

FINAL REPORT

**Geophysical Survey of the
Fanning Spring Basin**

For

**Florida Department of Environmental Protection
Florida Geological Survey**

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*Note: Many of the figures in this report are in color.
Reproduction in black and white will result in a loss of data
and the ability to visualize details in the data.*

TERMINOLOGY

The following terms are used in this report to describe karst conditions.

Anomaly:	In geophysical investigations, anomaly is the term used to describe a change in the condition of soil or rock (from “background” conditions) based upon a deviation in data values observed in a given geophysical measurement (e.g. gravity anomaly).
Cutter:	A dissolution trench in weathered limestone formed along a vertical fracture. Typically forms an irregular cutter-pinnacle profile of the top of bedrock. Often filled by residual soils with no surface expression.
Karst:	A landscape and its subsurface characterized by a variable suite of surface landforms and subsurface features, not all of which may be present or obvious. These include sinkholes, springs, caves, sinking streams, dissolution-enlarged joints and/or bedding planes, and other dissolution features. Most karst develop in limestone and/or dolomite, but they may also develop in gypsum, salt, or carbonate-cemented sandstones.
Lineament:	A linear topographic feature of “regional extent” that is related to subsurface soil or rock conditions. Lineaments are seen on aerial photographs as alignments of structure, joints, sinkholes, sinkhole lakes, stream beds, vegetation, and other surface features thought to be controlled by subsurface soil or rock conditions. Karst features such as sinkholes often appear as lineaments. On the ground they are related to zones of closely spaced joints. They are often the result of dissolution of the rock along these joints, with major karst depressions centered where two sets of joints intersect.
Paleokarst:	Ancient karst features (e.g., sinkholes); may be commonly buried by younger sediments. Paleokarst sinkhole lakes are abundant throughout Florida.
Sinkhole:	A topographic depression formed as a result of karst-related processes such as dissolution of bedrock, collapse of a cave roof, or flushing and/or collapse of soil and other sediment into a void within the bedrock.
Soil Piping:	Soil Piping or Soil Raveling refer to unconsolidated materials moving downward into voids in deeper unconsolidated material or rock. Soil piping features (voids) commonly migrate to the surface where they may become the initial stage of a large sinkhole.

BACKGROUND

The Florida Geological Survey (FGS) is currently conducting a study for the Florida Park Service on the nitrate contamination in Fanning Spring. This spring's discharge contains the highest concentration of nitrate of any of Florida's first magnitude springs. The FGS's study includes delineating Fanning's springshed boundaries and identifying the nitrate sources.

Although the springshed has been delineated using high-precision potentiometric data and other information, actual cave maps for this spring are unavailable since no openings into a conduit system are available for divers. Cave maps are very useful to researchers interested in determining the direction and source of water and identifying the formation contributing the water. The configuration of caves and conduits can also relate the type of porosity that has developed in the host rock. Additionally, their depth, size and other morphological features assist in understanding how they were originally formed.

In 2005, Technos, Inc. (Technos) demonstrated that geophysical methods offer a non-invasive and efficient means to map the locations of large conduits within the Woodville Karst Plain (Technos, 2005). Specifically, microgravity and resistivity imaging data can be used to identify large karst conduits and weathered zones that may contain fractures and smaller conduits, which affect groundwater flow. Butler (1984) successfully located the main conduits leading to Manatee Springs with microgravity. These geophysical methods can similarly be used in the Fanning Springs basin to locate large conduits and refine the hydrogeologic models of the springshed.

FANNING SPRINGS BASIN

Fanning Springs is located along the lower Suwannee River in northwestern Levy County, Florida (Figure 1). Fanning Springs lies in close proximity to Manatee Springs, with a combined springshed encompassing 450 square miles (SRWMD, 2005). The springshed is within a mature karst plain with rapid surface water infiltration and numerous sinkholes. The discharge rate at Fanning Springs ranges between 51.5 ft³/s and 139 ft³/s (Scott, et. al., 2004).

The stratigraphy consists of thin quartz sand overlying the highly karstified Ocala Limestone. The Upper-Eocene Ocala Limestone is a white to light-gray to light-orange limestone with a diverse fossil assemblage (Arthur, et. al., 2001). The highly permeable limestone contains solution conduits that convey groundwater to Fanning and Manatee Springs. The groundwater potentiometric surface gently slopes from east-to-west towards the Suwannee River (SRWMD, 2005).

PURPOSE AND SCOPE

The FDEP retained Technos to carry out microgravity and resistivity surveys within the Fanning Springs basin to aid in the hydrogeological characterization of the springshed. As a first step in the survey, microgravity and resistivity data were acquired over known conduits within the Manatee Springs basin to demonstrate the effectiveness of these methods in identifying conduits similar in expected size and depth to those at Fanning Springs (Figure 2). A microgravity survey was then implemented along approximately 4.8 miles of survey lines surrounding Fanning Springs (Figure 3). The locations of the survey lines were selected by FGS personnel to sample both regional and localized features surrounding Fanning Springs. Resistivity data were then collected along selected anomalous portions of these survey lines. Technos completed the survey between April 29th to May 21st, 2006.

TECHNICAL APPROACH

SURVEY LINES

The locations of the survey lines are summarized in Appendix A.

Manatee Springs

Two 1,100-foot long survey lines were established over diver-mapped conduits within the Manatee Springs basin (Figure 2). The survey lines include:

- Line 1 – 1,100 feet passing through Wells C1 and B2
- Line 2 – 1,100 feet passing over a radio-located position of the conduit

Fanning Springs

A total of 25,450 feet (4.82 miles) of survey lines were established within the Fanning Springs basin (Figure 3). The survey lines include:

- Line 1 - 16,300 feet (3.09 miles) along the west shoulder of U.S. 19
- Line 2 – 800 feet within Fanning Springs Park
- Line 3 – 1,700 feet within Fanning Springs Park
- Line 4 – 750 feet within Fanning Springs Park
- Line 5 – 500 feet within Fanning Springs Park
- Line 6 – 3,000 feet along south side of NW 175th Lane
- Line 7 – 2,400 feet along east shoulder of Old Fanning Highway

Station Labels

Stations are referenced to distance in feet from the eastern or southern end of each survey line and are annotated at the survey line endpoints shown in Figures 2 and 3. The geographic positions of the stations were determined with a Trimble Ag-132 differential GPS system. The geographic positions are listed in Appendix B in the Florida (north) State Plane coordinate system.

MICROGRAVITY MEASUREMENTS

A microgravity survey provides a measure of lateral changes in subsurface density such as variations in depth to bedrock, fractured zones, and voids. If subsurface conditions are laterally uniform, there will be no change in the gravity profile. Microgravity is the only surface geophysical method that can indicate the presence of a mass deficit (low density) within the subsurface. A more complete discussion of the microgravity method is provided in Appendix B. *Note: In this report the terms “Microgravity” and “Gravity” are synonymous.*

Data Acquisition

A Scintrex CG-5 gravimeter was used to acquire the microgravity data stations spaced at 50-foot intervals, along each of the survey lines. Measurements were acquired at a total of 47 stations in Manatee Springs and 517 stations in Fanning Springs. Repeated measurements were made at a total of 13 stations (28%) at Manatee Springs and 61 stations (12%) at Fanning Springs. The average deviation of these repeated measurements is ± 2 μ Gals at Manatee Springs and ± 4 μ Gals at Fanning Springs, indicating a relatively low level of noise, which is essential for this application of the microgravity method. The station elevations were surveyed with a Topcon DL-102 digital level with a precision of 0.01 feet and a loop closure error within 0.1 feet per linear mile.

Data Processing and Presentation

The data were processed using standard gravity reduction formulas in an EXCEL spreadsheet. The processed data are presented as profile lines that show both site-wide trends and a filtered component to show localized anomalies. Appendix B contains more details of the data processing and data quality.

2D RESISTIVITY IMAGING

Resistivity imaging provides a means of obtaining a two-dimensional (2D) cross-section of electrical resistivity, which is a function of soil and rock type, porosity, its permeability as well as the composition of fluids that fill the pore spaces. If a sufficient resistivity contrast exists, the data can be used to identify stratigraphic layers and anomalous zones such as fractures, voids, and weathered zones. A more complete description of the resistivity method along with details of the data quality and acquisition settings for this survey are provided in Appendix C.

Data Acquisition

Resistivity imaging data were acquired along two test lines (2,200 linear-feet) in Manatee Springs and along six survey lines (7,360 linear feet) within Fanning Springs (Figure 2 and 3). The resistivity data in Fanning Springs are located over anomalous areas identified in the microgravity survey.

Resistivity data were acquired with an AGI Sting R1IP resistivity system using 56 electrodes. A combination Wenner-Schlumberger array geometry was used to provide a high signal-to-noise ratio within the high resistivity surficial sand (Appendix C). Prior to making the measurements, the ground around the electrodes was wetted with saltwater to improve the electrical coupling.

Data Processing and Presentation

Resistivity models of the resistivity data were calculated with RES2DINV software (Loke), using an iterative, least-squares algorithm. The resulting models were contoured using Surfer (Golden Software) and presented as 2D cross-sections of resistivity. Appendix C contains more details of the data processing and data quality.

RESULTS

MANATEE SPRINGS TEST LINES

Microgravity Model

In order to assess the expected magnitude and width of anomalies in the Fanning Springs basin, forward models were compared with measured gravity over the diver-mapped tunnels at Manatee Springs.

Line 1 at Manatee Springs crosses through Well C1 that intersects the main conduit and through Well B2 that intersects the “blue water” conduit. Based on diver cross-sections, the main conduit at this location is 18 feet wide, 11 feet high, with a ceiling depth of 59 feet. The blue water conduit is 9 feet wide, 3 feet high, with a ceiling depth of 74 feet.

Figure 4 shows the theoretical and measured gravity response over these conduits at the same lateral scale used in this report. A density difference of 1.4 g/cc was assumed between the limestone and water-filled conduit, based on average values of weathered limestone (Telford, et. al., 1976). The blue water conduit is not large enough to produce a detectable anomaly. The theoretical anomaly due to the main conduit is approximately 16 μ Gals with a width of 300 feet. The measured gravity data fit the theoretical gravity well, but are laterally variable due to other density variations. The magnitude and width of the anomaly are consistent with data acquired by Butler (1984) over the main conduit.

Gravity models are inherently non-unique, meaning that different models (or geologic conditions) can produce the same gravitational response. Variations in depth to rock, weathered zones within the limestone, and additional conduits are all possible geologic conditions that could be contributing to the measured anomalies. However, the results of the forward modeling and the measured values over the known conduits provide an indication of the expected magnitude and width of anomalies in the Fanning Springs basin.

Microgravity and Resistivity Data

Figure 5 shows the microgravity profiles and resistivity imaging cross-sections along the Manatee Springs Lines 1 and 2. Along Line 1, the location of a low-resistivity anomaly correlates well with the center of the low-gravity anomaly and the main conduit intersected by Well C1. The low-resistivity anomaly (10-40 ohm-m) is caused by the relatively less-resistive water-filled conduit surrounded by limestone. However, the anomaly is not constrained to the depth of the conduit itself, and extends deeper and shallower than the conduit. This is likely due to water-filled fractures surrounding the conduit, which act to enhance the resistivity anomaly. This effect is commonly observed in resistivity data over natural conduits and is referred to as a “halo effect”.

The gravity data along Line 2 show no indication of an anomaly at the approximate location of the conduit (Figure 5). There is, however, a low-resistivity anomaly centered near this location, with resistivity values higher than those measured along Line 1. Narrow gravity anomalies are evident at other portions of Line 2, likely due to vertical weathered zones, but not due to a large conduit. Therefore, the conduit beneath Line 2 is not of sufficient size to be detected with microgravity and has a lower resistivity contrast than where it crosses Line 1.

FANNING SPRINGS

Microgravity Interpretation Criteria

The microgravity profiles are directly related to subsurface density variations. Therefore, low density zones such as conduits produce low gravity anomalies. The magnitude and width of the gravity anomalies are related to the size and depth of the subsurface feature. In general, wider anomalies are due to deep or broad features, while narrower anomalies are due to shallow features.

In this investigation, we are primarily interested in anomalies due to conduits of the size and depth representative of the Fanning Springs basin. In order to visualize these anomalies from the relatively wide range of measured gravity values, the data were filtered with a high-pass filter (see Appendix B). The gravity profiles (Figures 6 to 15) show both the filtered (blue line) and unfiltered (black line) data. The unfiltered data are presented as an indication of regional trends, but were not used in the interpretation of karst features. Low-gravity anomalies have values below the median filtered value and are shaded red in the gravity profiles (Figures 6 to 15).

Based on the forward models (Figure 4), the microgravity data over known conduits at Manatee Springs (Figure 5), and the results of a previous microgravity survey at Manatee Springs (Butler, 1984), the expected magnitude of the gravity anomalies due to the conduits is less than 20 μ Gals, with a width of approximately 300 feet. This size anomaly is small and can be masked by shallower features such as variations in the top of rock.

Microgravity Data

Profiles of the microgravity data along the Fanning Springs survey lines are shown in Figures 6 to 15. The filtered microgravity data have a small range of between -34 and 55 μGals . Low gravity anomalies (shaded red in the figure) show a large variance in width and spatial periodicity. The relatively small range of gravity values and their spatial variance indicates that the source of the low-density zones is likely a complex combination of small dissolution zones within the limestone and variations in shallower features such as the top of rock.

No large microgravity anomalies were identified in the Fanning Springs survey that compare to those measured in the Woodville Karst Plain (Technos, 2005). There are, however, numerous anomalies similar to the magnitude and width measured over the known conduit in Manatee Springs.

In order to visualize the spatial distribution of the anomalies a contour map of the microgravity data was developed (Figure 16). Low-gravity anomalies with a magnitude greater than 15 μGals (blue in Figure 16) are of the size measured over the known conduit in Manatee Springs. A north-south trend of low gravity is evident along Line 3, extending from U.S. 19 (Line 1) to south of Line 2. This trend appears to lie just east of the spring, but is not constrained by measurements in the immediate vicinity of the spring (Figure 16). Most of the other low gravity anomalies appear to be due to isolated features and do not form trends from line-to-line.

Resistivity Data

Six lines of resistivity imaging data were positioned along the microgravity survey lines closest to the spring (Figure 3). The resistivity cross-sections are shown with the microgravity profiles in Figures 9 to 14.

In general, the resistivity cross-sections indicate a shallow layer of high-resistivity due to unsaturated sand in the upper 20 feet. This layer overlies a zone of lower-resistivity, likely due to the saturated epikarst zone at the top of rock. Higher resistivity values are evident deeper in the cross-sections due to less porous limestone.

The resistivity cross-sections were assessed for low-resistivity anomalies of the character measured along the Manatee Springs test line (Figure 5). There are few resistivity anomalies of this type measured at Fanning Springs. However, some indications of vertically-trending low-resistivity zones are evident and are listed in Table 1. These low-resistivity anomalies generally correlate with small microgravity anomalies, possibly indicating water-filled conduits.

Table 1. Resistivity Anomaly Locations

Line	Station	Comments
3	450	100 ohm-m anomaly near a 20- μ Gal low-gravity anomaly
3	1480	100 ohm-m anomaly within a 15- μ Gal low-gravity anomaly
4	320	100 ohm-m anomaly within a 10- μ Gal low-gravity anomaly
6	2850	20 ohm-m anomaly within a 20- μ Gal low gravity anomaly Resistivity anomalies extend from Stations 2800 to 3300
6	2550	20 ohm-m anomaly, deep (>140 feet)

CONCLUSIONS AND RECOMMENDATIONS

Microgravity and resistivity data acquired over known conduits at Manatee Springs show a relatively small anomalous signature, consistent with forward models and previous studies. A 16- μ Gal microgravity anomaly was measured over one location of the conduit, while no microgravity anomaly was measured at another location, indicating the variable size of the conduit. Low-resistivity zones are evident in resistivity cross-sections at both locations of the Manatee Springs conduit due to the relatively low-resistivity water.

Microgravity data acquired at Fanning Springs have a small range of values. One north-south low-gravity trend was identified east of the spring location, extending from U.S. 19 (Line 1) to south of Line 2 (Figure 16). This trend may be related to a conduit or a zone of increased weathering leading to or near the spring. However, most of the anomalies have a variable spatial periodicity that generally do not form line-to-line trends, indicating that the source of the low-density zones is likely a complex combination of small dissolution zones within the limestone and variations in shallower features such as the top of rock.

In order to better define the cause of the microgravity and resistivity anomalies, we recommend three test borings be drilled at the locations listed in Table 2. The borings should extend to a depth of at least 100 feet. Also, additional microgravity data focused in the vicinity of the spring would help to better define the low-gravity trend.

Table 2. Recommended Boring Locations

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Anomalies
2	200	2466002	216889	25- μ Gal microgravity anomaly
3	1450	2466175	218027	Resistivity anomaly within 15- μ Gal microgravity anomaly
6	2850	2465811	216193	Resistivity anomaly within a 20- μ Gal low gravity anomaly

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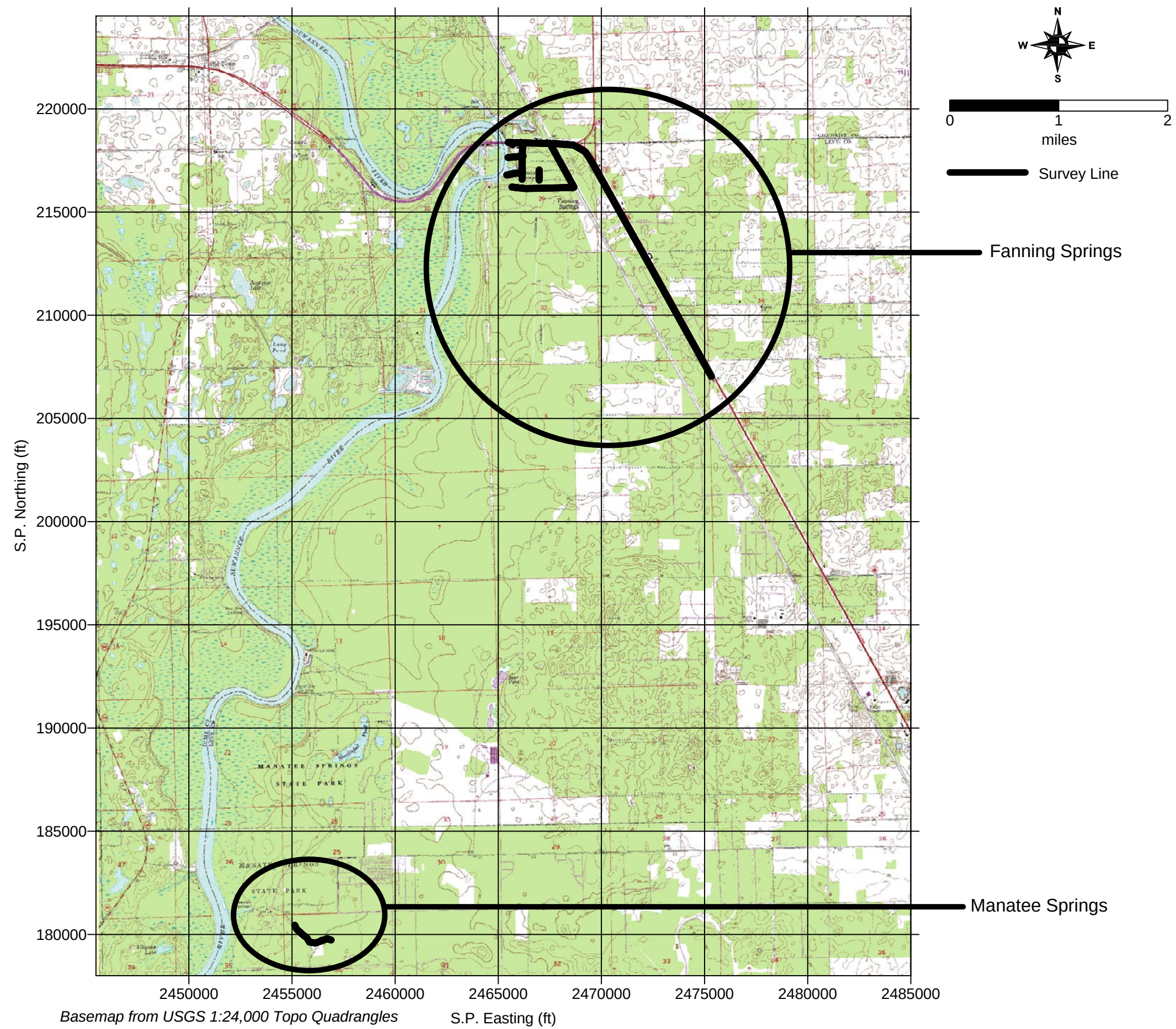


Figure 1. Survey line locations



Figure 2. Manatee Springs survey lines

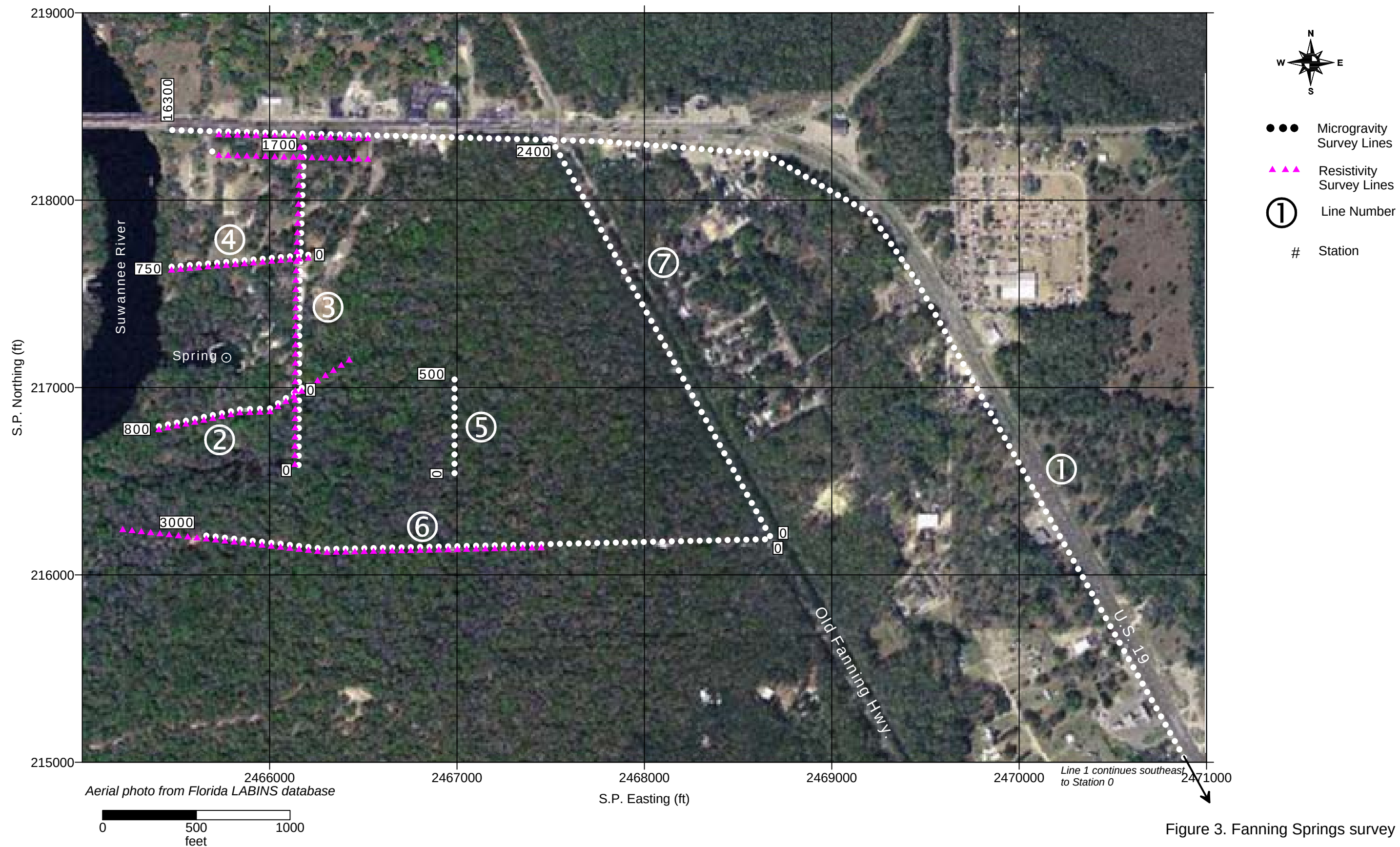


Figure 3. Fanning Springs survey lines

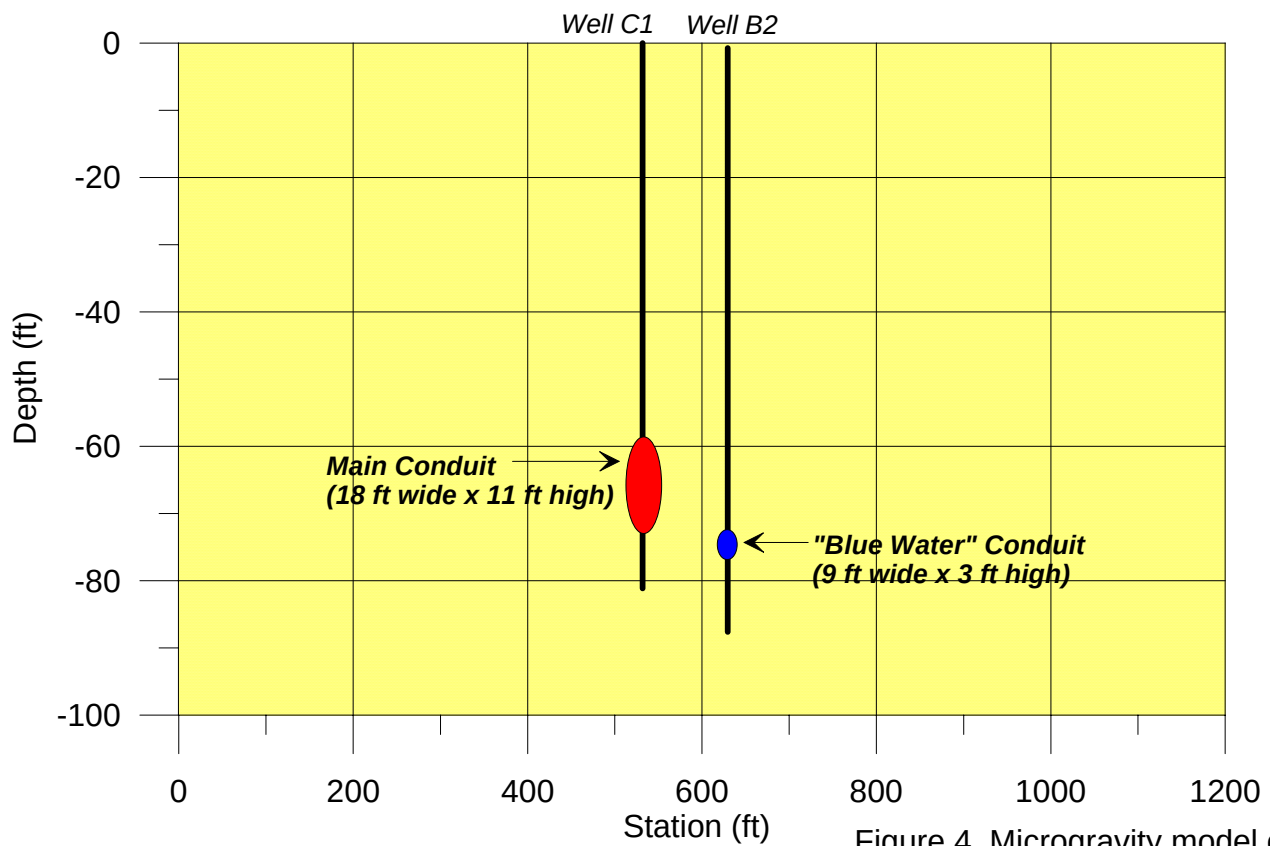
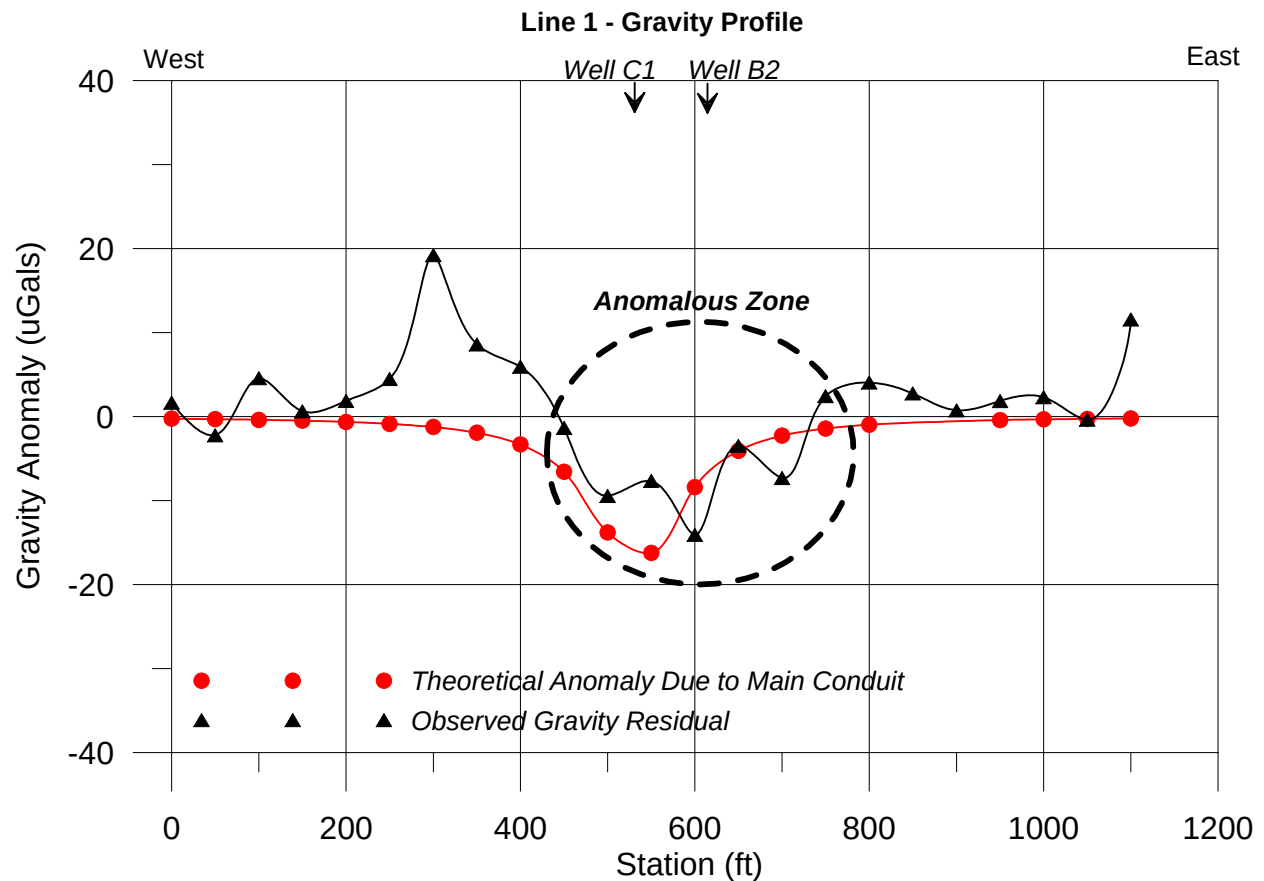
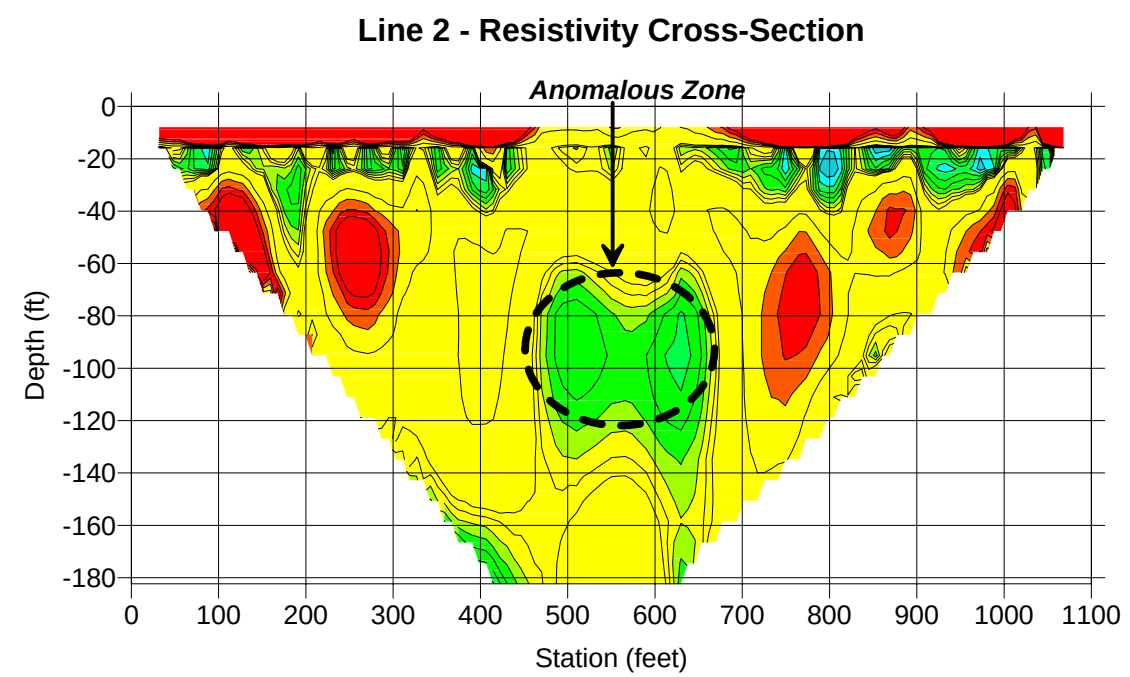
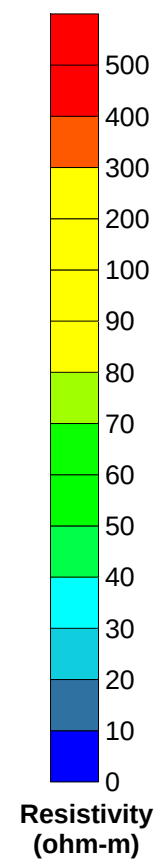
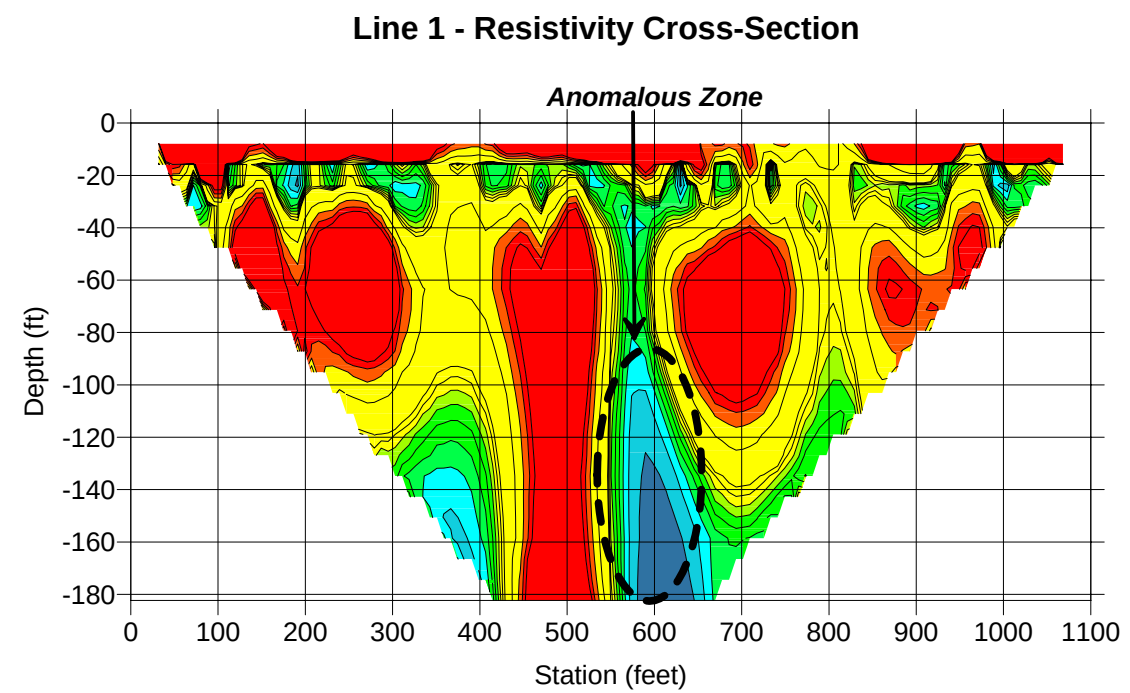
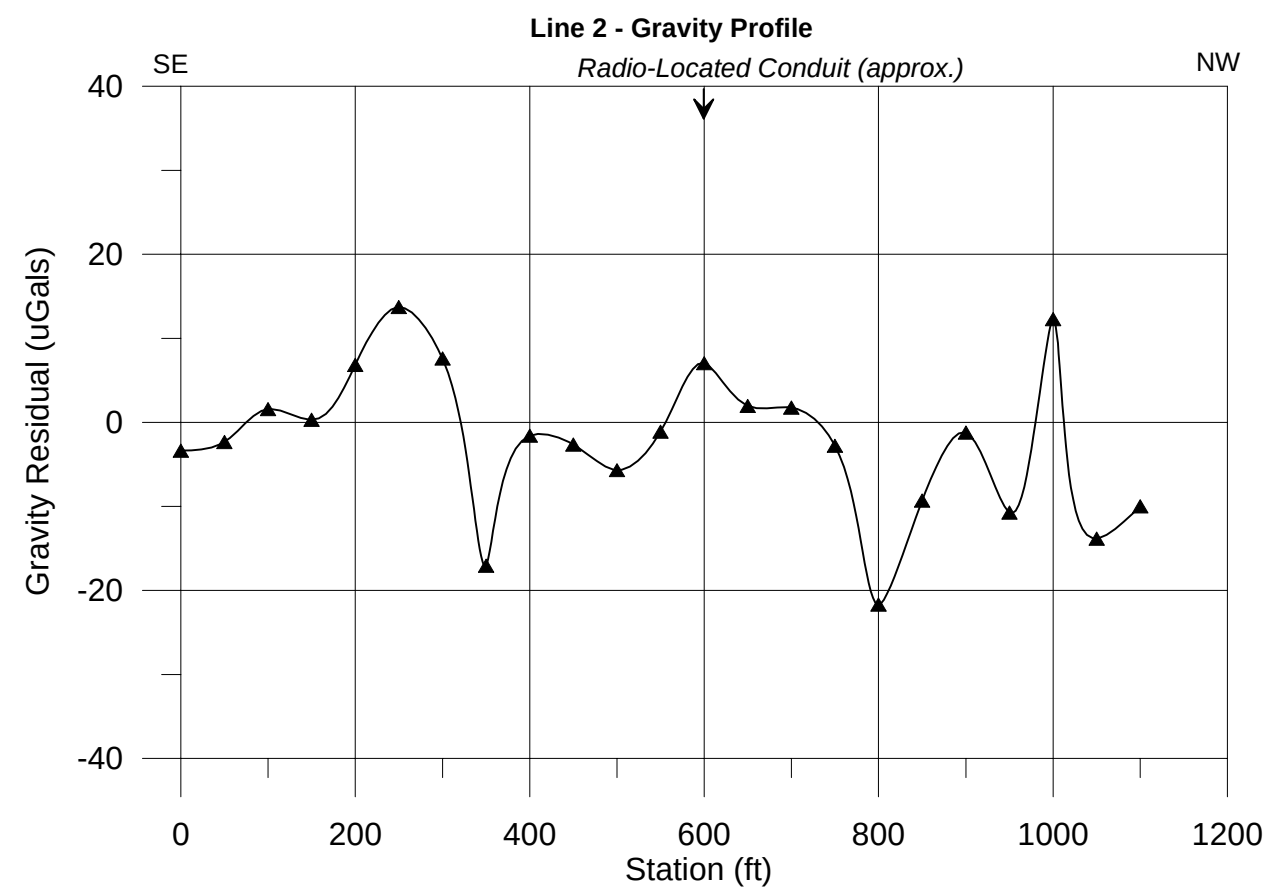
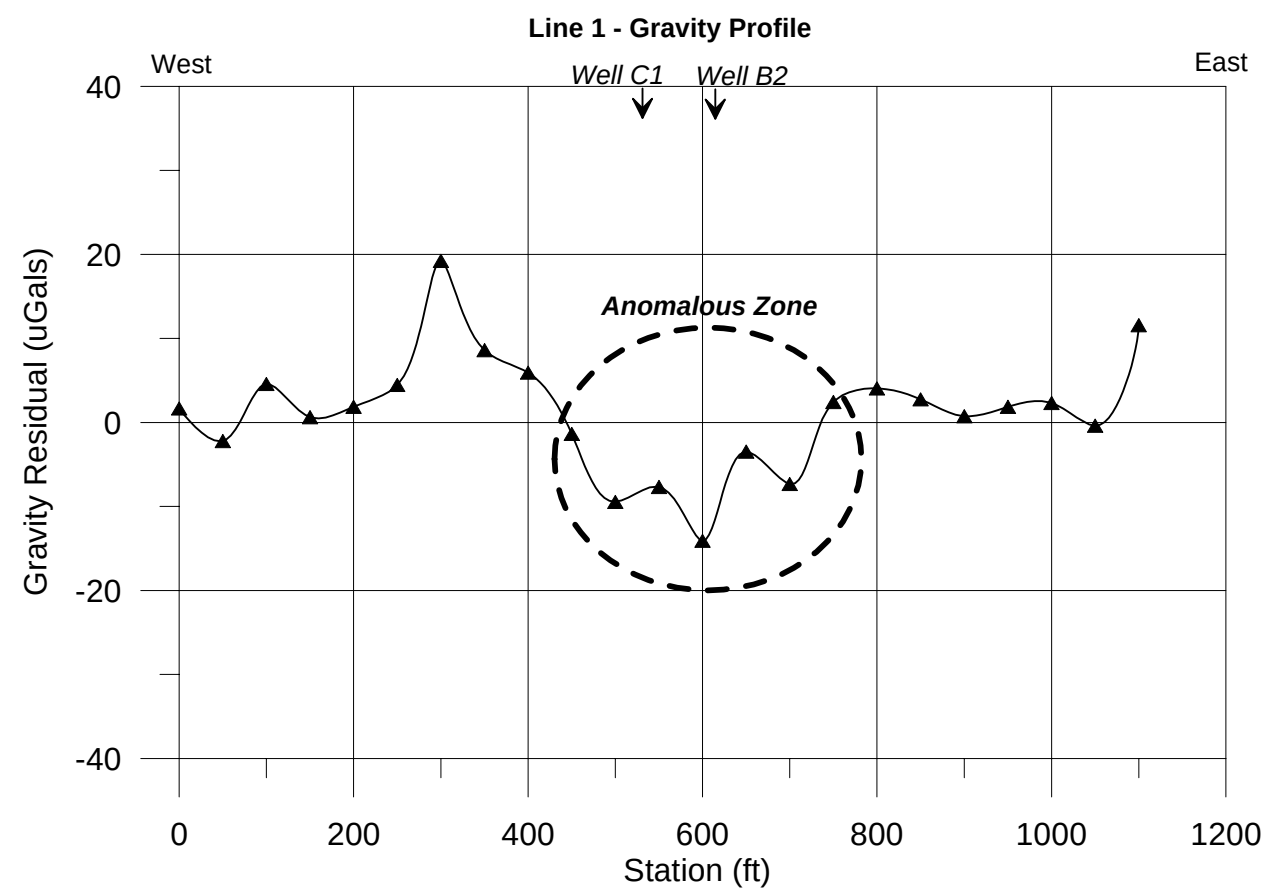


Figure 4. Microgravity model over known conduits



Note 3x vertical exaggeration

Figure 5. Manatee Springs geophysical data

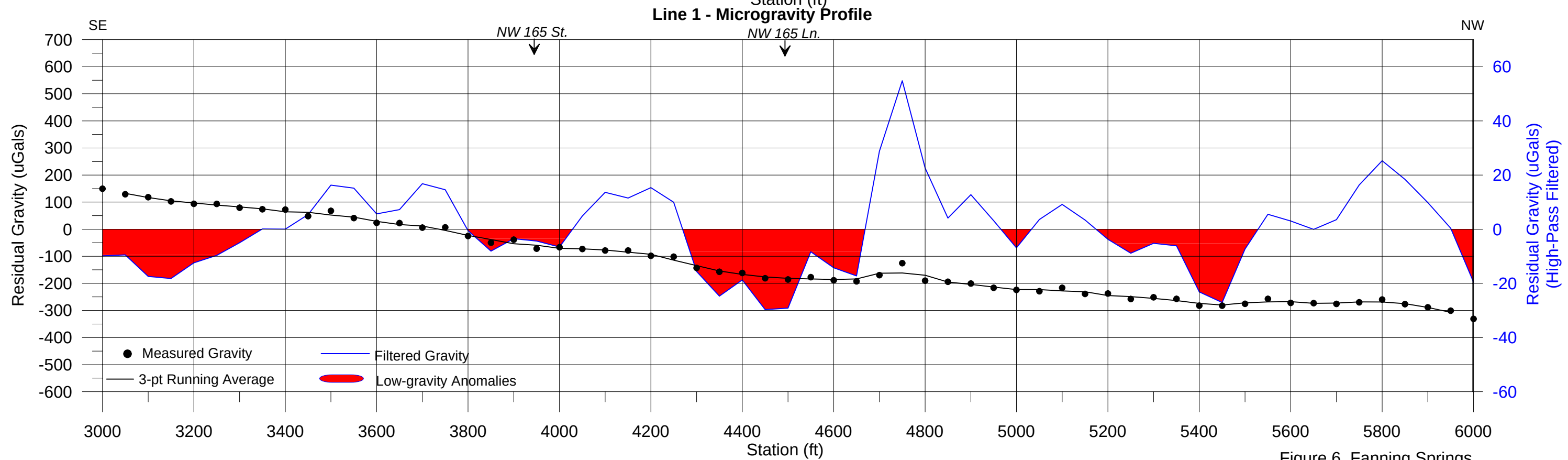
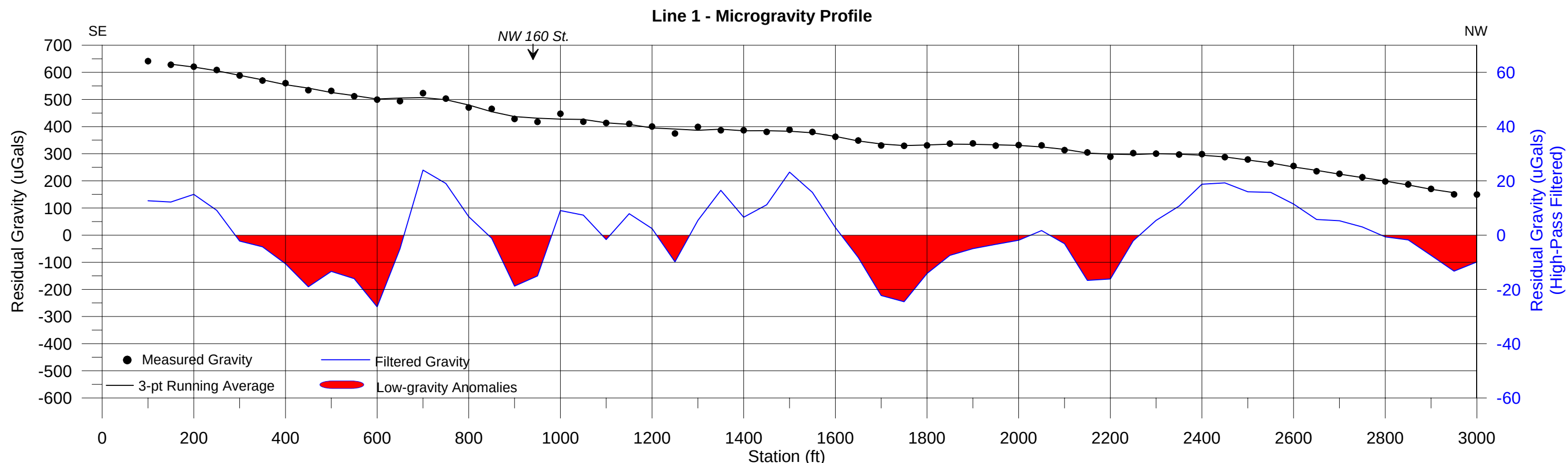


Figure 6. Fanning Springs
Line 1 microgravity profile

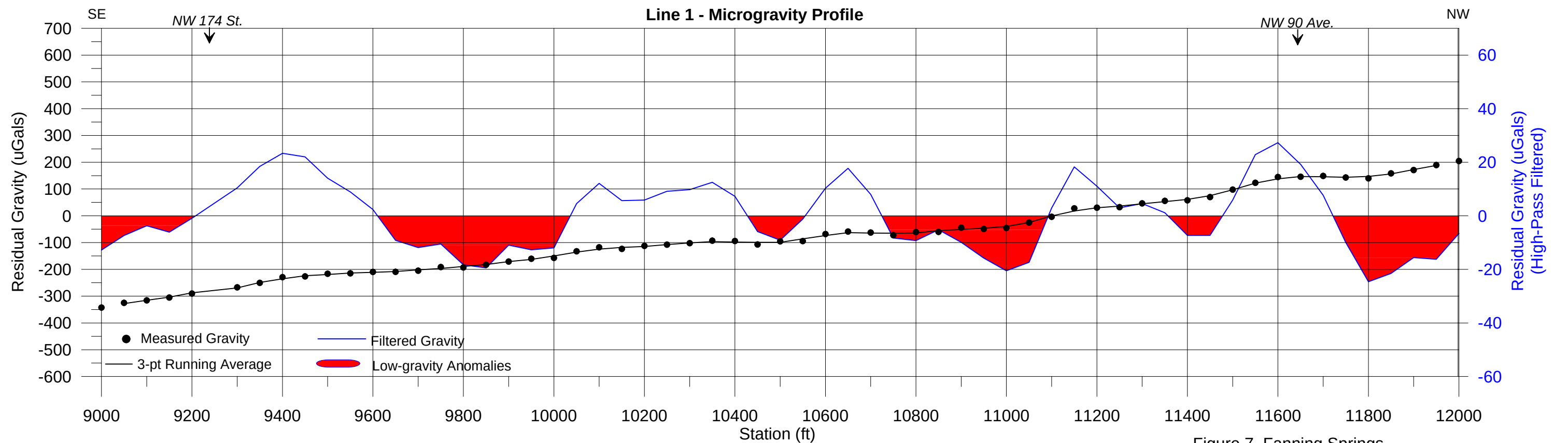
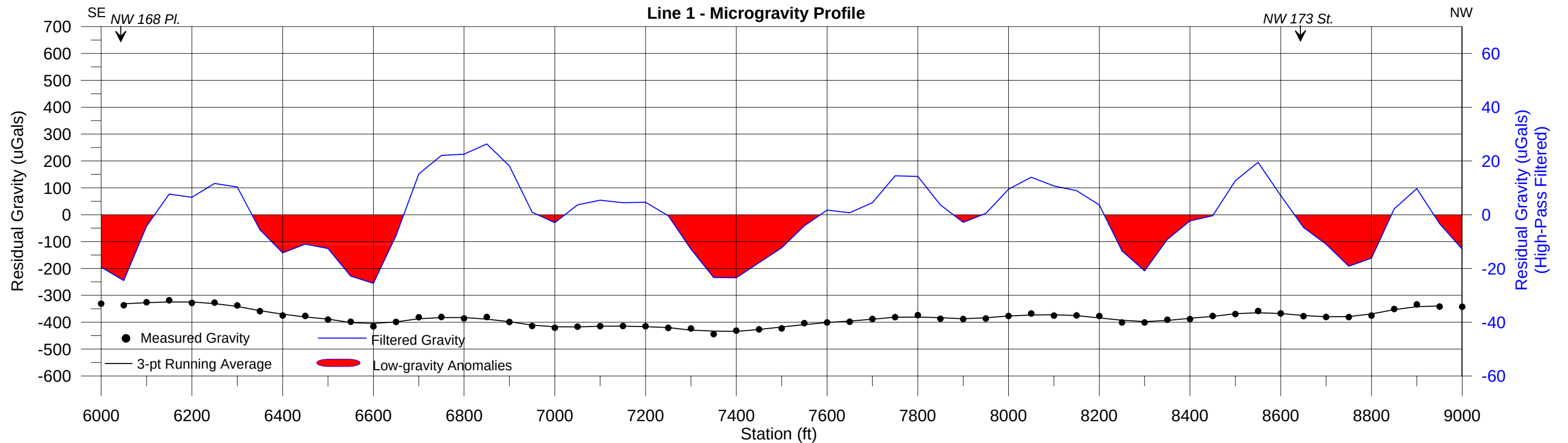


Figure 7. Fanning Springs
Line 1 microgravity profile (continued)

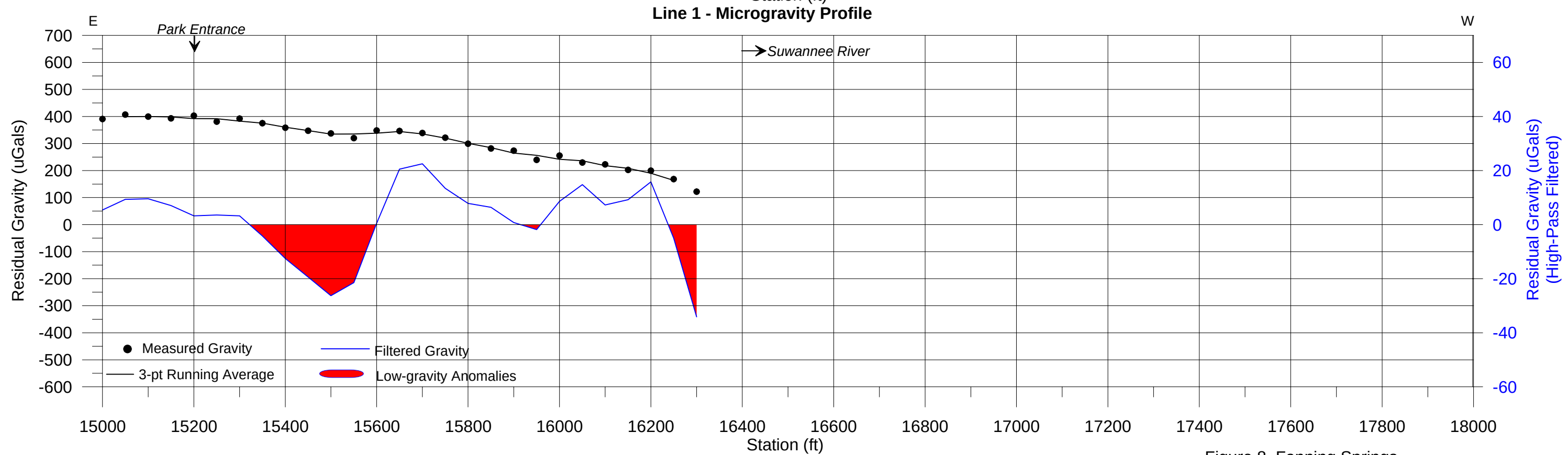
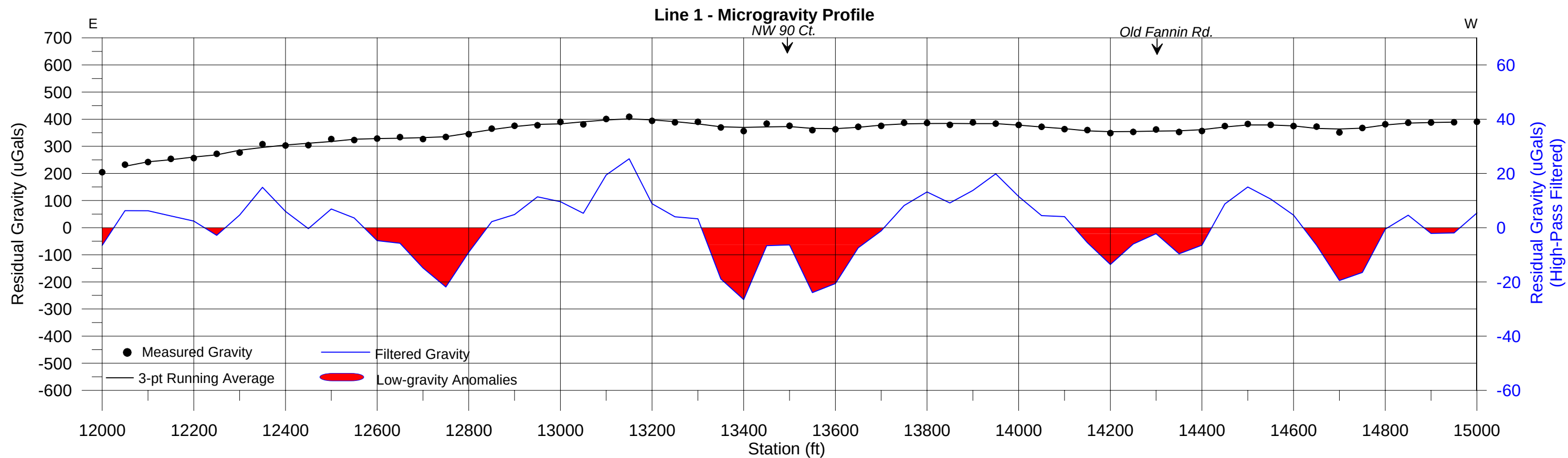
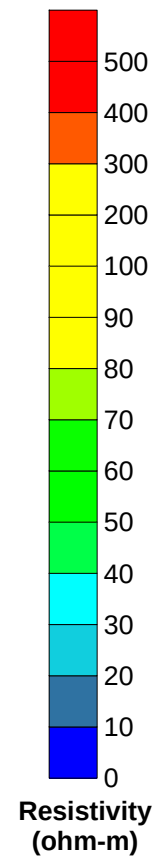
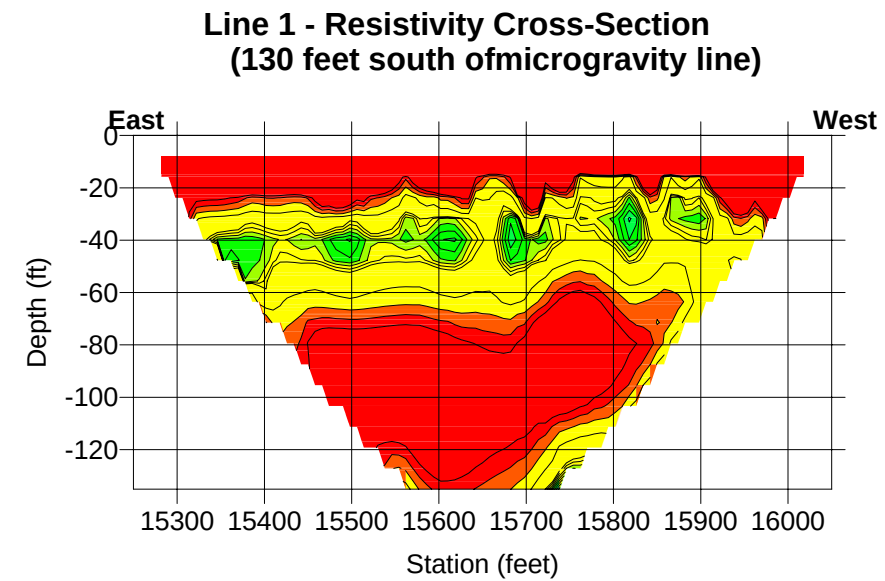
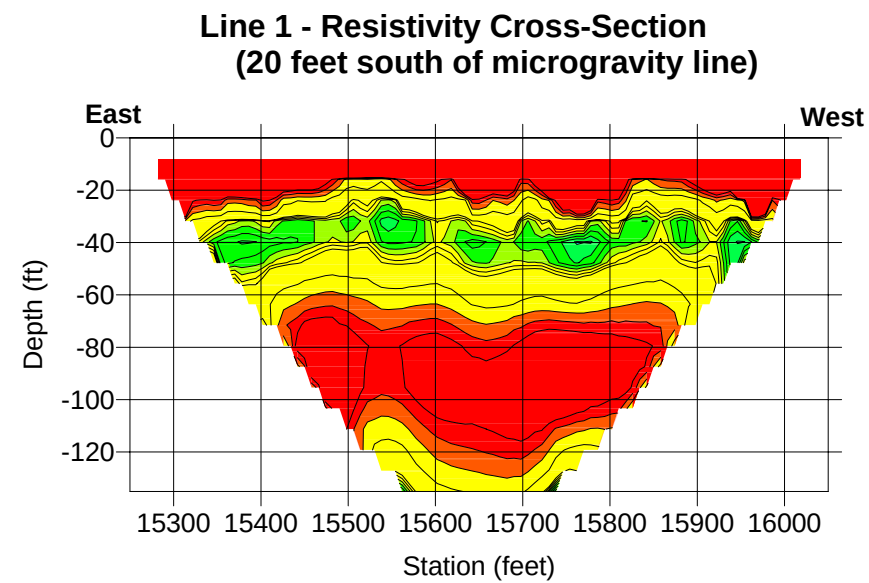
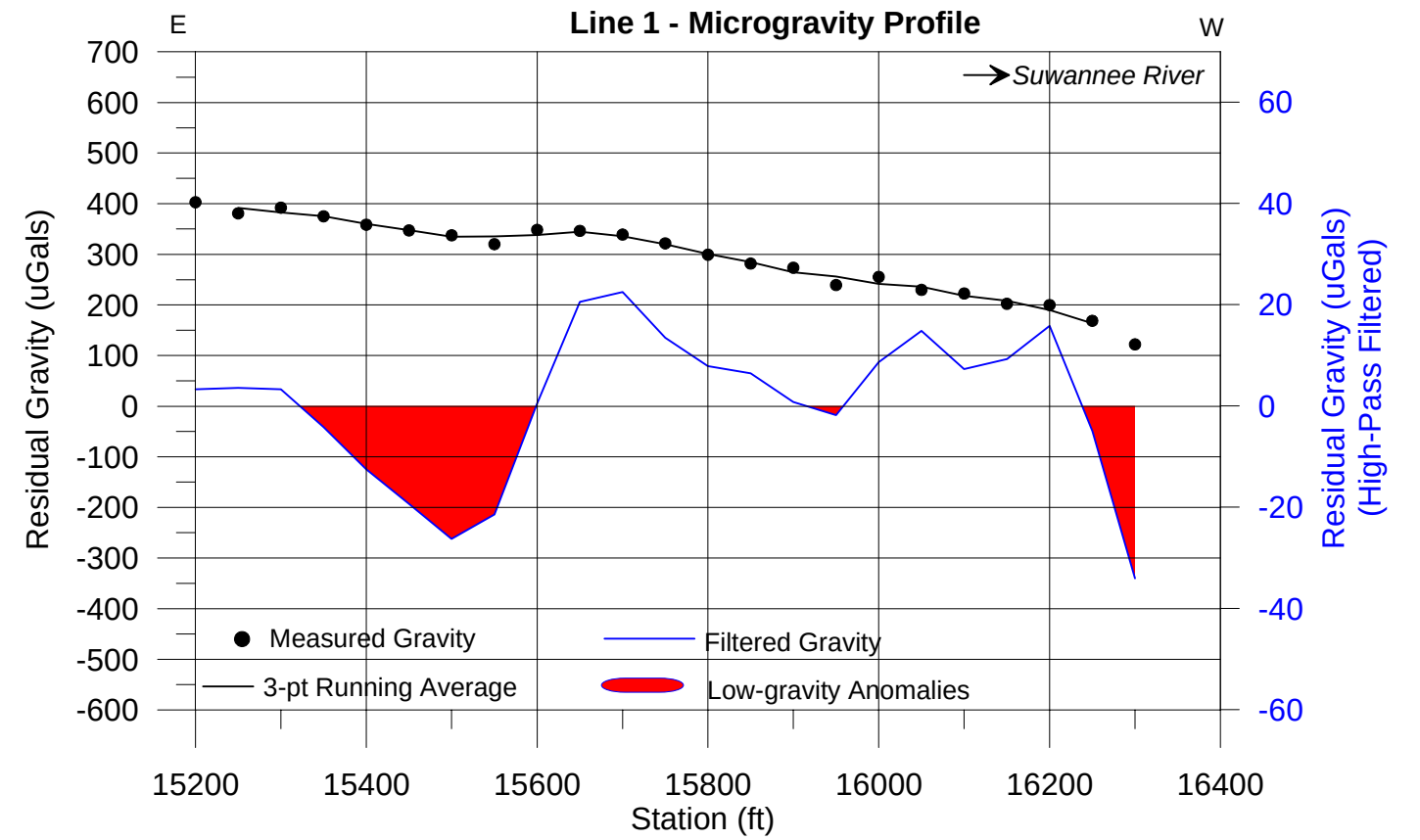
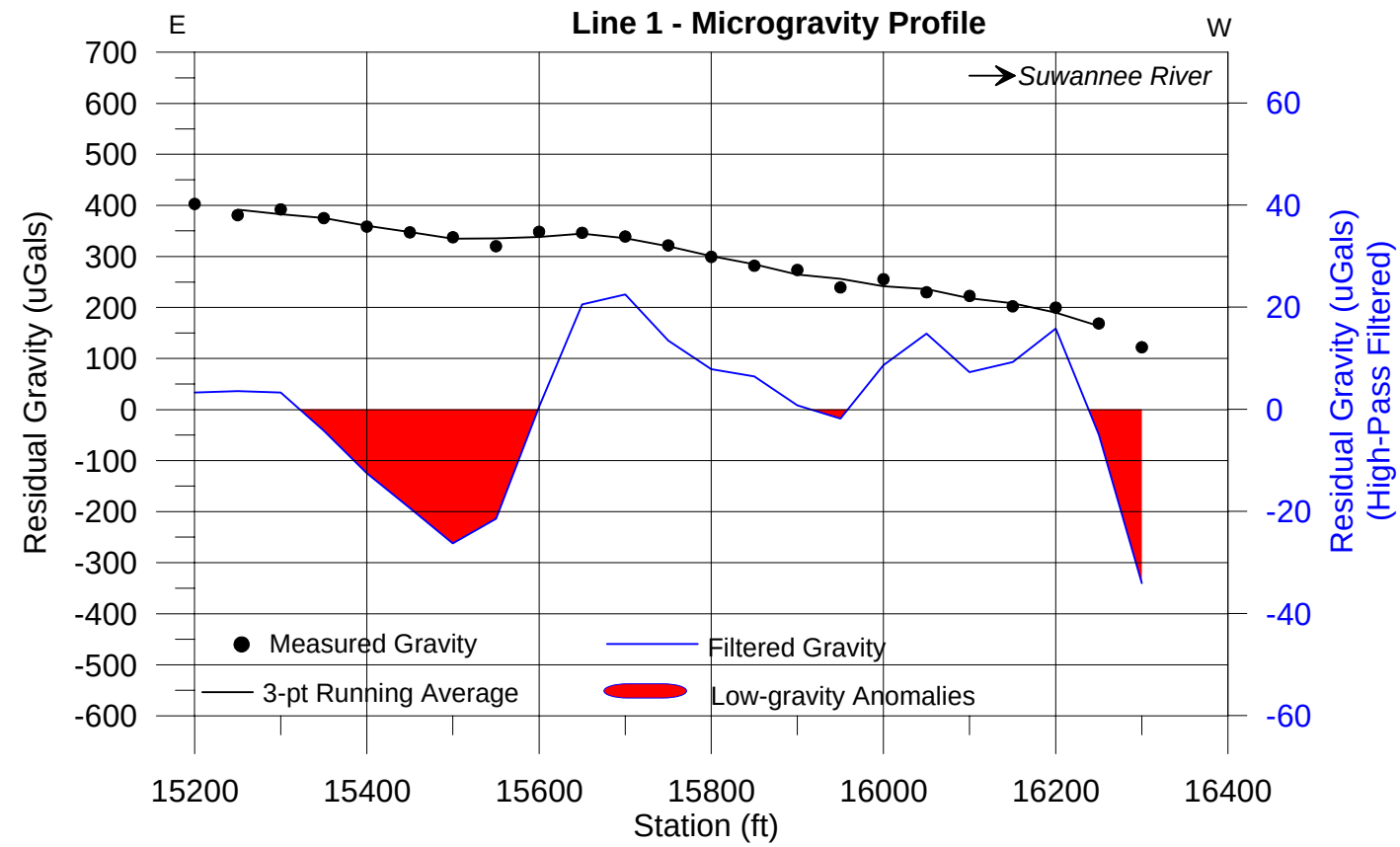
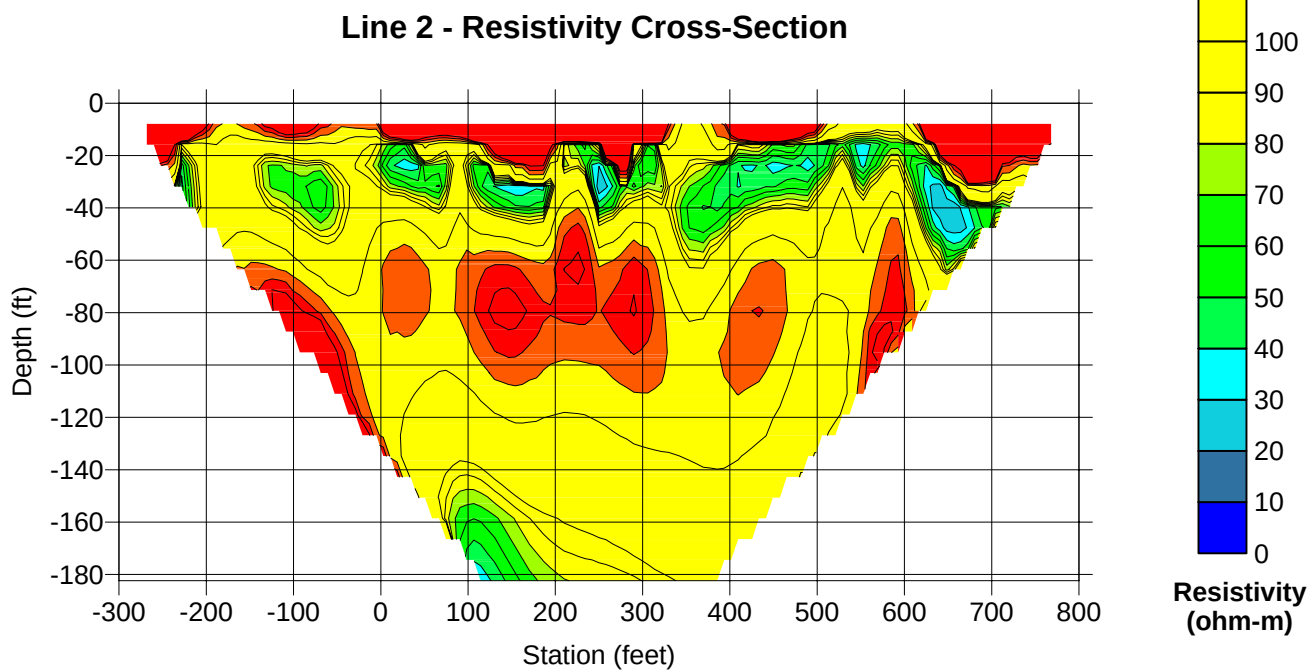
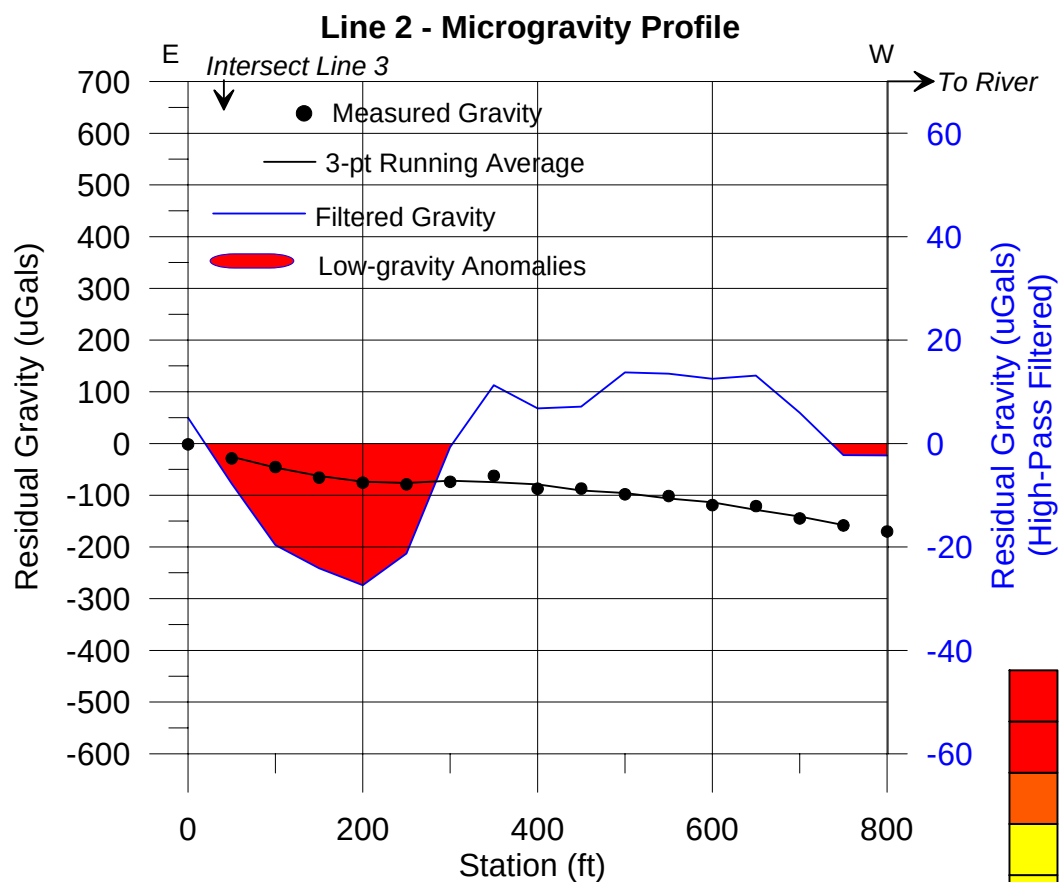


Figure 8. Fanning Springs
Line 1 microgravity profile (continued)



Note 3x vertical exaggeration

Figure 9. Fanning Springs Line 1
microgravity and resistivity data



Note 3x vertical exaggeration

Figure 10. Fanning Springs Line 2
microgravity and resistivity data

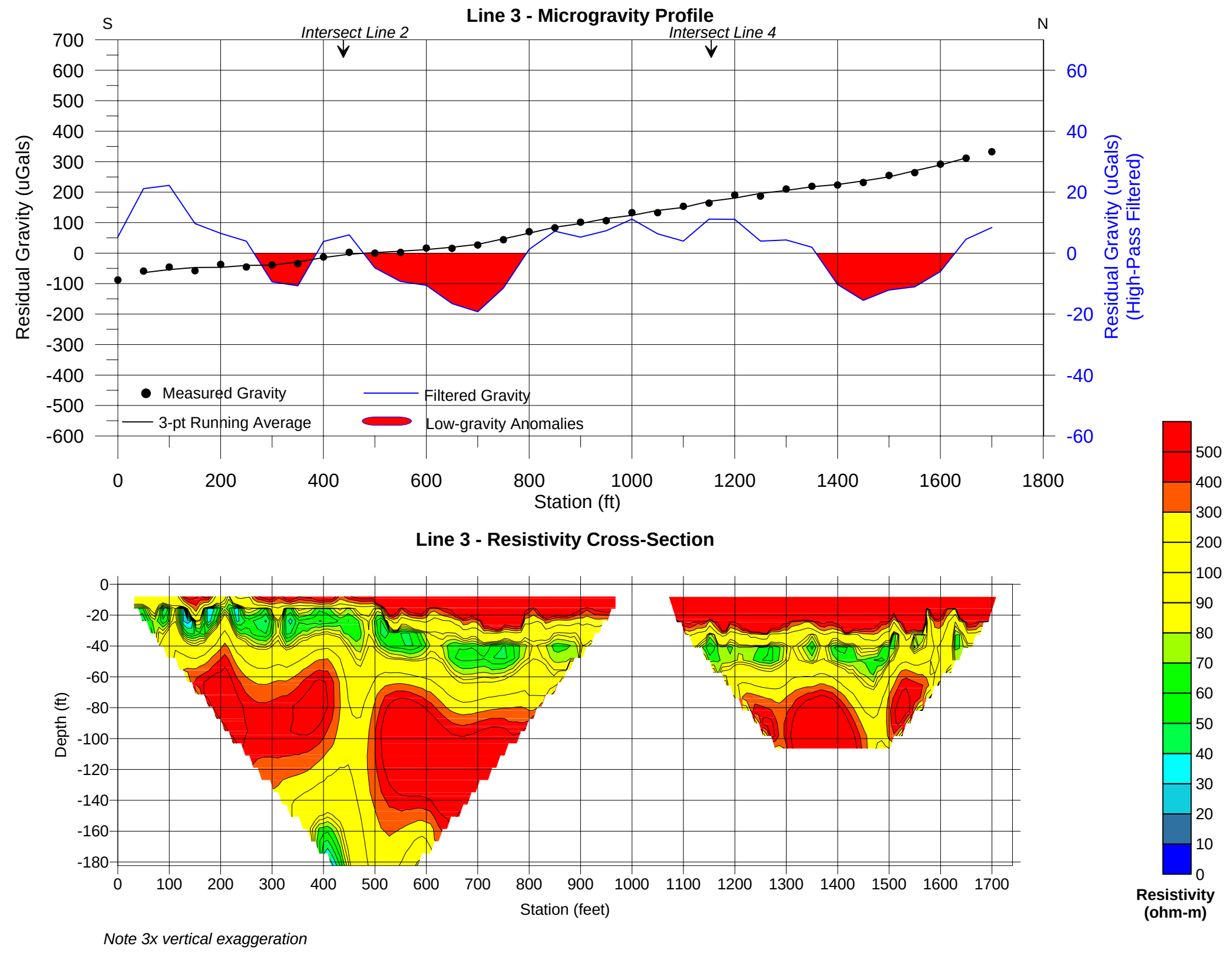
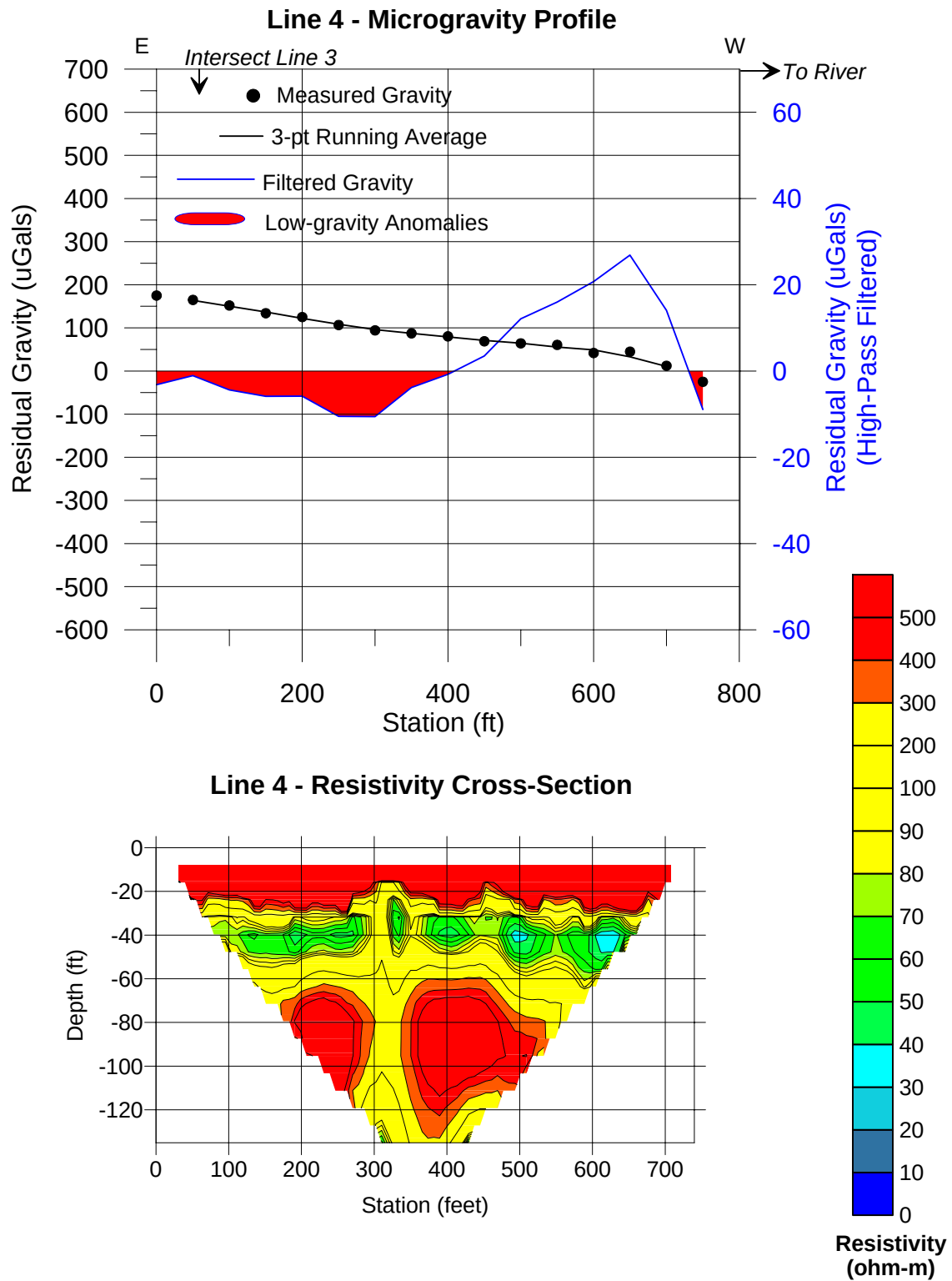


Figure 11. Fanning Springs Line 3
microgravity and resistivity data



Note 3x vertical exaggeration

Figure 12. Fanning Springs Line 4
microgravity and resistivity data

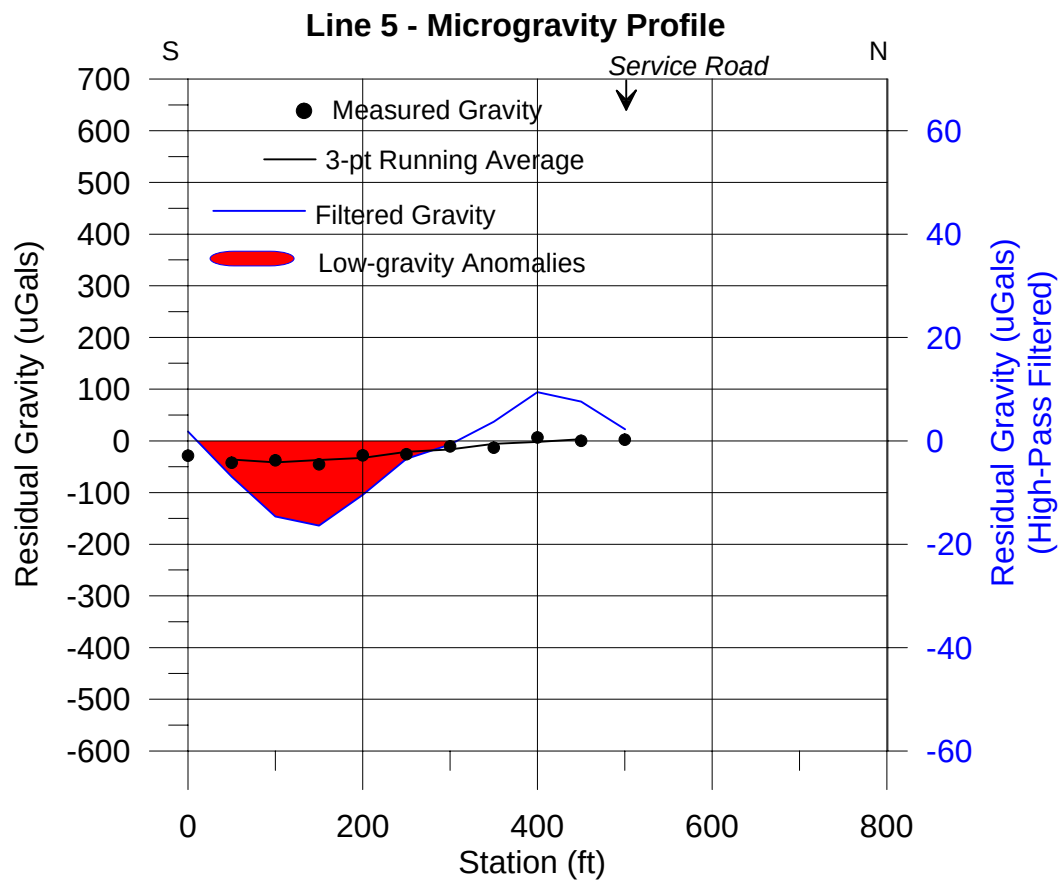


Figure 13. Fanning Springs
Line 5 microgravity profile

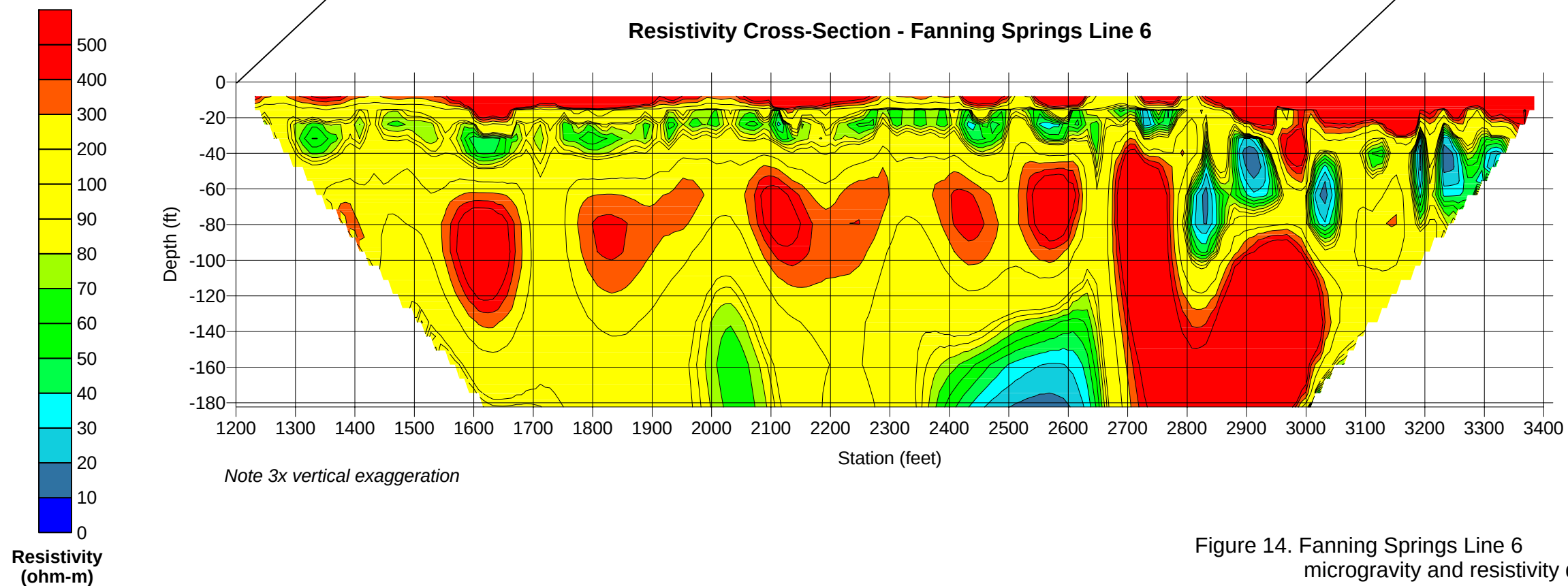
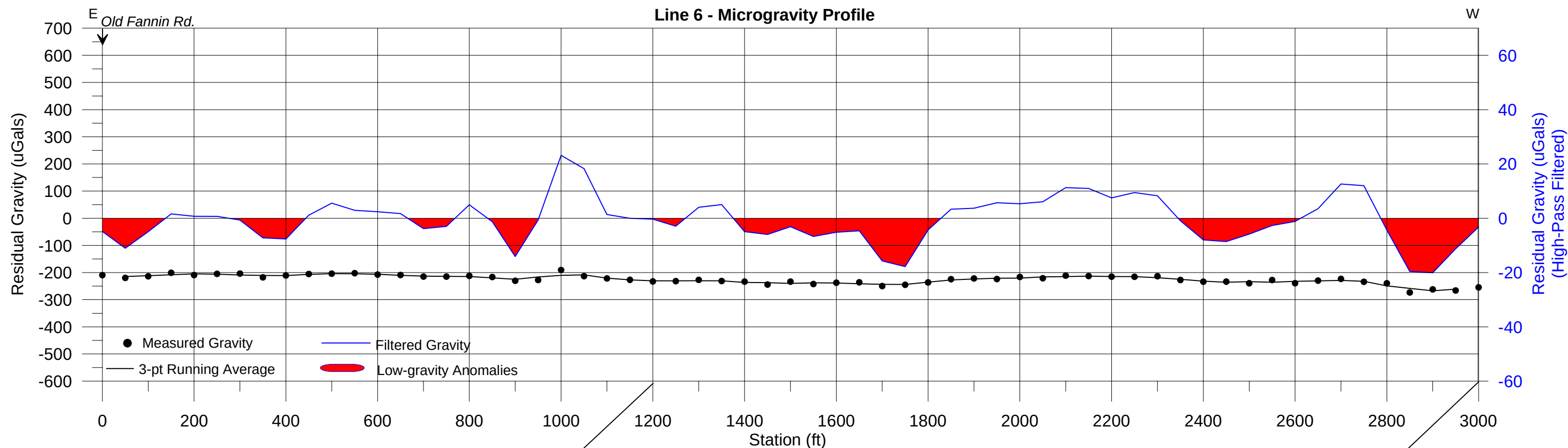


Figure 14. Fanning Springs Line 6
microgravity and resistivity data

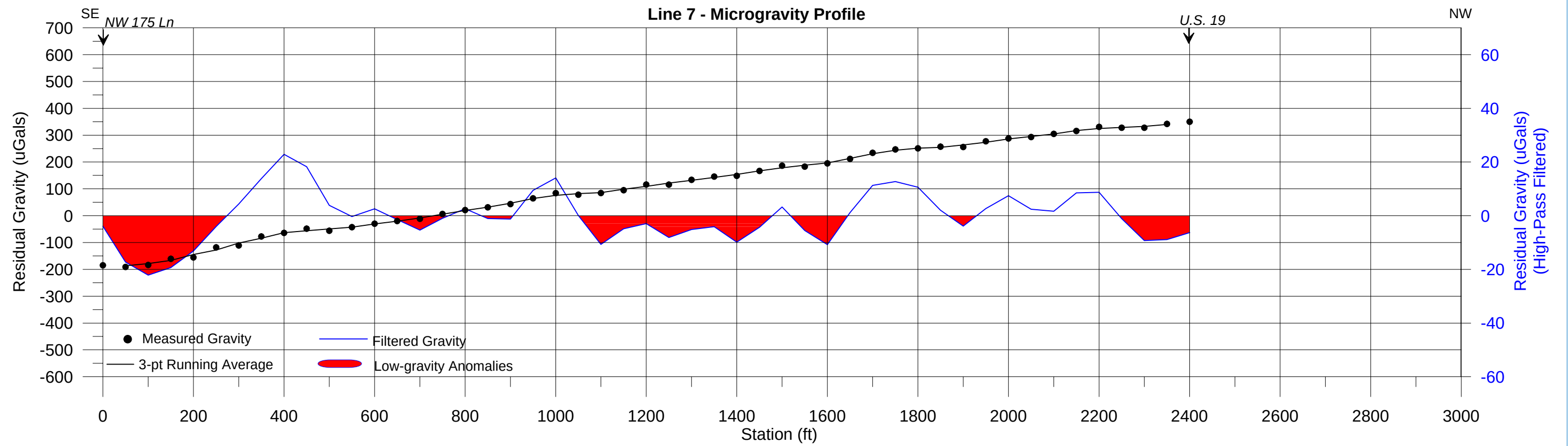
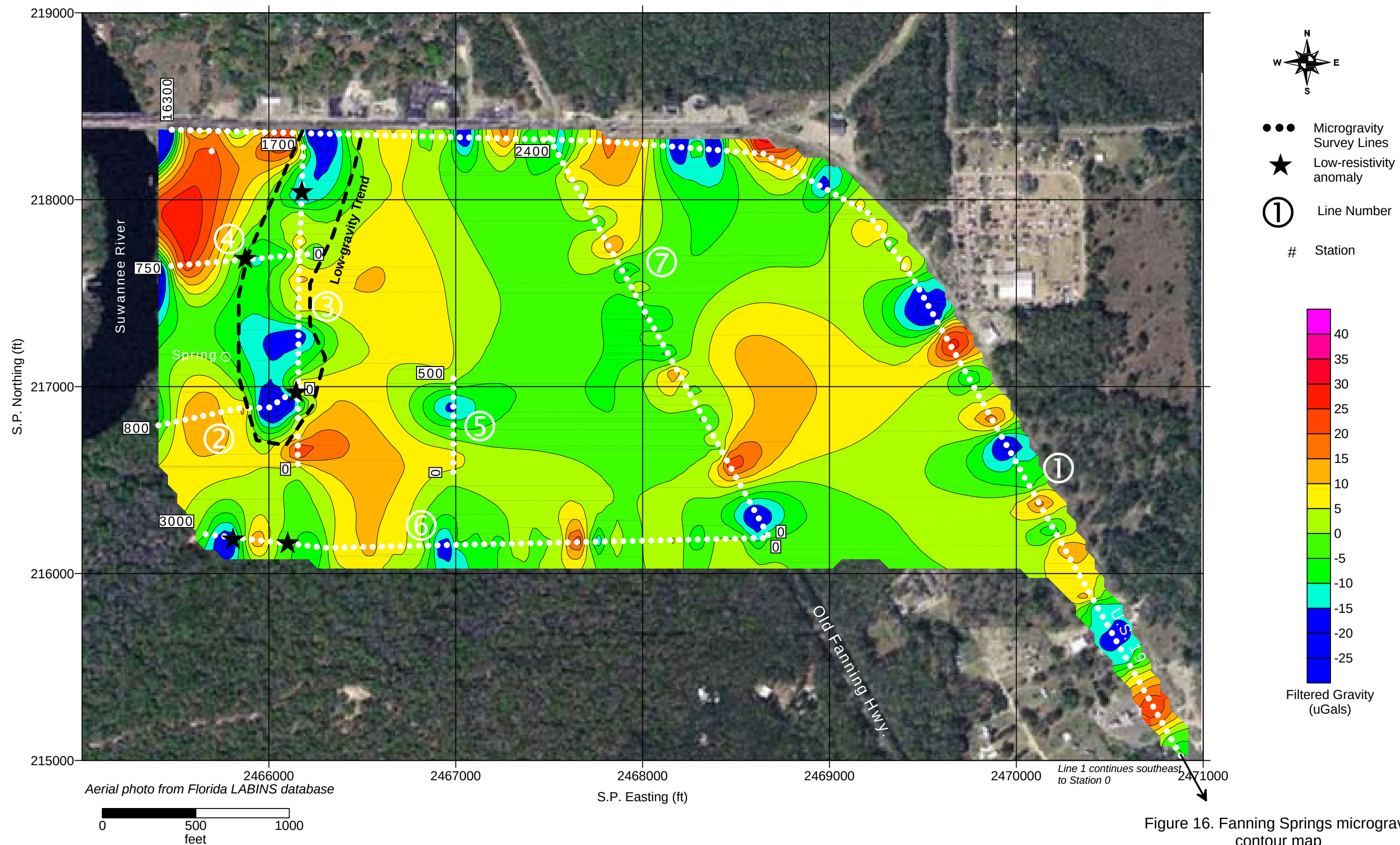


Figure 15. Fanning Springs
Line 7 microgravity profile



APPENDIX A
SURVEY STATION LOCATIONS

A total of 25,450 feet (4.82 miles) of survey lines were established at Fanning Springs and 2,200 feet were established at Manatee Springs. Survey lines were installed within the parks and along road shoulders using a survey distance wheel and marking paint. The survey lines include:

Fanning Springs

- Line 1 - 16,300 feet (3.09 miles) along the west shoulder of U.S. 19
- Line 2 – 800 feet within Fanning Springs Park
- Line 3 – 1,700 feet within Fanning Springs Park
- Line 4 – 750 feet within Fanning Springs Park
- Line 5 – 500 feet within Fanning Springs Park
- Line 6 – 3,000 feet along south side of NW 175th Lane
- Line 7 – 2,400 feet along east shoulder of Old Fanning Highway

Manatee Springs

- Line 1 – 1,100 feet centered at Well B-2
- Line 2 – 1,100 feet centered near borrow pit

The microgravity stations were marked at 50-foot intervals using a 60-penny nail and stake chaser. A Trimble Ag-132 differential global positioning system (DGPS) was used to obtain the geographic coordinates of the survey line ends and turning points with an accuracy within ± 3 feet. Geographic coordinates of stations between these control points were determined by linear interpolation. The geographic coordinates of all the microgravity stations are listed with the microgravity data in Appendix C. The coordinates are listed in Florida (North) State Plane (feet).

Relative elevations were obtained at each microgravity station using a Topcon DL-102 digital level. The elevations were recorded with a reading precision of 0.001 feet and a loop closure error within 0.1 feet per linear mile. The elevations are referenced to the NAVD-88 datum by referencing the elevations to a National Geodetic Survey benchmark in Fanning Springs and to a surveyed elevation of a monitoring well in Manatee Springs. Table A-1 lists the benchmarks used for each survey area.

Table A-1. Elevation Benchmarks

Benchmark	Survey Line(s)	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Comments
H-281	Fanning Springs	2469652.7	217212.9	28.71	NGS Benchmark
Concrete pad surrounding Well B-2	Manatee Springs	2456429.7	179709.7	15.08	Concrete pad

APPENDIX B

DESCRIPTION OF MICROGRAVITY METHOD

Introduction

A microgravity survey provides a measure of change in subsurface density. A microgravity survey consists of making sensitive gravity measurements at discrete points along a profile line or within a grid. After corrections for various factors are applied, the resulting values are known as the *Bouguer gravity*. Spatial changes in the Bouguer gravity data are referred to as gravity anomalies and are directly related to subsurface density changes (Telford, et al., 1976, Seigel, 1995). In this report, the terms *gravity* and *microgravity* are synonymous.

Gravity measurements respond to changes in the Earth's gravitational field caused by changes in the density of the subsurface geology and/or man-made structures. Gravity data can be obtained over very large areas to produce regional gravity maps, or over small areas to identify localized gravity anomalies. Gravity measurements are commonly made on land but can also be made at sea, from aircraft and from within boreholes.

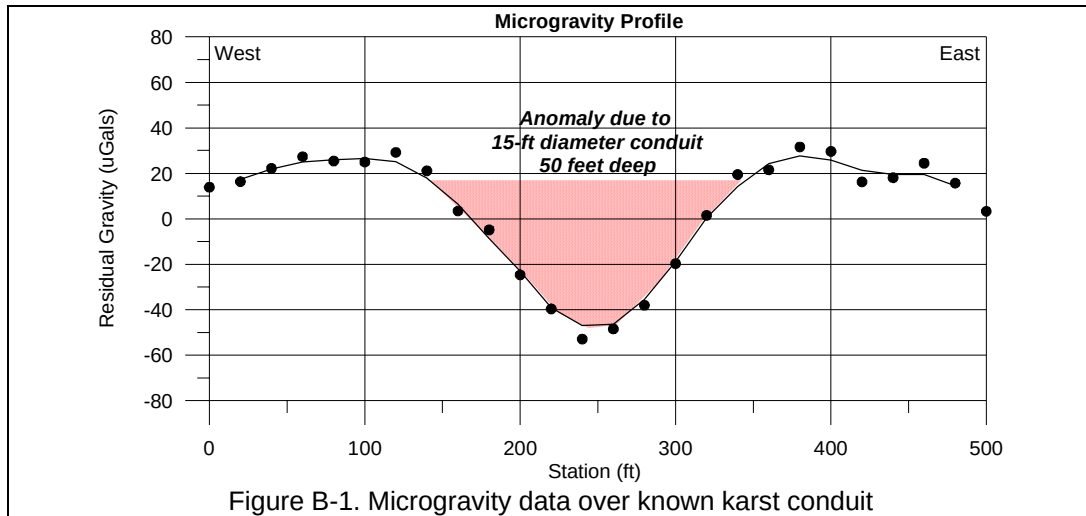
Applications

Gravity data obtained over very large areas are used to produce regional gravity maps to assess geologic structure, and to provide data for oil exploration, gas, minerals, and ground water resources.

Microgravity measurements over localized areas are used to determine geologic structure (e.g. identify and characterize large fracture zones, faults, cavities, and buried channels). The gravity method is particularly useful in locating and mapping steeply dipping formations and lateral changes in rock units. Microgravity measurements have also been applied to a wide range of problems including: assessment of landfill thickness, location of abandoned mines, location of larger buried tanks, and archeological investigations.

Detection and delineation of subsurface cavities is one of the most common applications of the microgravity method (Butler, 1984). Cavities may be solution cavities in limestones, dolomites, and evaporites; or man-made, such as tunnels or mines. They may be air-filled, water-filled, or filled in with some secondary geologic material. Microgravity comes closest of all the geophysical methods to allowing a positive statement regarding the presence or absence of subsurface cavities at a site (Butler, 1980).

Figure B-1 shows gravity data along a survey line over a known karst conduit. The gravity anomaly is the result of a water-filled conduit surrounded by limestone at a depth of approximately 50 feet.



Principles

Density (ρ) is the property measured by microgravity measurements. Density is a function of the type and distribution of minerals that make up the rock and of the type and amount of fluids found within the pore space.

Gravity anomalies occur where there is sufficient density contrast in materials and only as a result of horizontal variations in density. Vertical changes in density in horizontally layered materials will have no gravity anomaly associated with them. Gravity anomalies are proportional to the density contrast between different materials.

Gravity measurements are based upon Newton's Law of gravitation:

$$F_g = G \frac{M_1 M_2}{r^2}$$

where F_g is the force of gravity

G is the gravitational constant

M_1 and M_2 are the two masses involved and

r is the distance the two masses are separated.

From this, the acceleration of gravity g is:

$$g = G \frac{M}{r^2}$$

The unit of gravitational acceleration is the Gal after Galileo ($1 \text{ gal} = 10^{-2} \text{ m/s}^2$). The Earth's average gravity is approximately 980 Gals. The unit commonly used in regional gravity surveys is the milliGal (1/1000 Gals). Since the targets of interest for engineering or environmental surveys typically produce anomalies much smaller than one milliGal, gravity surveys for environmental and engineering applications require measurements with a resolution of a microGal (0.001 milliGals or one part per billion of

the Earth's gravity). Since measurements are made at the microGal level, the term "microgravity survey" is used to differentiate it from regional gravity surveys.

Microgravity measurements are normally made relative to a local reference station, and there is usually no attempt to tie the values to an absolute gravity station (Butler, 1980).

Shallow geologic structures will give rise to short wavelength (high spatial frequencies) anomalies. In contrast, the regional field will vary slowly in space (long wavelength) and can be approximated by a low order polynomial surface.

Depth

A gravity anomaly with a small lateral extent is inherently due to a shallow cause; however, an anomaly with a large lateral extent may be due to a local cause at great depth or a large lateral cause at shallow depth.

Maximum Depth of a Feature

For any well defined gravity anomaly, it is always possible to estimate the maximum depth of the feature producing the anomaly. An estimate for the maximum anomaly depth can be made by measuring the width of the anomaly at its inflection points (or half of its maximum height), dividing by 2 to get the half width and then multiplying by 1.3 (Butler, 1980). This maximum depth estimation assumes that the gravity anomaly is caused by a single isolated target. However, the same gravity response can be due to the combined effects of a variety of smaller causes at various depths (both shallower and deeper).

The maximum depth rules are based upon an assumption that the anomaly is caused by a simple single source (i.e. a spherical simple cavity or a horizontal tunnel). In practice, such sources are rare. However, these rules of thumb allow a maximum depth boundary to be calculated.

Maximum Depth of Detection

Gravity measurements are a measure of the vertical component of the Earth's gravitational acceleration. The gravitational acceleration is due to the mass of the entire Earth. In microgravity surveys, it is the lateral change in shallow, subsurface density that is of interest. These features are detected as localized anomalies within the background gravity values of the Earth.

As a rule of thumb, compact structures that can be approximated as spherical in shape, can be detected at a depth to center of about two times the effective diameter at the 10 microGal threshold level (Butler, 1980). In the real world, if the sphere (cavity) developed due to dissolution of rock it must have at least one input and one output tunnel. In addition, it is often associated with highly weathered fracture zones and bedding planes. Therefore, a low-density feature with a large lateral extent can be detected to depths of 5 to 10 times its thickness.

Detectability Threshold

The magnitude of a gravity anomaly is dependent on the depth, size and density contrast of a subsurface feature. In order to be detected in the gravity survey, a subsurface feature must be large enough or shallow enough to produce an anomaly above the noise threshold. Under normal field conditions, anomalies ≥ 10 microGals should be routinely detectable (Butler, 1984).

Equipment

Portable gravimeters measure relative differences in gravity from station to station. These gravimeters measure changes in gravity by balancing gravitational forces with a spring and mass system. A change in gravitational force results in a change of the length of the spring. The position of the mass is sensed and the amount of external force required to bring it back to a standard position is a measure of the gravity value.

Gravimeters used in regional geologic exploration have a sensitivity of 0.01 milliGals. A microgravimeter has a sensitivity of about 0.001 milliGals (Kaufmann and Doll, 1998). A modern gravimeter (Figure C-2) provides digital signal enhancement to increase the signal-to-noise ratio and allow much greater data acquisition rates than older meters.

All field gravimeters are subject to offsets (tares) due to shock and drift due to thermal effects. Therefore, great care must be taken in the transporting and the use of gravimeters.



Figure B-2. Scintrex CG-5 gravimeter

Quality Control

The gravimeter will be set-up and operated in accordance with the manufacturer's instructions and the Technos, Inc. SOP for Microgravity. Quality control procedures will

be followed to obtain a level of repeatability for the data and to ensure that the meter is operating correctly throughout the survey.

Gravimeter readings will drift with time due to mechanical and temperature changes within the instrument. To compensate for thermal changes, the instruments are temperature controlled. Bumping or jarring the instrument can cause a significant change (offset) in readings (referred to as a tare). This must be accounted for by repeat measurements during a gravity survey and incorporated into the data reduction process.

Resolution

Lateral resolution is limited by the spacing between measurements and by the geometry of subsurface targets. As the spacing between two targets becomes smaller, the ability to resolve the two targets diminishes since their anomalies merge into one. Very shallow targets produce short wavelength (narrow) anomalies. Deeper targets produce longer wavelength (wide) anomalies.

Accuracy and Precision

Under optimum conditions with simple targets (e.g. a buried channel with a large density contrast), depth estimates made by a skilled interpreter should be within 10 to 20 percent of the actual depths.

Instrument drift, instrument type and measurement skill of the operator are the major factors affecting precision. If a gravity measurement is repeated under identical, stationary conditions, the measurements should be consistent and have an average deviation of less than ± 0.005 milliGals. The average deviation of measurements acquired at stations at different times should be less than ± 0.010 milliGals under normal field conditions (Butler, 1984; Kaufmann and Doll, 1998). Site specific vibrations (e.g. vehicles, construction equipment, wind, or distant earthquakes) may produce average deviations above this level.

Calibration

Calibration may be done by placing the gravimeter on a tilt table and measuring the change in gravity, as the table is tilted out of the horizontal by known angular amounts. More accurate calibration is achieved by the use of a calibration range, usually consisting of five or more stations, fairly evenly spaced, over a gravity range of at least 100 mGals. Seigel (1995) provides a discussion of the calibration procedures.

Ease of Use

Typically, only one person is needed to make gravity measurements. A second crew (of two) can install the gravity stations ahead of the operator and obtain the elevations.

While gravity measurements are, in principle, relatively easy to make, the gravimeter is a very delicate instrument. Considerable care must be taken in shipment and general field use to avoid shock to the instrument. In addition, proper field procedures must be rigorously followed to produce high sensitivity data with minimum noise.

Data

Gravity data are typically presented as profile lines or contour maps. Prior to presenting the data, however, a number of necessary corrections are needed to reduce the data to Bouguer values. Reduction of gravity data consists of correcting the field measurements for all known effects. These corrections include:

- Instrument drift – Temporal changes in the meter readings are corrected by the reoccupations of base stations.
- Station latitude - at a latitude of 45 degrees, the gravity values will change at about 0.248 microGals per foot north and south of the station.
- Free air elevation correction - an increase of 1 foot in elevation results in a decrease of 94.06 microGals. This correction factor is added to the data.
- Bouguer Slab Correction – In order to account for mass differences below stations at different elevations, a Bouguer slab correction is applied. A factor of $12.77(\rho)$ microGals per foot of elevation is subtracted from the data (ρ is the mean density of near-surface rocks in g/cc).
- Tidal effects - the gravitational attraction of the Sun and the Moon will cause significant changes in the measured gravity values of as much as 300 microGals.
- Topography - terrain corrections compensate for variations in the terrain (hills and valleys) surrounding the point of measurement. Terrain corrections are negligible in flat terrain, and can become more than 1000 microGals in mountainous areas. Local microgravity surveys can be affected by smaller terrain effects, such as rolling hills, ditches, ravines, rivers, and large cultural features.

These corrections are applied to the data using standard formulas (Seigel, 1995, Telford et al., 1976) for calculating the Bouguer gravity. After these corrections are applied to the gravity data the result is known as the Bouguer gravity data. The Bouguer data consist of the regional Bouguer Anomaly, which is made up of deep-seated effects, and the local Bouguer Anomaly, which is made up of the shallow effects. It is possible, in principle, to "subtract out" the contribution of the whole earth (the regional field) leaving just the field due to the local conditions (the residual or anomaly field).

The local Bouguer Anomaly data are interpreted by creating geologically consistent density models that match observed field data, or by correlating the microgravity data with information from borings and complimentary geophysical measurements. While the gravity technique measures or reflects the changes in density in earth materials, it is the interpreter who, based on knowledge of the local conditions or other data, must interpret the data. Interpretation can simply be the location of a gravity anomaly or can require extensive modeling to support interpretation and calculations of mass deficit.

Two properties of an anomalous structure can be readily deduced: the location of the structure in plan view, and an estimate of the mass excess or deficiency. Both of these properties are of considerable importance in geotechnical and environmental applications of microgravity. Frequently, the location of an anomaly in plan view is all

that is really required, since drilling will usually be performed to verify an anomalous subsurface condition or structure.

Advantages

A major benefit of gravity measurements is that they can be made in culturally developed areas, where many geophysical methods would be limited or could not be used at all. For example, gravity measurements are not limited by geologic conditions (unlike radar in clay soils); or by electromagnetic measurements, which are affected by the presence of nearby metallic structures (e.g. utilities, fences, buildings and vehicles). Microgravity can be acquired over almost all land surfaces including paved and unpaved portions of an area.

The microgravity method comes closest of available geophysical methods for allowing a positive statement to be made regarding the presence or absence of subsurface cavities at a site (Butler, 1984). Gravity measurements do not have fixed depth of measurement.

Limitations

Density Contrast

Gravity measurements do not respond to features without significant change in density or smaller features, such as utilities.

Depth of Measurements

Although the depth of measurement for gravity is unlimited, longer survey lines are needed to identify deep features.

Vibration

Vibration is the major limitation in making gravity measurements. There will always be some level of noise (i.e. ground motion) at each gravity station caused by a combination of natural and man-made sources.

Ambient Sources of Noise

Local, small earthquakes seldom are a problem during gravity observations. They occur and are gone before they are of any inconvenience. Large, distant earthquakes can delay observations for several hours.

When long-period ocean waves strike the coast and reflect seaward, the resulting standing waves can initiate seismic waves in the earth's crust. Rayleigh waves generated from ocean waves can travel halfway across a continent.

Wind gusts can be particularly troublesome by tipping the meter out of plumb, and rocking the meter back and forth. A moderate to heavy rainfall may impact gravity measurements as large rain drops hit the gravity meter or very nearby.

Since gravimeters are extremely temperature sensitive, abrupt and wide swings in temperature can affect readings. Even though the instrument is temperature stabilized, it should be further protected from extreme changes in temperature that may be caused by sun light.

Changes in atmospheric pressure result in changes in the density of the air column above the gravity station. When a major pressure front (e.g. a thunderstorm) moves rapidly through the survey area, pressure changes may result (Seigel, 1995). An increase in atmospheric pressure will cause a decrease in the observed gravity and vice-versa.

Geologic Sources of Noise

Geologic sources of noise include unsuspected spatial variations in soil and rock densities (usually associated with variations in depth to rock). Nearby hills, mountains, and valleys will impact gravity measurements. These changes in topography out of the survey area often need to be accommodated for by terrain corrections. On-site changes in topography (such as creeks or ditches) near the gravity station, can also impact gravity readings.

Cultural Sources of Noise

Cultural sources of noise include temporal vibrations and the impact of unknown spatial variations of buried structures. Vibration of the ground can be caused by nearby vehicles, heavy equipment, trains, aircraft, and even personnel walking near the gravity meter. While blasting in quarries and construction sites will affect gravity measurements, the effects die away quickly and measurements can resume.

Cultural factors such as unknown buried structures (large concrete foundations, and culverts) under or near the survey line may also cause spatially variable noise leading to unsuspected variations in density.

Many of these sources of vibration noise can be dealt with by averaging measurements or minimizing the noise by making measurements in off hours when traffic and other noises are minimal. The authors have made gravity measurements at the edge of major highways within a few feet from vehicle traffic by working evenings, making measurements when vehicles were not immediately adjacent to the gravimeter, making many repeat measurements, and using extreme patience and care in making the measurements.

Personnel

The success of any microgravity survey is dependent upon many factors. One of the most important is the competency of the person(s) responsible for planning, carrying out the survey and interpreting the data. An understanding of the theory, field procedures and methods for interpretation of data along with an understanding of the site geology is necessary to successfully complete a microgravity survey. Personnel not having

specialized training and/or experience should be cautious about using the microgravity method and solicit assistance from qualified practitioners.

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SUMMARY OF MICROGRAVITY DATA

Microgravity data were acquired at a total of 517 stations at Fanning Springs and 47 stations at Manatee Springs, spaced at 50-foot intervals. A high-precision Scintrex CG-5 gravimeter, owned by Technos, Inc., was used to make the measurements.

Station Coordinates

The station coordinates are referenced to distance in feet along each survey line. The geographic locations of these stations were used in the data processing and are listed in Tables B-2 and B-3. The geographic coordinates are in Florida (north) State Plane (feet).

Elevations

Relative elevations were obtained at each gravity station using a Topcon DL-102 digital level. The elevations were recorded with a reading precision of 0.001 feet and a loop closure error within 0.1 feet per linear mile. The elevations of the stations are listed in Tables B-2 and B-3.

Base Stations

One gravity base station was used for the Fanning Springs survey and one gravity base station was used for the Manatee Springs survey (Table B-1). Data were acquired at a base station at the start of each survey day, at the end of each survey day, and at least one time in the middle of each survey day. At least two consistent measurements were acquired at each base station occupation for quality control.

Table B-1. Gravity Base Stations

Base Station	Gravity (mGals)	Easting (feet)	Northing (feet)	Elevation (feet)	Bouguer Gravity (mGals)	Comments
F1 - Fanning	979282.100	2465694.1	218259.9	27.557	1.629	On concrete pad surrounding picnic table
M1 - Manatee	980000.000 (assigned)	2456429.7	179709.7	15.08	726.851	At concrete pad surrounding Well B-2

Quality Control

Repeated measurements were made at a total of 61 stations (12%) at Fanning Springs and 13 stations (28%) at Manatee Springs at different times during the survey. The average deviation of these repeated measurements is ± 4 μ Gals at Fanning Springs and ± 2 μ Gals at Manatee Springs, indicating a relatively low level of noise, which is essential for this application of the microgravity method. After each day of data acquisition, the data were downloaded and backed up, and a preliminary review of the data was performed.

Data Reduction

Tables B-2 and B-3 contain a complete listing of the gravity data at Fanning Springs and Manatee Springs, respectively. The gravity data were reduced to simple Bouguer values along each profile line using standard reduction procedures. The following corrections were applied:

- Instrument drift (from base station occupations)
- Tidal correction
- Latitude correction
- Free Air correction (elevations measured with a reading precision of 0.001 feet and a loop closure accuracy within 0.1 feet per linear mile)
- Bouguer Slab correction (slab density = 2.0 g/cc)
- Regional removal (linear for each study area)

A Bouguer slab density of 2.0 g/cc was used to approximate the density of near surface material. A linear trend was removed from the data and the resulting values are defined as the *residual gravity*. The residual gravity calculation is shown below (where X and Y are the station coordinates in S.P. Easting and Northing). The residual gravity values have a median value of 0 μ Gals and range between -444 μ Gals and 648 μ Gals at Fanning Springs and between -22 μ Gals and 19 μ Gals at Manatee Springs.

$$[\text{Fanning Residual Gravity}] = [\text{Bouguer Gravity}] + [399.614] - [0.00019038 * X] + [0.000313190 * Y]$$

$$[\text{Manatee Residual Gravity}] = [\text{Bouguer Gravity}] - [50.768] - [0.000300663 * X] + [0.000347623 * Y]$$

In order to identify localized anomalies within the relatively broad range of residual gravity values at Fanning Springs, a high-pass spatial filter was applied to each survey line independently. The high-pass filter removed trends in the residual gravity data with spatial wavelengths longer than 1,500 feet. The filtered data are presented with a zero-mean value for each survey line.

Table B-2. Fanning Springs Microgravity Data

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
	BaseF1	2465694.12	218259.89	27.557	1.629	195	
1	0	2475330.07	207036.53	36.206	7.431	648	5
1	50	2475305.65	207080.47	35.672	7.400	635	10
1	100	2475281.22	207124.41	35.478	7.388	641	13
1	150	2475256.80	207168.36	35.565	7.356	628	12
1	200	2475232.37	207212.30	35.909	7.331	621	15
1	250	2475207.94	207256.24	36.231	7.300	609	9
1	300	2475183.52	207300.18	35.998	7.261	588	-2
1	350	2475159.09	207344.12	36.127	7.224	570	-4
1	400	2475134.67	207388.06	36.398	7.196	560	-11
1	450	2475110.24	207432.00	36.829	7.152	534	-19
1	500	2475085.82	207475.94	37.119	7.131	532	-13
1	550	2475061.39	207519.88	37.274	7.092	512	-16
1	600	2475036.97	207563.82	37.517	7.062	499	-26
1	650	2475012.54	207607.76	37.900	7.038	494	-5
1	700	2474988.12	207651.70	38.050	7.049	523	24
1	750	2474963.69	207695.64	38.120	7.011	503	19
1	800	2474939.26	207739.58	37.950	6.959	471	7
1	850	2474914.84	207783.53	38.106	6.936	465	-1
1	900	2474890.41	207827.47	38.586	6.880	428	-19
1	950	2474865.99	207871.41	39.068	6.851	417	-15
1	1000	2474841.56	207915.35	37.625	6.862	447	9
1	1050	2474817.14	207959.29	37.025	6.815	418	7
1	1100	2474792.71	208003.23	36.477	6.792	413	-2
1	1150	2474768.29	208047.17	36.220	6.770	410	8
1	1200	2474743.86	208091.11	36.135	6.742	400	2
1	1250	2474719.44	208135.05	36.425	6.698	375	-10
1	1300	2474695.01	208178.99	34.963	6.703	399	5
1	1350	2474670.59	208222.93	34.484	6.673	386	17
1	1400	2474646.16	208266.87	34.597	6.654	387	7
1	1450	2474621.73	208310.81	34.702	6.630	381	11
1	1500	2474597.31	208354.75	34.600	6.619	388	23
1	1550	2474572.88	208398.70	34.225	6.593	380	16
1	1600	2474548.46	208442.64	34.240	6.557	363	3
1	1650	2474524.03	208486.58	34.148	6.524	349	-8
1	1700	2474499.61	208530.52	34.190	6.488	330	-22
1	1750	2474475.18	208574.46	34.026	6.468	329	-25
1	1800	2474450.76	208618.40	33.751	6.451	331	-14
1	1850	2474426.33	208662.34	33.649	6.439	337	-7
1	1900	2474401.91	208706.28	34.044	6.422	338	-5
1	1950	2474377.48	208750.22	33.710	6.395	330	-3
1	2000	2474353.06	208794.16	33.605	6.379	332	-2
1	2050	2474328.63	208838.10	33.756	6.359	331	2
1	2100	2474304.20	208882.04	35.028	6.324	314	-3
1	2150	2474279.78	208925.98	35.026	6.296	305	-17
1	2200	2474255.35	208969.92	34.659	6.262	289	-16
1	2250	2474230.93	209013.86	32.845	6.257	302	-2
1	2300	2474206.50	209057.81	32.821	6.237	300	5

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
1	2350	2474182.08	209101.75	33.320	6.215	297	11
1	2400	2474157.65	209145.69	32.848	6.198	299	19
1	2450	2474133.23	209189.63	32.889	6.169	287	19
1	2500	2474108.80	209233.57	32.858	6.142	279	16
1	2550	2474084.38	209277.51	32.844	6.108	264	16
1	2600	2474059.95	209321.45	32.799	6.081	255	11
1	2650	2474035.53	209365.39	32.739	6.043	235	6
1	2700	2474011.10	209409.33	32.577	6.015	226	5
1	2750	2473986.67	209453.27	32.713	5.984	213	3
1	2800	2473962.25	209497.21	32.472	5.950	198	-1
1	2850	2473937.82	209541.15	32.532	5.921	187	-2
1	2900	2473913.40	209585.09	32.440	5.886	170	-7
1	2950	2473888.97	209629.03	32.310	5.847	150	-13
1	3000	2473864.55	209672.98	32.288	5.828	149	-10
1	3050	2473840.12	209716.92	32.185	5.789	129	-9
1	3100	2473815.70	209760.86	32.175	5.760	118	-17
1	3150	2473791.27	209804.80	32.214	5.726	103	-18
1	3200	2473766.85	209848.74	32.201	5.699	94	-12
1	3250	2473742.42	209892.68	31.925	5.680	94	-10
1	3300	2473717.99	209936.62	31.850	5.647	79	-5
1	3350	2473693.57	209980.56	31.570	5.624	74	0
1	3400	2473669.14	210024.50	31.395	5.604	72	0
1	3450	2473644.72	210068.44	31.443	5.561	48	5
1	3500	2473620.29	210112.38	31.372	5.563	68	16
1	3550	2473595.87	210156.32	31.199	5.517	41	15
1	3600	2473571.44	210200.26	31.385	5.481	24	6
1	3650	2473547.02	210244.20	31.325	5.462	23	7
1	3700	2473522.59	210288.15	31.508	5.427	6	17
1	3750	2473498.17	210332.09	32.199	5.409	7	15
1	3800	2473473.74	210376.03	32.827	5.359	-25	-1
1	3850	2473449.32	210419.97	33.491	5.316	-50	-8
1	3900	2473424.89	210463.91	31.809	5.308	-39	-4
1	3950	2473400.46	210507.85	33.369	5.257	-72	-4
1	4000	2473376.04	210551.79	33.412	5.244	-67	-7
1	4050	2473351.61	210595.73	31.435	5.219	-73	5
1	4100	2473327.19	210639.67	31.285	5.195	-78	14
1	4150	2473302.76	210683.61	31.153	5.177	-78	12
1	4200	2473278.34	210727.55	31.112	5.139	-98	15
1	4250	2473253.91	210771.49	31.134	5.117	-102	10
1	4300	2473229.49	210815.43	33.032	5.057	-143	-16
1	4350	2473205.06	210859.37	32.166	5.024	-157	-25
1	4400	2473180.64	210903.31	32.566	5.001	-162	-19
1	4450	2473156.21	210947.26	33.070	4.964	-181	-30
1	4500	2473131.79	210991.20	34.018	4.941	-186	-29
1	4550	2473107.36	211035.14	31.597	4.931	-177	-8
1	4600	2473082.93	211079.08	31.917	4.901	-188	-14
1	4650	2473058.51	211123.02	32.018	4.878	-193	-17
1	4700	2473034.08	211166.96	32.250	4.883	-170	29
1	4750	2473009.66	211210.90	32.318	4.909	-125	55

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
1	4800	2472985.23	211254.84	34.333	4.826	-190	23
1	4850	2472960.81	211298.78	32.073	4.803	-194	4
1	4900	2472936.38	211342.72	31.558	4.778	-201	13
1	4950	2472911.96	211386.66	31.293	4.744	-216	3
1	5000	2472887.53	211430.60	31.060	4.718	-224	-7
1	5050	2472863.11	211474.54	31.271	4.695	-229	4
1	5100	2472838.68	211518.48	31.187	4.689	-216	9
1	5150	2472814.26	211562.43	31.367	4.648	-239	3
1	5200	2472789.83	211606.37	31.612	4.631	-238	-4
1	5250	2472765.40	211650.31	33.946	4.592	-258	-9
1	5300	2472740.98	211694.25	31.552	4.580	-251	-5
1	5350	2472716.55	211738.19	31.741	4.556	-257	-6
1	5400	2472692.13	211782.13	33.464	4.513	-282	-23
1	5450	2472667.70	211826.07	32.661	4.494	-282	-27
1	5500	2472643.28	211870.01	32.096	4.483	-275	-7
1	5550	2472618.85	211913.95	31.509	4.482	-257	6
1	5600	2472594.43	211957.89	31.388	4.449	-272	3
1	5650	2472570.00	212001.83	31.169	4.430	-273	0
1	5700	2472545.58	212045.77	31.276	4.409	-276	4
1	5750	2472521.15	212089.71	31.241	4.396	-270	16
1	5800	2472496.72	212133.65	31.360	4.388	-260	25
1	5850	2472472.30	212177.60	31.275	4.352	-277	18
1	5900	2472447.87	212221.54	30.949	4.322	-289	10
1	5950	2472423.45	212265.48	31.279	4.291	-301	0
1	6000	2472399.02	212309.42	31.598	4.243	-331	-20
1	6050	2472374.60	212353.36	32.996	4.218	-337	-24
1	6100	2472350.17	212397.30	30.943	4.211	-326	-4
1	6150	2472325.75	212441.24	30.584	4.200	-319	8
1	6200	2472301.32	212485.18	30.400	4.172	-328	6
1	6250	2472276.90	212529.12	30.746	4.155	-327	12
1	6300	2472252.47	212573.06	30.592	4.126	-337	10
1	6350	2472228.05	212617.00	30.558	4.086	-359	-6
1	6400	2472203.62	212660.94	32.925	4.052	-375	-14
1	6450	2472179.19	212704.88	32.787	4.032	-376	-11
1	6500	2472154.77	212748.82	30.335	4.000	-390	-13
1	6550	2472130.34	212792.77	30.096	3.973	-398	-23
1	6600	2472105.92	212836.71	30.474	3.938	-415	-26
1	6650	2472081.49	212880.65	30.583	3.936	-399	-8
1	6700	2472057.07	212924.59	28.757	3.935	-382	15
1	6750	2472032.64	212968.53	28.035	3.917	-381	22
1	6800	2472008.22	213012.47	27.538	3.893	-386	23
1	6850	2471983.79	213056.41	26.933	3.880	-381	26
1	6900	2471959.37	213100.35	26.407	3.844	-399	18
1	6950	2471934.94	213144.29	25.776	3.810	-414	1
1	7000	2471910.52	213188.23	25.308	3.785	-420	-3
1	7050	2471885.97	213231.98	25.055	3.771	-417	4
1	7100	2471861.43	213275.72	24.874	3.754	-415	5
1	7150	2471836.89	213319.47	25.424	3.737	-414	4
1	7200	2471812.35	213363.22	25.259	3.717	-415	5

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1	7250	2471787.81	213406.96	25.455	3.693	-421	0
1	7300	2471763.27	213450.71	25.583	3.672	-423	-13
1	7350	2471738.72	213494.45	26.112	3.633	-444	-23
1	7400	2471714.18	213538.20	26.396	3.627	-431	-23
1	7450	2471689.64	213581.95	26.412	3.614	-427	-18
1	7500	2471665.10	213625.69	26.406	3.599	-423	-12
1	7550	2471640.56	213669.44	26.463	3.600	-403	-4
1	7600	2471616.01	213713.19	26.367	3.584	-401	2
1	7650	2471591.47	213756.93	26.788	3.569	-398	1
1	7700	2471566.93	213800.68	26.842	3.560	-388	4
1	7750	2471542.39	213844.42	26.803	3.549	-381	14
1	7800	2471517.85	213888.17	26.877	3.538	-374	14
1	7850	2471493.31	213931.92	29.051	3.506	-387	4
1	7900	2471468.76	213975.66	27.788	3.487	-388	-3
1	7950	2471444.22	214019.41	27.674	3.471	-386	0
1	8000	2471419.68	214063.16	28.418	3.462	-377	9
1	8050	2471395.14	214106.90	28.120	3.452	-368	14
1	8100	2471370.60	214150.65	27.797	3.426	-375	11
1	8150	2471346.06	214194.39	28.179	3.409	-374	9
1	8200	2471321.51	214238.14	28.523	3.388	-377	4
1	8250	2471296.97	214281.89	30.591	3.346	-401	-13
1	8300	2471272.43	214325.63	31.096	3.327	-401	-21
1	8350	2471247.89	214369.38	29.107	3.319	-391	-9
1	8400	2471223.35	214413.13	29.781	3.303	-388	-2
1	8450	2471198.81	214456.87	30.134	3.296	-377	0
1	8500	2471174.26	214500.62	30.579	3.285	-370	13
1	8550	2471149.72	214544.36	31.209	3.278	-358	19
1	8600	2471125.18	214588.11	31.735	3.251	-367	7
1	8650	2471100.64	214631.86	33.616	3.222	-377	-5
1	8700	2471076.10	214675.60	32.986	3.200	-381	-11
1	8750	2471051.56	214719.35	32.992	3.182	-381	-19
1	8800	2471027.01	214763.10	32.969	3.169	-375	-16
1	8850	2471002.47	214806.84	32.928	3.175	-351	2
1	8900	2470977.93	214850.59	32.994	3.174	-334	10
1	8950	2470953.39	214894.33	32.333	3.147	-342	-3
1	9000	2470928.85	214938.08	32.384	3.128	-342	-13
1	9050	2470904.31	214981.83	30.935	3.127	-325	-7
1	9100	2470879.76	215025.57	32.353	3.118	-316	-4
1	9150	2470855.22	215069.32	30.439	3.111	-305	-6
1	9200	2470830.68	215113.06	30.749	3.107	-290	-1
1	9300	2470781.60	215200.56	30.950	3.093	-267	10
1	9350	2470757.06	215244.30	31.497	3.092	-251	18
1	9400	2470732.51	215288.05	28.908	3.095	-229	23
1	9450	2470707.97	215331.80	29.324	3.079	-226	22
1	9500	2470683.43	215375.54	31.899	3.071	-216	14
1	9550	2470658.89	215419.29	31.436	3.054	-215	9
1	9600	2470634.35	215463.03	31.257	3.041	-210	2
1	9650	2470609.80	215506.78	31.369	3.023	-209	-9
1	9700	2470585.26	215550.53	31.154	3.009	-205	-12

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1	9750	2470560.72	215594.27	30.996	3.004	-191	-11
1	9800	2470536.18	215638.02	30.941	2.984	-193	-18
1	9850	2470511.64	215681.77	30.647	2.976	-183	-19
1	9900	2470487.10	215725.51	30.111	2.969	-171	-11
1	9950	2470462.55	215769.26	29.832	2.962	-160	-13
1	10000	2470438.01	215813.00	29.401	2.946	-157	-12
1	10050	2470413.47	215856.75	28.470	2.952	-132	5
1	10100	2470388.93	215900.50	28.388	2.949	-118	12
1	10150	2470364.39	215944.24	28.460	2.925	-123	6
1	10200	2470339.85	215987.99	28.222	2.917	-112	6
1	10250	2470315.30	216031.74	28.409	2.904	-108	9
1	10300	2470290.76	216075.48	28.802	2.891	-102	10
1	10350	2470266.22	216119.23	28.794	2.882	-93	13
1	10400	2470241.68	216162.97	29.131	2.862	-94	7
1	10450	2470217.14	216206.72	30.052	2.831	-107	-6
1	10500	2470192.60	216250.47	29.911	2.824	-95	-9
1	10550	2470168.05	216294.21	29.624	2.807	-95	-1
1	10600	2470143.51	216337.96	29.193	2.815	-68	10
1	10650	2470118.97	216381.71	28.956	2.806	-59	18
1	10700	2470094.43	216425.45	28.860	2.784	-63	8
1	10750	2470069.89	216469.20	29.332	2.755	-72	-8
1	10800	2470045.35	216512.94	29.272	2.748	-61	-9
1	10850	2470020.80	216556.69	28.588	2.731	-60	-5
1	10900	2469996.26	216600.44	28.358	2.728	-44	-10
1	10950	2469971.72	216644.18	28.384	2.705	-49	-16
1	11000	2469947.18	216687.93	28.456	2.690	-45	-21
1	11050	2469922.64	216731.67	28.787	2.692	-25	-17
1	11100	2469898.10	216775.42	29.143	2.695	-4	3
1	11150	2469873.55	216819.17	29.396	2.709	28	18
1	11200	2469849.01	216862.91	29.719	2.693	30	11
1	11250	2469824.47	216906.66	31.348	2.676	32	3
1	11300	2469799.93	216950.41	31.137	2.672	46	5
1	11350	2469775.39	216994.15	30.754	2.663	56	1
1	11400	2469750.85	217037.90	30.419	2.646	58	-7
1	11450	2469726.30	217081.64	30.226	2.640	70	-7
1	11500	2469701.76	217125.39	28.980	2.650	98	6
1	11550	2469677.22	217169.14	28.464	2.657	123	23
1	11600	2469652.68	217212.88	27.927	2.660	145	27
1	11650	2469628.14	217256.63	29.284	2.643	146	19
1	11700	2469603.60	217300.38	28.607	2.628	149	8
1	11750	2469579.05	217344.12	28.250	2.603	143	-10
1	11800	2469554.51	217387.87	28.039	2.582	140	-25
1	11850	2469529.97	217431.61	27.648	2.582	158	-22
1	11900	2469505.43	217475.36	27.775	2.576	171	-16
1	11950	2469480.89	217519.11	28.711	2.576	189	-16
1	12000	2469456.34	217562.85	28.638	2.573	205	-7
1	12050	2469428.40	217603.61	28.060	2.583	232	6
1	12100	2469400.46	217644.37	27.498	2.574	242	6
1	12150	2469372.51	217685.13	27.336	2.568	254	4

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1	12200	2469344.57	217725.89	27.372	2.552	256	2
1	12250	2469316.63	217766.65	27.477	2.550	272	-3
1	12300	2469288.68	217807.42	27.570	2.537	277	5
1	12350	2469260.74	217848.18	27.928	2.550	308	15
1	12400	2469232.80	217888.94	28.169	2.527	303	6
1	12450	2469204.85	217929.70	28.446	2.510	304	0
1	12500	2469161.94	217954.06	28.806	2.516	327	7
1	12550	2469119.02	217978.42	28.704	2.497	323	4
1	12600	2469076.10	218002.78	28.451	2.487	328	-5
1	12650	2469033.18	218027.15	28.259	2.476	334	-6
1	12700	2468990.27	218051.51	28.507	2.453	327	-15
1	12750	2468947.35	218075.87	28.660	2.446	335	-22
1	12800	2468904.43	218100.24	29.001	2.440	345	-9
1	12850	2468861.51	218124.60	29.363	2.444	365	2
1	12900	2468818.60	218148.96	29.506	2.439	376	5
1	12950	2468775.68	218173.32	29.920	2.425	378	11
1	13000	2468732.76	218197.69	29.636	2.422	390	10
1	13050	2468689.84	218222.05	28.683	2.397	381	5
1	13100	2468646.93	218246.41	27.619	2.401	401	19
1	13150	2468598.10	218250.18	27.538	2.399	409	25
1	13200	2468549.27	218253.95	27.339	2.373	394	9
1	13250	2468500.44	218257.72	27.643	2.357	389	4
1	13300	2468451.61	218261.48	27.541	2.349	390	3
1	13350	2468402.79	218265.25	27.781	2.317	369	-19
1	13400	2468353.96	218269.02	27.811	2.293	356	-27
1	13450	2468305.13	218272.79	27.883	2.310	384	-7
1	13500	2468256.30	218276.55	27.758	2.292	376	-6
1	13550	2468207.47	218280.32	28.253	2.265	360	-24
1	13600	2468158.64	218284.09	28.363	2.258	363	-21
1	13650	2468109.82	218287.86	28.635	2.257	372	-7
1	13700	2468060.99	218291.63	28.879	2.250	375	-1
1	13750	2468012.16	218295.39	29.137	2.251	387	8
1	13800	2467963.33	218299.16	29.422	2.240	386	13
1	13850	2467914.50	218302.93	29.454	2.222	379	9
1	13900	2467865.67	218306.70	29.988	2.221	388	14
1	13950	2467816.85	218310.46	30.188	2.206	384	20
1	14000	2467768.02	218314.23	30.487	2.190	379	11
1	14050	2467718.29	218315.53	30.744	2.174	372	4
1	14100	2467668.56	218316.83	31.001	2.155	363	4
1	14150	2467618.83	218318.13	31.235	2.142	360	-6
1	14200	2467569.10	218319.43	31.504	2.121	349	-14
1	14250	2467519.37	218320.73	31.311	2.115	353	-6
1	14300	2467469.64	218322.03	30.558	2.115	362	-2
1	14350	2467419.91	218323.33	30.686	2.095	353	-10
1	14400	2467370.19	218324.63	30.339	2.089	356	-6
1	14450	2467320.46	218325.93	30.013	2.097	375	9
1	14500	2467270.73	218327.23	29.674	2.095	382	15
1	14550	2467221.00	218328.52	29.348	2.082	379	11
1	14600	2467171.27	218329.82	28.949	2.068	375	5

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1	14650	2467121.54	218331.12	28.603	2.056	372	-6
1	14700	2467071.81	218332.42	28.285	2.025	351	-19
1	14750	2467022.08	218333.72	28.210	2.031	368	-17
1	14800	2466972.35	218335.02	28.285	2.035	381	-1
1	14850	2466922.62	218336.32	28.195	2.031	387	5
1	14900	2466872.90	218337.62	28.446	2.022	388	-2
1	14950	2466823.17	218338.92	28.597	2.013	389	-2
1	15000	2466773.44	218340.22	28.474	2.005	391	5
1	15050	2466723.71	218341.52	28.847	2.011	407	9
1	15100	2466673.98	218342.82	28.949	1.994	400	10
1	15150	2466624.25	218344.12	28.876	1.978	393	7
1	15200	2466574.52	218345.42	28.585	1.977	403	3
1	15250	2466524.79	218346.71	28.445	1.946	381	4
1	15300	2466475.06	218348.01	28.274	1.947	392	3
1	15350	2466425.33	218349.31	28.257	1.920	375	-4
1	15400	2466375.61	218350.61	28.195	1.894	358	-13
1	15450	2466325.88	218351.91	28.051	1.872	347	-19
1	15500	2466276.15	218353.21	27.902	1.853	338	-26
1	15550	2466226.42	218354.51	27.739	1.826	320	-21
1	15600	2466176.69	218355.81	27.691	1.844	348	1
1	15650	2466126.96	218357.11	27.725	1.832	346	21
1	15700	2466077.23	218358.41	27.639	1.815	339	22
1	15750	2466027.50	218359.71	27.509	1.788	322	13
1	15800	2465977.77	218361.01	27.738	1.755	299	8
1	15850	2465928.04	218362.31	27.973	1.728	282	6
1	15900	2465878.32	218363.61	28.225	1.710	273	1
1	15950	2465828.59	218364.90	27.965	1.666	239	-2
1	16000	2465778.86	218366.20	27.184	1.672	255	9
1	16050	2465729.13	218367.50	27.004	1.637	230	15
1	16100	2465679.40	218368.80	26.122	1.619	223	7
1	16150	2465629.67	218370.10	27.455	1.589	202	9
1	16200	2465579.94	218371.40	29.020	1.577	200	16
1	16250	2465530.21	218372.70	30.534	1.536	169	-5
1	16300	2465480.48	218374.00	32.780	1.479	122	-34
2	0	2466171.40	216998.88	23.358	1.918	-2	5
2	50	2466129.14	216971.30	23.073	1.891	-29	-8
2	100	2466086.87	216943.71	22.886	1.875	-45	-20
2	150	2466044.61	216916.13	23.206	1.855	-66	-24
2	200	2466002.34	216888.54	23.015	1.846	-76	-27
2	250	2465948.68	216886.81	21.928	1.833	-79	-21
2	300	2465895.03	216885.08	19.333	1.829	-74	-1
2	350	2465841.37	216883.35	17.272	1.831	-62	11
2	400	2465793.38	216873.30	16.584	1.799	-88	7
2	450	2465745.39	216863.25	16.777	1.794	-87	7
2	500	2465697.40	216853.20	16.250	1.777	-98	14
2	550	2465649.41	216843.15	15.129	1.768	-101	14
2	600	2465601.42	216833.10	16.070	1.744	-119	12
2	650	2465553.43	216823.05	17.335	1.736	-121	13
2	700	2465505.44	216813.00	18.576	1.706	-145	6

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
2	750	2465457.45	216802.95	18.673	1.687	-158	-2
2	800	2465409.46	216792.90	18.675	1.669	-170	-2
3	0	2466154.84	216586.45	11.425	1.958	-88	5
3	50	2466155.10	216635.66	11.119	1.971	-59	21
3	100	2466155.37	216684.87	12.887	1.969	-46	22
3	150	2466155.64	216734.08	17.262	1.942	-58	10
3	200	2466155.91	216783.29	19.493	1.947	-37	6
3	250	2466156.17	216832.50	21.287	1.923	-45	4
3	300	2466156.44	216881.71	21.804	1.915	-39	-9
3	350	2466156.71	216930.92	21.775	1.904	-34	-11
3	400	2466156.97	216980.13	22.587	1.910	-13	4
3	450	2466157.24	217029.34	24.293	1.910	3	6
3	500	2466157.51	217078.55	25.043	1.892	0	-5
3	550	2466157.78	217127.75	26.133	1.879	2	-9
3	600	2466158.04	217176.96	26.969	1.878	17	-11
3	650	2466158.31	217226.16	27.751	1.862	16	-17
3	700	2466158.58	217275.37	28.564	1.857	27	-19
3	750	2466158.84	217324.58	29.225	1.859	44	-11
3	800	2466159.11	217373.78	28.662	1.870	70	1
3	850	2466159.38	217422.99	28.979	1.867	83	7
3	900	2466159.65	217472.20	29.016	1.871	101	5
3	950	2466159.91	217521.40	29.099	1.860	107	7
3	1000	2466160.18	217570.61	28.603	1.871	133	11
3	1050	2466161.86	217621.32	29.652	1.856	133	6
3	1100	2466163.54	217672.03	29.643	1.861	154	4
3	1150	2466165.22	217722.74	29.439	1.856	164	11
3	1200	2466166.90	217773.46	29.546	1.867	191	11
3	1250	2466168.57	217824.17	29.575	1.848	187	4
3	1300	2466170.25	217874.88	29.086	1.855	210	4
3	1350	2466171.93	217925.59	29.236	1.849	219	2
3	1400	2466173.61	217976.31	29.005	1.837	223	-10
3	1450	2466175.29	218027.02	28.729	1.830	232	-15
3	1500	2466176.97	218077.73	28.282	1.838	255	-12
3	1550	2466178.64	218128.44	28.219	1.831	264	-11
3	1600	2466180.32	218179.16	27.878	1.843	292	-6
3	1650	2466182.00	218229.87	26.840	1.848	312	5
3	1700	2466183.68	218280.58	25.734	1.853	333	8
4	0	2466206.22	217708.94	28.947	1.879	175	-3
4	50	2466157.58	217704.68	29.439	1.861	165	-1
4	100	2466108.94	217700.41	29.727	1.840	152	-4
4	150	2466060.31	217696.15	30.004	1.814	134	-6
4	200	2466011.67	217691.89	29.446	1.797	125	-6
4	250	2465963.03	217687.63	29.329	1.771	107	-11
4	300	2465914.40	217683.37	28.932	1.751	94	-11
4	350	2465865.76	217679.11	28.342	1.736	87	-4
4	400	2465817.12	217674.85	28.098	1.721	80	-1
4	450	2465768.49	217670.59	27.452	1.702	69	3
4	500	2465719.85	217666.33	26.668	1.689	64	12
4	550	2465671.21	217662.07	25.707	1.677	61	16

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
4	600	2465622.58	217657.81	25.110	1.651	42	21
4	650	2465573.94	217653.55	23.743	1.646	45	27
4	700	2465525.30	217649.28	23.128	1.605	12	14
4	750	2465476.67	217645.02	22.135	1.560	-25	-9
5	0	2466986.75	217042.75	27.659	2.032	-29	2
5	50	2466986.75	216992.75	27.434	2.035	-42	-7
5	100	2466986.75	216942.75	26.758	2.055	-38	-15
5	150	2466986.75	216892.75	26.634	2.063	-45	-16
5	200	2466986.75	216842.75	25.992	2.096	-28	-10
5	250	2466986.75	216792.75	25.015	2.114	-26	-3
5	300	2466986.75	216742.75	23.564	2.145	-10	-1
5	350	2466986.75	216692.75	22.633	2.158	-13	4
5	400	2466986.75	216642.75	21.714	2.193	6	9
5	450	2466986.75	216592.75	21.418	2.202	0	8
5	500	2466986.75	216542.75	22.002	2.220	3	2
6	0	2468643.33	216190.15	31.412	2.434	-210	-5
6	50	2468593.60	216189.04	31.841	2.415	-220	-11
6	100	2468543.87	216187.93	31.757	2.412	-214	-5
6	150	2468494.14	216186.82	30.979	2.415	-201	2
6	200	2468444.42	216185.71	30.044	2.398	-209	1
6	250	2468394.69	216184.60	28.840	2.393	-205	1
6	300	2468344.96	216183.49	27.930	2.385	-204	-1
6	350	2468295.23	216182.38	27.296	2.362	-218	-7
6	400	2468245.51	216181.26	27.045	2.360	-211	-8
6	450	2468195.78	216180.15	27.015	2.356	-205	1
6	500	2468146.05	216179.04	27.132	2.348	-204	6
6	550	2468096.32	216177.93	26.857	2.341	-202	3
6	600	2468046.60	216176.82	26.893	2.327	-207	2
6	650	2467996.87	216175.71	27.363	2.316	-209	2
6	700	2467947.14	216174.60	28.148	2.301	-215	-4
6	750	2467897.41	216173.49	28.783	2.292	-215	-3
6	800	2467847.68	216172.38	28.900	2.285	-212	5
6	850	2467797.96	216171.27	28.626	2.272	-216	-1
6	900	2467748.23	216170.16	28.127	2.249	-230	-14
6	950	2467698.50	216169.05	27.929	2.243	-228	-1
6	1000	2467648.77	216167.94	27.989	2.271	-191	23
6	1050	2467599.05	216166.83	27.747	2.239	-213	18
6	1100	2467549.32	216165.72	27.351	2.221	-222	1
6	1150	2467499.59	216164.61	26.949	2.207	-227	0
6	1200	2467449.86	216163.50	26.667	2.192	-233	0
6	1250	2467400.13	216162.39	26.441	2.184	-232	-3
6	1300	2467350.41	216161.28	26.286	2.179	-227	4
6	1350	2467300.68	216160.17	26.217	2.166	-231	5
6	1400	2467250.95	216159.06	26.338	2.155	-233	-5
6	1450	2467201.22	216157.95	26.658	2.135	-244	-6
6	1500	2467151.50	216156.84	27.132	2.137	-233	-3
6	1550	2467101.77	216155.73	27.665	2.119	-242	-7
6	1600	2467052.04	216154.62	27.728	2.114	-238	-5
6	1650	2467002.31	216153.51	27.774	2.107	-236	-5

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
6	1700	2466952.58	216152.40	27.624	2.084	-250	-16
6	1750	2466902.86	216151.29	27.599	2.079	-245	-18
6	1800	2466853.13	216150.18	27.296	2.079	-236	-4
6	1850	2466803.40	216149.07	27.086	2.082	-224	3
6	1900	2466753.67	216147.96	26.768	2.075	-222	4
6	1950	2466703.95	216146.84	26.599	2.064	-224	6
6	2000	2466654.22	216145.73	26.268	2.063	-216	5
6	2050	2466604.49	216144.62	26.207	2.049	-221	6
6	2100	2466554.76	216143.51	26.151	2.049	-211	11
6	2150	2466505.03	216142.40	25.839	2.039	-213	11
6	2200	2466455.31	216141.29	25.193	2.027	-215	8
6	2250	2466405.58	216140.18	24.743	2.018	-215	9
6	2300	2466355.85	216139.07	24.007	2.011	-213	8
6	2350	2466306.12	216137.96	23.374	1.987	-227	-1
6	2400	2466256.59	216143.50	23.195	1.970	-234	-8
6	2450	2466207.06	216149.04	23.065	1.959	-233	-9
6	2500	2466157.53	216154.57	23.050	1.942	-239	-6
6	2550	2466108.00	216160.11	22.900	1.943	-228	-3
6	2600	2466058.47	216165.64	22.584	1.920	-239	-1
6	2650	2466008.94	216171.18	22.169	1.918	-230	4
6	2700	2465959.41	216176.72	21.717	1.913	-223	13
6	2750	2465909.88	216182.25	21.460	1.892	-234	12
6	2800	2465860.35	216187.79	20.269	1.875	-240	-4
6	2850	2465810.82	216193.33	20.169	1.830	-273	-20
6	2900	2465761.29	216198.86	20.247	1.830	-262	-20
6	2950	2465711.76	216204.40	21.238	1.815	-266	-11
6	3000	2465662.23	216209.94	22.161	1.815	-255	-3
7	0	2468670.50	216206.89	30.743	2.459	-185	-4
7	50	2468646.14	216251.08	30.440	2.434	-191	-17
7	100	2468621.78	216295.27	30.165	2.423	-184	-22
7	150	2468597.42	216339.45	29.448	2.427	-161	-19
7	200	2468573.06	216383.64	29.236	2.414	-155	-13
7	250	2468548.70	216427.83	29.005	2.433	-118	-4
7	300	2468524.34	216472.02	28.671	2.422	-111	4
7	350	2468499.99	216516.21	28.277	2.437	-77	14
7	400	2468475.63	216560.40	27.763	2.432	-64	23
7	450	2468451.27	216604.59	27.278	2.429	-49	18
7	500	2468426.91	216648.78	26.653	2.403	-56	4
7	550	2468402.55	216692.96	26.173	2.397	-43	0
7	600	2468378.19	216737.15	25.739	2.392	-30	3
7	650	2468353.83	216781.34	25.209	2.383	-20	-1
7	700	2468329.47	216825.53	24.662	2.373	-12	-5
7	750	2468305.11	216869.72	24.202	2.373	6	-1
7	800	2468280.75	216913.91	23.958	2.369	21	3
7	850	2468256.39	216958.10	23.784	2.360	31	-1
7	900	2468232.03	217002.28	23.911	2.354	43	-1
7	950	2468207.68	217046.47	24.080	2.357	65	9
7	1000	2468183.32	217090.66	24.318	2.358	84	14
7	1050	2468158.96	217134.85	24.762	2.334	78	0

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)	Filtered Gravity (μGals)
7	1100	2468134.60	217179.04	25.295	2.321	84	-11
7	1150	2468110.24	217223.23	26.019	2.314	95	-5
7	1200	2468085.88	217267.42	26.711	2.316	116	-3
7	1250	2468061.52	217311.60	27.382	2.297	116	-8
7	1300	2468037.16	217355.79	28.019	2.297	134	-5
7	1350	2468012.80	217399.98	28.722	2.290	146	-4
7	1400	2467988.44	217444.17	29.248	2.275	148	-10
7	1450	2467964.08	217488.36	29.875	2.274	167	-4
7	1500	2467939.72	217532.55	30.101	2.275	186	3
7	1550	2467915.36	217576.74	30.037	2.254	183	-6
7	1600	2467891.01	217620.92	29.976	2.247	195	-11
7	1650	2467866.65	217665.11	29.813	2.245	212	1
7	1700	2467842.29	217709.30	29.608	2.249	234	11
7	1750	2467817.93	217753.49	29.656	2.244	247	13
7	1800	2467793.57	217797.68	29.575	2.229	251	11
7	1850	2467769.21	217841.87	29.861	2.217	257	2
7	1900	2467744.85	217886.06	29.908	2.197	256	-4
7	1950	2467720.49	217930.25	30.098	2.200	277	3
7	2000	2467696.13	217974.43	30.098	2.192	288	7
7	2050	2467671.77	218018.62	30.000	2.179	293	2
7	2100	2467647.41	218062.81	29.691	2.172	305	2
7	2150	2467623.05	218107.00	29.263	2.165	316	8
7	2200	2467598.70	218151.19	28.855	2.161	331	9
7	2250	2467574.34	218195.38	28.881	2.140	328	-1
7	2300	2467549.98	218239.57	29.002	2.121	328	-9
7	2350	2467525.62	218283.75	29.399	2.117	342	-9
7	2400	2467501.26	218327.94	30.724	2.107	350	-6

Table B-3. Manatee Springs Microgravity Data

Line	Station	S.P. Easting (ft)	S.P. Northing (ft)	Elevation (ft)	Bouguer Gravity (mGals)	Residual Gravity (μGals)
	BaseM1	2456429.69	179709.67	15.08	726.851	-3
1	0	2455848.78	179628.33	19.47	726.710	2
1	50	2455898.84	179621.05	17.84	726.723	-2
1	100	2455948.91	179613.77	17.76	726.748	5
1	150	2455998.98	179606.49	19.17	726.761	1
1	200	2456049.05	179599.21	19.37	726.780	2
1	250	2456099.11	179591.93	18.66	726.800	4
1	300	2456149.18	179584.64	18.72	726.833	19
1	350	2456195.25	179601.73	19.28	726.830	9
1	400	2456241.31	179618.82	18.95	726.835	6
1	450	2456287.38	179635.91	18.70	726.836	-1
1	500	2456333.44	179653.00	17.72	726.836	-9
1	550	2456379.50	179670.09	15.61	726.845	-8
1	600	2456425.57	179687.18	14.50	726.847	-14
1	650	2456471.63	179704.27	15.06	726.865	-3
1	700	2456517.70	179721.36	17.16	726.869	-7
1	750	2456563.76	179738.45	17.86	726.887	2
1	800	2456609.83	179755.54	18.00	726.897	4
1	850	2456655.89	179772.63	17.57	726.903	3
1	900	2456701.96	179789.71	18.04	726.909	1
1	950	2456750.18	179774.63	18.54	726.930	2
1	1000	2456798.40	179759.55	18.52	726.950	2
1	1050	2456846.62	179744.47	18.97	726.967	0
1	1100	2456894.84	179729.39	19.09	726.999	12
2	0	2455848.78	179628.33	19.47	726.705	-3
2	50	2455822.72	179670.88	19.88	726.683	-2
2	100	2455796.67	179713.43	19.81	726.664	2
2	150	2455770.61	179755.98	19.75	726.640	0
2	200	2455744.56	179798.53	19.53	726.624	7
2	250	2455718.51	179841.09	18.14	726.609	14
2	300	2455677.47	179870.27	17.50	726.580	8
2	350	2455636.44	179899.46	18.33	726.533	-17
2	400	2455595.40	179928.64	17.97	726.526	-2
2	450	2455554.37	179957.83	17.89	726.502	-3
2	500	2455513.34	179987.01	17.61	726.477	-6
2	550	2455476.46	180023.69	17.02	726.457	-1
2	600	2455439.58	180060.36	16.18	726.442	7
2	650	2455402.70	180097.04	15.49	726.413	2
2	700	2455365.82	180133.71	14.70	726.389	2
2	750	2455325.43	180165.30	14.12	726.361	-3
2	800	2455285.04	180196.88	14.32	726.319	-22
2	850	2455244.65	180228.47	14.72	726.308	-9
2	900	2455221.54	180272.47	15.92	726.294	-1
2	950	2455198.43	180316.47	16.74	726.262	-11
2	1000	2455175.33	180360.47	16.49	726.263	12
2	1050	2455152.22	180404.48	16.42	726.215	-14
2	1100	2455129.11	180448.48	16.28	726.196	-10

APPENDIX C

DESCRIPTION OF THE RESISTIVITY METHOD

Introduction

The resistivity method measures the bulk resistivity of subsurface soil and rock layers. Electrical resistivity is a function of the type of soil and rock, its porosity, its permeability as well as the composition of fluids that fill the pore spaces.

Traditional resistivity measurements use electrodes that are in direct contact with the ground to inject a DC current and to measure the resulting voltage difference. This method is effectively used in a wide variety of environments to provide resistivity soundings, profiles, and cross-sections of the subsurface.

Applications

Resistivity measurements are often applied in geologic and geotechnical studies and hydrologic investigations. The resistivity method can be used to map geologic changes such as depth to bedrock, lithology, fractures, structure, karst features, and hydrologic conditions such as depth to water table, depth to an aquitard, groundwater salinity and in the exploration for groundwater.

Most resistivity surveys for geologic, engineering, hydrologic and environmental applications are carried out to determine depths of geologic layers or lateral changes in geologic conditions that are less than a few hundred feet (Mooney, 1980). However, with sufficient power and instrument sensitivity, resistivity measurements can be made to depths of 1,000 feet and more.

Natural variations in subsurface resistivity may be caused by changes in basic soil or rock types, changes in the thickness of soil and rock layers, as well as structural features, fractures and cavities. Changes in soil moisture content, specific conductance of pore fluids and ground water may also produce changes in resistivity (McNeill, 1980). Localized deposits of natural organics, clay, sand, gravel or salt-rich zones will also affect resistivity.

Resistivity measurements have been used in mapping soil salinity and saltwater intrusion as well as inorganic contaminant plumes at waste disposal sites. Resistivity measurements have been used to locate trench boundaries and buried wastes and map the lateral extent of disposal areas, landfills, burn pits, trenches with depth estimates of these features.

Measurements are commonly used to estimate the degree of corrosion of metal structures based upon the resistivity of soils. Similarly, resistivity measurements of soil are used to design grounding grids at power substations and radio transmission towers.

Principles

The resistivity method requires that an electric current be injected into the ground from a pair of electrodes. The resulting voltage produced at the surface of the ground is measured across the other pair of electrodes (Figure C-1).

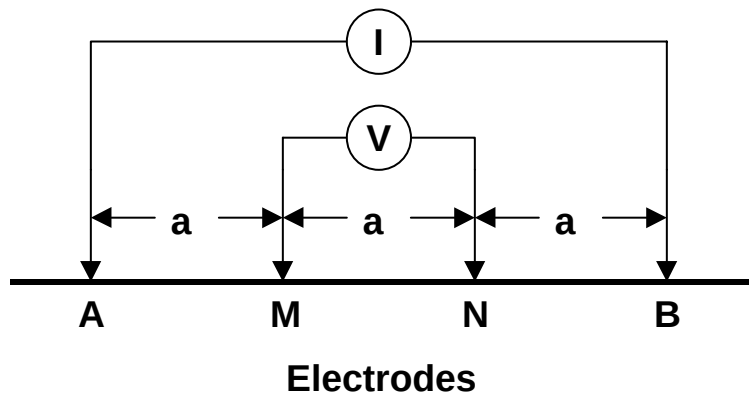


Figure C-1. Standard electrode geometry for a Wenner resistivity array.

The measured resistance is the ratio of the measured voltage divided by the current flowing into the ground. The apparent resistivity is computed as the measured resistance multiplied by a geometric factor (K) that is determined by the geometry and spacing of the electrode array.

$$\rho_a = \frac{V}{I} (K)$$

In a semi-infinite, homogeneous, isotropic medium, K is given by:

$$K = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}}$$

where AM, BM, AN, and BN are distances between the electrodes (A and B are the current electrodes, M and N are the potential electrodes).

UNITS

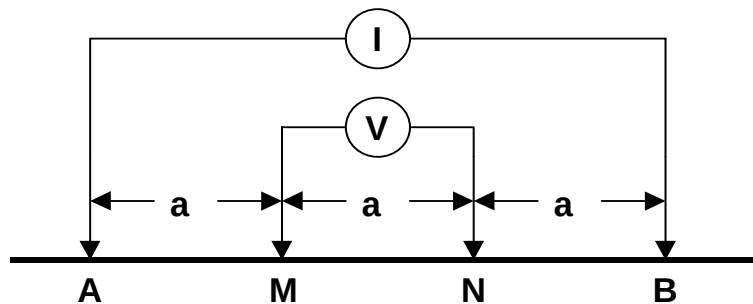
The units of resistivity are ohm-meters or ohm-feet (1 ohm-meter = 3.28 ohm-feet). The measured apparent resistivity will be different from the true resistivity unless the subsurface resistivity values are uniform laterally and with depth. True resistivity values

of layers can be calculated from apparent resistivity values obtained from a series of measurements made with increasing electrode spacing.

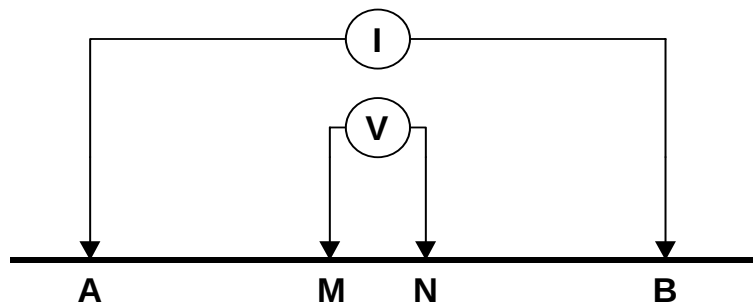
Electrode Arrays

DC resistivity electrodes are usually arranged in a straight line using one of several geometries. The Wenner, Schlumberger, and dipole-dipole arrays are the most commonly used electrode arrays (Figure C-2). The spacing between the current and voltage electrodes predominantly controls the depth of investigation in all arrays.

Wenner Array



Schlumberger Array



Dipole-Dipole Array



Figure C-2. Standard resistivity electrode geometries.

Depth of Measurement

The depth of measurement is related to the electrode spacing, and the distribution of current, which is influenced by the relative resistivity and thickness of the subsurface layers. An increase in electrode spacing increases the depth of measurement, however, the measured depth is usually less than the spacing between electrodes. A single measurement of apparent resistivity at a given electrode spacing represents a weighted average of the resistivity and geometric effects over a relatively large volume of material, with the shallow portions contributing most heavily.

Profiling measurements provide a means of mapping lateral changes in subsurface conditions. Profiling measurements are made using a fixed electrode spacing. The fixed-spacing electrode array is moved along the direction of the traverse to obtain data over the area of interest. Each measurement results in an apparent electrical resistivity value at the measurement point. A series of profile measurements along a line can be used to assess lateral changes in subsurface conditions.

Sounding measurements provide a means of determining the vertical changes in subsurface resistivity at a single location. Sounding measurements are made by incrementally increasing the spacing between electrodes to make a sequence of measurements at increasing depths, while the center point remains fixed. The electrode spacing is initially closely spaced and then is increased for each succeeding measurement. As the spacing between electrodes is increased, the depth of the measurement increases and the measured volume of material increases.

Automated arrays: The use of multi-electrode automated cable arrays is becoming common. A typical cable has 28 to 56 electrode take-outs. Electrodes are placed in the ground and measurements are made by switching to different combinations of electrodes. This process allows multiple measurements to be made with different electrode geometries (within the limits of the cable length and electrode spacing). These data can then be processed (inverted) to provide a detailed model of subsurface conditions. The repeated measurements also serve to improve data quality in noisy situations.

Equipment

Equipment for surface resistivity measurements includes a source of DC power, a power resistor to provide a means to measure the DC current, and a high impedance voltmeter. Two metal stakes are required for the current electrodes and two metal stakes for potential electrodes along with the necessary cables to connect the electrodes to the DC power source and the voltmeter (Figure C-1).

For shallow surveys, portable battery powered units (approximately 100 watts) are used. These are typically microprocessor-controlled instruments where data can be

stored in memory. Deep surveys require higher-power transmitters that are often powered by 1 to 10KW generators. Voltages of a few hundred to 1000 volts may be used along with currents from 0.010 to several amps.

Care must be taken to assure good electrical contact of the electrodes with the ground. Electrodes should be driven 4 to 6 inches into the ground or until they are in firm contact. Contact resistance may be decreased by driving stakes further into the ground, wetting the soil around the stake with water (preferable salty water) and finally increasing the size of the electrode area by use of multiple electrodes or the use of metal foil buried in moist soil. The insulation of the wire and other measurement equipment must be intact with no breaks so as to minimize leakage currents. The only electrical contact with the ground must be at the four electrodes.

In areas covered by asphalt or concrete pavement, holes must be drilled through the pavement so that electrodes can be driven into the underlying soils.

Safety Caution

- Electrical resistivity measurements utilize current sources and voltages that may result in a shock to field personnel. Adequate safety precautions must be taken to eliminate contact of personnel with the high voltage associated with the equipment, wire and electrodes when the electrical current is flowing.
- Since electrode arrays are well grounded to the earth, they are good targets for lightning. Measurements should never be attempted during electrical storms.

Quality Control

The resistivity meter will be set-up and operated in accordance with the manufacturer's instructions and the Technos, Inc. SOPs for Resistivity Measurements. Quality control procedures detailed in the SOPs will be followed to obtain a level of repeatability for the data and to ensure that the instrument is operating correctly throughout the survey.

Field conditions can be monitored by observing instrument readings and trends in the data. Profiling and sounding data should be plotted as it is acquired. Sounding curves should be smooth, and discontinuous jumps in the data should not occur. Profiling data should also show a general trend in the data from one station to the next.

Resolution

Lateral resolution of profiling measurements is a function of electrode spacing as well as the spacing between station measurements. Measurements with closely spaced electrodes and with closely spaced measurements will provide higher lateral resolution.

Up to 3 to 4 layers can be resolved by sounding measurements assuming a sufficient resistivity contrast and layer thickness are present. If we have additional data such as

resistivity or induction logs, 4 to 5 layers may be resolved by the resistivity sounding method. Each layer must have a sufficient thickness and resistivity contrast in order to be detected.

Lateral resolution of the imaging methods is related to electrode spacing and depth of measurement. Resolution decreases with larger electrode spacings and deeper measurements.

Accuracy and Precision

The accuracy of the resistivity values and the interpreted layer depths depends on a number of factors including: survey procedures, station spacing, electrode geometry, topography, noise, and site-specific geologic limitations. The depth to a layer will typically be defined to within 30% by the resistivity method. The precision or repeatability of a resistivity survey depends on the instrumentation, contact resistance, electrode geometry, soil moisture, and noise.

Calibration

Field equipment should be standardized at least once per day by using a test resistor. Measurements should agree with the resistor value to within 1%.

Data

Profile data are plotted as apparent resistivity values versus distance along a profile line with little if any processing. The results of a series of profile measurements can be shown as geo-electric profiles or a contour map.

Sounding data must be processed to obtain depth and thickness of layers. Processing can be done by curve matching or by using forward and inverse computer models. Sounding data are often presented as simple geo-electric section. When a number of soundings are made along a line, they may be shown as a fence diagram. If soundings have been made on a grid, then the interpreted sounding data may be used to develop a contour map.

Imaging data must be processed using inverse computer modeling. Apparent resistivity values from a number of different electrode separations are inverted to provide a resistivity cross-section.

Ease of Use

Resistivity measurements are made on a station-by-station basis. They are technically easy to make, but are slow and labor intensive since good ground contact requires driving metal electrodes into the ground and the deployment of long cables.

Limitations and Sources of Noise

Ambient Sources of Noise

When using large electrode spacings of a few 100 feet or more, small currents may be induced in the resistivity cables by thunderstorms.

Hydrogeologic Sources of Noise

Geologic sources of noise include local inhomogeneities near the electrodes that may distort the current or voltage (potential) field leading to a bias in the measurements. In some situations, it may be difficult to get DC current into highly resistive ground (i.e. clean dry quartz sand), and water or the use of multiple electrodes may be required.

Cultural Sources of Noise

Resistivity measurements may be influenced by nearby electrical and electromagnetic fields (such as power lines, or radio stations) that may couple to long resistivity cables.

Resistivity measurements may couple to nearby grounded metallic objects such as underground metallic pipelines or utilities, metal fences and buildings. The impact of a wire fence or power line grounding system will depend upon how well the structure is grounded and its geometry and relation to the resistivity array. Small metallic structures and metallic scrap on or near the surface are usually unimportant if they are small in relation to array size. Vehicles are isolated by rubber tires and therefore will not affect resistivity measurements.

Cathodic protection devices attached to pipelines or other metal structures to control corrosion will generate voltages that may bias resistivity measurements.

Personnel

The success of any resistivity survey is dependent upon many factors. One of the most important is the competency of the person(s) responsible for planning, carrying out the survey and interpreting the data. An understanding of the theory, field procedures and methods for interpretation of data along with an understanding of the site geology is necessary to successfully complete a resistivity survey. Personnel not having specialized training and/or experience should be cautious about using the resistivity method and solicit assistance from qualified practitioners.

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SUMMARY OF RESISTIVITY DATA

Land Resistivity Data

Resistivity data were acquired using a Sting resistivity meter in conjunction with the Swift multi-electrode switching system manufactured by Advanced Geosciences, Inc. A Wenner-Schlumberger array configuration with a maximum of 56 electrodes was used along the survey lines at both Manatee Springs and Fanning Springs. The Wenner-Schlumberger array was chosen in order to maximize the signal-to-noise ratio at the two sites. For shorter survey lines, fewer than 56 electrodes were used. For longer survey lines requiring more than 56 electrodes, a roll-along technique was implemented, rolling 28 electrodes at a time. The electrodes were attached to stainless steel stakes that were driven into the ground approximately 8 inches. Approximately 0.5 gallons of saltwater were poured around each stake to improve the electrical coupling to the ground and minimize high contact resistance.

MANATEE SPRINGS

Data were acquired along two survey lines in the Manatee Springs area. A total of 56 electrodes with a 20-foot electrode spacing was used along each survey line, obtaining measurements to create models with depths of approximately 180 feet.

Electrical contact resistance between adjacent electrode pairs was measured prior to making the measurements. The contact resistance values were very high along Line 1 and ranged from approximately 12 k-ohm to much greater than 20 k-ohm. The high contact resistance along Line 1 limited the output current to as little as 5 mA for many of the readings, resulting in noisy data. Along Line 2, the contact resistance values were considerably lower and generally ranged from between 3 k-ohm and 15 k-ohm.

FANNING SPRINGS

Data were acquired along a total of six survey lines in the Fanning Springs area. One of the lines (Line 3) was broken up into two segments in order to avoid traffic flow in and out of the park. A 20-foot electrode spacing was used to collect data along all of the survey lines, and the line lengths ranged from 700 to 2,220 feet requiring between 36 and 112 electrodes, respectively. Measurements were obtained to create models with depths ranging from approximately 100 to 180 feet in the Fanning Springs area.

Electrical contact resistance between adjacent electrode pairs was measured prior to making the measurements. The contact resistance values were much lower than those encountered in the Manatee Springs area and were generally much lower than 10 k-ohm. This relatively low contact resistance allowed a maximum output current of as much as 200 mA, resulting in high signal-to-noise ratios along all of the survey lines.

Data Processing

Two-dimensional cross-sectional models showing subsurface resistivity were created from the apparent resistivity data using M.H. Loke's RES2DINV software. The models are created using an iterative inversion process in which calculated apparent resistivity values are matched to measured apparent resistivity values within a given degree of misfit. Prior to data inversion, obvious data spikes and repeated data points with standard deviations greater than 2% were removed from the dataset.

Data Quality

Table C-1 summarizes the data and the calculated model RMS error for each dataset. Data quality is excellent along the survey lines at Fanning Springs. Nearly all of the data points had a high degree of repeatability and the model RMS error values are very low. The data quality is poorer along the two survey lines at Manatee Springs. While the data from Line 2 produced a fair-quality model, the model along Line 1 is considered to be of poor quality, with over half of the data points having been removed from the inverted data set due to a lack of repeatability. This lack of data repeatability was the result of very high electrical contact resistances ($>20\text{kohms}$) encountered along portions of the Manatee Springs survey lines.

Table C-1. Resistivity Data Summary

Location	Line #	Stations	Number of Measurements	Number of Noisy Measurements Removed	Model RMS Error
Manatee Springs	1	0 to 1100	750	421 (56.1%)	12.7%
Manatee Springs	2	0 to 1100	750	105 (14.0%)	7.4%
Fanning Springs	1A	15250 to 16050	399	None	2.5%
Fanning Springs	1B	15250 to 16050	399	None	3.8%
Fanning Springs	2	-300 to 800	750	1 (0.1%)	3.2%
Fanning Springs	3a	0 to 1000	611	3 (0.5%)	3.2%
Fanning Springs	3b	1040 to 1740	302	None	5.0%
Fanning Springs	4	0 to 740	338	None	3.0%
Fanning Springs	6	1200 to 3420	1,904	None	3.4%