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GEOPHYSICAL STUDIES OF THE THREE SISTERS ANDESITE, WEST EL PASO, TEXAS

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Master's Program Geological Sciences

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2019

Dedication

I dedicate this thesis to my wife Annmarie Garcia who has been a constant source of support and encouragement during the challenges of graduate school and life. Without her belief in me I would have never made it this far in life and attempted to obtain my Master’s. I am truly thankful for having you in my life.

GEOPHYSICAL STUDIES OF THE THREE SISTERS ANDESITE, WEST EL PASO, TEXAS

by

ALEXANDER D'MARCO GARCIA, BSc., A.A.

THESIS

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for the Degree of

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Abstract

The Three Sisters andesite intrusion is part of series of three small igneous bodies that crop out in western El Paso to the north of the more extensive intrusions found on the University of Texas at El Paso campus and at Mount Cristo Rey. These Oligocene age intrusions are believed to form part of a deeper, more extensive igneous body that may lie beneath much of western El Paso and the southern Mesilla Valley. I used several geophysical techniques to determine the size and shape of the Three Sisters intrusion to better understand its connection to other andesite outcrops and deeper structures. Gravity was used to determine the lateral extent of the bodies below the surface and their possible connection to other intrusions. Magnetic techniques were used to further constrain the size of the intrusion and to examine variations in mineralogy of the outcrops that appear to be related to whether the andesite intruded into limestone or shale host rock. It appears the intrusions are related to narrow dikes that were the conduits from a deeper magma source and small near surface sills likely controlled by the shales.

Table of Contents

List of Figures

Chapter 1: Introduction

Eocene age andesites (47-48mya) (Barnes et al., 1991; Chapman et. al., 2018) intrude an extensive region of western El Paso and northern Ciudad Juarez, Mexico (Figure 1). The purpose of this thesis is to study the Three Sisters Intrusion, one of the smaller intrusions found in northwestern El Paso located midway between the Rio Grande and the crest of the Franklin Mountains. The goal of this study is to use geophysical techniques to better determine the subsurface extent and structure of the intrusion. Understanding the size and shape of the intrusion can help provide insight on the role of the intrusions in the tectonics of the region during the transition between Laramide compression and the initiation of Basin and Range/Rio Grande rift extension, how previous geologic structures may have controlled the location of the intrusions and also understanding how the intrusions control surface and subsurface water flow.

Geophysical surveys are conducted to collect information about the spatial distribution of the physical properties of the earth's interior by acquisition of geophysical data at the earth's surface. The acquisition of a single data set using a geophysical method can often present certain limitations that will make it difficult to obtain a unique model of the subsurface (Roy, 1962). Combined use of different data acquisition methods will lead to a more reliable solution that can be carried out at any stage of an investigation such as processing, modeling or interpretation. The interpretation of geophysical data is important in modeling the geological structures at depth, which can be used for a better understanding of various geological processes, e.g., regional metamorphism within certain geological units.

The purpose of this study was to determine the size, extent, shape, and orientation of the Three Sisters igneous intrusion. During this study I utilized gravity and magnetics to determine how deep the intrusion extended and how it may connect to deeper structures. Gravity and magnetics were chosen for this study because of the contrast in the physical properties of andesite with the surrounding shale and limestone rocks. Andesite is not only denser than shale and limestone but contains more magnetite, making these techniques ideal for this type of study.

Initially, I wanted to incorporate seismic methods to further constrain the data. However, in the summer of 2018 several seismic lines were collected along the North Sister (hill) by community college students participating in a summer research experience (Gillman, 2018). The results of their study were re-interpreted and incorporated into my study to assist in determining the geometry of the intrusion of the North Sister.

Previous gravity data collected near Three Sisters by former University of Texas at El Paso (UTEP) students for regional studies were incorporated, as well as new data I collected, to fill any gaps in gravity coverage. All my gravity data were collected using a differential GPS unit to obtain the accuracy of position required for processing the data and interpreting the results.

Along with gravity, magnetic surveys were conducted across each of the Three Sisters to help constrain the size and shape of each intrusive body (Figure 2). The only previous magnetic study at the Three Sisters was completed by several UTEP graduate students in 1970 (Cathey et al., 1970). These data were not incorporated into this study because the data were collected with a less sensitive instrument and a less dense sampling grid was used.

In 2012 some UTEP students conducted a series of microgravity and magnetic surveys to determine the length, width, and if possible, depth extent of an andesitic dike adjacent to the Rio Grande River. Initial data collected in December 2011 showed that the andesite body was much larger than expected and that the study was successful in determining the size and shape of the andesite body (Baker et al., 2012). This gave me confidence that a similar study of the Three Sisters using gravity and magnetics would be successful.

My second objective was to create several 2-D cross sectional profiles of density and magnetic variations within the study area. This will help determine the sub-surface geology of the intrusions and of older Cretaceous (100-113 mya) rocks surrounding the intrusions and how they may influence the localization of the intrusions. Based on geologic mapping and analysis conducted by community college students in the summers of 2017, 2018 and 2019 (Lamborn, 2018; Gillman, 2018; Khisty et al., 2019), we are beginning to believe that the smaller igneous bodies are not stocks but are sills or dikes that are controlled by the location of shale units that have been stacked by Laramide thrust sheets that abut the western Franklin Mountains. The larger intrusive bodies (Cristo Rey and Campus andesite), however, are laccoliths or stocks.

Chapter 2: Location

2.1 Field Site

The Three Sisters are three small hills located on the west side of El Paso, west of the Franklin Mountains (Figure 3). The three intrusions are located within the Westside Community Park which is surrounded by urbanization. To determine how far the Three Sisters extend outward from the park I collected gravity data in the nearest neighborhoods that surround the park.

The highest elevation of the Three Sisters is 4165 ft. (1270 m). The North Sister, which is the largest of the three, is surrounded by Quaternary alluvium, except on the southern side where there is some contact with Cretaceous shales thought to be part of the Muleros formation (100-113 mya). (Phelps et al., 2019) The Middle Sister, which is the smallest, has an elevation of 4085 ft. (1246 m) and is also surrounded by Cretaceous shales and limestone believed to be part of the Muleros formation. The Southern Sister is the second largest of the Three Sisters. Portions of the igneous body on the southern sister outcrop at the top of the hill and at the base on the north side to the southeast side. The middle slope of the southern sister is a Cretaceous limestone layer. A Cretaceous shale layer crops out at the base of the west side of the southern sister. Quaternary alluvium surrounds the middle and southern sister (Figure 4).

2.2 Geologic History

In the Jurassic Period (156 -159 mya) El Paso was located near the head of an arm of the Gulf of Mexico called the Chihuahuan Embayment, also called the Chihuahua Trough (Le Mone et al., 1989; Haenggi, 2002) . This major sedimentary basin of Mesozoic age (65-144 mya) was located at the southern margin of the North American craton (Carciumaru and Ortega, 2008). Thick sequences of sedimentary rocks including limestones, shales, and evaporites were deposited within the trough. The Laramide orogeny (40-75 mya) caused crustal shortening which strongly deformed the rocks of the Chihuahua Trough creating intense folding and imbrication of the older rocks due to the near horizontal subduction of the young, warm Farallon plate off of western North America (Gries, 1970; Barnes et al., 1991). It is now suggested that crustal shortening caused upper-mantle upwelling near the Rio Grande rift–Great Plains craton boundary (Reiter and Chamberlin, 2011). This upper mantle upwelling caused the slab to "roll back" producing melting of the slab and continental crust which has been confirmed by the geochemistry of the andesite that forms the Three Sisters and other Eocene igneous bodies (47-48 mya) (Barnes et al., 1991). Major element geochemical data presented by Barnes et al., (1991) shows the Three Sister intrusions are calc-alkaline, which is representative of subduction related magmatism. Trace element spider diagram (after Thompson et al., 1984) shows negative Nb-Ta anomalies, suggesting the involvement of crustal material in the petrogenesis of these rocks. The igneous bodies were emplaced at depths of 16 ± 4km as suggested by amphibole thermobarometry values of 5.5kbar (Barnes et al., 1991).

The Rio Grande rift is a north-south trending zone of lithospheric extension expressed in the upper crust by a series of north-south–trending en-echelon basins of middle to late Cenozoic age (30-35 mya) that extend more than 1000 km from central Colorado through New Mexico into west Texas (Figure 1) (Reiter and Chamberlin, 2011). The tensional forces and rifting have helped create numerous elongated basins, separated from one another by mountains (Le Mone, et al., 1989). Some local examples include the Hueco Mountains, the Hueco Bolson (or basin), the

Franklin Mountains, and the Mesilla Bolson (or basin). As they were uplifted, the material from the mountains began erode to accumulate in the basins, a process that continues to this day.

Chapter 3: Previous Studies

Previous petrographic studies have been conducted on the ten largest andesitic plutons that outcrop from El Paso and Ciudad Juarez to Vado, New Mexico. The rocks in all ten andesitic plutons are porphyritic and range in composition from andesite to rhyodacite (Garcia, 1970). All the plutons are assumed to be post-Cretaceous and pre-Pleistocene in age. (Garcia, 1970). The average mineral composition and grain size in samples of the Three Sisters Andesite are Plagioclase (67.9%), K-Feldspar (11.6%), Hornblende (12.2%), Biotite (5.8%), Magnetite (1.3%), and Quartz (1.2%) (Garcia, 1970). The rock found at the Three Sisters is porphyritic, at times it can be glomeroporphyritic, containing white to very light-gray plagioclase and dark mafic mineral phenocrysts and large crystalline inclusions in a grayish fine-grained matrix (Garcia, 1970). The phenocryst minerals include plagioclase, a small amount of K-feldspar, hornblende, biotite and magnetite. The most abundant feldspar found in the Three Sisters is plagioclase and the amount of hornblende found in the rock makes the Three Sisters a hornblende andesite porphyry (Garcia, 1970).

In 1970 a magnetic study was conducted over the Three Sisters. The goal of the study was to determine the subsurface extent of the andesite pluton at the Three Sisters (Cathey et al., 1970). They conducted 4 survey lines, three placed in the east-west direction along each sister and one in the north-south direction covering all three sisters (Figure 5). Andesite typically has a high magnetic susceptibility, which should allow delineation of its boundaries in the subsurface to be evident after conducting a magnetic survey. However, during this study Cathey et al. recorded sharp local changes in the magnetic field leading them to believe that the andesite at the Three Sisters had varying percentages of magnetite throughout the intrusion (Figure 6) (Cathey et al, 1970). The plots for each survey show erratic increases/decreases of 200 gammas within the andesite intrusion. After analyzing the data collected, no delineation between the andesite and the outlying sediments was seen, making it difficult to confidently determine the outer limits of the andesite intrusion (Cathey et al, 1970). The dams were in place by 1970 when this study took place, so the only things that have changed since this study are likely the construction of the cell tower on North Sister and the various buildings near South Sister.

In 2018 five seismic lines were recorded on the eastern side of the North Sister (Gillman, 2018). Four of those lines were oriented perpendicular to what was thought to have been the contact between the andesite and sedimentary units, and one was oriented parallel to the supposed contact (Figure 7). Each line was 70.5 meters long, with geophones spaced every three meters. Lines four and five overlapped one another in order to create one continuous line about 35 meters longer than the others. The seismic source for the surveys was a sledgehammer that was hit approximately 10 times at each shot location. The shot locations were spaced 9 meters apart, starting 1.5 meters before the first geophone. First arrivals were picked with Pickwin, and then Plotrefa was used to model these data.

There was also a conductivity study performed on the North Sister in 2019 (Martin et al., 2019). The EM31-MK2 device used measured the conductivity of the rocks by using Geonics “patented electromagnetic inductive technique”. The data were collected over the course of two days in a radial pattern around the north hill.

The seismic results were expected to support the idea that the east side of the hill contains more andesite like it was originally mapped in 1970 by Garcia. Although a small outcrop is present on the eastside of the North Sister, the velocities that were observed were too low to indicate andesite at a depth of < 20 meters (Gillman, 2018). This suggests that the andesite outcrop observed along the eastern side of the hill is most likely a piece that fell off the upper part of the hill. The results of this study do not indicate an abrupt change in velocities in any of the lines and only suggest the presence of alluvium and shales that become more competent with depth (Figure 8). Without andesite present on the east side, the intrusion cannot be a laccolith since it does not appear to be a radially symmetric body. Results of the EM-31 study were in good agreement with Gillman's work – indicating there is little andesite at depth on the south and east sides of North Sister.

Although no gravity study had specifically been conducted at the Three Sisters there have been gravity studies conducted within the southern Mesilla Basin (e.g., Hiebing et al., 2018). The results of this study indicated that the high residual anomaly values (Figure 15) are associated with most outcrops of Eocene intrusions in the southeastern Mesilla Basin, with suggestions that some of the smaller outcrops (e.g., the River, Westerner, and Three Sisters intrusions) may be linked to Cerro de Cristo Rey by feeder dikes (Hiebing et al., 2018).

Chapter 4: Methodology and Data Processing

According to Zhdanov (2002), the most important geophysical techniques for subsurface investigations are gravity, magnetic, electromagnetic, and seismic. The data collected with each method are mainly a function of the physical properties of the material, the ambient noise at each measuring point, and the data acquisition system (Zhdanov, 2002). In this section all geophysical methods used will be briefly described.

Gravity and magnetic data are known as potential field data and are often used for exploration geophysics. These data are then combined and modelled and assist in the interpretation of the geology beneath the subsurface. The data collected are values of the vertical component of the gravitational acceleration and total magnetic field. The sources of the fields are the different variations of the physical properties of rocks, dissimilarities in density and magnetization. The measured data provide a better image of the structures beneath the Earth's surface. These data are collected at the earth's surface (on the ground).

4.1 Gravity Method

The gravity method has been widely used in exploration geophysics (Blakely, 1996). The gravity method works by measuring the vertical component of the gravitational acceleration at different locations within a certain area. The measured values are directly related to the variation of subsurface density and therefore can be used as a powerful tool to investigate subsurface geology. Before any interpretation is made the measured data values must be processed and corrected. Different corrections such as latitude, free-air correction, Bouguer correction, and terrain correction are often required before the variations in gravitational acceleration caused by a geologic structure can be examined. For a qualitative interpretation the processed data are used to create maps of the Bouguer or free air anomaly that help geologists and geophysicists study the variation of the geometry and density of rocks in the area. Depending on the rock type, the density has a wide range of variations that can be helpful when mapping different types of bedrock. Rocks like gabbro and basalt are formed of higher density minerals such as pyroxene and calcic plagioclase and therefore generate greater Bouguer anomalies than more acidic/felsic rocks like rhyolite granite that is rich in lighter minerals like feldspar and quartz.

To determine the extent of the igneous intrusion I created a sampling plan for the region surrounding the Three Sisters site to detect the change from the igneous body to the surrounding sedimentary rocks. A grid with a spacing of 100 to 200 meters (Figure 10) was created and existing data were utilized to enhance the grid. The existing data were collected using the same gravimeter as I used and the resulting data processing to obtain the Bouguer anomaly was also the same. To guarantee no overlap occurred, I eliminated any planned grid point if existing data had been collected within 50 meters of the grid point.

The existing data were collected by former UTEP students Salma Khatun (Khatun, 2003) and Imana Ekal (Ekal, 1994). Salma Khatun used GPS for latitude/longitude control and leveling for elevation control. Imana Ekal collected his data using precision leveling to determine his elevations and distances from known bench marks. Since all these data were collected after the construction of Redd Road, both surveys used the same gravimeter and used surveying techniques that give comparable position accuracy to my GPS positions these data should be directly comparable to my collected data.

Figure 8 shows the final map of the Three Sisters' grid with the green squares on the map indicating where new data were collected. The Three Sisters site is surrounded by established neighborhoods, so some flexibility with exact spacing was needed in the data collection process. I used a LaCoste & Romberg G Meter with microgal precision for this study. To ensure proper location and elevation of each station I used a Topcon GB-1000 GPS to obtain measurements with sub-meter accuracy. A gravity base station was placed at the Westside Community Park east of the middle hill next to the children's playground. This gravity base station was marked and surveyed several times before data were collected. To be able to calculate instrument drift, I returned to the gravity base station every four hours to close the current loop. Whenever data were collected, the GPS base station was left on for at least 2 hours with antennas to ensure location precision.

4.2 Gravity Data Processing

Once data collection was complete, then standard corrections were applied to the gravity data. Some of these corrections included drift, terrain, and free-air correction (Telford et al., 2010). Varying temperatures, pressures and the Earth's tides cause the Lacoste and Romberg instrument to drift. By returning to the base station every four hours I could calculate the drift per minute to be used for the drift correction. To remove the topographic features of the study area terrain corrections were used. To correct the readings for elevation differences at each station (causing the distance to the center of the earth to vary), the free-air correction was implemented that reduced the readings to a common reference level (datum). The last correction to the data was to conduct the Bouguer correction. This 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., 2010). The correction assumes a horizontally infinite slab of constant density. For my calculations I assumed a slab density of 2670 g/cm^3. Next the data were integrated with existing data from Khatun's and Ekal's studies to create a series of simple Bouguer maps to help determine the shape and size of the igneous body. Minimum curvature was the main interpolation method used for this study due to its ability to create the smoothest surface from the data.

4.3 Magnetic Method

The magnetic method is a geophysical method that compares the considerable differences in the magnetic properties of Earth forming materials with the ultimate objective of characterizing the earth's subsurface (Brodie, 2002). The magnetic method typically involves the measurement of the intensity of the earth's total magnetic field. Distinctive magnetic minerals such as magnetite (Fe_3O_4) or remnant hematite (Fe_2O_3) interact with Earth's magnetic field to create magnetic anomalies. Magnetization is the net effect of all magnetic materials in a rock (Blakely, 1996). The total magnetization of rocks is equal to the sum of induced and remnant magnetizations. Induced magnetization is the temporary magnetization that exists when a magnetic field is applied to a material. It wanes when the magnetic field is removed. Remnant magnetization is the magnetization that exists when the external field is removed. Remnant magnetization helps determine not only the atomic structure of the rock, but also their geologic, tectonic and thermal history (Blakely, 1996).

Magnetic surveys are carried out to assist in mapping the subsurface geology in relation to the distribution of magnetic minerals. The magnetic susceptibility of rocks is extremely variable depending on the rock type and the environment it is formed in (Mariita, 2007). This method is effective in mapping the location and the shape and size of ferromagnetic ore bodies at depth.

Magnetic data were collected around each of the three small hills of the Three Sisters to determine the furthest extent of the igneous body (Figure 3). The andesite was expected to be more magnetic then the surrounding sedimentary rock, allowing us to determine the outer extent of the igneous body. Previous petrologic studies of the Three Sisters intrusion show that the main constituents of the Three Sisters Andesite are andesine, potassium feldspar, biotite, hornblende, and magnetite with minor amounts of quartz, and apatite. Mineral alteration to sericite, magnetite, kaolinite, and chlorite is evident in the 14 hand samples collected during the study (Streicker, 2018). The North Sister samples showed opaque rings of magnetite around the biotite and hornblende while the middle and south sisters' samples did not have a similar presence of these opaque magnetite rings (Garcia, 1970). This made the magnetics of the area more difficult to interpret.

Utilizing the Geometrics Model G-856 portable proton magnetometer I collected data at 50-meter intervals created in ArcGIS (Figure 11). I used a Chromebook tablet connected to a Garmin GLO 2 Mobile GPS+GLONASS Receiver to find my positions within my grid. The Chromebook ran QGIS which assisted in determining the location of the points on the grid. The magnetometer was mounted on a 2 m pole to eliminate small surface variations and when collecting data, I attempted to avoid placing stations near any power lines or automobiles. There are several areas within the Three Sisters area that were avoided, like dams that separate each of the sisters to control flooding and make this area more accessible to the residents of the area to walk. On the North Sister there is a telephone tower that needed to be avoided in surveying as well as the local library on the southwestern side of the south sister and some metal signage and picnic tables scattered throughout the site.

4.4 Magnetic Data Processing

The measured values of the total magnetic field were corrected according to the diurnal variation of the earth's magnetic field obtained from the measurement of the total magnetic field at the base station approximately every 1-min. The magnetic base station data was fit to a polynomial trend and then subtracted from the rover data. The location of the base station was determined using differential GPS (31.86655311° N -106.5632175° W).

4.5 GPS Processing

For the gravity portion of this study the GPS data were collected by a *Topcon GB-1000* differential GPS which has sub meter accuracy. I collected the GPS points in a static mode survey, which uses a fixed location (base) and a rover unit for the survey. The fixed receiver was placed at the same base station throughout the study. When beginning the survey, the first GPS readings collected on each field day were based on the data collected in a 300 second (5 minutes) period in the same location as the base station in order to achieve excellent pairing of the base and rover units. The subsequent data points were collected with 180 seconds of GPS data.

After each survey was complete the data were transferred from the Topcon GB-100 differential GPS base and rover to an excel sheet and added to the other collected sets. Once all the data were collected, the data from the fixed base station were sent to the Online Positioning User Service (OPUS https://www.ngs.noaa.gov/OPUS/). OPUS generates a solution which helps to better locate the base station and provided accuracy within a centimeter of error. The solution is then applied to the roving data and locations are modified to reflect the corrected base location and increased accuracy.

For the magnetic portion of the study I utilized a magnetic grid that was created in ArcGIS and then upload to a Garmin GLO 2 Mobile GPS+GLONASS Receiver to find my positions within my grid. The accuracy of positions using this technique will give an error of about 3 meters. Since magnetics surveys do not require as great of accuracy in terms of positioning as gravity surveys require this accuracy was acceptable.

4.6 Seismic Data Re-Interpretation

To further constrain the gravity and magnetic data, I re-interpreted the seismic data collected on the North Sister in 2018. Five seismic lines were conducted on the eastern side of the North Sister (Figure 8). Four of those lines were oriented perpendicular to what was thought to have been the contact between the andesite and sedimentary units, and one was oriented parallel to the supposed contact. In 2018 a seismic study was conducted near the Rio Grande River (G. Kaip, personal communication, 2019). The results of this study indicated that the velocity of the andesite was at least 3500 m/s. The P-wave velocities of the North Sister never increase beyond 3000 m/s, leading me to believe that no andesite was mapped in this survey. The initial velocities of 300-1500 m/s are likely to be attributed to the loose unconsolidated sediments and alluvium material found around the North Sister. The faster velocities of 1500-2999 m/s are likely to be the shales found on the east side of the North Sister. This data helped constrain the contacts for my 2-D cross-sections.

Chapter 5: Results and Discussion

The Bouguer gravity anomaly map (Figure 12) has a range of values of -124 mGal to -139.5 mGal. The low Bouguer anomalies are likely to be associated with the basin fill in the study area, consisting of the Oligocene to lower Pleistocene Santa Fe Group and Pleistocene to Holocene Rio Grande alluvium (Hawley and Kennedy, 2004). Figures 13 and 14 are magnetic maps that show the magnetic variation of the Three Sisters area. The magnetic map of the North Sister (Figure 13) shows an increasing magnetic gradient to the west. The magnetic low on the eastside of the North Sister is due to the presence of shale and alluvium. The magnetic high within the North Sister corresponds to the andesite. Figure 14 shows a magnetic high over the Middle and South Sister. The South Sister has more magnetic variation occurring throughout the sister.

5.1 Gravity Data Interpretation

5.1.1 ANOMALY A AND B:

Area A and B on Figure 12 are both high gravity anomalies. The North Sister (Area A) is known to have the largest presence of andesite at the surface. The previous seismic study on the eastside of the North Sister concluded that the andesite seen at the surface must be a piece that fell off the upper part of the North Sister. (Gillman, 2018) This high gravity anomaly indicates that a portion of the eastside must not only have andesite at the surface but it must extend further beneath the surface as well. Area B covers the Middle and South Sister on Figure 12. This area has a higher presence of carbonate and sedimentary rocks at the surface.

Figure 15 is a Bouguer residual anomaly map of the Three Sisters by fitting a third-order polynomial to the Bouguer map for the Three Sisters and then subtracting the polynomial to eliminate longer wavelength, deeper seated variations in gravity. Figure 15 has several high gravity anomalies. On the west side of the map there is a high gravity high that trends north-south and on the north side from west-east towards the Three Sisters. Along the Three Sisters there are two large high gravity anomalies, one over the North Sister and the second that covers the Middle and South Sister. In between the high gravity anomalies there are slightly lower gravity values that likely correspond to the Paleozoic carbonates known to occur in the area. On the east side of Figure 15 the anomaly lows correspond to Quaternary alluvium.

5.2 Magnetic Data Interpretation

5.2.1 NORTH SISTER:

A magnetic low corresponding to the shale and alluvium present at the surface of the North Sister can be observed on its east side (Figure 13). The magnetic values increase toward the center portion of the North Sister where the magnetic high corresponds to the location where andesite is observed at the surface. To the west of the magnetic high the values decrease, likely indicating that there is some andesite present but it is mostly fragments of the larger andesite body on top of the North Sister.

Figure 16 shows the North Sister magnetic map with a Gaussian filter applied. The Gaussian filter deals with random noise more effectively and smooths indiscriminately across the edges of the highs. The Gaussian filter increases the size of the magnetic high on the North Sister.

5.2.2 MIDDLE AND SOUTH SISTER:

The top portion of the Figure 14 is showing high magnetic values over the Middle Sister. The center portion of the map is blanked out due to no magnetic readings because of the dams in place at that location. South of the blank area is the South Sister. The magnetics at the South Sister indicate that the structure and igneous body are more complicated than the North and Middle Sister. The presence of multiple andesitic intrusive events is suggested by a magnetic pattern showing two distinctive high anomalies in the South Sister (Figure 14). The higher anomaly is located at the top of the South Sister and the second one occurs outside of the first one creating semicircular concentric pattern. Based on xenolith characteristics and structural data, the South Sister can be divided into two injections of andesite with unique xenoliths. There is an upper suite with a high density of large diorite and monzodiorite xenoliths as well as a lower suite with fewer diorite and smaller monzodiorite xenoliths (Cooper, 2018). This could explain why the South Sister has a magnetic high at the center of the intrusion but to the south there is an area of slightly lower magnetic values that almost surrounds the initial andesite body.

5.3 DATA MODELING

In order to help illustrate the shape and size of the Three Sisters intrusion, the final step was to create several various 2-D cross-section profiles. The locations of the cross-sections were chosen to ensure that the profiles cross each of the Three Sisters (Figure 17). Utilizing a previous study (Hiebing et al., 2018) helped constrain the density models. Profile A-A' runs from east-west and crosses the North Sister. This profile was chosen since there are multiple studies over the North Sister with enough data to constrain the cross-section. Profile B-B' runs Northwest-Southeast intersecting the Three Sisters.

The density profiles were created using GM-SYS forward modeling software found within Oasis Montaj. The GM-SYS forward modeling technique is centered on the Talwani 2.5D modeling approach of Talwani and Heirtzler (1964) and Talwani et al. (1959). To model the profiles I created series of polygons based on known and assumed geology that were each assigned a density value. My densities were based on values from Hiebing et al. (2018). The software then calculated a gravity response based on the polygons and densities. I then compared the observed and calculated values of gravity and adjusted my models so that a reasonable error was found that did not violate any known geologic constraints. I used three polygons in my modeling. These were (from surface to depth): Andesite (D=2800 kg/m^3), Sedimentary (D=2300 kg/m^3), and Lower Paleozoic (D=2600 kg/m^3.

5.3.1 PROFILE A-A’

Profile A-A’ is the North Sister density profile that runs east-west along the north side of the study area (Figure 16). The profile also includes gravity data from Imana (1994). A-A’ was placed in this location to incorporate some of the previous studies to constrain the profile.

The Bouguer anomaly map (Figure 16) shows highs in the center of the profile and decreases to the east of the profile. A total difference of 11 mGals is observed over the length of the profile. To match the gravity anomaly highs seen in the center I added two andesite bodies about 500 meters wide and 300 meters deep altogether. The profile (Figure 17) indicates that the North Sister consists of two vertical dikes with the dike to the west containing a sill. Although this improved the model, I still had a very high error (rms error of 2.8 mGal). This indicated that more changes needed to be made to structure of the andesite body. I added a dike to the western sill and extended it to the surface and this lowered my error (rms error of 1.18 mGals).

5.3.2 PROFILE B-B’

Profile B-B’ is the Middle and South Sister density profile that runs northwest to southeast along the center portion of the study area (Figure 16). The profile also includes gravity data from Imana (1994). B-B’ was placed in this location to use the previous mapping project of Khisty et al. (2019) to help constrain the model.

The Bouguer anomaly map (Figure 16) shows highs in the center of the profile and decreases to the east of the profile. A total difference of 11 mGals is observed over the length of the profile. The profile (Figure 18) indicates that the Middle and South Sister consist of one vertical dike. Although this improved the model, I still had a very high error (rms error of 3.17 mGal). This indicated that more changes needed to be made to structure of the andesite body. I added a multiple sills to the dike and extended the sills beyond the profile. By creating the sills, I achieved an rms error of 1.05 mGals. The profile (Figure 18) is consistent with 3rd order polynomial (Figure 15) where the Middle and South Sister are composed of one major andesitic body.

Chapter 6: Conclusion

Understanding the Three Sisters intrusion is important to determine the regional volcanic history of El Paso. The Three Sisters are one of ten andesitic bodies located from Juarez, Mexico to Vado, New Mexico (Figure 2). Although regional studies have been conducted, no gravity study across the Three Sisters had been conducted to determine the size and shape of the intrusion. My study incorporated geological studies and geophysical techniques to help determine the size and shape of Three Sisters. Utilizing gravity in the surrounding neighborhood and shopping plazas demonstrated the usefulness of using gravity studies where other geophysical methods might be difficult to conduct.

Originally the Eocene intrusions (47-48 mya) were thought to be individual intrusions not connected. The Three Sisters were thought to be three laccoliths due to the amount of andesite present at the surface. After recent mapping projects Khisty et al. (2019) was able to reduce the amount of andesite seen at the Three Sisters, adding more shale and limestone than previously thought. Further seismic studies on the North Sister (Gillman, 2018) determined that the southeast portion of the North Sister has no andesite immediately below the surface (< 6m depth) and the andesite present must have fallen of the top of the North Sister. Recent studies Hiebing et al. (2018) suggested that the Three Sisters, River and Westerner intrusions may be connected to Cerro de Cristo Rey by feeder dikes. Profile A-A' indicates that the North Sister is composed of multiple dikes with associated sills. Profile B-B' indicates that the Middle and South Sister are composed of one large dike that also contains multiple sills.

In order to better determine the local and regional structure I suggest collecting more gravity data, especially to the east, south and north of the Three Sisters. This would allow us to determine if the Three Sisters outcrops might have a deeper connection with the Coronado or Thunderbird intrusions to the east or the Westerner intrusion to the south (Figure 20), as well as the relationship of the intrusions to the Cristo Rey and Campus laccoliths. Additional gravity data might also help to resolve the role thrust faulting played in the emplacement of these intrusions and in the development of normal faulting during creation of the Rio Grande rift.

Hiebing et al. (2018) have found that the quality of groundwater in the southernmost Mesilla Bolson is influenced by the presence of the Eocene intrusions. It is likely the Three Sisters and other nearby intrusions on the western flank of the Franklin Mountains also influence the quality of groundwater as it flows toward the Rio Grande.

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Figures

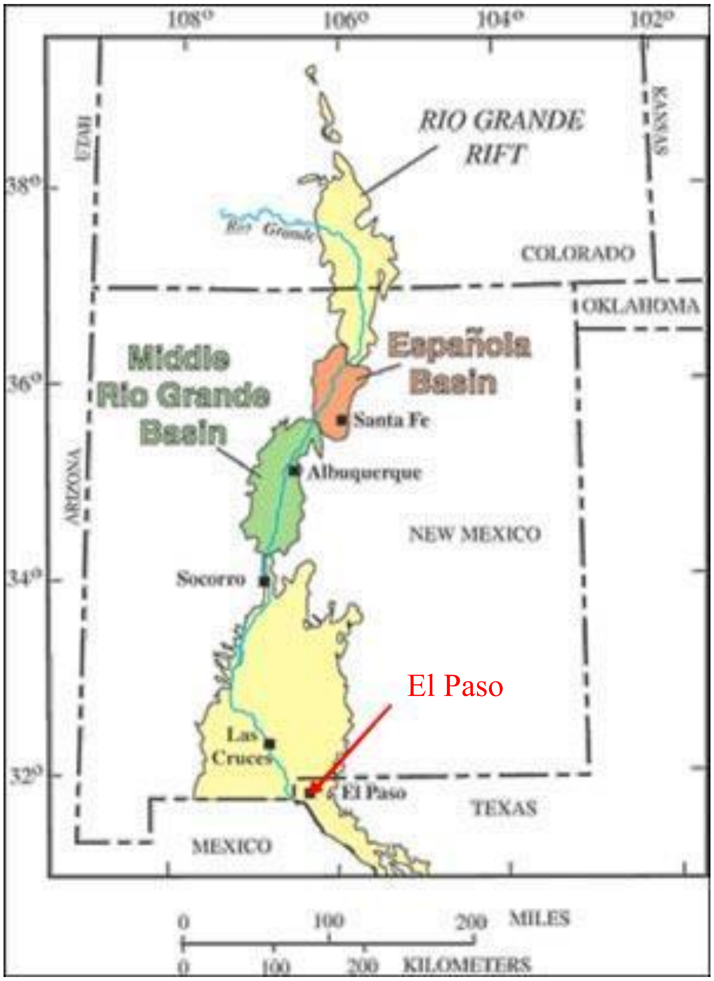

Figure 1. Map of the Rio Grande Rift Basins (yellow). El Paso is positioned in the lower rift basin. Image courtesy of the U.S. Geological Survey.

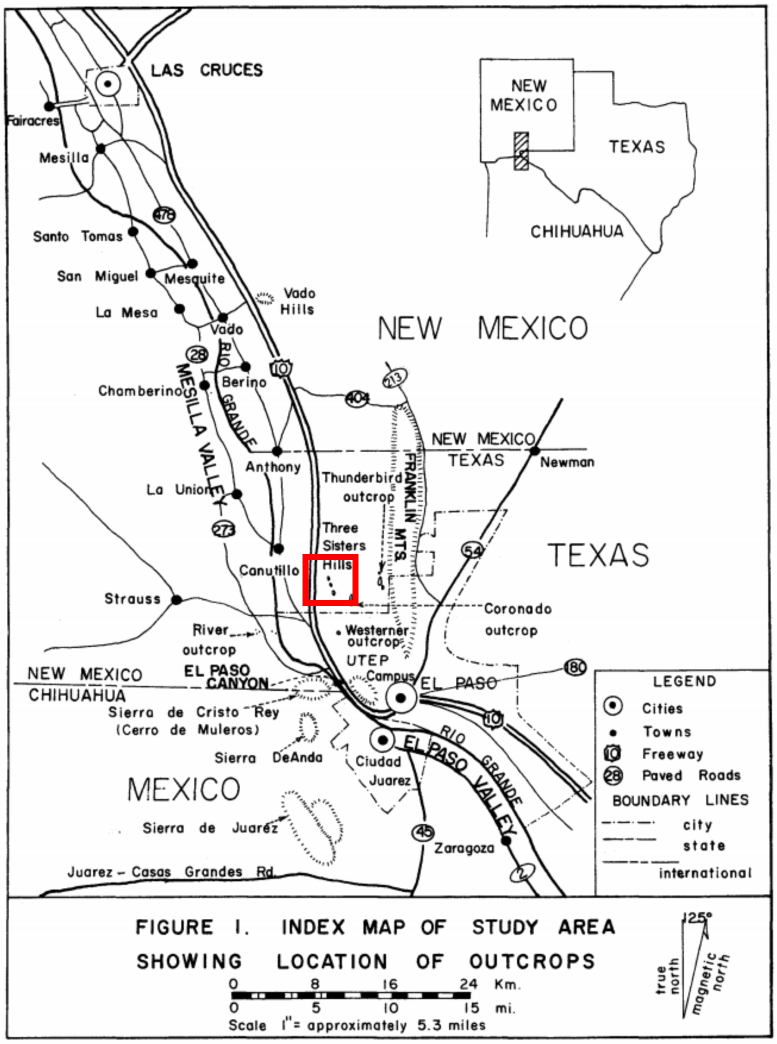

Figure 2. Map of the ten andesitic outcrops from Vado, NM to Juarez, Mexico. The Three Sisters is located within the red box. (modified from Garcia, 1970)

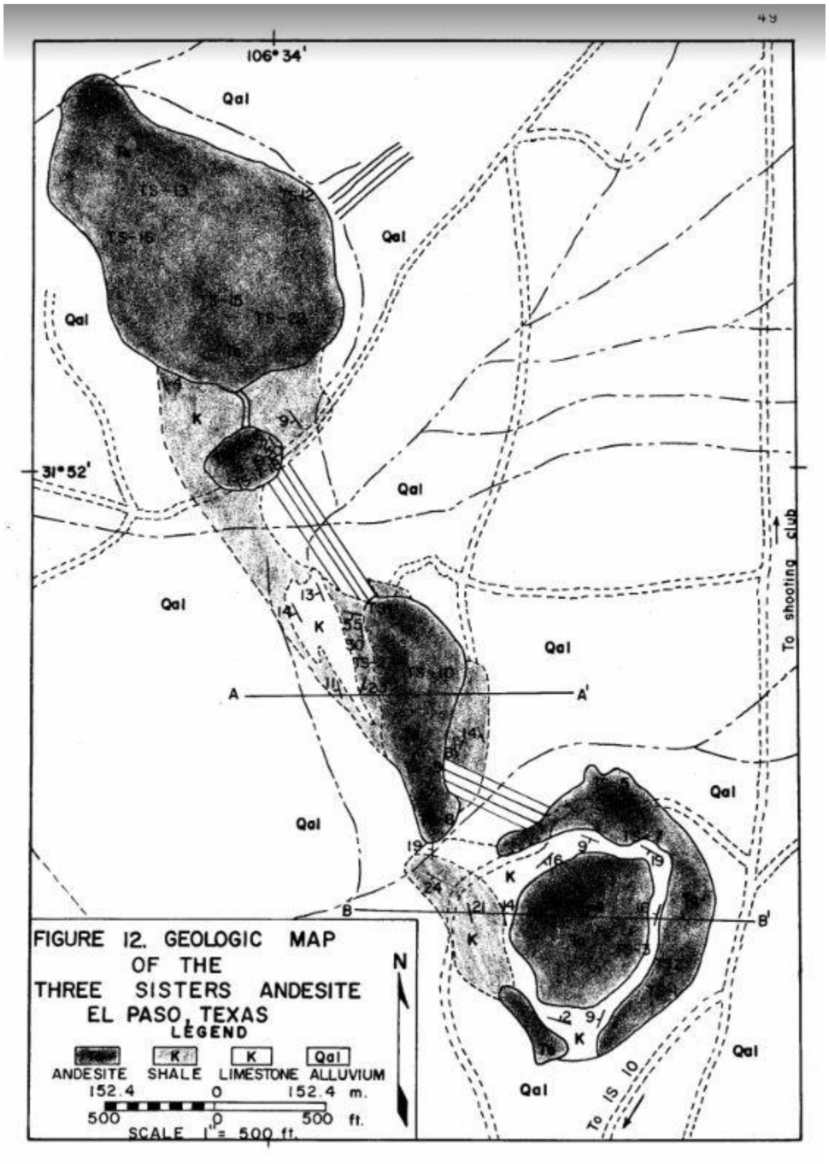

Figure 3. Geologic map of the Three Sisters modified from Garcia (1970)

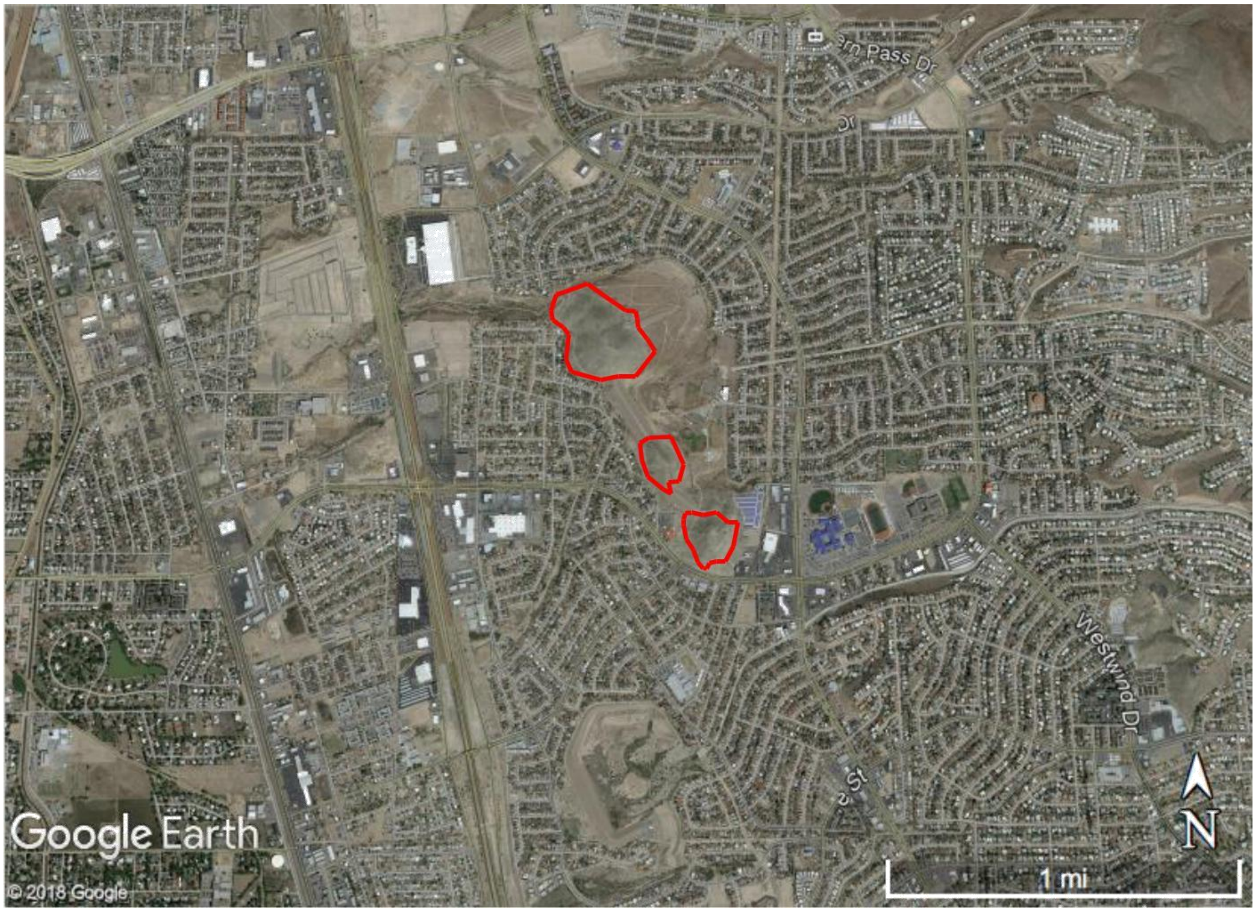

Figure 4. Aerial view of the Three Sisters. The red outlines denote the Three Sisters intrusions.

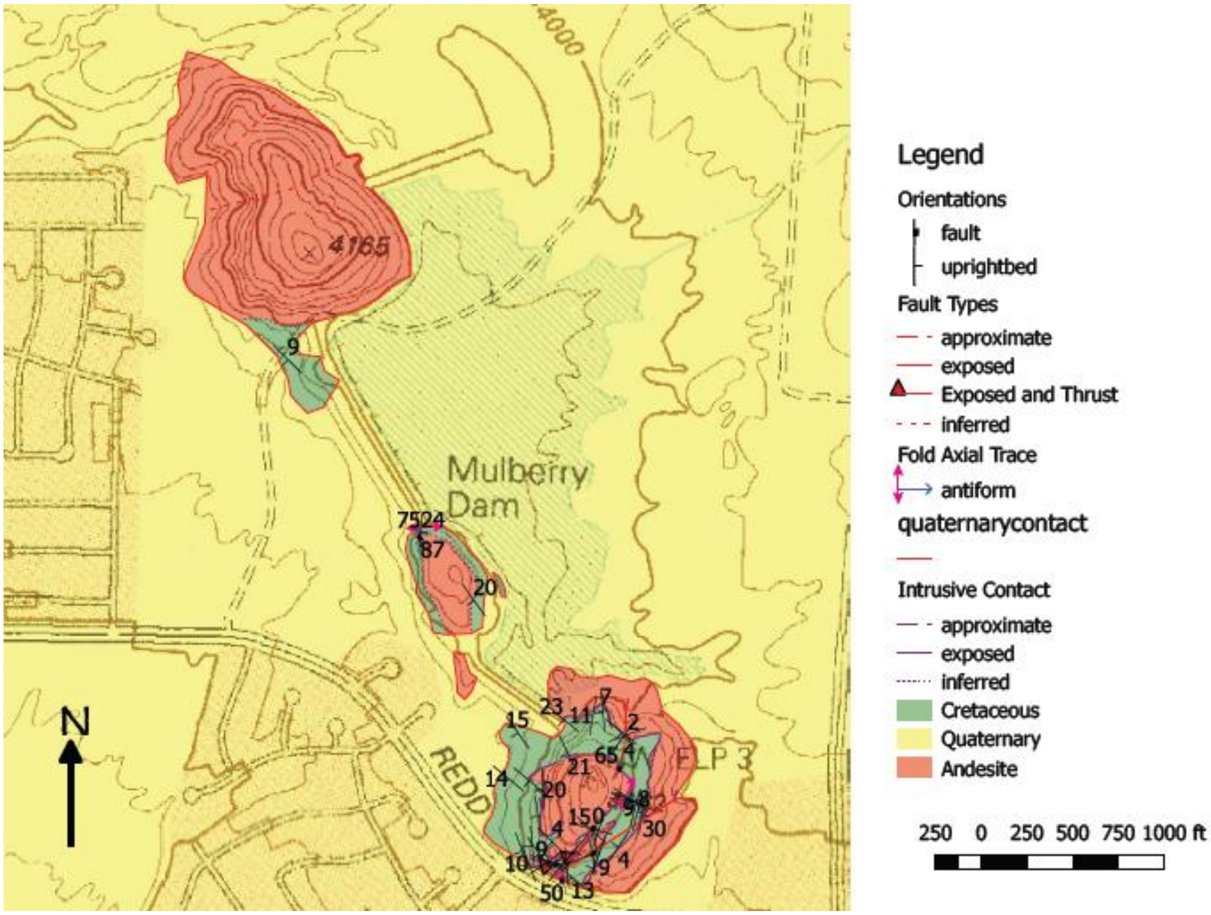

Figure 5. Updated geologic map of the Three Sisters region (Khisty et al., 2019)

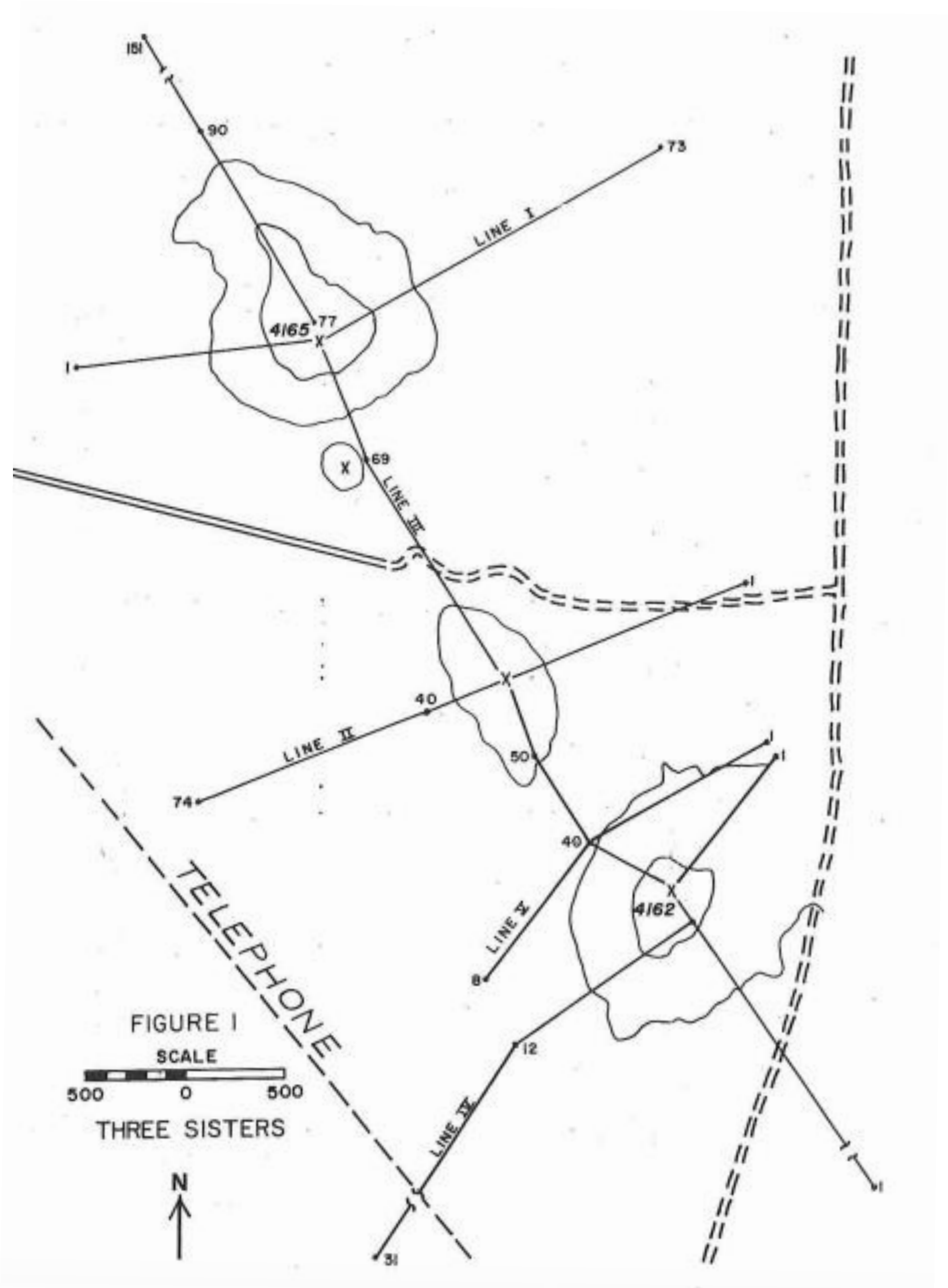

Figure 6. Map of the magnetic survey conducted over Three Sisters by Cathey et al. (1970).

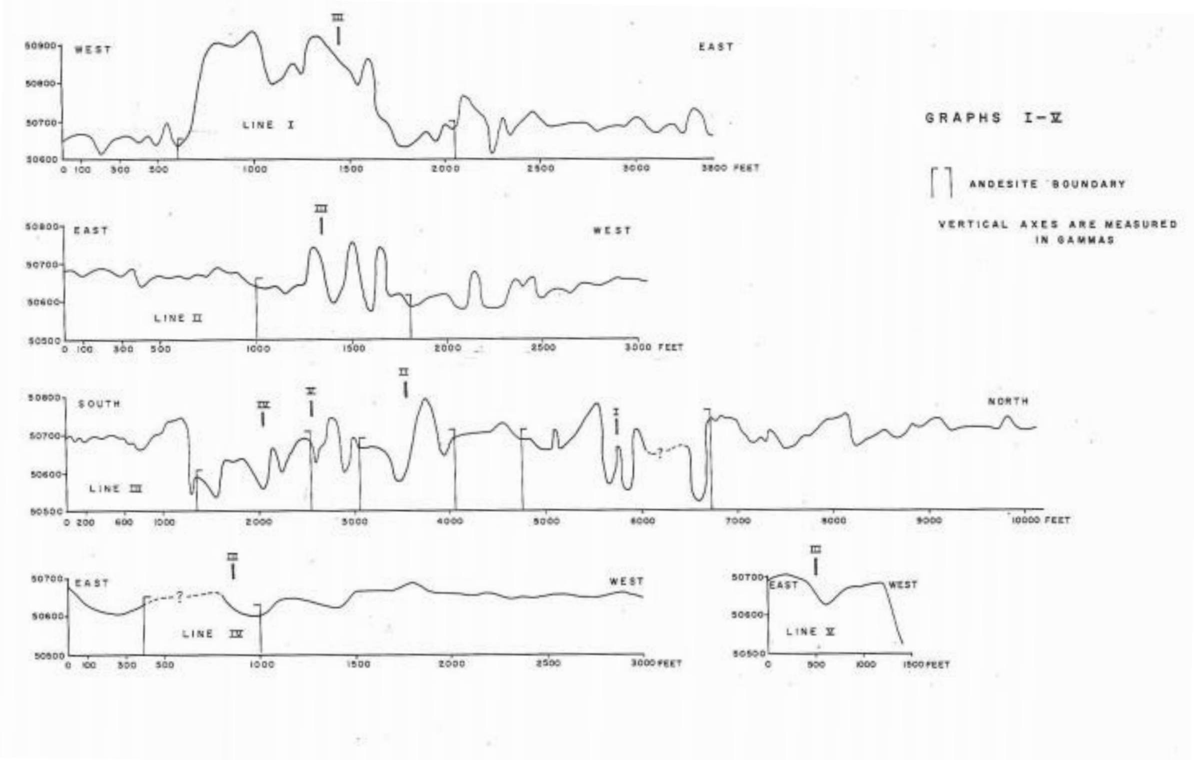

Figure 7. Magnetic data collected at Three Sisters by Cathey et al. (1970). See Figure 6 for locations of profiles.

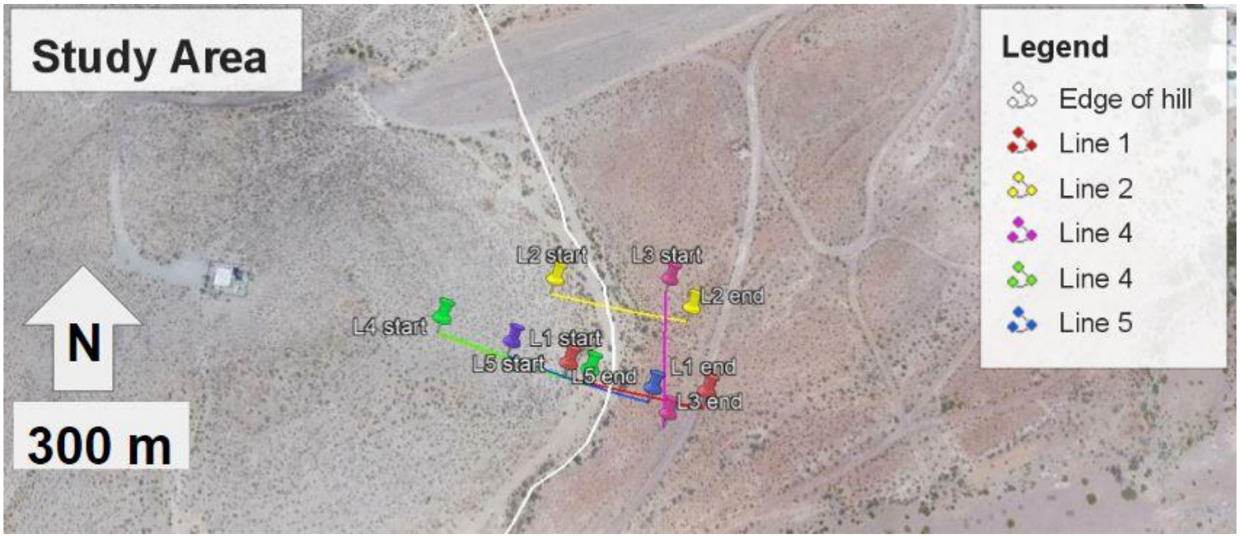

Figure 8. Map of the five seismic lines recorded over the east side of the North Sister (Gillman, 2018).

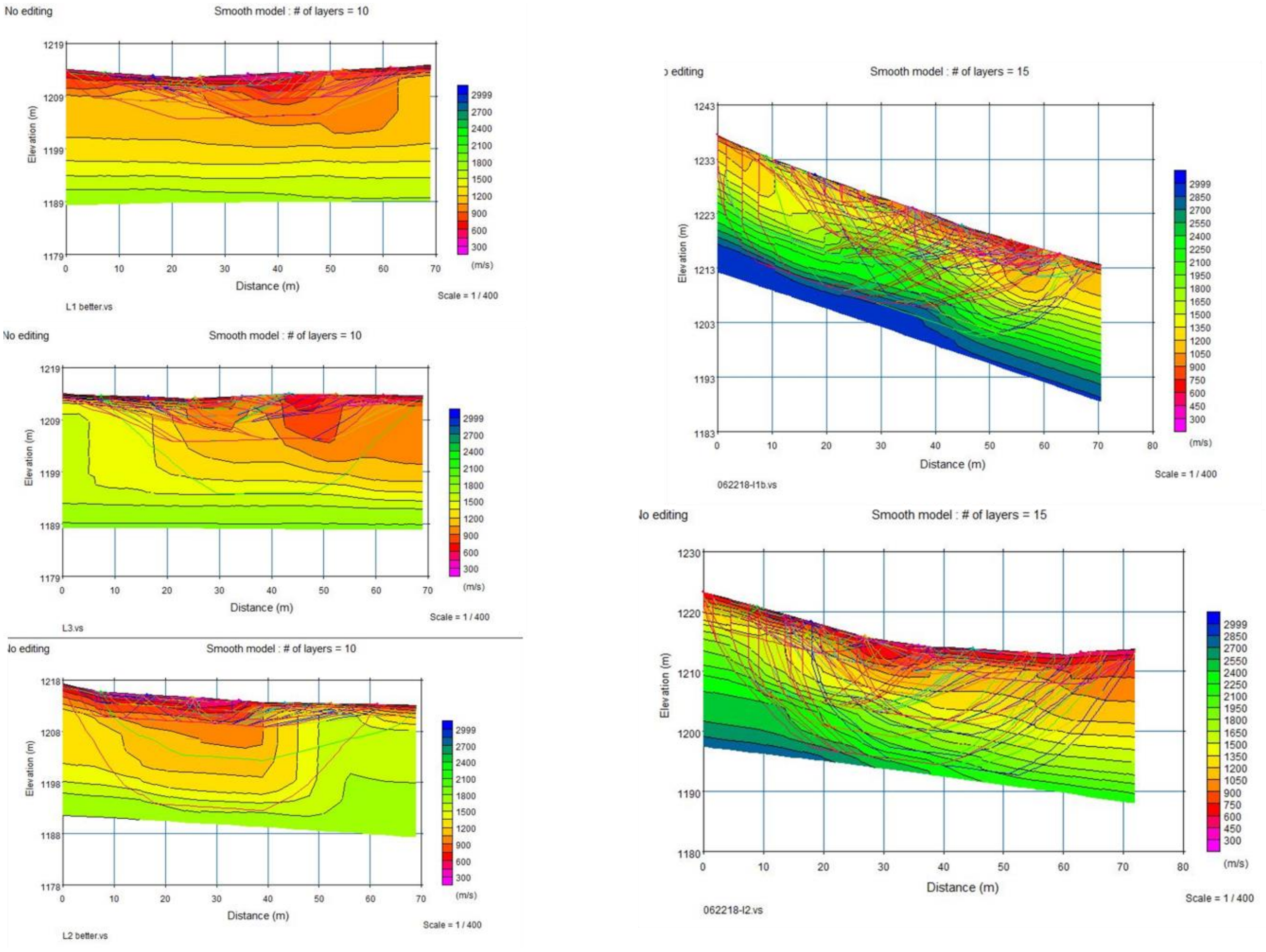

Figure 9. Interpretations of data from the five seismic lines located on the east side of the North Sister (Gillman, 2018).

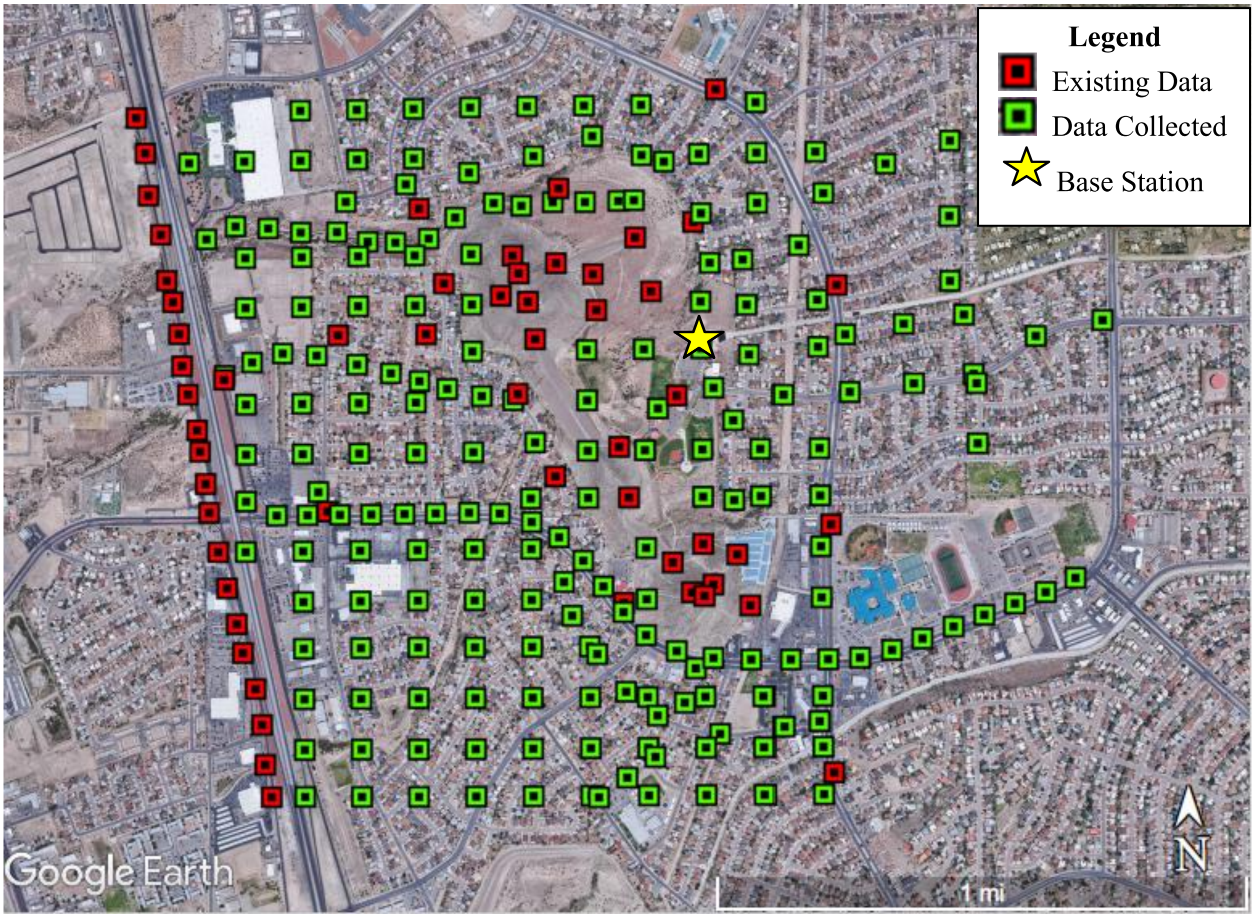

Figure 10. Map of the gravity grid for the Three Sisters showing what data were collected and what data were available for this project from other sources (e.g. Khatun, 2003; Ekal, 1994)

Figure 11. Magnetic grid for the Three Sisters area.

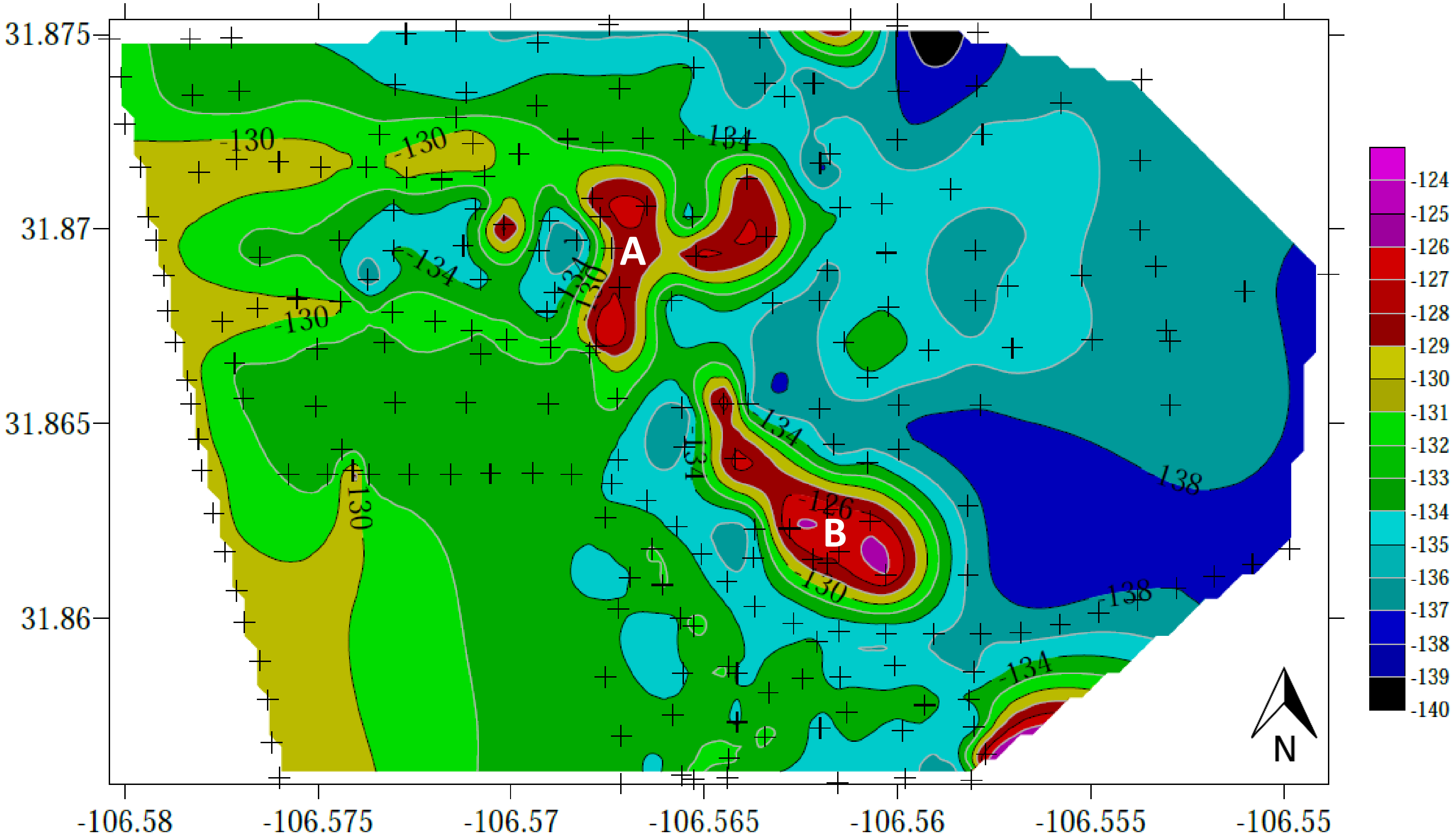

Figure 12. Simple Bouguer Gravity map of the Three Sisters area. Anomalies A and B are discussed in text. Plusses are sample locations, contour intervals are every mGal

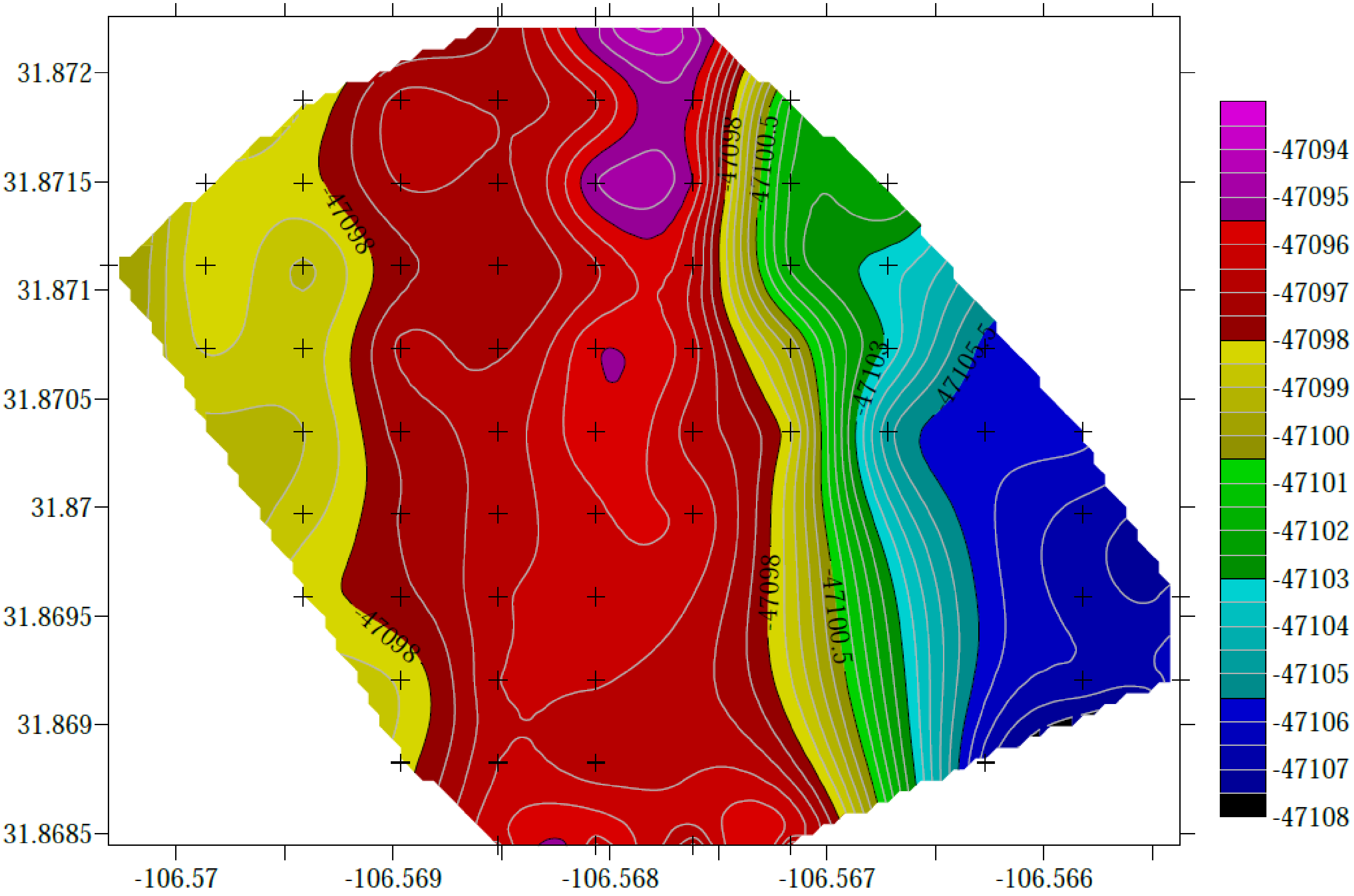

Figure 13. Magnetic map of the North Sister. Plusses are sample locations, contour intervals are every 0.5 nT

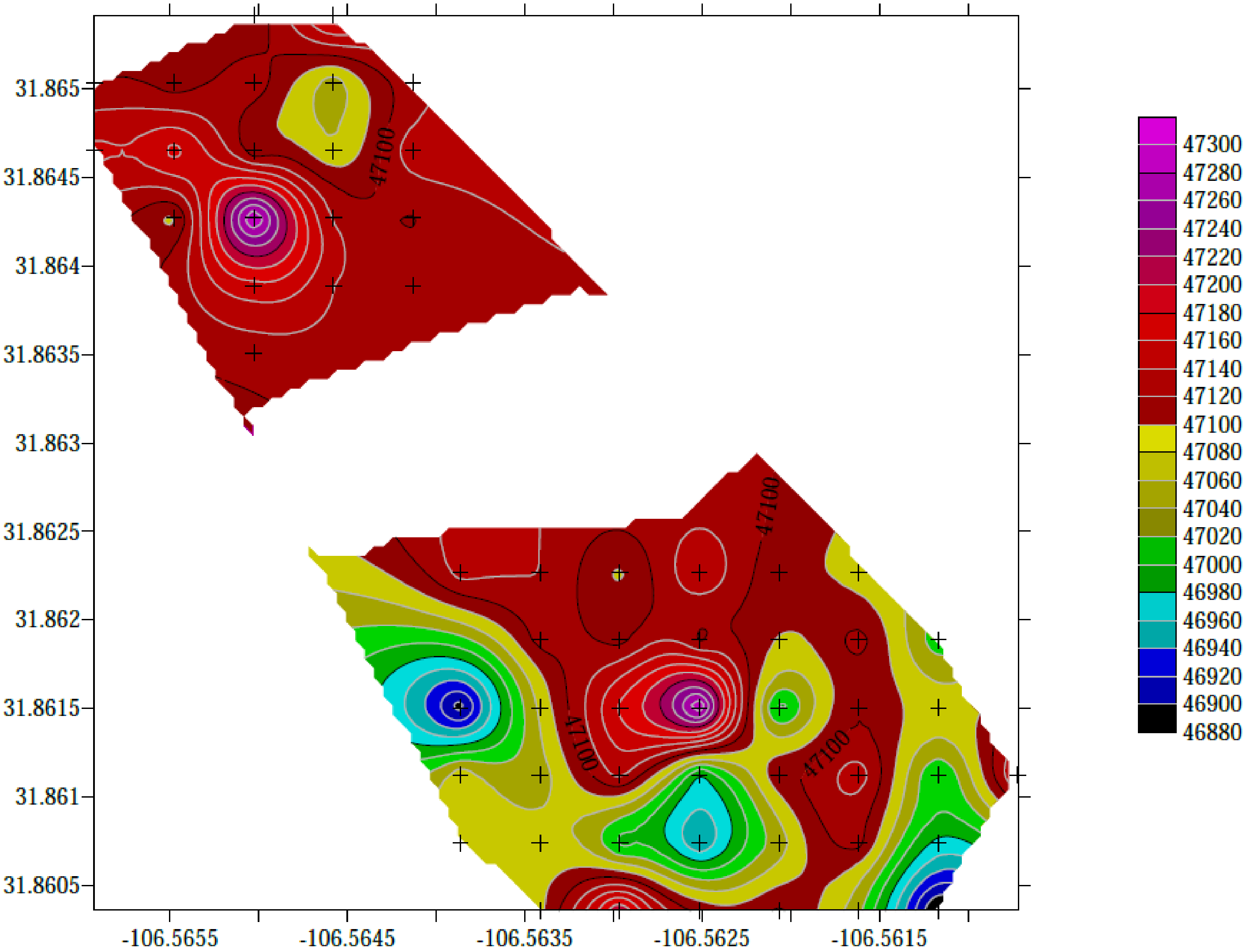

Figure 14. Magnetic map of the Middle and South Sister. Plusses are sample locations, contour interval is every is 20nT

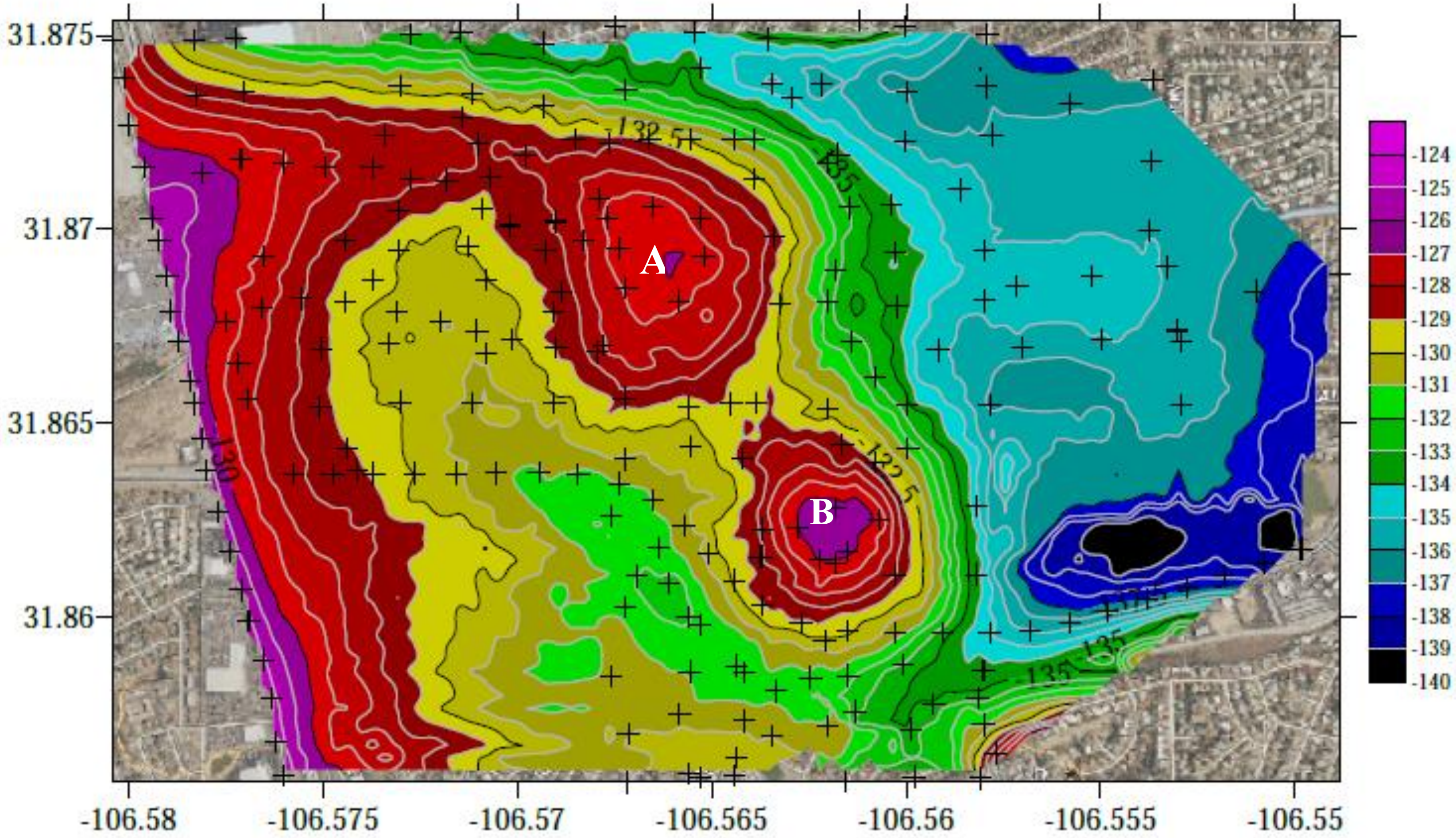

Figure 15. Third order polynomial gravity map of the Three Sisters area. Anomalies A and B are discussed in text. Contour interval is every 0.5 mGals

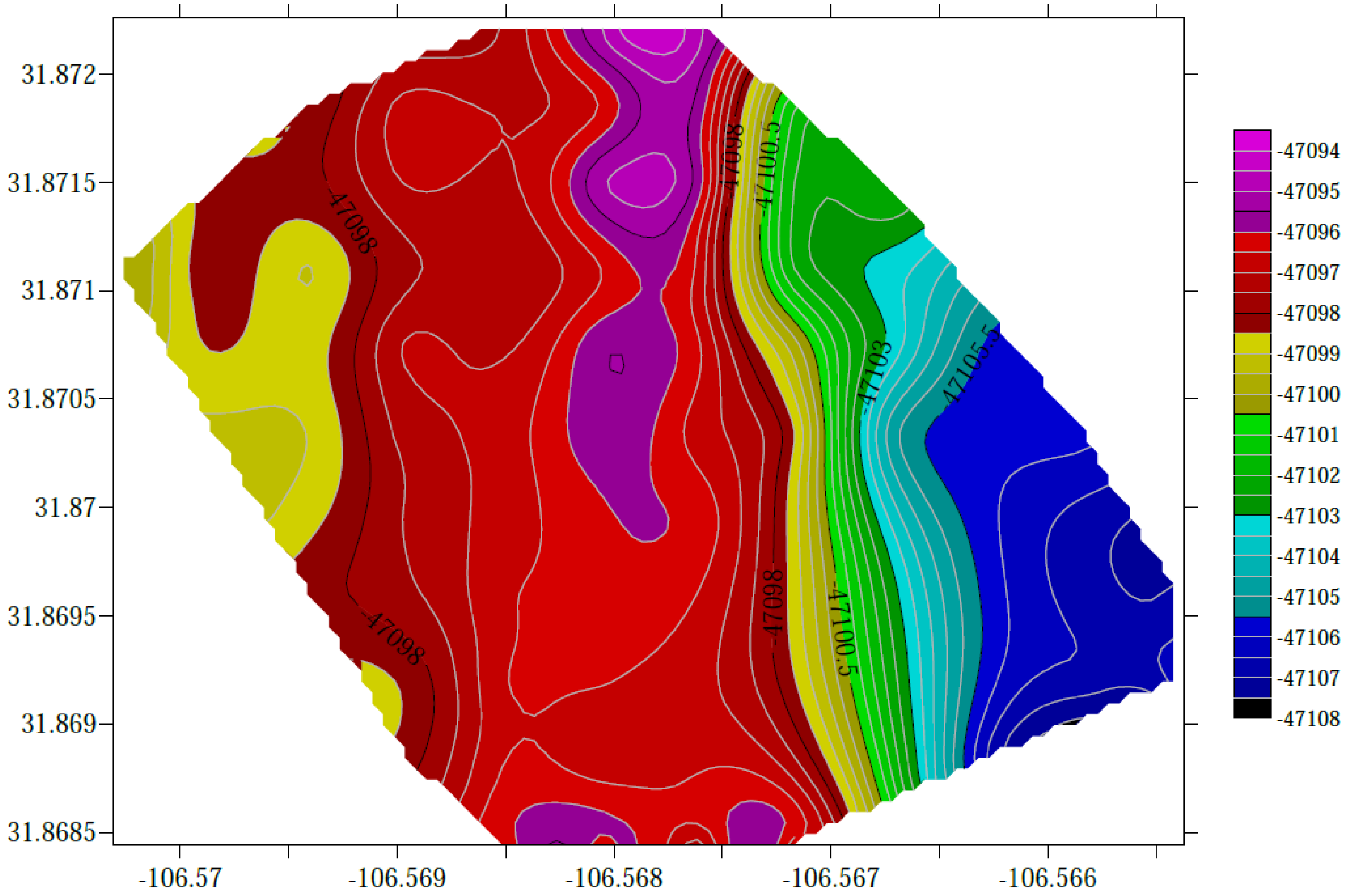

Figure 16. Magnetic map of the North Sister with a Gaussian filter applied. Contour interval is every 0.5 nT.

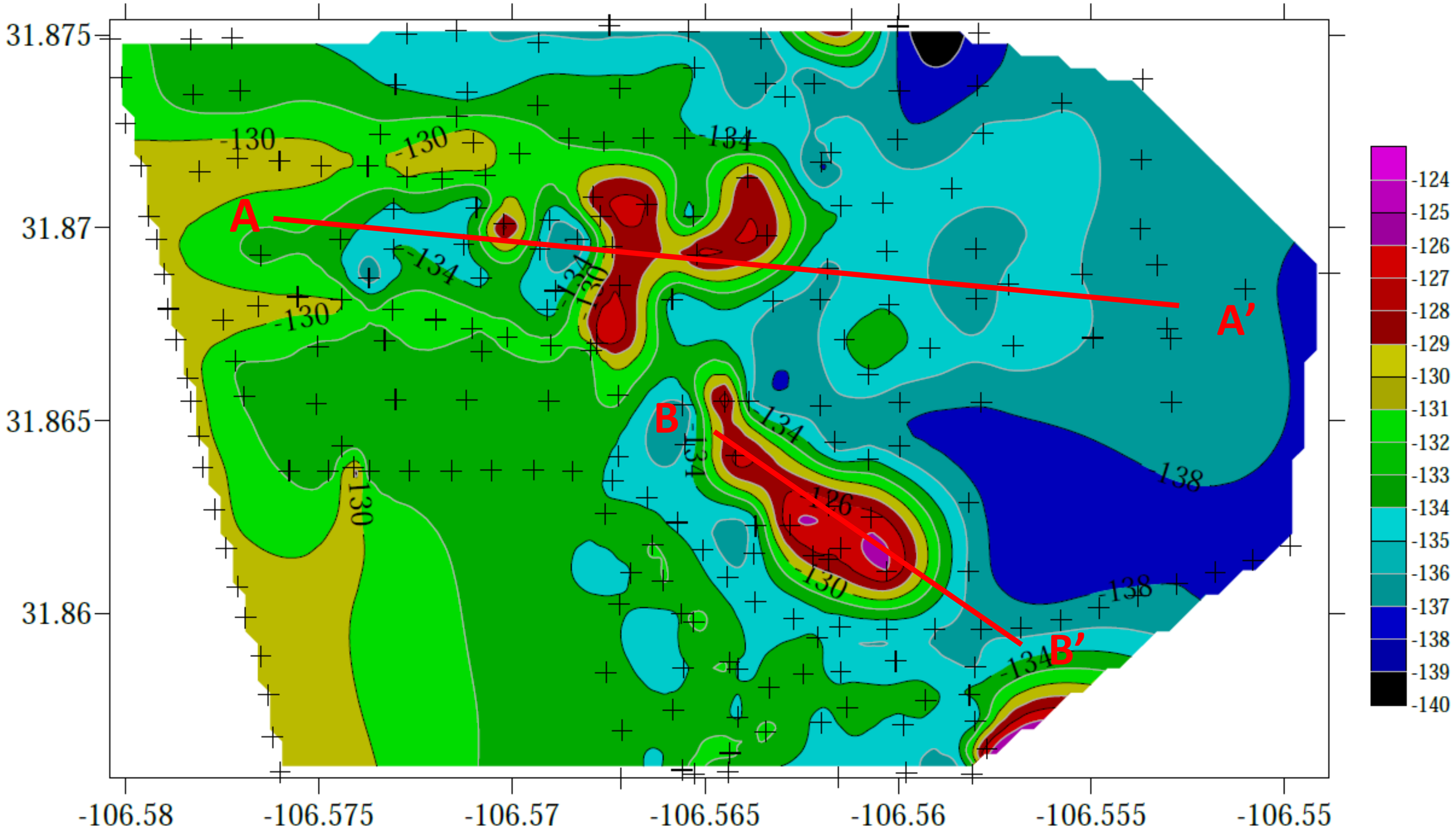

Figure 17. Map with locations of 2-D cross-section density profiles

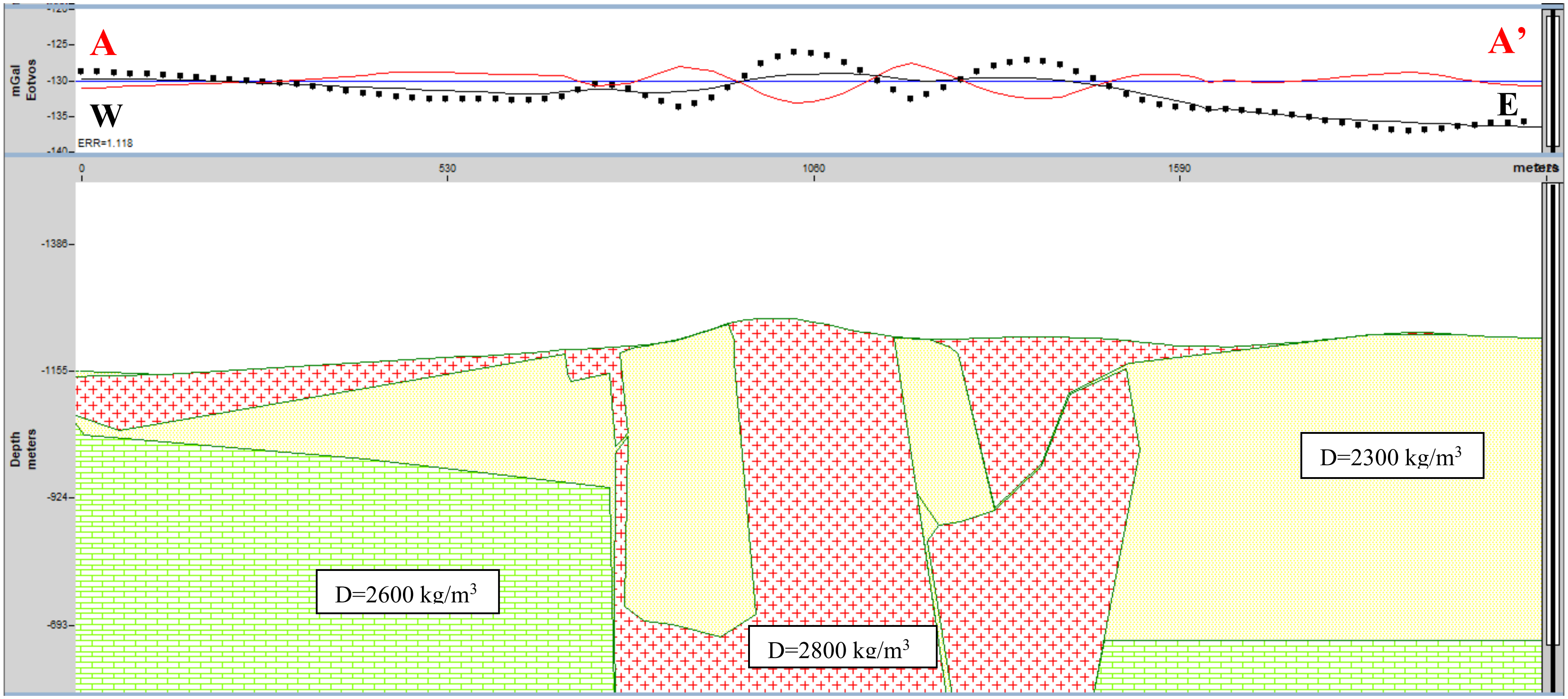

Figure 18. Density profile along A-A’ (west to east) (see Figure 17) created using 3 density layers. The red layer is andesite, (2800 kg/m^3) the yellow layer is a sedimentary layer (2300 kg/m^3), green is the lower Paleozoic (2600 kg/m^3). The red line is the predicted gravity, dots are observed gravity.

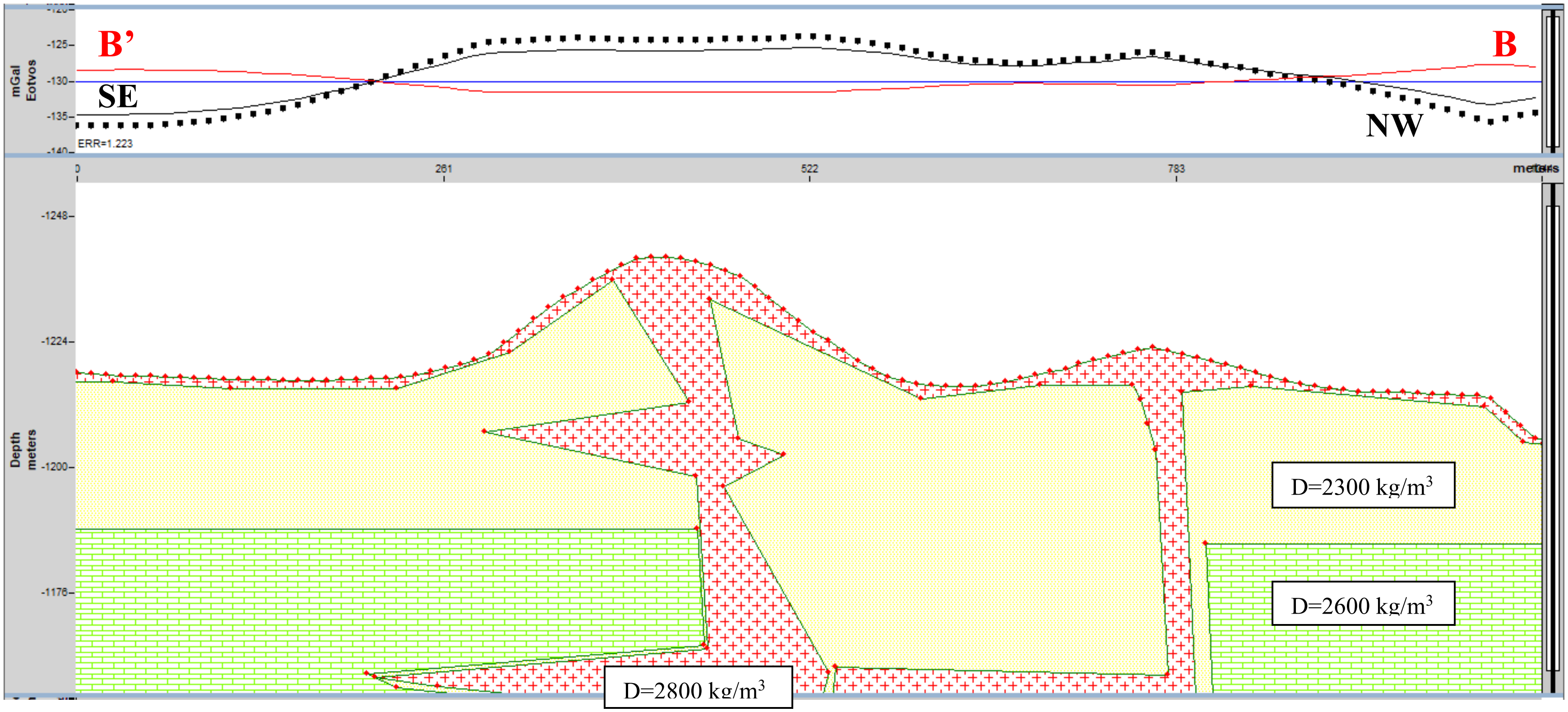

Figure 19. Density profile along B-B’ (northwest to southeast) (see Figure 17) created using 3 density layer.The red layer is andesite, yellow layer is sedimentary layer, green is the lower Paleozoic. The red line is predicted gravity, dots are observed gravity.

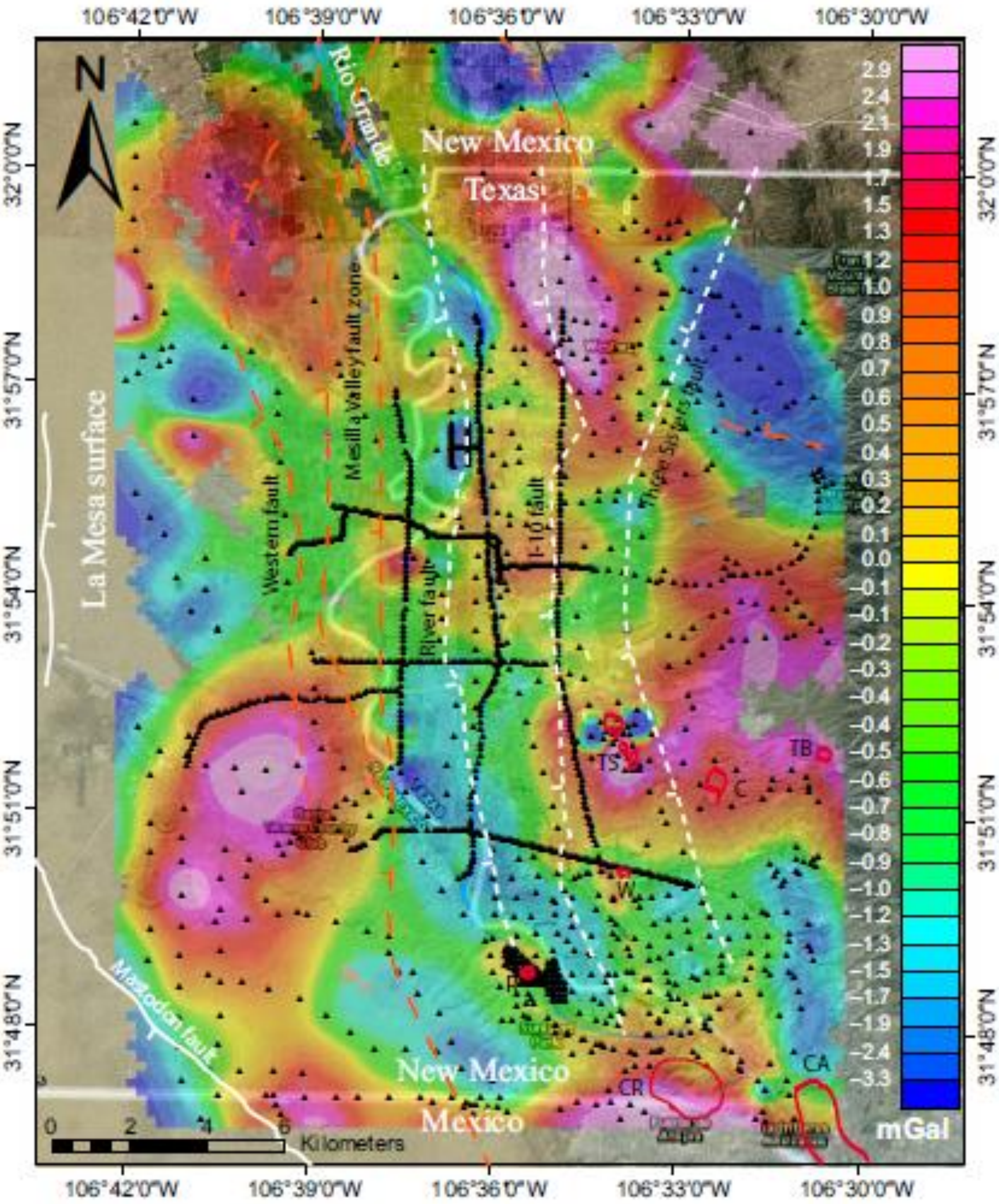

Figure 20. Bouguer residual anomaly map of the El Paso area from Hiebing et al. (2018). TS is Three Sisters, C is Coronado, TB is Thunderbird, CR is Cerro de Cristo Rey

Vita

Alexander D'Marco Garcia was born in Miami, Florida on July 21st, 1987. He obtained his bachelor's degree in Honors Geology from Florida Atlantic University 2015. After graduation, he progressed forward to graduate studies at the University of Texas at El Paso (UTEP) where he obtained his Master of Science in Geophysics in December 2019. Alex served as an active member of the American Association of Petroleum Geologists (AAPG) and as Vice President for the Society of Exploration Geophysicists (SEG). During his tenure at The University of El Paso, Alex was selected to participate in the Student Education Program hosted by ExxonMobil and the Student Leadership Symposium by Chevron. Alex was also awarded several scholarships from SEG. Further he completed several internships with NASA Kennedy Space Center where Alex worked with the Environmental Assurance Branch and conducted research for future space mining missions. He also worked as a Geophysicist Intern for Anadarko. Upon graduation, Alex will work for NASA Kennedy Space Center.

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