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Two-Dimensional Gravity Modeling Of The Rattlesnake Springs Watershed, Carlsbad Caverns National Park, New Mexico

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TWO-DIMENSIONAL GRAVITY MODELING OF THE RATTLESNAKE SPRINGS WATERSHED, CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

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Dedication

This Master thesis is dedicated to the two most important people in my life, my mother Antoaneta Boykova and my sister Adriana. They kept me sane in the past few months, encouraged me during the development of my thesis, and gave me strength and faith that I can accomplish the task. I am very grateful for their unconditional love and support. Their love and support at all times kept me working and enabled me to complete this work. I also would like to dedicate this thesis in the memory of my father Dimitar Boykov who has always been by my side when I needed him, has given me precious advice, and who made me a stronger person.
TWO-DIMENSIONAL GRAVITY MODELING OF THE RATTLESNAKE SPRINGS WATERSHED, CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

By

NIKOLAY D. BOYKOV

THESIS

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Abstract

A series of non-invasive geophysical investigations at the Rattlesnake Springs part of Carlsbad Caverns National Park, New Mexico, were performed in an effort to better delineate the watershed of the springs. The goal of this project is to determine possible locations of fractures and faults that may control the distribution of groundwater that feeds Rattlesnake Springs. Once the water flow paths are identified, the park will be able to better protect Rattlesnake Springs from environmental hazards, such as oil and gas drilling, as well as from upstream water development. As part of this effort I conducted a precision gravity survey of the area surrounding the springs. The survey used 200- to 300-m grid spacing with station positions and elevations determined using differential Global Positioning System (GPS) receiver. The survey was designed to map the depth to gypsum bedrock in the study area, and to pinpoint the locations of faults and fractures that could control groundwater movement toward the springs. I generated gravity maps from the gravity data, and also constructed two-dimensional (2D) gravity models in order to gain more complete understanding of the subsurface including the locations of the probable geological structures that are controlling the water flow towards the springs. From the models, the approximate maximum depth to the gypsum bedrock in the small basins was found to be anywhere between 800 to more than 2000 meters in the study area. Verification of the locations and orientation of these hypothetical geological structures (fractures) was done as a part of my effort.

The study is important to the National Park Service personnel from an environmental point of view due to the fact that it will assist them to protect the Rattlesnake Springs area from potential groundwater contamination due to oil and gas drilling performed at nearby sites. Once the Park Service knows the orientation of the possible fracture zones, they will be able to perform more accurate hydrologic modeling of the area in order to better define the ground water flow paths.
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Chapter 1

GEOLOGY OF RATTLESNAKE SPRINGS AREA, CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

The Rattlesnake Springs area is located in the upper Black River Valley in the southwestern part of Eddy County, situated in the northwestern part of the Delaware Basin (Figure 1.1 and Figure 1.2). The spring is a high-discharge artesian spring that is mainly recharged by precipitation falling on the Guadalupe Mountains (Bowen, 1999). In addition, it is suspected that the groundwater flow is structurally controlled by fractures or faults around the area of Rattlesnake Springs (Doser, 2008 personal communication). The main focus of this research is to determine the locations of probable fracture zones that may be controlling the water flow towards the springs. Non-invasive geophysical methods such as the gravity method are an effective tool for imaging Earth structures where other methods such as Ground Penetrating Radar have failed. The gravity technique is a rapid, low-cost geophysical procedure that can be used to examine possible structures and determine the geometry of basins containing these features. In addition, it can be used to examine the groundwater flow regime to help with assessment of potential environmental and groundwater problems. However, when working with gravity data it is essential to incorporate geologic observations to ensure that the interpretations made are consistent with the geology. Since Rattlesnake Spring is an important source of fresh drinking water for Carlsbad Caverns National Park and the neighboring Washington ranch, this research can have important implications for the study of the groundwater flow in that area. The research will also assist hydrologists in future hydrological modeling of the Rattlesnake Springs area.
Figure 1.1: Location of Rattlesnake Springs in southern Eddy County, NM, with respect to the Guadalupe Reef Escarpment and the Delaware Basin (modified after Hill, 1996)

Figure 1.2: Map showing general location of Rattlesnake Springs, NM
1.1 **Overview of the Delaware Basin**

The Delaware Basin is a sedimentary basin that covers approximately 33,670 km$^2$ and is part of the larger Permian Basin, which covers about 233,100 km$^2$. Figure 1.3 covers an area of more than 23,310 km$^2$, including the northwest corner of the Delaware Basin, and nearly the entire so-called Northwest Shelf Area. The Guadalupe Mountains dominate the central part of the photograph; their rugged southern end sticks out like a dark thumb toward the parched plains of the Salt Basin. Extending diagonally across the southern part of the photo is the bold southeast facing Captain Reef Escarpment. The escarpment marks the southern boundary of the high limestone plateau forming the Guadalupe Mountains (Delaware Basin Exploration Guidebook, 1968). To the south are the lower lying Delaware Mountains. The alluviated Pecos River Valley occupies the northeast corner of the photo. The northwest corner of the photo is occupied by the Sacramento Mountains. The Rattlesnake Springs area is located in the central part of the photograph in the foothills of the Guadalupe Mountains.

![Figure 1.3: Aerial photograph of the Northwestern Part of the Delaware Basin](Delaware Basin Exploration Guidebook, 1968)
Surface topography within the area is dominated by a north-northwestward-trending regional positive topographic feature known as the Delaware-Guadalupe Mountain uplift. The uplift is an asymmetric, faulted anticline extending for more than 160 kilometers along the western edges of the Delaware and Guadalupe Mountains in New Mexico and West Texas (Delaware Basin Exploration, 1968).

The topographic form of the mountains greatly resembles the structural character of the uplift. The structure is characterized by a broad, gently inclined eastern flank and a narrow, highly faulted, steeply dipping western limb. According to King (1948), the Guadalupe-Delaware Mountain uplift was formed during several mountain-building phases beginning in the Miocene and ending in the Pleistocene. He suggests that the mountains were uplifted as a result of vertical compression, and were block-faulted and fractured due to these stresses.

The north-northwestward–trending Guadalupe-Delaware Mountain uplift and associated Cenozoic structural features diagonally intersect the older geologic trend lines, and, in places, tend to obscure their details. Several pre-Cenozoic features are distinctly visible in this area. The exhumed Permian Captain Reef forms a prominent escarpment that descends eastward, reflecting Cenozoic tilting, to the area a few kilometers southwest of Carlsbad where it plunges beneath the surface. The reef is paralleled on the north by several northwestward plunging folds that probably developed as a result of differential subsidence simultaneously with the forming of the Captain Reef and possibly older reefs (Delaware Basin Exploration Guidebook, 1968). It is controversial whether the trends of the Captain Reef and associated Permian features developed in accordance with pre-existing structural trend lines or purely as a result of subsidence (King, 1948). The Captain Reef, a restricting barrier formed in Permian-Guadalupian time, represents the inner boundary of the Delaware Basin. The curving pattern of the exposed reef front west of Carlsbad is an interesting phenomenon. It is possible that the northeastern deflection of the reef is a result of structural control. Several miles northwest of the area west of Carlsbad is a linear structurally disturbed zone that parallels the curving trend of Captain Reef. This zone is characterized by a series of sharp anticlines and synclines and numerous faults and fractures. The alignment of this
zone and its parallelism with the Captain Reef suggests that it is related to basin subsidence and is described in the literature as a product of deposition rather than tectonism (Delaware Basin Exploration, 1968).

1.2 Delaware Basin Stratigraphy

Basin stratigraphy consists of the Castile formation overlying the Delaware Mountain Group Bell Canyon, Cherry Canyon, and Brushy Canyon formations (Figure 1.4). These formations consist of sandstone, shales, and minor carbonates. The lower Permian is represented by the Bone Springs Limestone. Beneath the Permian deposits are Pennsylvanian deposits of the Canyon, Cisco, Atoka, Strawn, and Morrow formations (Christiansen, 1989). The Morrow Formation is the most significant source for natural gas in southeastern New Mexico and includes most of the Pennsylvanian deposit roughly 580 meters thick (Hill, 1996).

Figure 1.4: Stratigraphic cross section through the Guadalupe Reef Escarpment taken slightly east of the Carlsbad Caverns (modified from Hill, 1996)
The Castile formation, along with the Salado formation, outcrops over an area of 2590 km$^2$ in New Mexico and West Texas. In the Upper Black Valley it is either present at the surface or is overlain by alluvium. The Castile Formation was named by Richardson (1904) and the name comes from the Castile Spring, located 19.3 kilometers south of the Texas-New Mexico border. The Castile formation consists of finely banded gypsum (anhydrite in the subsurface) and halite with a measured depth in the Rattlesnake Springs area of about 310 meters (Bowen, 1999). The halite units were removed by dissolution from the western portion of the basin, with collapsed breccias recording their removal. The Castile anhydrite consists of fine laminations that are highly continuous throughout the Delaware basin (Hill, 1996). The Castile formation represents the initial unit of the final phase of filling of the Delaware Basin, and it has been considered to be a deep water evaporate.

1.3 GEOLOGY OF RATTLESNAKE SPRINGS

Groundwater flow at Rattlesnake Springs seems to be driven by precipitation recharge along the topographically high Guadalupe Reef Escarpment. This water then flows to the low-lying Delaware Basin. The oldest rocks exposed in the area are those belonging to the limestone facies of the Permian Guadalupe series (Hale, 1955). These rocks crop out in the Guadalupe Mountains along the northwest boundary of the study area (Figure 1.5). Along the Guadalupe Reef Escarpment the reef talus beds dip steeply to the southeast and terminate in the subsurface where they interconnect with sandstone beds. In the vicinity of Rattlesnake Spring, the limestone and sandstone beds are overlain by anhydrite and gypsum beds belonging to the lower part of the Permian Ochoa series (Hale, 1955). Quaternary alluvial sediments mantle most of the bedrock (Bowen, 1999). Subsequent to the Permian, tectonism in the region created a set of bedrock fractures in the gypsum and limestone.
Figure 1.5: Geologic map of Carlsbad Caverns National Park, NM. Map after Paul Burger, National Park Service (personal communication, 2009)

Geological mapping performed by Langford (2008, personal communication) suggests that the landscape at Rattlesnake Springs is composed of two main elements: younger terraces and older fill (Figure 1.6). Boulder gravel terraces, shed from canyons in the Guadalupe Mountains, have created a set of smoothly sloping surfaces that incline eastward toward the Pecos River. Incision during the Quaternary cut through these terraces, creating a younger set of inset terraces. All of the terraces are probably Quaternary in age based on the well-developed calcic soils observed within them (Langford, 2008, personal communication).
Figure 1.6: Geomorphic map of the Rattlesnake Springs area showing features that may control regional drainage. Shades of yellow indicate terraces, and blue indicates Quaternary fill. Mapping by Langford (personal communication, 2008)

Several interesting valleys that incise the terraces surround Rattlesnake Springs (Figure 1.6). These valleys are filled with clay-rich Holocene sediment and they are closed at one end. One hypothesis is that these valleys are karst features (Langford, 2008, personal communication). The valleys may have sinkholes at their upper reaches and may have formed through spring outflow, which caused dissolution and collapsed the surfaces. No detailed field studies or drilling programs have been performed on the area around Rattlesnake Springs, so no reliable age estimates can be made. Interpretations of the shallow geology are based on a few shallow well logs (Hale, 1955) as well as other hydrological studies (Bowen, 1999) that have been conducted in the region.
Chapter 2

PREVIOUS STUDIES IN THE RATTLESNAKE SPRINGS AREA,

CARLSBAD CAVERNS NATIONAL PARK, NEW MEXICO

A few previous hydrological studies have been performed in the Rattlesnake Springs area (Hale, 1955; Cox, 1963; Bowen, 1999). These studies were focused on the effects of the groundwater pumping in the area of Rattlesnake Springs and how it affected the actual flow of the springs. The studies did not determine the mechanisms that are responsible for groundwater recharge in the Rattlesnake Springs area. In addition, none of these hydrological studies used geophysical information to determine the potential subsurface structures present in the area of Rattlesnake Springs that may control groundwater flow. However, these studies will serve as building blocks for my two-dimensional (2D) gravity modeling work, since they discuss the geology of the area, which was beneficial in building my 2D gravity models. Preliminary geophysical studies whose purpose was to evaluate the research side, and to help in identifying possible fracture zones, were also performed. These studies represent the first geophysical investigation of the Rattlesnake Springs area, and they used ground conductivity, resistivity, and gravity as geophysical methods for investigation of the side. The preliminary results from this survey were published at the Symposium on the Application of Geophysics to Engineering and Environmental (Boykov et. al, 2009). The published paper is attached as an appendix at the end of this thesis. The following sections present a literature review of the hydrological work that has been completed within the area of Rattlesnake Springs.

Hale (1955) performed the first hydrological study to investigate the ground-water conditions in the vicinity of Rattlesnake Springs. The area Hale (1955) included in his investigation was approximately 518 km² in southeastern New Mexico (Figure 2.1). The main emphasis of his study was centered on Rattlesnake Springs. The report states that the National
Park Service at the Carlsbad Caverns used the water from the springs as a fresh water supply at their facilities. Moreover, Hale (1955) states that the water from Rattlesnake Springs was used for irrigation of the neighboring properties adjacent to the spring. Hale’s study was initiated because concerns over the effects of irrigation wells on the surface-water supply had arisen. The main goal of his research was to determine the groundwater conditions in the Rattlesnake Springs and upper Black River Valley, and the effects that the irrigation wells might have on them. Geological information for the Rattlesnake springs area from his study was used as constraining information for the subsurface geology in my gravity models.

Figure 2.1: Irrigated lands in the upper Black River valley; red rectangle shows the location of Rattlesnake Springs (modified from Hale, 1955)
Hale describes that the Black River’s course is usually dry as the river moves through the Guadalupe Mountains, and also that the river stays dry as it cuts through the alluvial fan of Black Canyon. Black River is located in Black River Valley giving the name of the valley. In addition, the valley is described to be between 6.4 km and 14.5 km in width (Hale, 1955).

His study involved collection of water well data, measurement of water levels, determinations of elevations at wells, and collection of water samples for mineral analyses. He also established a network of observation wells in order to measure the water fluctuations in the wells on a monthly basis. Hale concluded that Rattlesnake Springs represents the discharge from an aquifer in the alluvium whose source is considered to be located southwest of the spring. Three of the wells that were used for irrigation had a definite effect on the spring flow (flow declined when the wells were pumped). He also suggested that any new wells in the same vicinity would result in a further decline in the flow of Rattlesnake Springs. His study provided detailed information about the geology of Rattlesnake Springs area, and I used this information to better constrain the models in my gravity modeling.

Another hydrologic study of Rattlesnake Springs was performed by Cox in 1963. This investigation was conducted in conjunction with the National Park Service and the New Mexico Department of Game and Fish. It was initiated because of a lawsuit filed in the U.S. District Court in Albuquerque in 1959 to prevent certain private irrigators in the area of Rattlesnake Springs from using their wells, due to the diminishing flow of Rattlesnake Springs during summer months. The main goal was to study how three irrigation wells surrounding the springs had affected the flow of Rattlesnake Springs. Cox collected hydrologic data and made interpretations of the effects of pumping in the nearby irrigation wells on the flow of the springs. He continuously monitored the wells and found out that pumping water out from two of the wells directly had an effect on the water levels at the third well located about 167 meters southwest of Rattlesnake Springs (Figure 2.2). The flow from the pool was also affected within two hours of pumping. He concluded that pumping from the pool at Rattlesnake Springs to Carlsbad Caverns lowered the pool level itself, but that it did not affect the flow of Rattlesnake Springs or the water
level in the third well he monitored. Some of the well information from his study reveals the shallow sedimentary fill composition in the area, and that helped me to better determine the appropriate rock densities to use in my gravity models.

Figure 2.2: Approximate locations of the wells described by Cox, 1963

Bowen (1999) probably performed the most complete hydrogeological study of the Rattlesnake Springs area. The purpose of her study was to assess the aquifer system supplying Rattlesnake Springs using numerical modeling and simulation. She used previously published geological information, as well as information from shallow wells, in order to set the initial conditions for her water flow numerical model. The geologic data she obtained was primarily from drilling logs of shallow groundwater wells obtained from the State Engineer’s Office of New Mexico. She also used Hill’s (1996) description of the geology of Delaware Basin to further
delineate the geology of the Rattlesnake Springs area. In addition, she analyzed the chemistry of ten of the water wells in order to determine possible environmental hazard due to gas drilling in the area. Moreover, Bowen also used meteorological data about annual precipitation in the area from National Oceanic and Atmospheric Association (NOAA) to further constrain groundwater flow in her modeling. Considering all of this information—hydrological, meteorological, and geological—she developed a conceptual model of the flow through the system, which was then used as a basis for construction of her numerical model. The idea behind her numerical model was to assess the validity of the assumptions she made for the system by providing a mathematical simulation that behaved as a close approximation to the actual system.

Bowen (1999) concluded that her numerical model produced results equivalent to the seasonal trend of measured discharge from Rattlesnake Springs. In addition, she found that the discharge from Rattlesnake Springs depends on and is controlled by the annual precipitation in the area. The shallow well data from Bowen’s work provided information about the subsurface geology of the Rattlesnake Springs area. The information from the well closest to the springs was used to further constrain the geology in my gravity modeling.
Chapter 3

METHODOLOGY

The major objective of this study was to test the feasibility of using the precision micro-gravity technique to locate possible fractures and faults in the area of Rattlesnake Springs. In gravity surveying, subsurface geology is estimated on the basis of variations in the Earth’s gravitational field generated by differences of density between subsurface rocks. A rock unit of different density from its surroundings represents a subsurface zone of anomalous mass and causes a localized perturbation in the gravitational field known as a gravity anomaly.

The precision gravity technique is a rapid and inexpensive method that can be used separately or in combination with other techniques, such as conductivity surveying, ground resistivity profiling, reflection/refraction seismic profiling, well logging, etc., to evaluate subsurface geological structures (Sharma, 2002). In addition to its use as the focus of this thesis (watershed studies), the micro-gravity method can also be applied to hydrocarbon and mineral exploration, determination of the shape of the earth (geodesy), detection of sub-surface cavities, and monitoring (Sharma, 2002).

3.1 DATA ACQUISITION

3.1.1 Gravity Data Collection

Micro-gravity surveys are conducted on very small areas—on the order of hundreds of square meters. The precision gravity technique requires accurate gravity measurements (less than \(<1 \text{ milligal } [\text{mGal}]\)) and precise determination of geographical position (\(\pm 3-5 \text{ centimeters}\)). A LaCoste Romberg model G gravity meter was used to collect the gravity measurements. The meter has a range of 200 mGal with a measurement precision of \(\pm 0.01 \text{ mGal}\).

I conducted a precision gravity survey of the area surrounding Rattlesnake Springs. Data were collected using a grid with 200- to 300-spacing between the gravity stations. The station
positions and elevations were determined using Trimble differential Global Positioning System (GPS) receiver. The survey was designed to map the depth to gypsum bedrock in the study area and to pinpoint the locations of faults and fractures that could control groundwater movement toward the springs. The small spacing between the gravity stations was chosen in order to detect small changes (< 1mGal) in the gravity values reflecting density contrasts underground. That allows one to precisely determine changes in the subsurface geology and therefore locate possible fracture zones or faults.

I collected the gravity data for this project in two phases: during October–December 2007, and in August 2008 (Figure 3.1). The first dataset collected covers 6.76 km² with 200-meters spacing between the station grid points. The data were collected in 13 parallel east-west trending lines with 13 gravity points collected along each line, for a total of 169 points. In August 2008, 40 additional gravity points were collected in the area to the immediate west of the 2007 survey covering an additional 3.6 km² (Figure 3.1). Larger station spacing was chosen to cover the region west of the original survey more rapidly.

3.1.2 Global Positioning System (GPS) Data Collection

For the current survey, a reference station was set within an open space in the park right next to the field gravity base station and about 2.5 to 3.5 kilometers from the farthest gravity survey lines. For both gravity surveys, the GPS data were collected using a Trimble 4000 SSI differential GPS receiver. The precision of the locations is estimated to be within ± 3 centimeters (x, y). Observations were made using fast static survey mode in which a baseline solution between two stationary receivers is determined. A fast static survey is a less precise technique compared to other procedures (e.g., kinematic surveying), but it is substantially faster. It requires synchronized observations of at least four satellites for a period of 5 to 20 minutes prior to the beginning of the survey. Because of the relatively short observation time needed, a single mobile receiver usually is used to make observations at several unknown marks during the course of a survey.
Figure 3.1: Map showing the gravity surveys performed during October–December 2007 (denser grid) and during August 2008 (sparser grid). Crosses indicate locations of individual gravity measurements. Location of the springs indicated by brown oval.

After the data were collected, data files from both base and rover receivers were then downloaded to a personal computer, and the data were processed using the GPSurvey software package, version 2.35, produced by Trimble. The components for the baselines from the known reference station A to remote station B were computed and applied to the known coordinates of the reference stations to provide 28 positions for all remote stations relative to the known point.

3.2 Gravity Data Corrections

Gravity readings are generally influenced by five factors: latitude, elevation, the topography of the surrounding terrain, earth tides, and density variations in the surface. Before the results of a gravity survey can be interpreted in geological terms, these raw gravity data have to be corrected to a common datum, such as sea level (or geoid), in order to remove the effects of
features that are only of indirect geological interest. The gravity survey data in this study have been corrected for instrument drift, instrument response, latitude, elevation, and excess mass.

3.2.1 Instrumental Drift

Gravimeter readings drift with time as a result of elastic creep in the springs, producing an apparent change in gravity at given station (Reynolds, 2003). The instrumental drift can be determined by simply repeating measurements at the same stations at different times of the day. Here, a base field station was established and measurements were taken at this station several times a day to determine the drift factor in milligals per minute. Observed gravity values from intervening stations can be corrected by subtracting the amount of drift from the observed gravity value knowing the time that has elapsed since leaving the base station.

3.2.2 Free-Air Correction

Since gravity varies inversely with the square of distance between two masses, it is essential to correct for changes in elevation between stations to reduce field readings to a datum surface. This correction, called the free-air correction, does not take into account the density of the material between the station and the datum plane. In other words, the free-air correction is the difference between gravity measured at sea level (or some other datum) and at an elevation of \( h \) meters with no rock in between (Reynolds, 2003). The free-air correction is calculated using the formula:

\[
C_F = 3.086h \text{ gravity units (g.u.)},
\]

where \( h \) is the elevation in meters, and a constant value of 3.086 g.u./meter is accepted for most practical applications (Sharma, 1997). The correction, \( C_F \), must be added to a measured gravity value if the station is above the datum plane (i.e., above sea level) and subtracted if below sea level (Reynolds, 2003).
3.2.3 Bouguer Correction

The Bouguer correction accounts for the attraction of material between the station and datum plane that was ignored in the free-air calculation. The Bouguer correction calculates the extra gravitational pull exerted by a rock slab of thickness $h$ meters and average rock density (usually taken as 2670 kg/m$^3$). The correction assumes a slab of uniform density and infinite horizontal extent. The formula used to calculate this correction is:

$$C_{\text{Bouguer}} = 2\pi G \rho h,$$  \hspace{1cm} (2)

where $G$ is Newton’s gravitational constant ($6.673 \pm 0.001 \times 10^{-11}$ m$^3$/(kg s$^2$)), $\rho$ is the average rock density (usually 2670 kg/m$^3$), $h$ is the height of the gravity station above the reference ellipsoid (in meters).

3.2.4 Terrain Correction

The terrain correction accounts for surface irregularities in the vicinity of the gravity station. Hills near a gravity station would apply an upward pull on the gravimeter, whereas valleys would fail to pull downward on it. Thus both types of topographic undulations affect gravity measurements in the same sense and the terrain correction is added to the station reading (Reynolds, 2003). In this study, the terrain correction was not applied due to the fact that changes in elevation within the study area were minimal.

3.2.5 Earth Tide Correction

Instruments for measuring gravity are sensitive enough to record the changes in $g$ caused by the movement of the Sun and Moon, changes that depend on latitude and time. Their range is about 0.3 mGal. The correction can be made from the knowledge of the locations of the Sun and Moon. However, because the variations are smooth and slow, the correction may be included in the instrument drift correction (Reynolds, 2003).
3.2.6 Latitude Correction

The latitude correction is done to compensate for the increase in gravity field from equator to poles (Reynolds, 2003) due to the bulging of the earth at the equator. It can be calculated by subtracting the theoretical gravity using the International Gravity Formula from the observed gravity value. For small-scale surveys that extend over a total latitude range of less than one degree, the following formula for latitude correction can be used:

$$\Delta C_{\text{Latitude}} = 8.108 \sin^2 \phi \text{ g.u. per km north-south} \quad (3)$$

where $\phi$ is the latitude of the base station, with the correction either subtracted or added to the measured gravity value depending on whether a station is at a higher or lower latitude relative to the base station.
Chapter 4

DATA ANALYSIS

Conductivity, resistivity, and self-potential (SP) geophysical studies were completed at the Rattlesnake Springs area prior to the gravity studies. This initial effort was done to locate possible positions of fractures and faults. Initially, I collected conductivity data within a small area inside the park. Later on, Dr. Diane Doser and MS student Ms. Claudia Santiago collected more conductivity data, as well as resistivity and self-potential data not only to enhance the data set, but also to help in planning the gravity surveys. Descriptions of how these data were prepared for modeling and the modeling techniques are given in the following sections.

4.1 CONDUCTIVITY SURVEY

The conductivity survey was done because it is simple to implement, and it also gives the user the opportunity to perform rapid, near surface geophysical investigations. Changes in ground conductivity reflect changes in ground moisture content and/or grain size. Thus, possible locations of underground structures (fractures and faults) controlling the water flow towards the springs could possibly be inferred from a conductivity survey. Conductivity data were collected using an EM-31 ground conductivity meter operating in both vertical and horizontal loop modes, providing information on the average ground conductivity at ~ 3 m (horizontal loop) and ~ 6 m (vertical loop) depths. Conductivity readings were taken every 5 to 10 m. The initial readings were made along all roads within the park unit located upslope from the spring, as well as some of the perimeter. Additional readings were then taken to investigate several regions of higher conductivity and increase data coverage. Ms. Santiago collected additional data mainly to the northeast of the spring, as well as to the western side and outside the park boundary. High conductivity anomalies (> 40 mS/m) are found near the spring and northeast of the spring. A small anomaly is located along the western side of the map. The larger anomalies have a general
east-west strike (Figure 4.1). These results, coupled with resistivity soundings and SP surveys, suggest the highs near the spring are related to moister soils, while the highs in other regions reflect increased clay content in the soil.

Figure 4.1: Ground conductivity in mS/m at approximately 6 meters depth (vertical dipole mode Qv used) with locations of the sample points shown in yellow

4.2 SELF-POTENTIAL (SP) AND DC RESISTIVITY

The self-potential (SP) technique is based upon measuring the spontaneous or natural potentials developed in the earth by electrochemical reactions between minerals and subsurface fluids or electrokinetic signals generated by the movement of fluids. The SP technique is used in a variety of geothermal, environmental, and engineering applications, mainly as the simplest
method to identify groundwater and thermal movements in the subsurface (Sharma, 2002). Changes in SP range from a few to hundreds of millivolts are usually indicators for groundwater flow and its direction (Sharma, 2002).

The DC resistivity method is widely used in geophysical surveying to investigate anomalous conditions or inhomogeneities within the ground. By measuring the subsurface variations in electrical resistivity, one can infer information about the variation in subsurface structures with depth. At Rattlesnake Springs, SP and DC resistivity surveys were performed using a Pole-Pole electrode configuration. The results from the surveys are shown in Figure 4.2 and Figure 4.3 (Doser, 2007, personal communication). Doser (personal communication, 2007) and Santiago (personal communication, 2009) conducted vertical DC resistivity soundings using the Wenner and Schulmberger arrays in other portions of the park to further investigate observed conductivity anomalies.

**Figure 4.2:** Pole-Pole apparent resistivity survey results. Green dots show electrode locations, and dashed red lines indicate 10 ohm-m resistivity contour (after Doser, 2007). Box shows approximate position of main springs.
The greatest negative values on the self-potential plot (Figure 4.3) indicate that water is flowing away from these locations (in this case the western side of the springs). The resistivity data (Figure 4.2) indicate higher resistivity both west and south of the spring. This is likely due to lower moisture content in the near surface layers.

4.3 Gravity Survey Analysis

Gravity data reflect the subsurface density contrast between different rock layers, providing one with an image of what potential subsurface structures may look like. The density
contrasts are usually due to either structural or lithologic variations. Examples of structural variations are the presence of a fault that brought a block of denser material closer to the surface producing gravity high, or a thick basin of sedimentary fill that would produce a gravity low. An example of a lithologic contrast would be a sequence of sedimentary rocks intruded by a denser igneous body. Steep gradients in the gravity data are normally associated with steeply dipping contacts between rocks of different densities, such as those exposed at faults (Griffiths and King, 1965).

Free-air and Bouguer anomalies were calculated assuming an average density of 2670 kg/m³ for the Bouguer correction. The resulting Bouguer anomaly map created in Surfer using the minimum curvature grid option, with gridding interval of 400 meters and contour interval of 1 mGal, shows gravity highs (~-80 mGal) in the western part of Rattlesnake Springs research area, and gravity lows (~-90 mGal) towards the center of the map (near the spring), as well as in the southern part of the map (Figure 4.4). One could expect thicker alluvium and sedimentary fill to overlay the bedrock in areas indicated by the gravity lows, while the bedrock is probably closer to the surface in the western and northern part of the study area (Figure 4.4).

Figure 4.5 represents Bouguer map of Rattlesnake Springs. The black lines drawn indicate possible fracture zones. The position of the lines is based on the gravity anomalies that the map reveals and on the two-dimensional modeling. Changes in the gravity from high to low are indicators for change in the subsurface geology. Therefore, zones of low density (gravity low) are indicators for possible fractures. Gravity data indicate linear trends in the EW and NS directions that are probably associated with the suspected fracture zones.
Figure 4.4: Bouguer gravity map of Rattlesnake Springs, NM

Figure 4.5: Bouguer map of Rattlesnake Springs, NM. Dashed black lines indicate locations of possible fracture zones.
The gravity data were imported into the OASIS Montaj software package developed by Geosoft Inc. in order to grid it and prepare it for the modeling in GM-SYS. A new Bouguer anomaly map was created in the OASIS software, which was used as a base for constructing the 2D gravity profiles (Figure 4.6). The cell size used for gridding was 120 meters, and the minimum curvature gridding technique was used to perform the gridding interpolations. As seen in Figure 4.6, the map created in OASIS shows the same trends in the gravity and geological structures as the map created in Surfer.

![Bouguer anomaly map of Rattlesnake Springs, NM](image)

**Figure 4.6:** Bouguer anomaly map of Rattlesnake Springs, NM

In order to investigate possible structural trends in the gravity data, I applied a series of low-pass and strike filters to the data. First, I applied a low-pass filter with a wavelength of about 4 kilometers. The results from the low-pass filtering (Figure 4.7) show that the gravity anomalies on the west side (indicated as 1) and to the southwest part of the research area (indicated as 2) are
buried deeper and extend to probably more than 4 kilometers depth. This is indicated by their increase in size compared to the original Bouguer map. On the other hand, it can be seen that the anomaly located west of the springs (anomaly 1) decreases in size. This might mean that the two anomalies (1 and 2, ~78 mGal and ~77 mGal, respectively), are located at different depths or that the rock types causing these anomalies differ in density. I also subtracted the low-pass filter from the original Bouguer map to enhance shallower features of interest (indicated as 1', 2', and 3') above 4 km depth (Figure 4.8).

Figure 4.7: Bouguer gravity map of Rattlesnake Springs, NM, filtered using a low-pass filter with ~4km wavelength.
Prior to modeling the 2D profiles, I applied several strike filters to my data. Application of a strike filter may enhance features on a map that have a particular orientation. This type of filter can also remove “geological noise.” Two parameters are used to define the filter: the direction that is to be enhanced, and the severity of the filter. The filter works by upward continuing the map, except for features that lie in the direction to be enhanced. Hence the severity is a distance that is measured in the same units as the map itself. The equation is given by Syberg (1972) as:

$$A(u,v) = A(u,v)e^{h \sqrt{u^2 + v^2} \cos \Theta + \phi}}, \tag{4}$$

where $h$ is the continuation height, $\phi$ is $\tan^{-1}(u/v)$, $u$ and $v$ are spatial frequencies, and $\Theta$ is the direction that is to be enhanced. In my case, strike filtering of the data using 45- and 90-degree
rejection angles revealed interesting trends in the gravity data as shown in Figure 4.9 and Figure 4.10.

**Figure 4.9:** Strike-filtered (0 to 45 degrees rejected) Bouguer map of Rattlesnake Springs, NM

**Figure 4.10:** Strike-filtered (0 to 90 degrees rejected) Bouguer map of Rattlesnake Springs, NM
These filters were designed to reject any trends in NE-SW directions and to enhance features striking east-west to northwest-southeast. The NE-SW trend was rejected because the original Bouguer map (Figure 4.7) shows predominant linear features in an EW direction that I wanted to enhance. From the figures, it can be observed that there is a predominant trend in the gravity data in the east-west direction. In addition, there are two east-west trending highs on either side of the springs that are visible in the filtered images (Figures 4.9 and 4.10). As one moves from west to the east side of the maps (Figure 4.9) the gravity contours get smoother. Based on these two observations, and the eastward decrease in gravity values, it can be concluded that geological features, such as possible fractures, may have a predominant east-west trend. Additional filtering at -45 and 45 degrees and 45 and 90 degrees shown on Figures 4.11 and 4.12 further confirm that the EW trends in the data are the most dominant.

Figure 4.11: Strike-filtered (-45 to 45 degrees rejected) Bouguer map of Rattlesnake Springs, NM
Figure 4.12: Strike-filtered (45 to 90 degrees rejected) Bouguer map of Rattlesnake Springs, NM
Chapter 5

TWO-DIMENSIONAL GRAVITY MODELING TECHNIQUE

AND RESULTS

The following section describes the modeling technique used to perform the two-dimensional (2D) modeling of the Bouguer gravity anomaly data for the Rattlesnake Springs research area. The initial interpretations of the gravity data were presented in the previous chapter. I conducted the 2D modeling to better determine the depth to bedrock and the presence of any faults that may control groundwater flow.

5.1 TWO-DIMENSIONAL GRAVITY MODELING TECHNIQUE

In order to develop a more detailed interpretation of the subsurface structures that might control the water flow towards Rattlesnake Springs, I constructed computer models of gravity data along two profiles of specific interest using GM-SYS modeling software. The software uses a forward modeling technique based on the methods developed by Talwani (1959), Won and Bevis (1987), and Ramussen and Pedersen (1979). It computes the vertical component of gravitational attraction due to any two-dimensional body. Moreover, GM-SYS uses a two-dimensional, flat-earth model for the gravity calculations. Each structural unit (block) extends to plus and minus infinity in a direction perpendicular to the profile. The model also extends to plus and minus 30,000 km at the ends of the profile to eliminate edge effects. The forward modeling first requires the creation of a hypothetical geologic model and calculation of the gravity response to that earth model. The user then interactively manipulates the geologic model, and performs real time calculation of the gravity response to develop a model consistent with the gravity observations and with minimum residual. The first profile (A-A') constructed crosses the research area in west-east direction, and the second (B-B') crosses the Rattlesnake Springs area in
north-south direction (Figure 5.1). Both profiles were selected to cross important Bouguer gravity anomalies.

**Figure 5.1:** Bouguer anomaly map of Rattlesnake Springs, NM, showing the locations of the two GM-SYS modeled gravity profiles (A-A' and B-B')

There are several steps required for constructing gravity models using GM-SYS. First, one needs to make a skilled guess of an initial geologic model that is compatible with what is known about the subsurface stratigraphy. This is done by dividing the profile into a number of two-dimensional polygons, each with its own density and thickness. GM-SYS then computes the corresponding gravity anomalies ($\Delta g_{\text{calc}}$) of these blocks along the profile summing them to
produce a calculated gravity profile. GM-SYS then compares the calculated anomaly with the observed gravity anomaly \( \Delta g_{\text{obs}} \) and computes residual error. The user can then interactively adjust the polygon sizes, shapes, and densities to improve the fit between the computed and observed gravity. The process is repeated iteratively until the residual between observed and calculated gravity values \( \Delta g_{\text{observed}} - \Delta g_{\text{calculated}} \) at each observation point becomes small (Sharma, 2002).

I used shallow groundwater well information from Bowen (1999) to constrain the depth to the water table and the subsurface stratigraphy. The deepest wells shown by Bowen (1999) extend to about 350 m depth, with depth to the water table levels varying anywhere between 18 and 40 m (Figure 5.2).

Figure 5.2: Approximate well locations given by Bowen, 1999
The closest and deepest well to the research area shows that the unsaturated alluvium material is between zero and 50-60 m depth. The layer below the alluvium represents sediment fill that extends to depths from 50 to 350 m below the surface. Some of the wells show that the gypsum bedrock (interpreted to be the Castile formation) outcrops at depths of 50 to 350 m below the surface. Gypsum also outcrops on the surface around the spring, as seen on the geological map (Figure 5.3).

**Figure 5.3**: Geological map of Rattlesnake Springs area, NM, with springs outlined by box

There is no other available deep well information for the area, and therefore I made assumptions about the geology beneath the gypsum layer. The assumptions about the rock types were made based on the work of Hale (1955) and Cox (1963). Both authors claim that the layers below the Castile formation are comprised of sandstones and limestones. Figure 5.4 shows the average densities used when constructing the profiles.
<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Average Densities, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvium Unsaturated</td>
<td>1.7</td>
</tr>
<tr>
<td>Sediment Fill Saturated</td>
<td>2.2</td>
</tr>
<tr>
<td>Gypsum</td>
<td>2.5</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.75</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.8</td>
</tr>
</tbody>
</table>

**Figure 5.4:** Rock types and associated densities used in the gravity modeling (from Sharma, 2002)

Since there was little well information to constrain the subsurface geology for the modeling, the profiles I constructed were kept as simple as possible. However, the models therefore represent a non-unique solution that could change as the model is updated with more detailed information about the subsurface geology at the Rattlesnake Springs area.

5.2 **MODELING RESULTS FOR GRAVITY PROFILES A-A' AND B-B'**

Profile A-A' extends in an east-west direction for 4.4 km as shown in Figure 5.5. The profile was chosen to cross over gravity highs and lows on the Bouguer anomaly map as shown in Figure 5.1. Gravity highs are observed on the west side of the profile. The interpretation for the gravity high on the west side of A-A' (~ 79 mGal) is gypsum bedrock. Gypsum is close to the surface, which makes the sedimentary fill above it very thin. The gypsum also outcrops at the surface about 400 meters from the west side of the profile. Moving east along profile A-A' the gravity values slowly decrease to a low (~ -94 mGal) at about 2600 m, immediately followed by gravity high (~ -87 mGal). In the model, a thickening in the alluvial fill to about 2600 m reflects this. From Figure 5.5 it can also be observed that the matching of the observed gravity values and the values calculated by GM-SYS are in very good agreement and that the residual error is minimal (match ~2 mGals). The gravity model suggests the presence of geological structures as
indicated on the model (Figure 5.5). They could be interpreted as fractures cutting through the area, or they may be reflecting changes in the topography of the basement rock. They are likely to be fractures because: 1. They do not extend very deep into the subsurface; and 2. They do not cut through all of the layers in the model.

![Graph and Diagram](image)

**Figure 5.5:** East-West GM-SYS gravity profile, Rattlesnake Springs, NM

Based on Figure 5.5, the area through which the profile was chosen to cross contains two main fracture zones. The first zone is located on the west end of the profile (between 0-2 km) corresponding to a large gravity high. The second zone is located on the east end (at ~ 3.6 km), corresponding to the edge of a gravity low. An alternate interpretation is that these gravity highs and lows could be caused by differences in bedrock topography and not fractures.
Profile B-B' extends in a north-south direction and it also crosses gravity highs (on the north end) and gravity lows (on the south end), as can be seen in Figure 5.1. The profile is approximately 2.6 km long (Figure 5.6).

![GM-SYS model of gravity profile B-B', Rattlesnake Springs, NM](image)

**Figure 5.6:** GM-SYS model of gravity profile B-B', Rattlesnake Springs, NM

The profile reveals three shallow, basin-like features consisting of unsaturated alluvial material. Another interesting observation is the fact that all rock layers dip towards the center of the profile, which might be an indication that the area is situated in a large syncline or basin. The sedimentary fill crops out at both the north and the south sides of the profile. There are two noticeable spikes on the profile-gravity high immediately followed by gravity low, at about 1 km from the northern starting point. Three possible fracture zones are located at about 1 km, 1.8 km, and 2.2 km from the northern edge of the profile.
Profiles A-A' and B-B' suggest that possible fractures may be present in the subsurface. No indication of displacement along a possible fault is observed in the data or from the models. If more information about the subsurface geology becomes available, the gravity models could be better constrained and may yield different interpretations.
Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

This is the first high-precision gravity survey conducted in the Rattlesnake Springs area. The study shows the results from the 2D gravity modeling performed in order to interpret the subsurface of the Rattlesnake Springs area. The results of the study have better constrained the depth to bedrock in the area of Rattlesnake Springs. The models showed that the depth to the gypsum layer varies anywhere from 800 m to more than 2000 m. The study has also located and characterized possible fracture zones that maybe controlling the direction of the groundwater flow. The major trends of the possible fractures around the springs are found to be in EW direction. Moreover, the results of the gravity modeling will help in modeling of the hydrological conditions around the springs. It is of great importance to further study the area since the fracture system may affect the flow of the springs. The suspected fractures in the area will result in increased rock permeability, allowing potential contaminants from oil and gas drilling in nearby areas to be transported much faster towards the springs.

The models can be further developed and refined, if more geological or other geophysical information become available. As an example, in this study I did not have access to detailed lithologic information from well logs, so I did not have constraints on the depth to the sandstone and limestone layers in my 2D model. In addition, it would have helped if I had density well logs to determine more accurate densities of the sandstone and limestone layers.

More gravity data could be collected especially to the west of the study area. With additional data, three-dimensional modeling of the free-air anomaly could be performed. Furthermore, if a seismic survey is performed, the integrated results will provide high-resolution information about the subsurface geological features (fractures, faults, channels, etc.) that control the groundwater flow towards the springs. The study can also be used as a base for future studies of watersheds in arid regions, and assist researchers in their hydrological models, because the
method proved to be effective in detecting geological features in desert environments when other methods such as ground penetrating radar have failed. In addition, one must keep in mind that the technique is also rapid, inexpensive, and works well over small areas. Also, the gravity method provides more details about the subsurface allowing modeling of greater depths (to a few kilometers)—something that could not be achieved with some of the electrical methods such as conductivity.
References


Hale, J. R., 1955, Ground water conditions in the vicinity of Rattlesnake Springs, Eddy County, New Mexico, Technical Report No 3, State of New Mexico State Engineer’s Office, 54 pp.


APPENDIX

USING MICROGRAVITY TO DELINEATE THE WATERSHED OF

RATTLE SNAKE SPRINGS, CARLSBAD Caverns National Park

(paper presented in poster form at the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP), Ft. Worth, Texas, March 29-April 2, 2009)
USING MICROGRAVITY TO DELINEATE THE WATERSHED OF
RATTLESNAKE SPRINGS, CARLSBAD CAVERNS NATIONAL PARK

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ABSTRACT

We performed a series of geophysical investigations at the Rattlesnake Springs portion of the Carlsbad Caverns National Park, New Mexico in an effort to characterize the watershed of the springs. As part of this effort we conducted a precision microgravity survey of the area surrounding the springs using a grid with 200 to 300 m spacing with station positions and elevations determined using differential GPS. The survey was designed to map the depth to gypsum bedrock in the study area and pinpoint the locations of faults/fractures that could control groundwater movement toward the springs. A free-air anomaly map generated from our initial survey results clearly reflects known bedrock highs and lows. The map contours suggest an underlying fracture system that is mimicked by surficial drainage patterns and features we believe are the remnants of dissolution structures within the gypsum bedrock. These results suggest groundwater flow from the west-northwest into the springs (in agreement with other geophysical surveys we conducted near the springs). The gravity data suggest an east-north east trending fault/fracture located just east of the springs serves as a barrier to groundwater flow causing upflow at the springs.

Introduction

In this paper we discuss how we have planned and performed geophysical investigations at the Rattlesnake Springs, Carlsbad Caverns, New Mexico, in order to outline the watershed of the springs. Using this framework we were then better able to plan and execute geophysical surveys to investigate shallow subsurface structures and to map the depth to gypsum bedrock in the area of interest, and to locate the positions of fault/fractures that control groundwater flow toward the springs. We present a case study of where we have applied our methods within the Rattlesnake Springs and our results would help to identify the underground channels that feed them. In addition, this study would provide the Carlsbad Caverns National Park personnel and the neighboring Washington Ranch with important information, since the springs are an important source of fresh drinking water in the area.

Methodology

We have used previous studies developed (Hale, 1955, Cox 1961), as a starting point for our development of a framework for geophysical and geological studies of the subsurface in the area of the Rattlesnake Springs. According to Hale (1955) the general geology of the area consists of rocks of Permian age. The oldest rocks exposed in the area are those belonging to the limestone facies of the Guadalupe series of Permian age. These rocks crop out in the Guadalupe Mountains along the northwest boundary of the area. Along this escarpment the reef talus beds
dip steeply to the southeast and terminate in the subsurface where they interfinger with sandstone beds. In the region of the springs limestone and sandstone beds of equivalent age to the escarpment are covered by anhydrite and gypsum beds of the lower part of the Ochoa series, also of Permian age. Above the gypsum beds, the much younger alluvial sediments mantle most of the bedrock. Rattlesnake Spring is located in the upper Black River Valley in southern Eddy County close to New Mexico- Texas border (figure 1). Groundwater flow seems to be driven by precipitation providing recharge to the topographically high Guadalupe Reef Escarpment and flowing to the low-lying Delaware basin. Geological mapping for this project performed by Dr. Richard Langford suggest that the landscape at Rattlesnake Springs is composed of two main elements (figure 2). Boulder gravel terraces, shed from the canyons in the Guadalupe Mountains, have created a set of smooth sloping surfaces that grade eastward toward the Pecos River. Incision during the Quaternary cut through the older terraces and the younger terraces are inset within the older. All of the terraces are probably early late Holocene or older, based on the well developed calcic soils within them.

Surrounding Rattlesnake Springs, several interesting valleys incise these terraces (Figure 2). The valleys are filled with clay-rich Holocene sediment, unlike the soils in drainages derived from the mountains. These valleys are blind, and, although they are broad, they do not appear to have tributaries, or other significant overland flow to have eroded them. Therefore, one can infer that the valleys are karst features. They may represent extensive sinkholes, or solution valleys. Alternatively, they may have sinkholes at their upper end and may have formed through spring out flow, which created dissolution and collapsed the surfaces. Linear trends of these solution valleys suggest north-south and northwest oriented caves that created the features.

**Figure 1:** ASTER image showing the location of the spring’s area observed (outlined with yellow box)
We have performed a conductivity survey in the area and from the results from this survey, northwest-southeast striking conductivity highs were found and their trends would suggest a relationship to these possible dissolution structures. The gravity data collected is also consistent with a north-south trending fracture system which may control bedrock, groundwater and surface water drainage patterns.

The variation in the earth’s gravity field over an area reflects variations in density. In the case of Rattlesnake Springs, the density variations can help map the depth to bedrock in the research area and to pinpoint the locations of faults/fractures that might control the groundwater movement (Doser, 2005).

We collected the initial gravity data for this project during October-December 2007 survey (figure 3). More data collection is still in process, and the data collection is expected to be finished by the end of December, 2008. The first data set was collected using a grid setup with 200 m spacing and an area of 2700 by 2700 m was covered. Each gravity measurement was located in the field using high precision GPS measurements. The current survey focuses on the region northwest of the original survey. It has a 300m grid spacing covering area of 3000 by 3000 m.
Initial results of our gravity survey are shown in Figures 4 and 5. These data have been corrected for instrument drift, instrument response, latitude, and elevation. The difference between these corrected readings and an ideal earth is called the free air anomaly (FAA) and is shown in Figures 4 and 5 (Khatun, 2003). Figure 4 indicates the changes in FAA (light blue contours) over the entire grid as compared to the conductivity values (vertical dipole mode) within the smaller study area. Note that conductivity lows (dark blue, less than 10 mS/m) are associated with the edge of a FAA high located north of the park boundary. The FAA high (36 mGals and above) indicates that bedrock is at or near the surface. Conductivity highs (red, more than 45 mS/m) are found at the edge of the FAA high. Note how the gravity high is truncated on its eastern side, suggesting fault control in the bedrock. The contours south of the gravity high indicate a low within the region of the park (representing loose basin fill) that is also truncated abruptly just east of the springs. The gravity changes suggest that the loose basin fill is about 250 feet (~76 m) thick near the springs. South of the park boundary the gravity contours again indicate bedrock closer to the surface. The pattern of contour lines suggests underlying fractures/faults as indicated by the yellow dashed lines. We believe that groundwater may be flowing down the path indicated by the blue arrow.
Figure 4: Free air gravity anomaly (light blue contours, 1 mGal contour interval) of study area from October-December 2007 survey. Purple symbols indicate sample points. Red and dark blue contour represent conductivity highs (>45 mS/m) and lows (< 10 mS/m) within smaller study area from vertical dipole survey performed. Yellow dashed lines indicate probable locations of fractures/faults that may control bedrock structure. Possible direction of groundwater flow toward springs is indicated by bold blue arrow.
**Figure 5:** Close-up view of free air gravity anomaly data in vicinity of park (park outline shown in green). Gravity data are contoured at 1 mGal intervals. Dark blue and red lines indicate vertical dipole conductivity lows and highs, as in Figure 4. Dashed line indicates possible location of fault/fracture that might control groundwater flow (and hence the location of the springs).
Conclusions

The pattern of contour lines shown on Figures 4 and 5 suggests underlying fractures/faults as indicated by the yellow dashed lines. We believe that groundwater may be flowing down the path indicated by the blue arrow drawn on Figure 4. The fracture or fault located just east of the springs appears to be a barrier to groundwater flow, causing the water to come to the surface at the springs. The fracture system indicated by the yellow lines seems to be mimicked by drainage patterns and other features as discussed in the section on geological mapping. Figure 5 is a close-up view of the park region with FAA contours (yellow) and conductivity anomalies from previous studies we performed (as in Figure 4). The approximate location of a fracture/fault suggested by the gravity data is indicated by the dashed line. We have shared this information with the Carlsbad Caverns National Park personnel to aid them with hydrological modeling of the area. We feel that the technique used could be applied to other regions where determination of the watershed is necessary.

We plan to initiate detailed 3D modeling (Khatun, 2007) of the complete gravity data set supplemented by regional data obtained from the UT El Paso gravity data base to better determine the pattern of fracturing within the region and estimate the shape of the basin containing the springs.
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Vita

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