion, rather than actual faults. The Three Sisters fault is very evident of this due to its proximity to the edge of the deep intrusion shown in the density profile J-J'.

The shape of the pre-Cenozoic beds suggests complex flexure or folding (between ~5 and 10 km along the profile) related to Laramide deformation. Since this cross sections cuts at an angle to the trend of these structures and I lack deep geologic information for this portion of the Mesilla bolson, it makes it difficult to infer the structures. Averill (2007) and Averill et al., (2013) indicate that thrusting within the Mesilla bolson due to Laramide deformation can be found approximately at 4 to 5 km depth based on seismic data collected along a line located just north of the International border. The Laramide structure described by Averill (2007) shows a thrust ramp that is beginning to curve upward in the same region where I see the flexure or folding of the basin.

5.3.2 Profile A-A’

Profile A–A’ (Figure 14) is a section located just north of section Q-Q’ of Hiebing et al., (2018). This cross section was updated in order to reflect the additional data collected for this study. The igneous intrusion labeled as “T” is a continuation of the intrusion observed on density profile J-J’ that could be the possible magma source for the Vado outcrop and several outcrops in western El Paso (Three Sisters, Coronado, Thunderbird). The eastern La Mesa fault can also be identified in this density profile. This southern east-west profile shows thickening Cenozoic fill as we pass the eastern La Mesa fault (offset of 350 m across Lower Santa Fe Group) which slowly shallows eastward. The MVF appears to only offset the Lower Santa Fe Group 60 m.

5.3.3 Profile O-O’

My profile O–O’ (Figure 15) is a section from profile O–O’ from Hawley and Swanson (2017). Hawley and Swanson’s profile was used to help constrain the density profile to the established hydrogeologic model of the subsurface geology. Faults in this profile are interpreted from the residual Bouguer anomaly map which updates/combines the Mesilla Valley fault and the west River fault from Hiebing et al. (2018). Hawley and Swanson (2017) show an offset of the Mesilla Valley fault of 50 m, while this profile shows 60 m offset. The profile shows a gravity low in its northern section and a gravity high in the southern region that appears to be related to igneous intrusions. The igneous outcrop exposed at surface at 31.813 °N is shown on the southeastern end of the profile. Its location and extent is constrained by Baker et al. (2012), Montana et al. (2012) and Kaip (personal communication, 2015).

6. Conclusions

The Mesilla Bolson is crucial for the water use of El Paso and its surrounding regions. This research aids in understanding the fault networks within the Mesilla bolson to help constrain groundwater flow models for the region.

The Mesilla Valley fault has an updated location (Figure 12) ~ 1.5 km to the east of previous maps (e.g., Hawley and Kennedy, 2004; Hawley and Swanson, 2017) and has about a 60 m offset. This fault does not show up as a major geologic structure in the gravity. Due to its proximity to the River fault and lack of significant gravity anomalies, it seems that the MVF and the River fault should be combined into just one structure. The MVF does not appear to extend south into Chihuahua, Mexico; yet it is still a significant fault in terms controlling of groundwater flow and chemistry within the bolson (Hiebing et al., 2018).

Various other north-south and northwest-southeast trending faults with Quaternary surface offsets appear to be major structural controls within the southeastern portion of the bolson. The ELM fault is a major fault with 350 m offset. Previously inferred faults on the eastern side of bolson (Three Sisters and I-10 fault) may not be faults but rather gravity anomalies associated with the edges of intrusions that extend from Mount Cristo Rey to Vado, New Mexico.

An apparent flexure or fold has been identified within the bolson that is likely related to Laramide tectonism. This structure is visible as a northwest – southeast feature in both the residual Bouguer (Figure 8 and 9) and Horizontal Gradient Magnitude (HGM) (Figure 10 and 11). The structures could be related to a thrust system that Averill (2007) and Averill et al., (2013) interpreted to lie at 4-5 km depth beneath the international border. The HGM map also shows edges of the igneous intrusions which appear to be more extensive at depth than suggested

in previous studies.

For future research, I recommend further gravity data collection west of the ELM in order to further constrain the horst and the offset along the western bounding fault. Increasing the collection of gravity data perpendicular to the new MVF location would further constrain its fault location and total offset. This would also aid understanding the effects of Laramide tectonism. The complex nature of the bolson requires the use of three-dimensional modeling to better determine the extent of Laramide deformation, Eocene volcanism and Quaternary faulting within the region.

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Figures

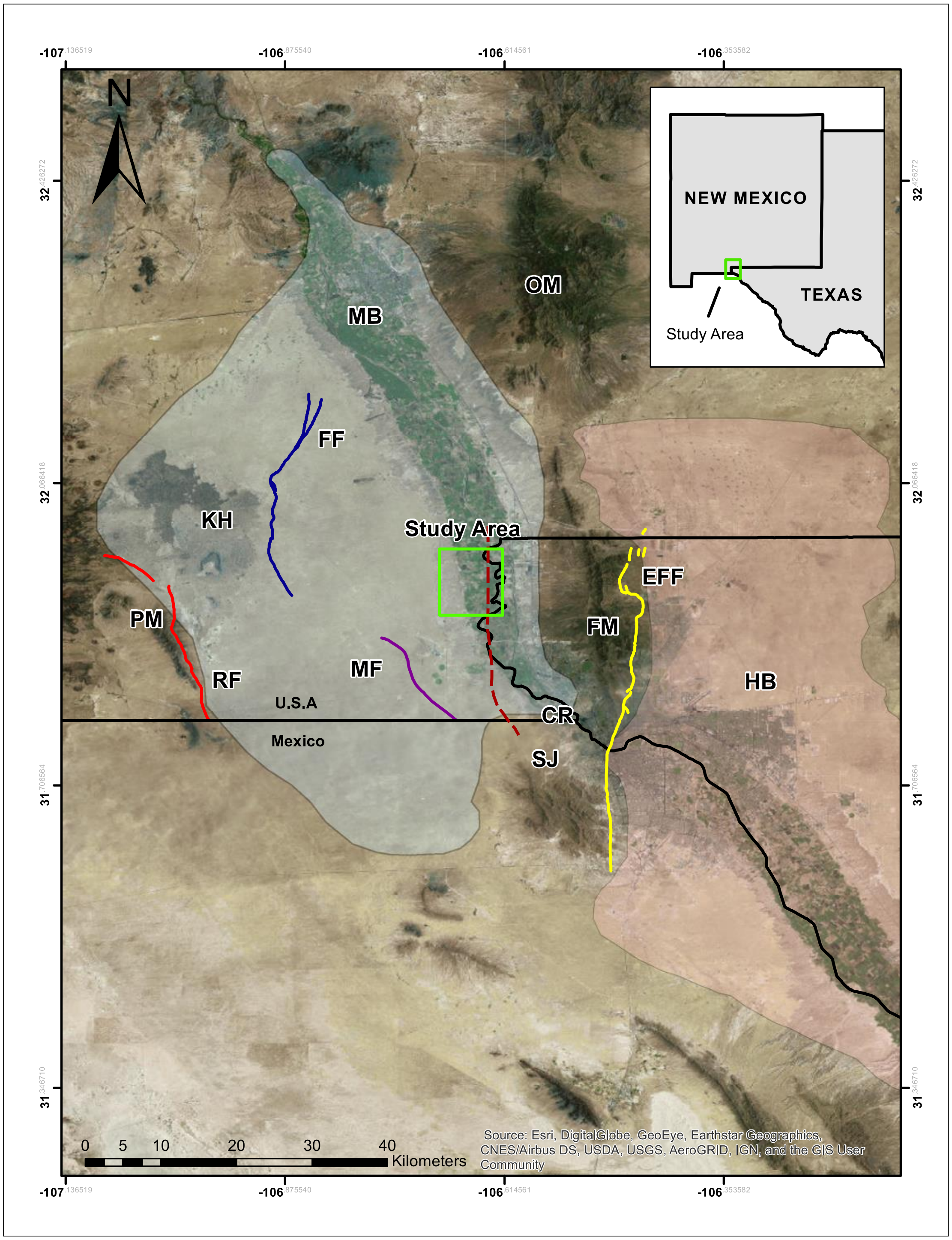

Figure 1: Regional Map with USGS Quaternary Fault map (RF=Robledo, FF=Fitzgerald, MF=Mastodon, EFF=East Franklin Fault). Mesilla Valley Fault is identified by the red dashed line. OM=Organ Mountains, MB=Mesilla Bolson, HB=Hueco Bolson, KH=Kilbourne Hole, CR=Mount Cristo Rey, SJ=Sierra de Juarez.

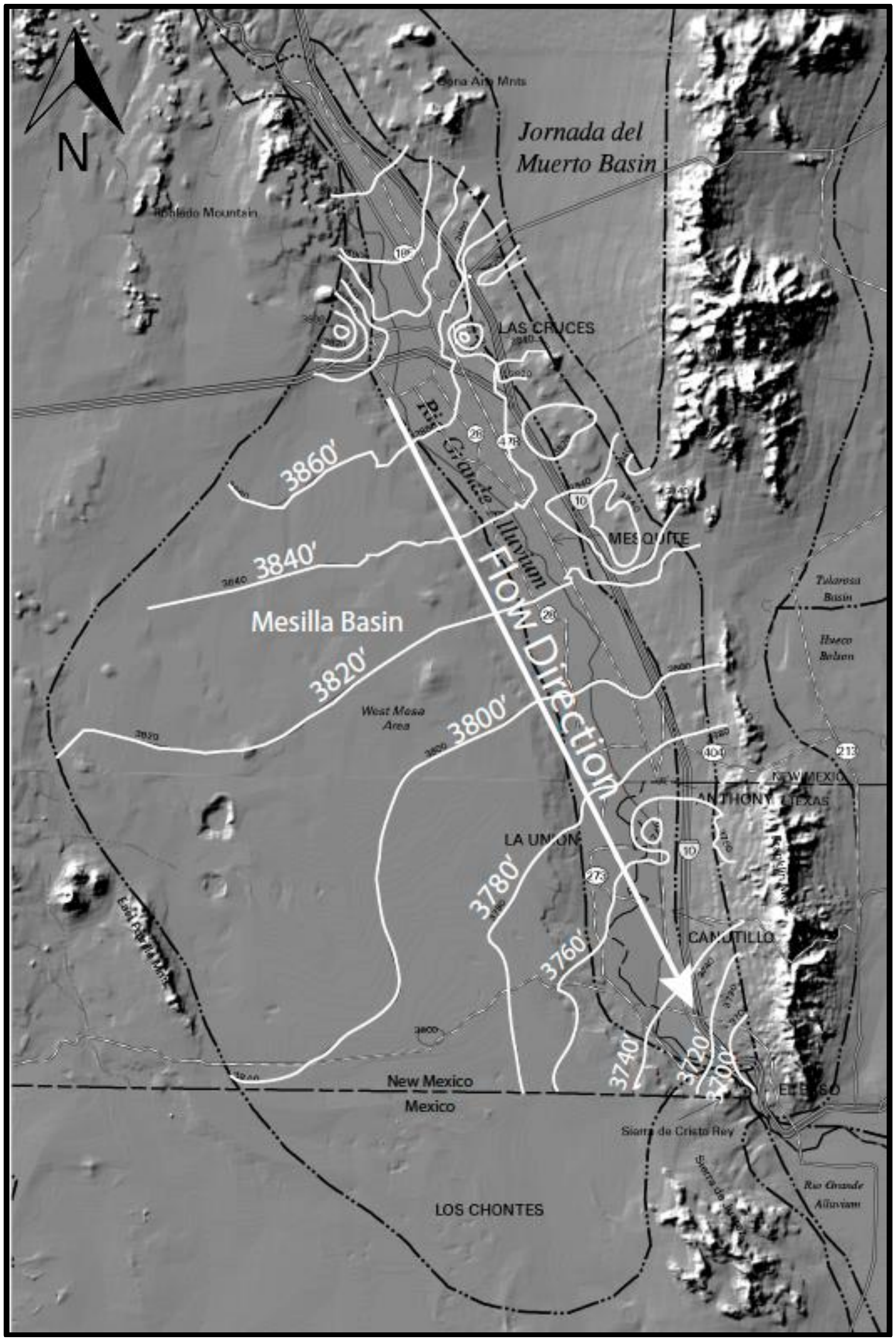

Figure 2: Shaded-relief index map of the Mesilla Bolson area of southern New Mexico and adjacent parts of Texas and Chihuahua showing extent of modeled basin-fill (Santa Fe Group) and Mesilla Valley aquifer systems. General water-table configuration and groundwater-flow direction (white lines) in the top aquifer units of the Santa Fe Group are also illustrated (adapted from Hibbs and others (1997), shaded relief from the U.S. Geological Survey DEM database). Groundwater-flow direction lines are in feet and the contour index is 20 ft. Modified from Hiebing, 2016.

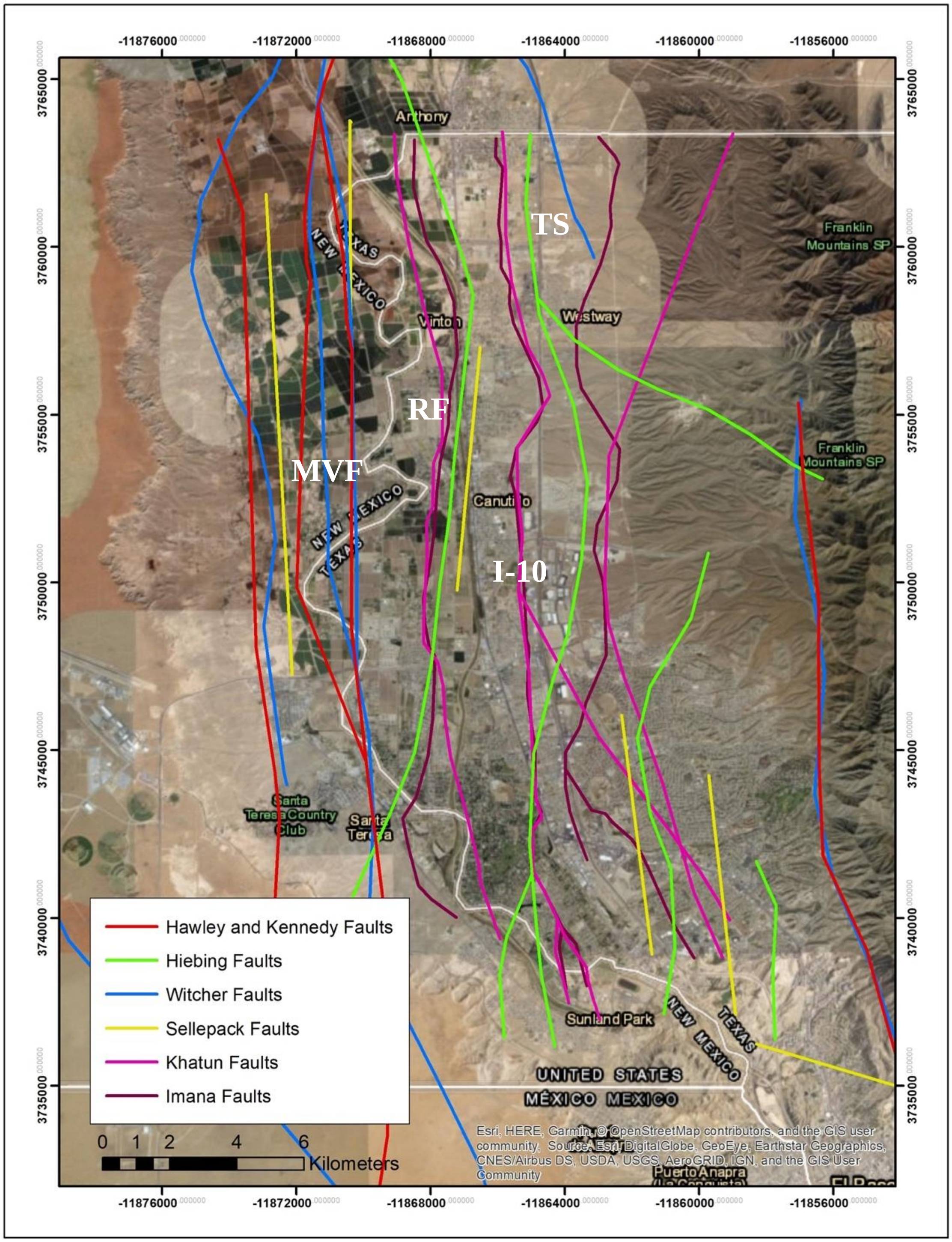

Figure 3: Map showing variation in fault locations as determined by other researchers including Hawley and Kennedy (2004), Hiebing (2016), Witcher et al., (2004), Sellepack (2003), Khatun (2004), and Imana (2002). This shows how fault location have evolved as more geological and geophysical data became available. MVF= Mesilla Valley Fault, RF=River Fault, I-10= I-10 Fault, TS=Three Sisters Fault.

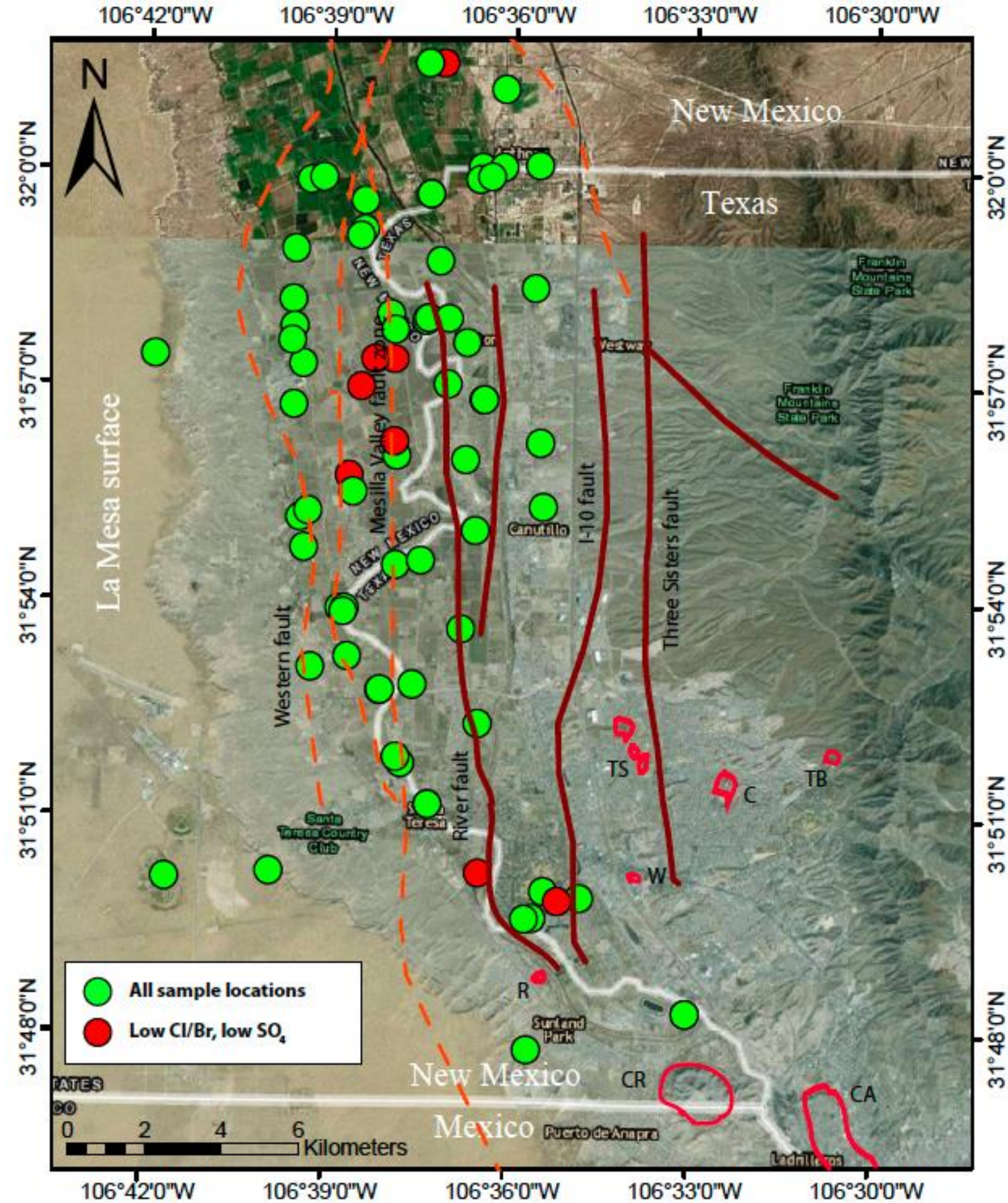

Figure 4: Updated faults from Hiebing et al. (2018). Brown lines are faults interpreted from gravity data, dashed lines are faults that could not be verified from the study. Red lines outline exposed Eocene andesite intrusions. C=Coronado, CA=Campus Andesite, CR=Cristo Rey, R=River, TB=Thunderbird, TS=Three Sisters, W=Westerner. Symbols show sites where

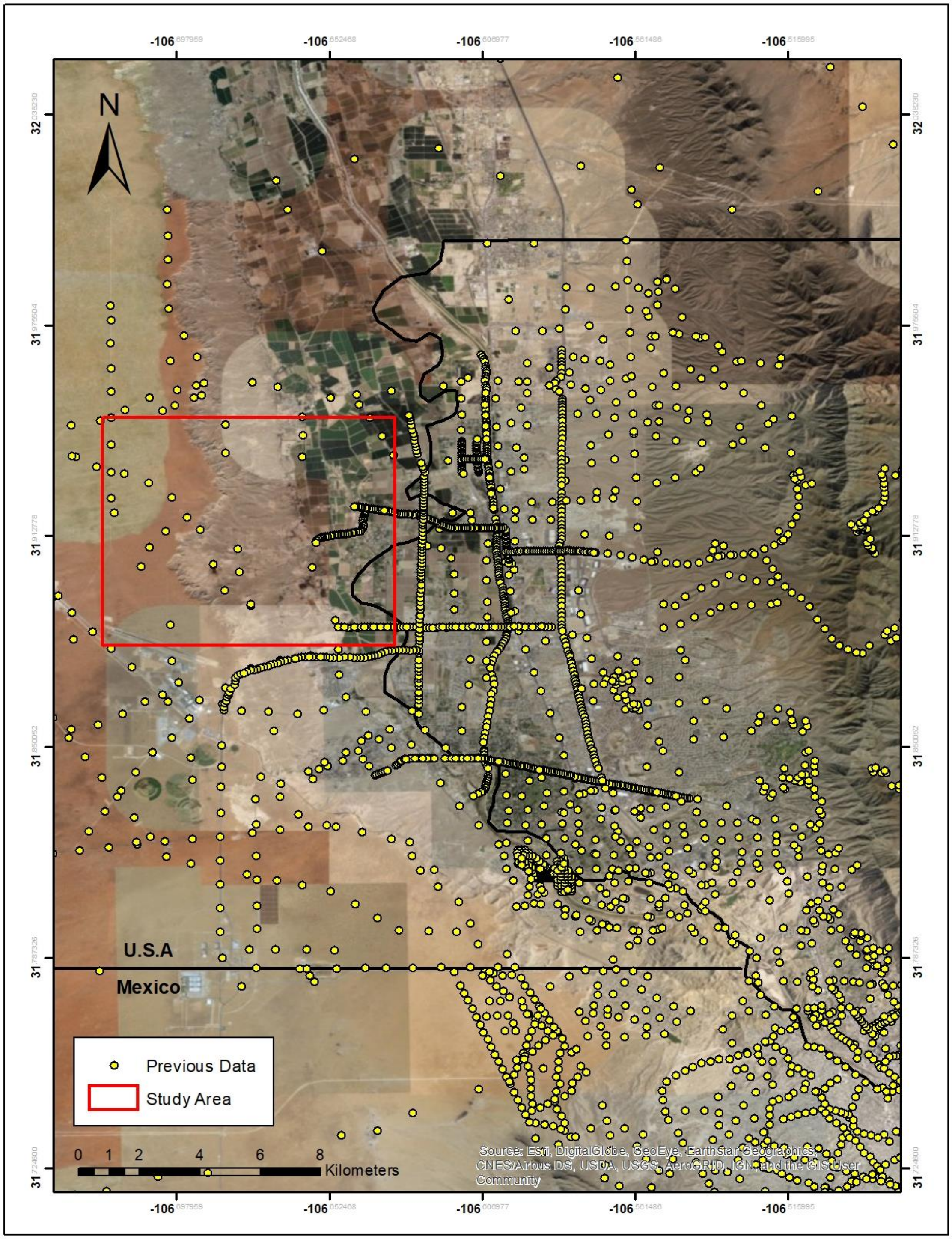

Figure 5: Previous gravity stations. Study area, indicated by red box, had insufficient data to map position of Mesilla Valley fault.

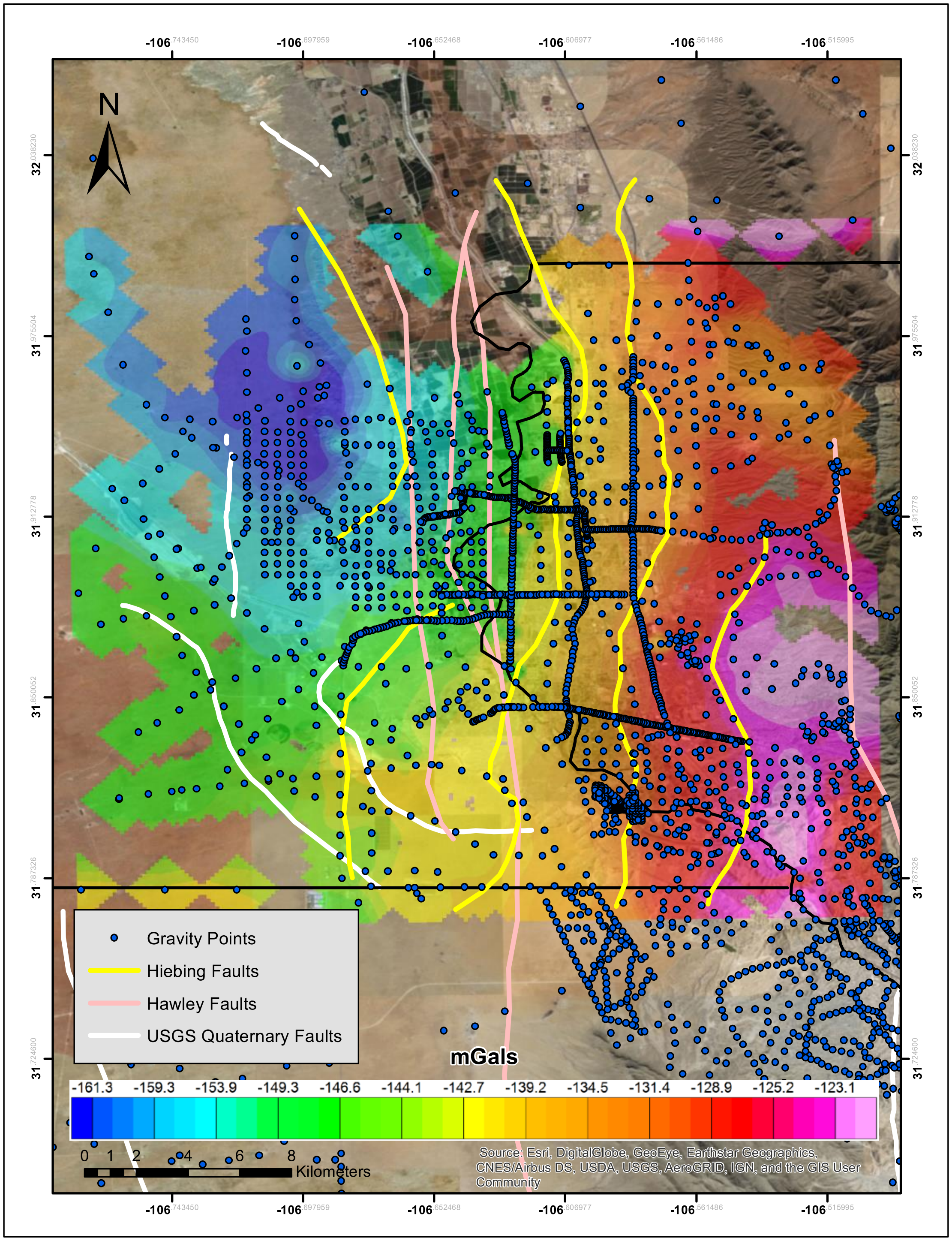

Figure 6: Regional complete Bouguer anomaly map of region with all data points (blue symbols) used in this study. Yellow are faults from Hiebing (2016), pink are faults from Hawley and Kennedy (2004) and Witcher et al., (2004) and white are faults with Quaternary surface offsets (USGS, 2018).

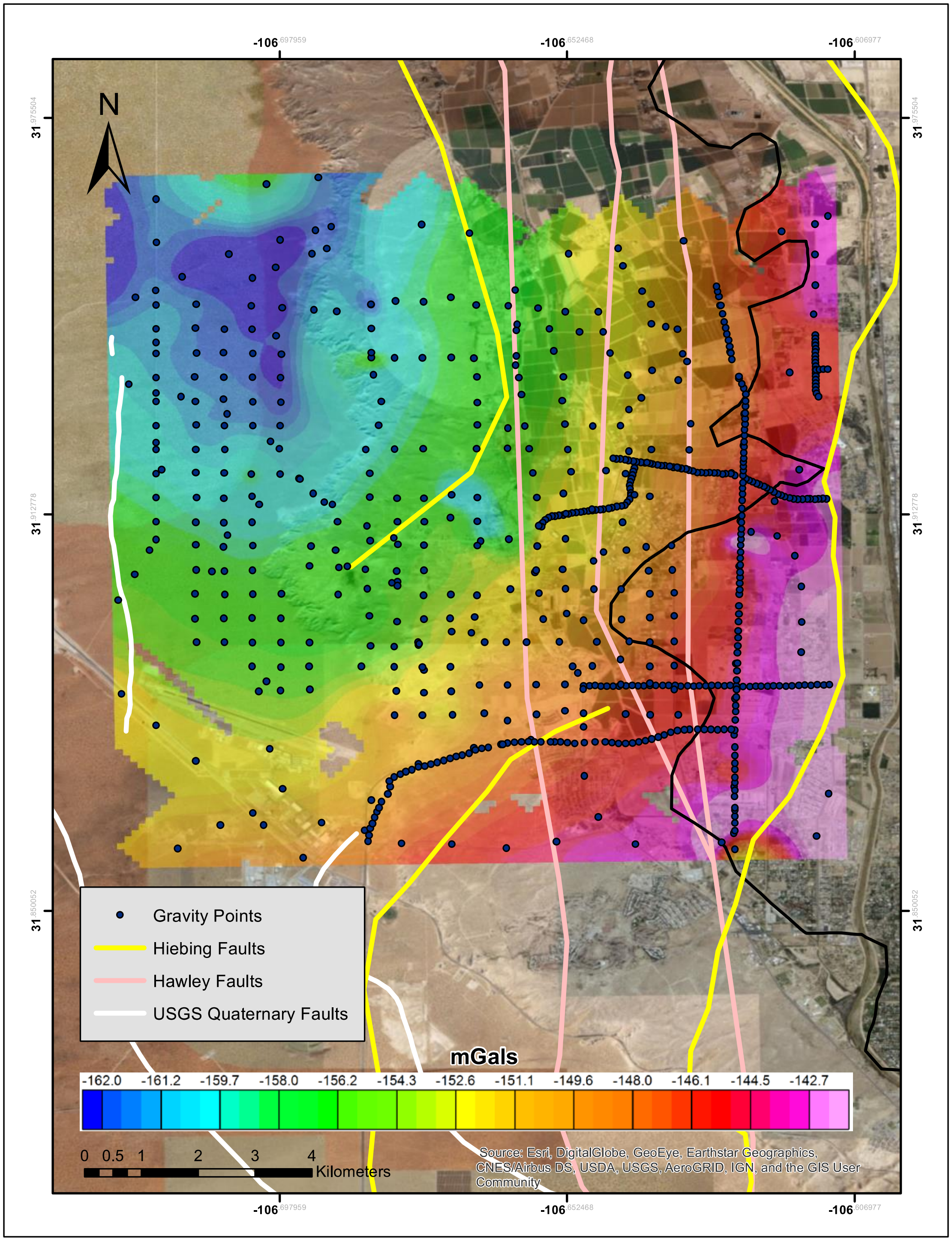

Figure 7: Local Complete Bouguer Anomaly Map

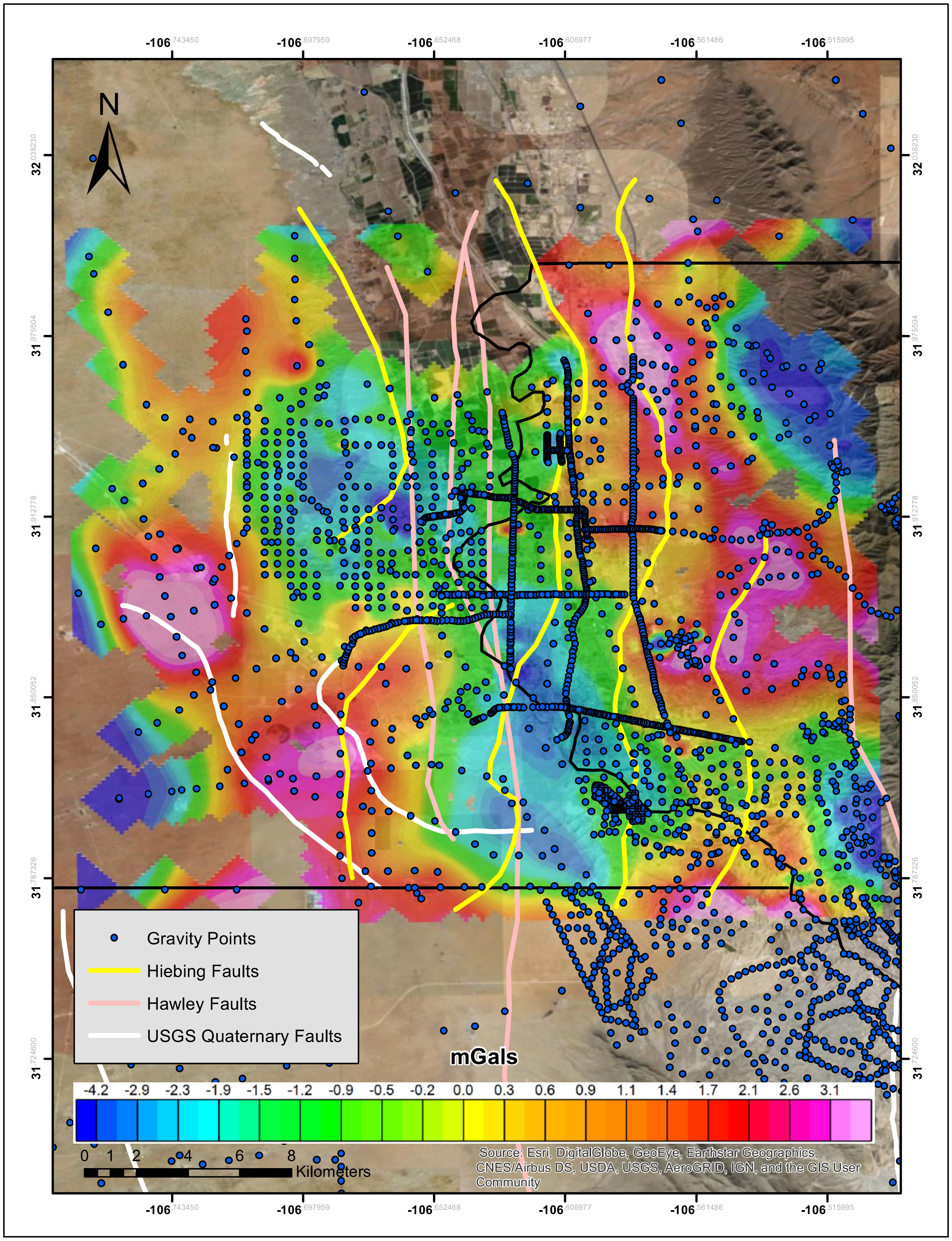

Figure 8: Regional residual Bouguer anomaly map over study area. Created by subtracting third polynomial from complete Bouguer anomaly map. Removes deep regional gravity field from the basin gravity lows (Hiebing, 2016). Yellow are faults from Hiebing (2016), pink lines are faults inferred by Hawley and Kennedy (2004) and Witcher et al. (2004), white are faults with mapped Quaternary offsets (USGS, 2018)

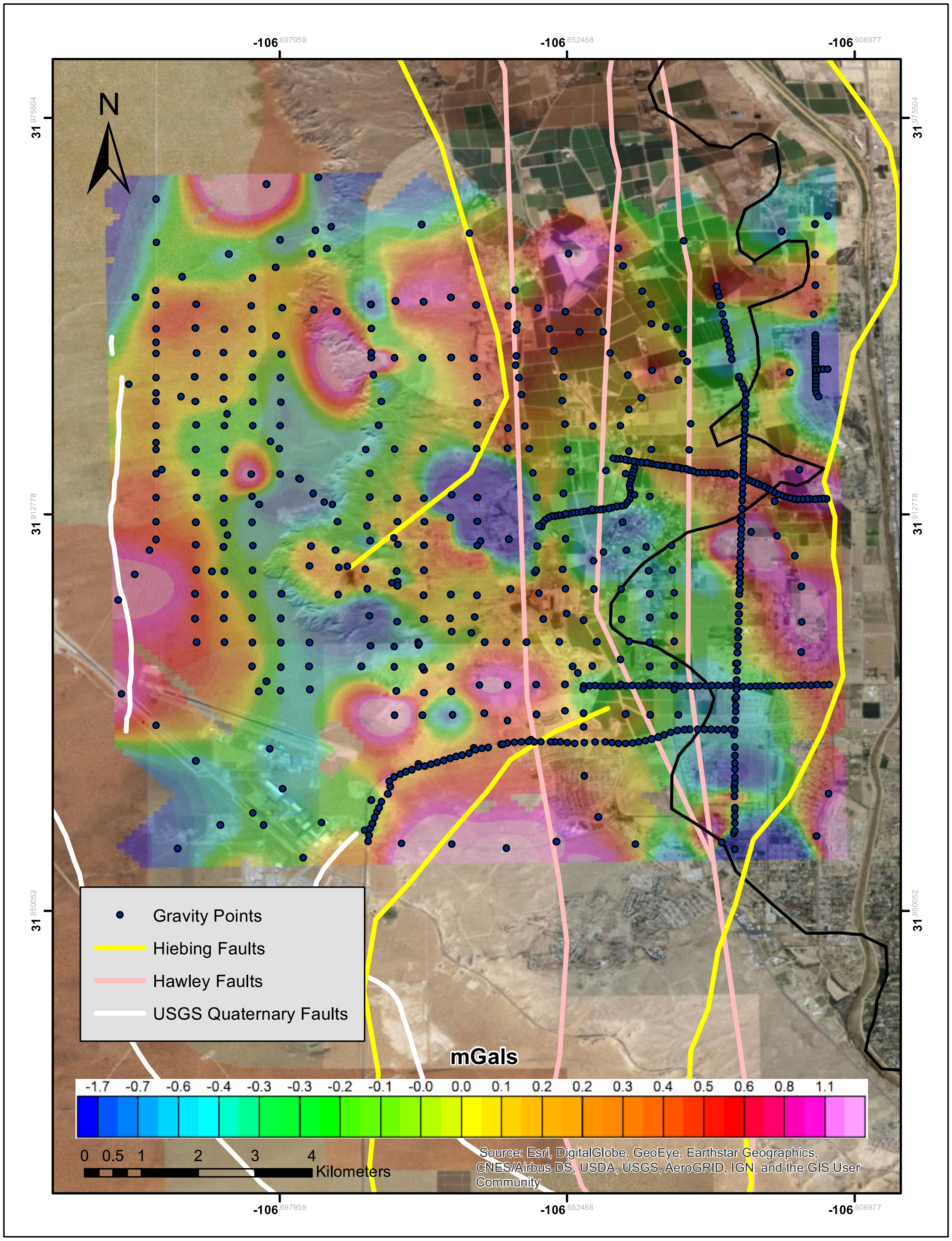

Figure 9: Local Residual gravity map.

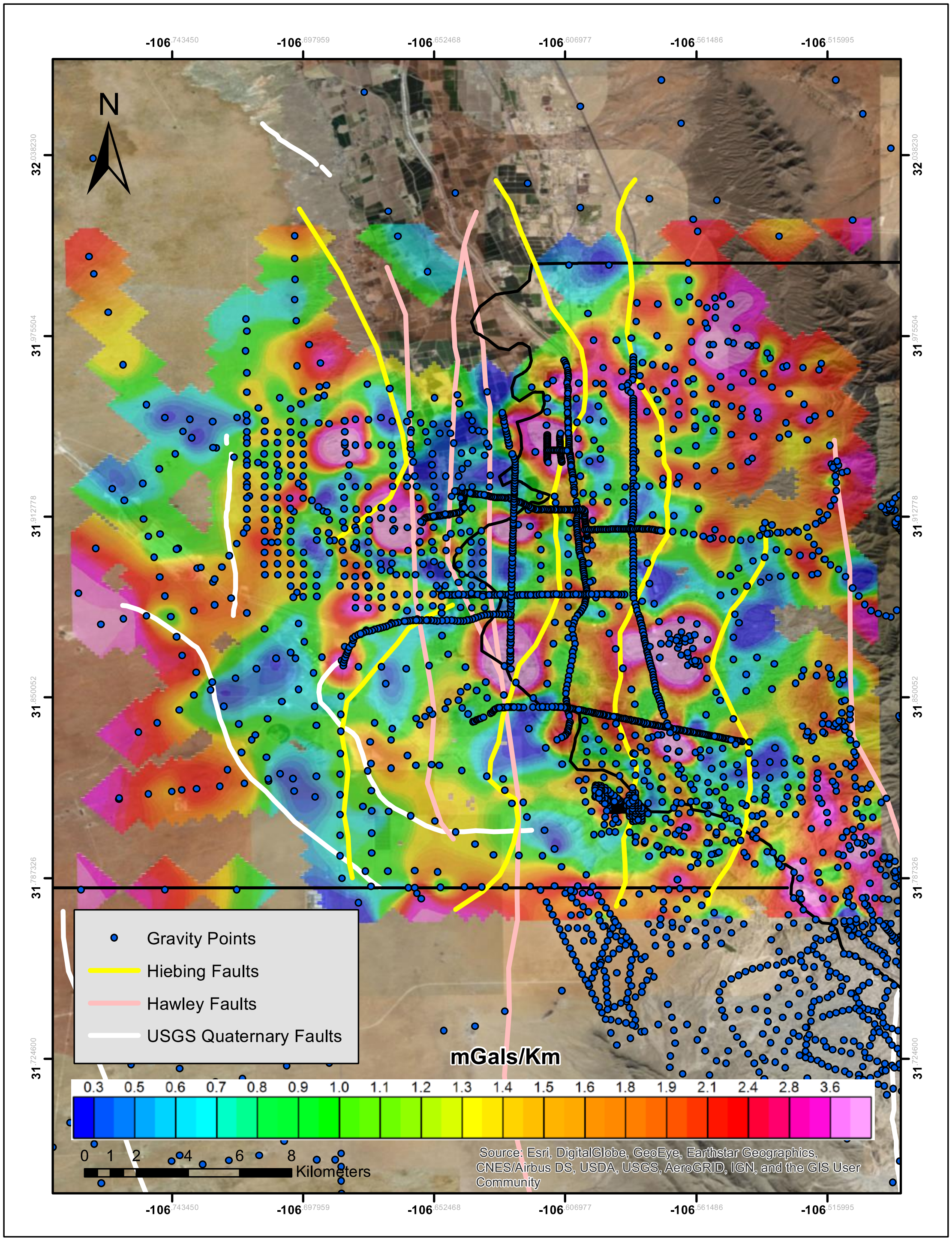

Figure 10: Horizontal Gradient Magnitude (HGM) map showing deep and shallow structures. High contrasts between colors indicate abrupt vertical changes in structure (Hiebing, 2016).

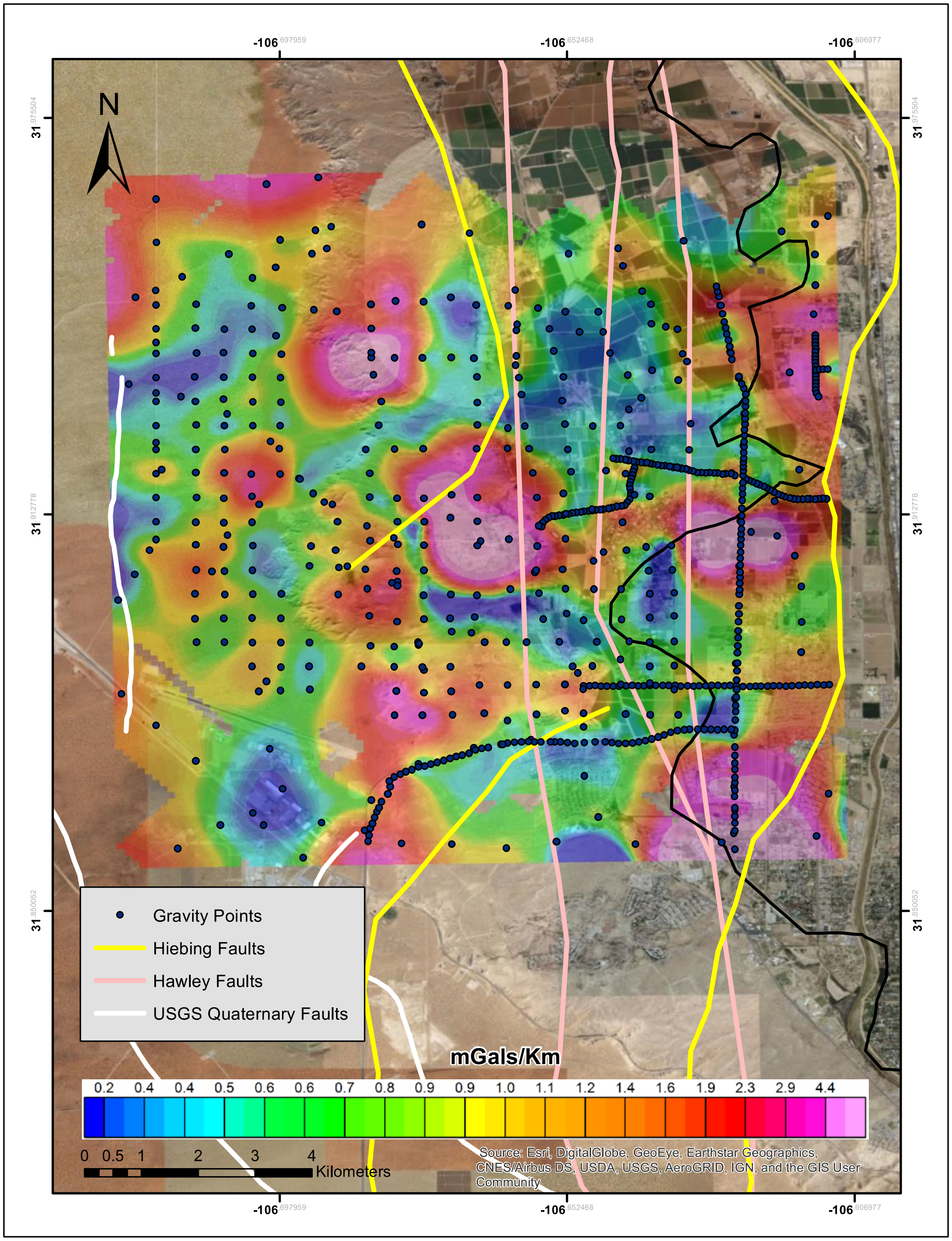

Figure 11: Local Horizontal Gradient Magnitude Map.

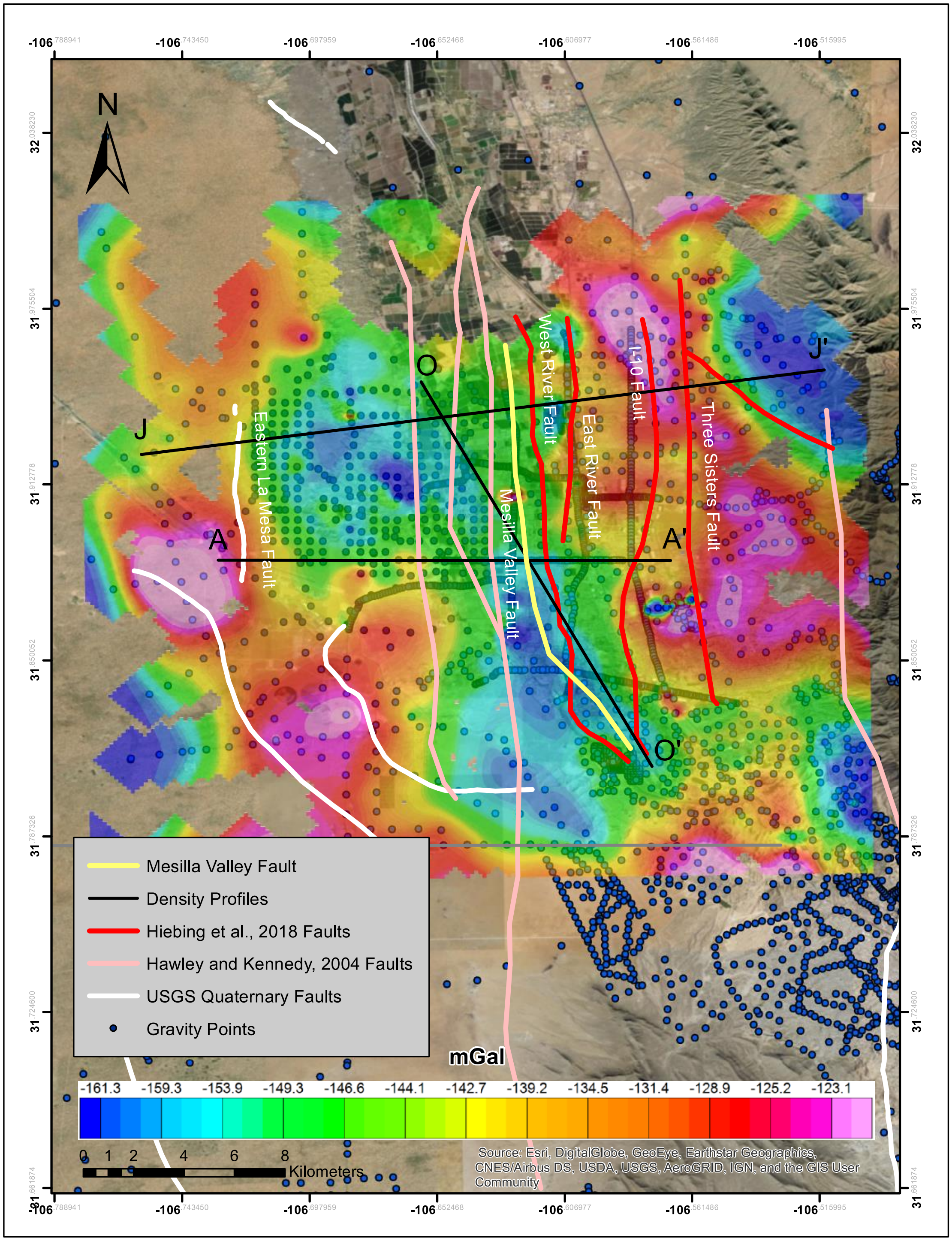

Figure 12: Complete Bouguer Anomaly map overlain with various faults based on my study the new position of the Mesilla valley fault is indicated by Yellow line (Hawley and Kennedy 2004; Hiebing et al. 2018; USGS Quaternary Faults).

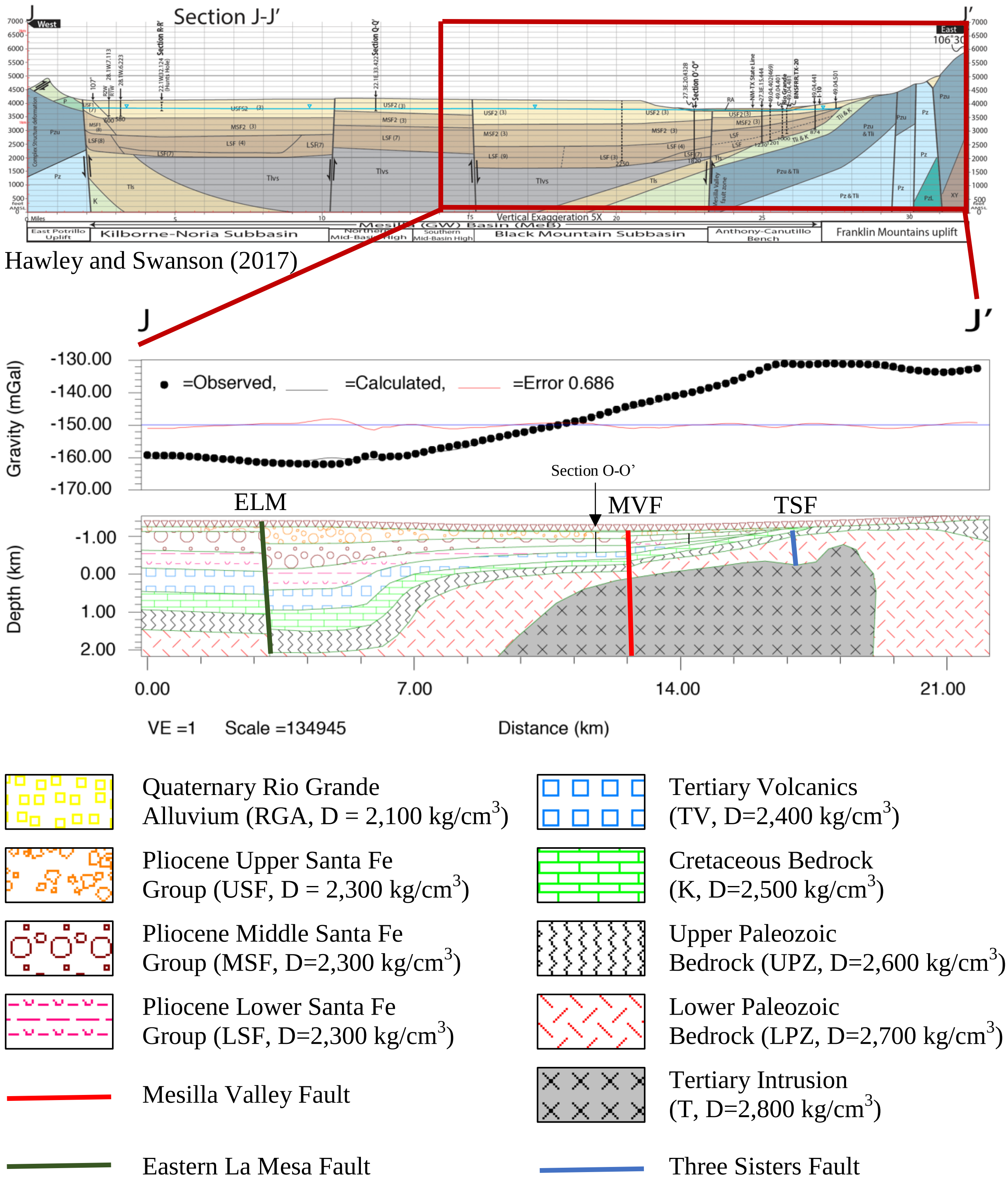

Figure 13: Density Profile from J-J' shows the hydrogeological cross section from Hawley and Kennedy (2004) as well as Hawley and Swanson (2017). A portion of this cross section (indicated by the red box) was the area used to constrain the two-dimensional density profile J-J'. Black lines indicate water well locations. ELM=Eastern La Mesa Fault. MVF=Mesilla Valley Fault. TSF=Three Sisters Fault

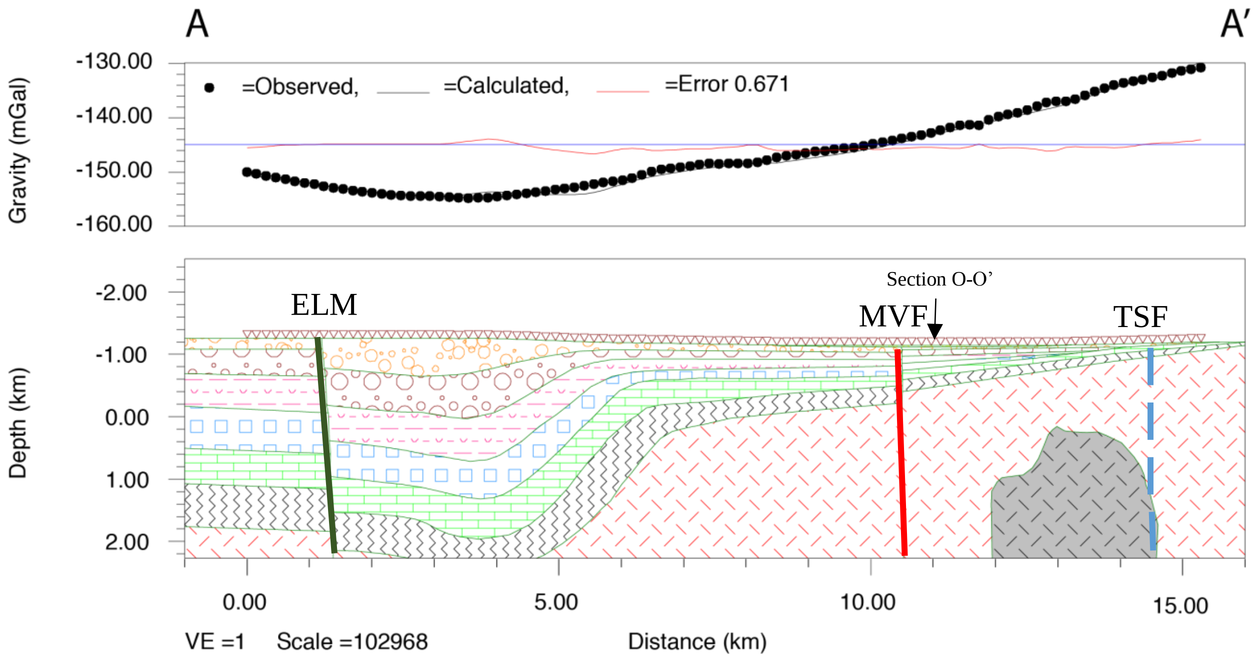

Figure 14: Density Profile A-A' is a two-dimensional gravity profile just north of Cross Section A-A' from Hiebing et al., (2018). ELM=Eastern La Mesa Fault. MVF=Mesilla Valley Fault. See Legend in Figure 14.

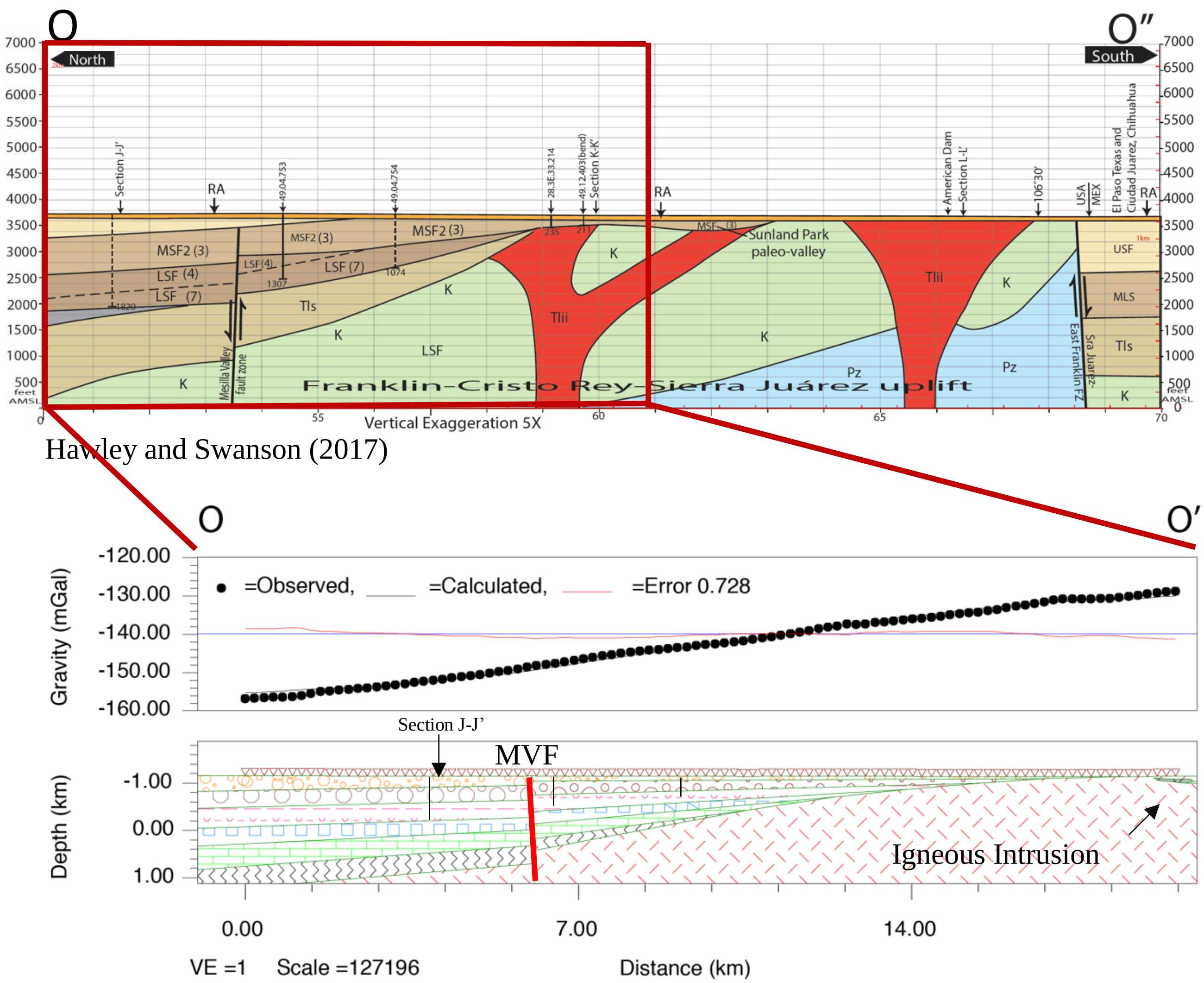

Figure 15: Density Profile O-O’ MVF=Mesilla Valley Fault. See legend in Figure 14.

Vita

José Pablo Cervantes was born and raised in El Paso, Texas. He obtained his Bachelor's degree in Geological Science from the University of Texas at El Paso in 2015. After graduation, he continued his graduate studies at the University of Texas at El Paso where he obtained his Master's of Science in Geophysics in August 2018. He attended the Geological Society of America annual meeting in Seattle, WA, to present his research as well as Earth Educators Rendezvous 2017 in Albuquerque, NM, to present his research-based labs experience. José served as President of the student chapter of the Society of Economic Geology in 2015 and as Secretary to the student chapter of the Society of Explorational Geophysicist in 2016.

During his studies, he received the South Texas Geological Society, Jones-Amsbury research grant in 2017. José was also awarded a geology department scholarship for study abroad at the La Salle Polytechnic University in Beauvais, France in 2016. Jose worked with the United States Department of Energy – National Energy Technology Laboratory in Morgantown, West Virginia as a research associate for summer and fall 2017 during his graduate studies. He plans to pursue a career in geographic information systems and data science with applications in the oil and gas industry.

Contact Information: José Pablo Cervantes
cervantes.josepablo@outlook.com

This thesis was typed by José Pablo Cervantes