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Microgravity Gradiometry Survey

North Spokane Aquifer

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Microgravity Gradiometry Survey

North Spokane Aquifer

1. INTRODUCTION

Northwest Geophysical Associates, Inc.(NGA) conducted a microgravity gradiometry survey in the North Spokane area. The objective of the survey was to provide constraints on the thickness of sediments and the basement topography in the Hillyard Trough.

Forty-one (41) microgravity station "triplets" (and an additional single station) were obtained along a profile line extending from Waiki Road on the southwest to Dart Hill in the northeast (Figure 1 & Plate 1). An additional leg of the profile extended to the Dakota Well on the east. Nominal station spacing was 300 feet. Data are included in Tables 1 and 2.

Field work was conducted on May 6-8, 1997. The survey included portions of Sections 7 & 8, T26N, R43E, W.M. Spokane County, Washington. It is covered by the southeast quarter of the USGS 7.5 minute Dartford quadrangle.

Several water wells, identified on the site maps, Figure 1 and Plate 1, were on, or close to, the line of the profile. The Whitworth Water District well (WWD) and the Dakota well were on the line of the profile, and gravity stations were located within 50 feet of the well heads. The Mayfair well is approximately 300 feet northwest of the profile, and the Lafferty well is approximately 100 feet east at the northern end of the profile.

2. MICROGRAVITY TECHNIQUE

Gravity is a common geophysical technique used to estimate thickness of sediments or depth to basement in restricted basins or graben structures. By measuring the local changes in gravitational attraction, we can deduce information about the local density structure. In many geologic settings, less dense sediments overlie more dense bedrock or "basement", creating an appropriate "target" for a gravity survey.

Microgravity surveys (with measurement resolution in the order of 5 to 20 microGal (μGal)) provide increased resolution of near-surface structures. Modern instruments enable us to achieve this accuracy with careful measurement techniques. The goal for this survey was to achieve a 5 μGal accuracy.

The gravity gradient is the rate of change of the observed gravity. It is measured as the difference of two closely spaced measurements. The gravity gradient provides additional resolution of near surface changes in density.

2.1 Measurement Techniques

Several factors become increasingly important as the accuracy of the measurement is increased:

2.1.1 Elevation

The elevation correction (i.e., change in gravity with elevation) is approximately 70 μGal/foot. That is, if the elevation survey has an accuracy of ±0.1 feet, an uncertainty of ±7 μGal is introduced into our measurement. The goal for this survey was to achieve a 0.05 foot accuracy, with a resulting variation of ±3.5 μGal. To achieve the desired 0.05 foot accuracy, the ground surface at the point of measurement must be accurately measured and the height of the instrument above the survey point must be accurately measured.

2.1.2 Instrumental Variations

Variations in instrument tilt and temperature are automatically compensated for by the CG-3M gravity meter. However, care must be taken to minimize these corrections. Excessive vibration noise is also rejected by the stacking software, but may still result in noisy data.

2.2 Gradient Measurements

To obtain gradient data, gravity was measured at three locations (the gradiometry triplet) for each station, the primary station and two secondary stations separated from the base by 10-20 meters in orthogonal directions. The change in the vertical gravity in two orthogonal horizontal directions, or the gradient vector, is then calculated and broken into two consistent components (either N-S, E-W or along-profile, cross-profile).

The unit for gravity gradient data is the Eötvös unit, where 1 Eötvös = 10^{-4} mGal/m.

3. FIELD PROCEDURES

3.1 Gravity Instrumentation

NGA utilized a Scintrex CG-3M high resolution automated gravity meter for the North Spokane survey. This meter has a "reading resolution" of 1 μGal and a "standard deviation of measurements from the mean" of 5 μGal using normal procedures. The instrument automatically integrates the signal over time, using spike noise rejection filters, to obtain the a mean and standard deviation for each station. The instrument makes automatic corrections for instrument tilt, temperature, and earth tides.

3.2 Survey Position Control

A conventional land survey was conducted by Mr. Larry Benson of J. Paul Ramer and Associates, Inc., Spokane, Washington. Each gravity station (the base point of each triplet) was surveyed to a vertical accuracy of 0.05 feet and a horizontal accuracy of better than 0.1 feet. Elevations were referenced to the Spokane County datum (USGS datum) and horizontal positions were referenced to an arbitrary datum. That datum was later "best fit" adjusted to a UTM datum from the USGS 7.5-minute Dartford quadrangle. Absolute UTM coordinates are estimated to be ±20 meters. Relative coordinates have survey accuracy of better than 2 cm.

Positions of the second and third points of the gradiometry triplets were measured relative to the surveyed base station of the triplet. Distance and azimuth were measured with a 300 foot tape and a Brunton compass, respectively. Relative elevations were measured using a laser level. Instrument height was measured from the survey pin to a reference on the meter (top of the meter) to the nearest 1/8 inch.

3.3 Loop Closure

Station 300 was used as a relative base station and was occupied three times each day (first reading, mid-day, and the last reading of each day) to monitor instrument drift.

3.4 Reference Base Station

The survey base station (Station 300) was tied to the Gravity reference base station at the Spokane main Post Office (NW corner of Riverside Ave. and Lincoln Street). A single loop was run from Station 300 to the Post office and back to Station 300 to close. The absolute "adopted gravity value" for that base station is published by Defense Mapping Agency as 980673.39 mGal. Observed gravity data from this survey have been adjusted to that datum.

3.5 Error Estimates

The overall precision of the survey is indicated by the 59 repeat stations, with a total of 150 repeat measurements. Average mis-tie was 5.9 μGal with a standard deviation of 14.0 μGal. Most of the repeats were a return to the primary station of the triplet after the other two stations had been measured.

Another measurement of precision is the standard deviation reported by the gravity meter. The meter automatically stacks or averages over a preset interval, and reports the average, and standard deviation of those measurements. On this survey, 60 to 120 measurements were stacked at each station. Reported standard deviations generally were in the range of 15-30 μGal.

For the gradient calculations (assuming a 10m separation, and adding errors x1/√2) this translates to a standard deviation of 19.8 Eötvös.

If we consider the "resolution" of the measurement as two standard deviations of the mis-ties, then the resolution of the gravity data is ±28 μGal and the resolution of the gradient data is ±30 Eötvös.

4. DATA PROCESSING

The following corrections have been made to the observed gravity data:

1. earth tide correction
2. instrumental drift correction (from loop closure)
3. latitude correction including spheroid and centrifugal effects (theoretical gravity)
4. free air (elevation) effect
5. simple Bouguer correction (density 2.20 gm/cm^3; "infinite slab")
6. terrain effects (Complete Bouguer)

Reduced data, including gradient data, are reported in Table 1 following the text.

Gravity data processing was carried out using the Geosoft software GRAVRED (Geosoft, 1994). The corrections are discussed below:

4.1 Earth Tides

Earth tides are the deformation of the solid earth in response to the gravitational forces of the moon and the sun. Like the ocean tides they have periodicities of approximately 12 hours and 24 hours. Solid earth tides are much more predictable than the ocean tides.

Theoretical values for the earth tides, given the date, time, latitude and longitude, are calculated by the microprocessor in the CG-3 gravimeter, and the appropriate correction is made to the data. Earth tide displacements can be up to 10 cm. (Sheriff, 1984). The gravity corrections applied for this survey were up to 100 μGal.

Tide corrections used for the final data compilation were calculated and applied in the GRAVRED processing using algorithms from the Dominion Observatory of Canada.

4.2 Instrument Drift

Instrument drift is corrected for assuming a linear drift over time, between the previous base station reading and the subsequent base station reading. Base station readings (station 300) were taken a minimum of three times per day (first reading, mid-day, and last readings of the day).

4.3 Theoretical Geoid

"Theoretical Geoid" takes into account the shape of the earth (a flattened oblate ellipsoid) and includes the latitude effect and the effect of centrifugal force. Geoid calculations were carried out and applied in the GRAVRED processing using the 1967 gravity formula:

$$g_l = 978031.846 \cdot [\ 1+0.005278895\sin^2(l)-0.000023462\sin^4(l)\ ]$$

where:

- g_l theoretical gravity in mGal (latitude correction),
- l latitude of the station

4.4 Free Air Correction

This correction is made for the differences in distance of the observation points from the center of the mass of the earth. Free air corrections were calculated and applied in the GRAVRED processing using the formula:

$$g_f = 0.308596 \cdot h_s$$

where:

- g_f free air correction in mGal
- h_s station elevation in meters.

The free air anomaly is:

$$g_{fa} = g_{obs} - g_l + g_f$$

where:

- g_{fa} free air gravity anomaly
- g_{obs} observed gravity (tide and drift corrected)
- g_l theoretical gravity in mGal (sect 4.3),

4.5 Simple Bouguer Correction

The simple Bouguer correction accounts for the attraction of the mass of rock between the station elevation and the datum (mean sea level). That mass is assumed to have a density equal to a chosen "Bouguer correction density". This correction should remove or reduce elevation effects in the data.

The Bouguer correction density of 2.2 gm/cm^3 was selected on the basis of "Nettleton plots" which are cross-plots of Bouguer corrected gravity versus station elevation.

The Bouguer anomaly calculations were carried out and applied in the GRAVRED processing using the formula:

$$g_{ba} = g_{fa} - 0.0419088\,(\rho \bullet h_s)$$

where:

- g_{ba} Bouguer anomaly in mGal,
- g_{fa} Free air anomaly (sect. 4.4),
- ρ Bouguer density of rock in g/cm^3 (2.2 gm/cm^3 for this survey),
- h_s station elevation in meters.

Simple Bouguer terrain correction was calculated and applied in the GRAVRED processing.

4.6 Complete Bouguer Correction

The complete Bouguer, or terrain correction, accounts for the topography of the land surface, and variations from the horizontal slab which is assumed for the simple Bouguer correction.

For this survey a digital topographic database from the U.S. Geological Survey (USGS, 1993) was used. The digital elevation model (DEM), which is a raster form of the 7.5 minute quadrangle with a grid cell size of 30 meters, was employed for topography beyond 250 meters. Geosoft software program TERRAIN was used to calculate the correction for each point. All three stations in each gradient triplet were corrected independently. Corrections for each station are listed in Table 1.

4.7 Near field Terrain Correction

Additional manual near-zone terrain corrections were made for a dozen stations where there was significant topographic relief within 250 feet of the station. These corrections were calculated from field notes made at the time of the survey. Corrections for each station are listed in Table 1.

5. MODELING AND INTERPRETATION

Prior to modeling, the corrected data were first gridded and then data were extracted from the grid along the line of the profile. This procedure has two effects: 1) it reduces some of the "off-line" effects, due to changes occurring in a direction perpendicular to the profile line, 2) it acts as a smoothing filter. The ungridded data have a data spacing which is approximately the same as the grid interval (20 m), depending also on the profile azimuth. Hence the modeled "observed data" in Figures 2, 3, and 4 have a "station spacing" of approximately 20 meters.

The profile data were then modeled using NGA's 2½-D modeling software, ***GM-SYS™***. Well data from the WWD well and the Dakota well were used as constraints on the model, as was the Mayfair well which did not encounter bedrock. Bedrock outcrops at the southwest end of the line, and on Dart Hill were also used as constraints.

6. DISCUSSION OF RESULTS

The gravity data have been interpreted to show the thickness of sediments along the gravity transect across the Hillyard Trough in North Spokane. Figure 1 and Plate 1 are site maps showing the locations of the gravity stations, and showing the straight line profiles which were modeled. Figure 1 is at a scale of 1:20,000 and gives an overview of the area, whereas Plate 1 is at a scale of 1:10,000 and provides more detail. Figures 2 and 3 show that interpretation: Figure 2 along the transect through the Dakota Well, and Figure 3 extending north to Dart Hill.

6.1 Microgravity Profiles

Several comments concerning the modeled microgravity profiles:

- There is some ambiguity, or non-uniqueness, in the depth interpretation in that we do not know the density of the trough sediments. The interpretation in Figures 2 & 3 uses a density of 1.95 gm/cm^3. Figure 4 shows an alternate interpretation using a density of 2.10 gm/cm^3, which was the density selected throughout the Spokane Valley by Purves (1969) on the basis of some samples and on the fit to well data. Both models (Figures 2 & 4) fit both the Whitworth Water District well (WWD) and the Dakota well. The shape and morphology of the basin is the same in both models, as it will be for any given density, but the depth scale is "stretched" somewhat for the higher density.
- This interpretation used a uniform density for the sediments throughout the basin. Changes in density will, of course, alter the interpretation. However, *a priori* we have no justification for inserting density variations without some additional geologic input. The well data does show some stratigraphic variations which could be included in the model. However the observed stratigraphic variations will result in relatively minor density variations. With only limited borehole data, any model including those stratigraphic features would be highly speculative.
- The Lafferty well, 300 meters west of the Dart Hill gravity profile, reached its total depth (TD) at 433 meters elevation (MSL) and did not encounter bedrock. This is deeper than the interpreted depth-to-bedrock on either of the adjacent

Further microgravity surveys are recommended in the North Spokane valley wherever that depth-to-bedrock information would prove useful in constructing and constraining the hydrologic model of the area, or where that information would otherwise aid in the geologic interpretation.

The gradient data proved difficult to collect and analyze. Data from this survey did not provide the increased resolution we had hoped for. We still believe that with some incremental improvements in field techniques and procedures the desired resolution of 10-20 Eötvös can be obtained and modeled to provide increased near surface resolution.

Gradiometry is currently a developing technique and not readily offered by other geophysical contractors. Our familiarity with the process would lead to several minor procedural changes in instrumental operation and data processing. Also, for future surveys, we would recommend that all three points of the gradiometry triplet be surveyed by the land survey, and that coordinates be referenced to UTM coordinates.

NGA would again collect and analyze the additional gradiometry data at no additional cost to the client if contracted to perform another microgravity survey.

8. REFERENCES:

Geosoft Inc., 1994, *Gravity processing system:* Geosoft Incorporated, Toronto.

Purves, W.J., 1969, *Stratigraphic control of the groundwater through Spokane Valley:* Washington State University Masters Thesis.

Sheriff, 1984, *Encyclopedic dictionary of exploration geophysics:* Society of Exploration Geophysicists, Tulsa, OK.

U.S. Geological Survey, 1993, Digital elevation models --data users guide 5: Reston, Virginia, U.S. Geological Survey, 48 p.

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TABLE 1
Gravity Data Listing

/ North Spokane Gravity Data
/
/ field survey: NGA; 5/6/97 to 5/8/97
/ NGA Proj.# 382
/ from spgv_ab.xyz 8/19/97
/ UTM coordinates given here to nearest meter due to rounding limitations
/ for gradient calculations positions more accurate positions were used.
/
/ Stn # - Field station number = Station # x10 plus triad leg # (0, 1, or 2)
/ Gsb - Simple Bouguer Anomaly density = 2.2 gm/cc
/ TC - Terrain correction from DEM (>250m)
/ Gb2 = Gsb + Tc
/ Tnf - near field (<250m) terrain correction from field notes
/ Gcb - Complete Bouguer Anomaly = Gb2 + Tnf
/
/

30-Dec-97

/ UTM Coordinates (meters)				Gravity (mGal):				
/ EAST	NORTH	Stn#	Elev(m)	Gsb	TC	Gb2	Tnf	Gcb
/								
467,977	5,289,440	110	552.124	-59.1315	0.4350	-58.6970	0.0251	-58.6719
468,221	5,289,448	300	547.909	-60.2690	0.3510	-59.9180	0.0002	-59.9178
468,209	5,289,456	301	547.945	-60.2680	0.3570	-59.9110	0.0033	-59.9077
468,212	5,289,437	302	548.186	-60.2330	0.3520	-59.8810	0.0032	-59.8778
468,412	5,289,348	710	541.410	-60.3090	0.4370	-59.8720	0.0000	-59.8720
468,425	5,289,343	711	540.868	-60.2740	0.4480	-59.8260	0.0000	-59.8260
468,417	5,289,359	712	540.956	-60.3830	0.4230	-59.9600	0.0000	-59.9600
468,507	5,289,374	800	536.911	-60.4405	0.4080	-60.0330	0.0019	-60.0311
468,521	5,289,388	801	536.948	-60.5410	0.3910	-60.1500	0.0000	-60.1500
468,521	5,289,360	802	536.789	-60.5440	0.4210	-60.1230	0.0000	-60.1230
468,521	5,289,450	900	537.240	-60.6657	0.3410	-60.3250	0.0000	-60.3250
468,512	5,289,442	901	537.152	-60.5980	0.3470	-60.2510	0.0000	-60.2510
468,515	5,289,460	902	537.240	-60.6470	0.3340	-60.3130	0.0000	-60.3130
468,536	5,289,527	1000	537.554	-60.8900	0.2970	-60.5930	0.0000	-60.5930
468,528	5,289,543	1001	537.701	-60.8810	0.2910	-60.5900	0.0019	-60.5881
468,521	5,289,517	1002	537.497	-60.8120	0.3020	-60.5100	0.0000	-60.5100

/ UTM Coordinates (meters)				Gravity (mGal):				
/ EAST	NORTH	Stn#	Elev(m)	Gsb	TC	Gb2	Tnf	Gcb
/								
468,550	5,289,602	1100	540.636	-61.1227	0.2720	-60.8510	0.0076	-60.8434
468,550	5,289,582	1101	540.477	-61.1295	0.2750	-60.8540	0.0000	-60.8540
468,570	5,289,598	1102	539.645	-61.0980	0.2700	-60.8280	0.0076	-60.8204
468,627	5,289,589	1200	541.267	-61.2632	0.2640	-60.9990	0.0000	-60.9990
468,618	5,289,597	1201	541.179	-61.2500	0.2640	-60.9860	0.0000	-60.9860
468,640	5,289,605	1202	541.535	-61.3180	0.2600	-61.0580	0.0046	-61.0534
468,686	5,289,624	1300	542.239	-61.4248	0.2490	-61.1750	0.0000	-61.1750
468,675	5,289,627	1301	541.770	-61.4700	0.2500	-61.2200	0.0000	-61.2200
468,690	5,289,635	1302	542.331	-61.4600	0.2470	-61.2130	0.0058	-61.2072
468,745	5,289,658	1400	543.891	-61.5963	0.2390	-61.3570	0.0000	-61.3570
468,739	5,289,677	1401	544.260	-61.6300	0.2360	-61.3940	0.0000	-61.3940
468,727	5,289,650	1402	543.346	-61.5565	0.2420	-61.3150	0.0019	-61.3131
468,734	5,289,716	1500	545.229	-61.7352	0.2290	-61.5060	0.0027	-61.5033
468,754	5,289,717	1501	545.321	-61.7740	0.2260	-61.5480	0.0011	-61.5469
468,734	5,289,736	1502	545.662	-61.7980	0.2250	-61.5730	0.0000	-61.5730
468,722	5,289,776	1600	546.250	-61.9110	0.2200	-61.6910	0.0000	-61.6910
468,711	5,289,781	1601	546.445	-61.9110	0.2210	-61.6900	0.0000	-61.6900
468,717	5,289,766	1602	546.342	-61.8750	0.2220	-61.6530	0.0000	-61.6530
468,784	5,289,776	1700	545.949	-62.0517	0.2160	-61.8360	0.0000	-61.8360
468,796	5,289,776	1701	545.918	-62.0720	0.2150	-61.8570	0.0000	-61.8570
468,784	5,289,788	1702	546.055	-62.1093	0.2150	-61.8940	0.0000	-61.8940
468,839	5,289,776	1800	545.735	-62.1755	0.2100	-61.9660	0.0000	-61.9660
468,851	5,289,775	1801	545.723	-62.2035	0.2080	-61.9950	0.0000	-61.9950
468,840	5,289,788	1802	545.955	-62.2180	0.2080	-62.0100	0.0000	-62.0100
468,912	5,289,776	1900	545.747	-62.3455	0.2010	-62.1450	0.0000	-62.1450
468,899	5,289,776	1901	545.278	-62.3900	0.2020	-62.1880	0.0000	-62.1880
468,912	5,289,761	1902	545.650	-62.3355	0.2030	-62.1330	0.0000	-62.1330
468,978	5,289,776	2000	546.211	-62.5155	0.1990	-62.3160	0.0000	-62.3160
468,978	5,289,788	2001	546.180	-62.5370	0.1980	-62.3390	0.0000	-62.3390
468,992	5,289,775	2002	546.046	-62.5595	0.1990	-62.3610	0.0000	-62.3610
468,993	5,289,854	2100	546.485	-62.7245	0.1940	-62.5300	0.0000	-62.5300
468,997	5,289,843	2101	546.391	-62.6780	0.1950	-62.4830	0.0000	-62.4830

TABLE 1

UTM Coordinates (meters) EAST	NORTH	Stn#	Elev(m)	Gravity (mGal): Gsb	TC	Gb2	Tnf	Gcb
469,010	5,289,860	2102	546.439	-62.7390	0.1950	-62.5440	0.0000	-62.5440
469,054	5,289,893	2200	546.689	-62.8735	0.1960	-62.6770	0.0000	-62.6770
469,042	5,289,899	2201	546.750	-62.8810	0.1960	-62.6850	0.0000	-62.6850
469,061	5,289,909	2202	546.823	-62.9490	0.1980	-62.7510	0.0000	-62.7510
469,109	5,289,924	2300	546.573	-63.0140	0.2090	-62.8050	0.0004	-62.8046
469,097	5,289,931	2301	546.689	-63.0510	0.2060	-62.8450	0.0004	-62.8446
469,116	5,289,939	2302	546.567	-63.0680	0.2140	-62.8540	0.0004	-62.8536
469,164	5,289,954	2400	546.141	-63.1215	0.2370	-62.8840	0.0000	-62.8840
469,165	5,289,966	2401	546.220	-63.1840	0.2370	-62.9470	0.0000	-62.9470
469,152	5,289,956	2402	546.052	-63.1980	0.2300	-62.9680	0.0000	-62.9680
469,225	5,289,988	2500	545.912	-63.3240	0.2560	-63.0680	0.0000	-63.0680
469,218	5,289,978	2501	545.875	-63.2670	0.2600	-63.0070	0.0005	-63.0065
469,215	5,289,995	2502	545.455	-63.3840	0.2500	-63.1340	0.0005	-63.1335
469,225	5,290,058	2600	545.732	-63.4697	0.2190	-63.2510	0.0000	-63.2510
469,217	5,290,052	2601	545.263	-63.5190	0.2210	-63.2980	0.0000	-63.2980
469,218	5,290,070	2602	545.754	-63.4910	0.2160	-63.2750	0.0000	-63.2750
469,225	5,290,120	2700	546.942	-63.6330	0.2000	-63.4330	0.0000	-63.4330
469,225	5,290,108	2701	546.714	-63.6040	0.2040	-63.4000	0.0000	-63.4000
469,237	5,290,119	2702	546.631	-63.6120	0.2010	-63.4110	0.0000	-63.4110
469,308	5,290,121	2800	545.580	-63.6930	0.1930	-63.5000	0.0000	-63.5000
469,317	5,290,116	2801	545.501	-63.6300	0.1940	-63.4360	0.0000	-63.4360
469,299	5,290,116	2802	545.245	-63.7480	0.1940	-63.5540	0.0000	-63.5540
469,392	5,290,123	2900	543.797	-63.7285	0.1960	-63.5320	0.0000	-63.5320
469,395	5,290,112	2901	543.154	-63.7940	0.1990	-63.5950	0.0000	-63.5950
469,381	5,290,121	2902	543.666	-63.7770	0.1950	-63.5820	0.0000	-63.5820
469,477	5,290,125	3000	543.166	-63.7930	0.2100	-63.5830	0.0000	-63.5830
469,476	5,290,137	3001	542.992	-63.8000	0.2090	-63.5910	0.0000	-63.5910
469,465	5,290,124	3002	543.340	-63.7757	0.2090	-63.5670	0.0000	-63.5670
469,494	5,290,183	3100	542.730	-63.8700	0.1960	-63.6740	0.0000	-63.6740
469,483	5,290,177	3101	542.590	-63.8570	0.1970	-63.6600	0.0000	-63.6600
469,489	5,290,194	3102	542.913	-63.8690	0.1930	-63.6760	0.0000	-63.6760
469,511	5,290,240	3200	542.840	-63.9140	0.1860	-63.7280	0.0000	-63.7280

UTM Coordinates (meters)				Gravity (mGal):				
EAST	NORTH	Stn#	Elev(m)	Gsb	TC	Gb2	Tnf	Gcb
469,520	5,290,246	3201	542.425	-63.9180	0.1850	-63.7330	0.0000	-63.7330
469,504	5,290,248	3202	542.864	-63.9370	0.1840	-63.7530	0.0000	-63.7530
469,529	5,290,301	3300	542.410	-63.9750	0.1850	-63.7900	0.0000	-63.7900
469,515	5,290,298	3301	542.617	-63.9560	0.1840	-63.7720	0.0000	-63.7720
469,525	5,290,316	3302	542.389	-63.9770	0.1880	-63.7890	0.0000	-63.7890
469,541	5,290,374	3400	542.151	-63.9490	0.2120	-63.7370	0.0000	-63.7370
469,533	5,290,367	3401	542.072	-63.9600	0.2070	-63.7530	0.0000	-63.7530
469,534	5,290,382	3402	542.184	-63.9680	0.2130	-63.7550	0.0000	-63.7550
469,641	5,290,536	3800	541.252	-63.8873	0.3130	-63.5740	0.0000	-63.5740
469,621	5,290,535	3801	541.691	-63.8920	0.3120	-63.5800	0.0000	-63.5800
469,644	5,290,556	3802	541.730	-63.8690	0.2880	-63.5810	0.0000	-63.5810
469,719	5,290,536	3900	540.200	-63.8827	0.2190	-63.6640	0.0012	-63.6628
469,699	5,290,537	3901	540.389	-63.8880	0.2410	-63.6470	0.0000	-63.6470
469,720	5,290,556	3902	541.090	-63.8420	0.2120	-63.6300	0.0016	-63.6284
469,846	5,290,533	4100	539.066	-63.9190	0.1770	-63.7420	0.0004	-63.7416
469,826	5,290,535	4101	539.206	-63.8980	0.1780	-63.7200	0.0008	-63.7192
469,847	5,290,553	4102	539.240	-63.8720	0.1750	-63.6970	0.0000	-63.6970
469,851	5,290,611	4200	539.142	-63.8490	0.1710	-63.6780	0.0000	-63.6780
469,852	5,290,631	4201	538.792	-63.8330	0.1680	-63.6650	0.0000	-63.6650
469,831	5,290,611	4202	539.155	-63.8480	0.1720	-63.6760	0.0000	-63.6760
469,856	5,290,688	4300	539.045	-63.6690	0.1660	-63.5030	0.0000	-63.5030
469,864	5,290,707	4301	539.210	-63.6340	0.1660	-63.4680	0.0000	-63.4680
469,875	5,290,681	4302	538.886	-63.6770	0.1660	-63.5110	0.0000	-63.5110
469,925	5,290,768	4410	538.886	-63.5663	0.1790	-63.3870	0.0000	-63.3870
469,945	5,290,767	4411	539.267	-63.5430	0.1830	-63.3600	0.0000	-63.3600
469,924	5,290,748	4412	539.142	-63.5780	0.1760	-63.4020	0.0000	-63.4020
470,043	5,290,838	4430	537.503	-63.3293	0.2430	-63.0860	0.0046	-63.0814
470,056	5,290,823	4431	537.292	-63.3680	0.2420	-63.1260	0.0000	-63.1260
470,060	5,290,849	4432	536.817	-63.3050	0.2460	-63.0590	0.0000	-63.0590
470,143	5,290,846	4440	537.664	-63.2935	0.2720	-63.0220	0.0000	-63.0220
470,162	5,290,851	4441	538.060	-63.3400	0.2810	-63.0590	0.0043	-63.0547
470,138	5,290,866	4442	537.847	-63.2410	0.2720	-62.9690	0.0000	-62.9690

/ UTM Coordinates (meters)				Gravity (mGal):				
/ EAST	NORTH	Stn#	Elev(m)	Gsb	TC	Gb2	Tnf	Gcb
/								
469,883	5,290,920	4600	537.984	-63.2770	0.1940	-63.0830	0.0010	-63.0820
469,891	5,290,905	4601	538.018	-63.3395	0.1920	-63.1480	0.0002	-63.1478
469,897	5,290,929	4602	538.222	-63.2300	0.1920	-63.0380	0.0000	-63.0380
469,902	5,290,996	4700	537.628	-63.0005	0.1950	-62.8060	0.0044	-62.8016
469,911	5,290,981	4701	536.991	-63.0200	0.1910	-62.8290	0.0040	-62.8250
469,917	5,291,004	4702	536.777	-62.9310	0.1920	-62.7390	0.0040	-62.7350
469,930	5,291,151	4900	536.594	-62.3985	0.2200	-62.1780	0.0058	-62.1722
469,935	5,291,135	4901	537.698	-62.4880	0.2150	-62.2730	0.0038	-62.2692
469,946	5,291,156	4902	537.362	-62.4680	0.2250	-62.2430	0.0031	-62.2399
469,853	5,291,316	5100	535.552	-61.9065	0.2420	-61.6650	0.0163	-61.6487
469,866	5,291,331	5101	535.500	-62.0210	0.2490	-61.7720	0.0376	-61.7344
469,864	5,291,305	5102	535.494	-61.9860	0.2470	-61.7390	0.0067	-61.7323
467,386	5,289,018	9900	591.312	-73.9600	0.7400	-73.2200	0.0000	-73.2200

/ end of data

TABLE 2
Gravity Gradient Listing

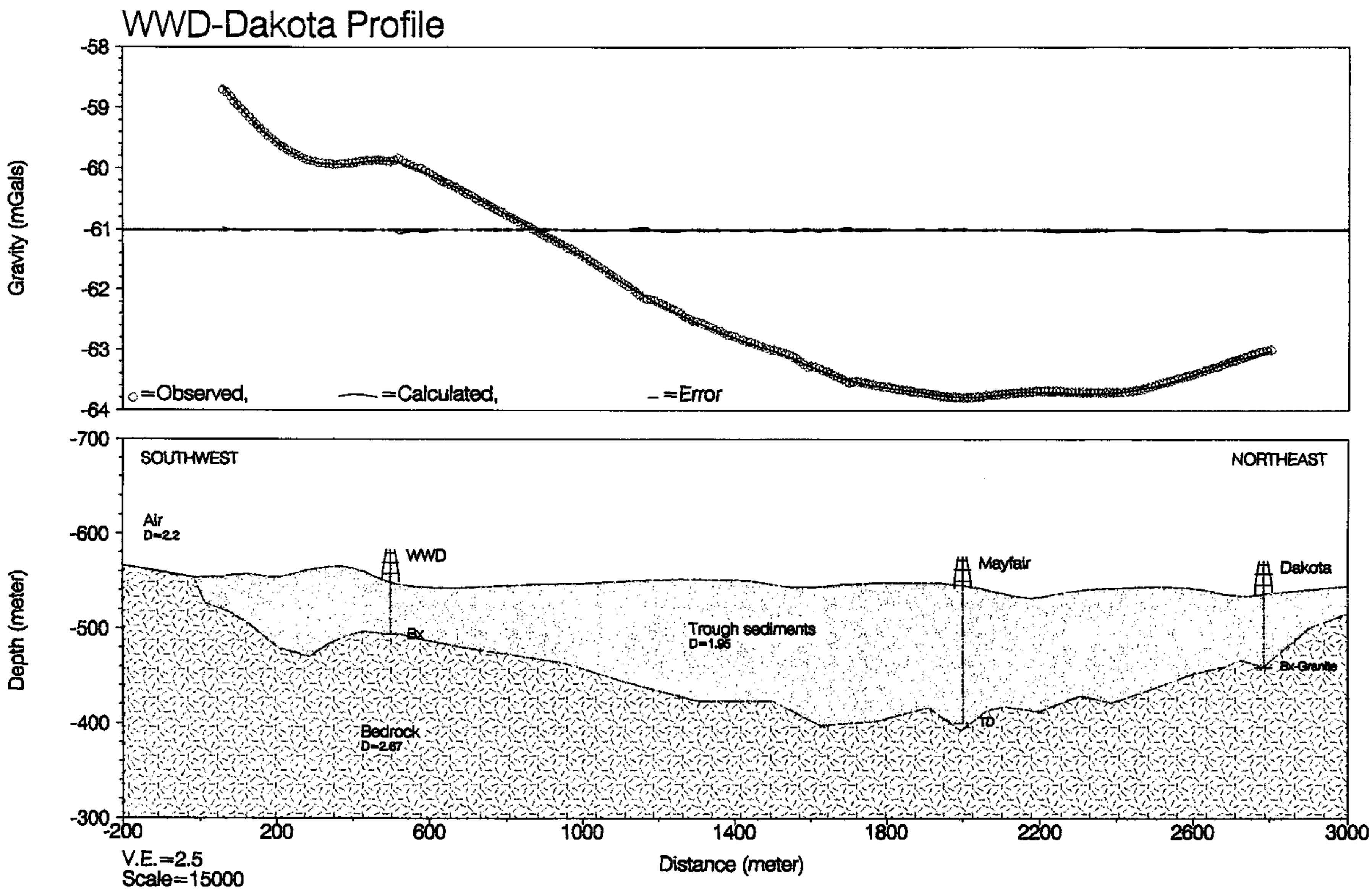
/ North Spokane Gravity Data
/
/ field survey: NGA; 5/6/97 to 5/8/97
/ NGA Proj.# 382
/ from GRAD.XLS spreadsheet 30-Dec-97 2:30 PM
/ Gz -Complete Bouguer Gravity (mGal); density 2.2 gm/cm3
/ Gzx, Gzy, GzE, & GzN - Gravity gradients (Eotvos units)
/ Magnetude & Azimuth - Mganetude and azimuth of gradient vector
/

/	UTM Coordinates (meters)					Gradients (Eotov units)					
/	EAST	NORTH	Stn#	Elev(m)	Gz	Gzx	Gzy	GzE	GzN	Magnitude	Azimuth
	467976.78	5289439.83	11	552.120	-58.671	*	*	*	*	0.0	0
	468220.61	5289447.37	30	547.910	-59.918	-18.6	-22.8	-22.6	-18.9	29.5	230
	468412.12	5289347.56	71	541.410	-59.872	-53.2	-63.2	2.1	-82.6	82.6	179
	468506.74	5289373.47	80	536.910	-60.031	-61.3	42.3	-74.0	-9.0	74.5	263
	468521.30	5289449.81	90	537.240	-60.325	-61.8	19.4	-59.1	-26.5	64.8	246
	468535.90	5289526.37	100	537.550	-60.593	-44.2	15.1	-43.1	-18.0	46.7	247
	468550.16	5289601.15	110	540.640	-60.843	12.8	-4.8	12.8	4.9	13.7	69
	468627.08	5289588.76	120	541.270	-60.999	-28.6	7.7	-26.5	-13.3	29.6	243
	468686.01	5289623.12	130	542.240	-61.175	-4.1	-45.9	27.4	-37.1	46.1	144
	468745.11	5289657.57	140	543.890	-61.357	-25.7	-8.6	-13.6	-23.5	27.1	210
	468733.55	5289715.63	150	545.230	-61.503	-38.5	-11.5	-21.2	-34.1	40.2	212
	468721.62	5289775.57	160	546.250	-61.691	-32.3	-12.5	-15.9	-30.8	34.6	207
	468783.51	5289775.56	170	545.950	-61.836	-45.1	-24.6	-17.5	-48.3	51.4	200
	468838.57	5289775.56	180	545.740	-61.966	-43.2	-5.9	-28.4	-33.0	43.6	221
	468911.66	5289775.55	190	545.750	-62.145	19.5	-27.9	33.1	-8.0	34.0	104
	468977.61	5289775.55	200	546.210	-62.316	-36.2	9.5	-33.4	-16.9	37.4	243
	468992.60	5289853.75	210	546.490	-62.530	-21.6	-33.6	6.1	-39.5	39.9	171
	469053.63	5289892.95	220	546.690	-62.677	-37.1	-23.6	-12.1	-42.3	44.0	196

/ UTM Coordinates (meters)					Gradients (Eotov units)					
/ EAST	NORTH	Stn#	Elev(m)	Gz	Gzx	Gzy	GzE	GzN	Magnitude	Azimuth
469108.64	5289923.36	230	546.570	-62.805	-16.0	-35.5	11.5	-37.2	38.9	163
469163.49	5289953.68	240	546.140	-62.884	3.7	-85.3	59.4	-61.4	85.4	136
469224.78	5289987.56	250	545.910	-63.068	-38.3	-64.4	14.0	-73.5	74.9	169
469224.69	5290057.37	260	545.730	-63.251	45.3	-29.5	53.4	8.0	54.0	82
469224.61	5290119.07	270	546.940	-63.433	-5.9	-31.5	16.5	-27.5	32.0	149
469308.43	5290120.96	280	545.580	-63.500	39.4	-56.9	67.2	-16.4	69.1	104
469392.44	5290122.85	290	543.800	-63.532	62.6	24.0	30.9	59.5	67.0	27
469476.70	5290124.75	300	543.166	-63.583	-14.4	2.4	-12.4	-7.8	14.6	-122
469493.77	5290182.40	310	542.730	-63.674	-11.6	1.5	-9.7	-6.6	11.7	236
469510.60	5290239.24	320	542.840	-63.728	-7.0	-24.7	11.2	-23.1	25.7	154
469528.80	5290300.72	330	542.410	-63.790	-11.2	6.3	-12.6	-2.7	12.9	258
469540.63	5290373.87	340	542.150	-63.737	15.0	-17.4	22.7	-3.1	22.9	98
469641.08	5290535.38	380	541.250	-63.574	-0.3	-5.1	3.1	-4.0	5.1	142
469718.94	5290535.15	390	540.200	-63.663	6.7	17.7	-6.7	17.7	18.9	339
469845.55	5290532.81	410	539.070	-63.742	8.5	23.5	-9.2	23.2	25.0	338
469850.97	5290610.23	420	539.140	-63.678	3.8	5.4	-0.8	6.5	6.6	353
469856.38	5290687.59	430	539.040	-63.503	13.5	11.9	2.3	17.9	18.0	7
469924.47	5290767.38	441	538.890	-63.387	15.0	-3.9	13.8	7.0	15.4	63
470043.07	5290837.44	443	537.500	-63.081	15.1	22.2	-3.4	26.6	26.8	353
470142.75	5290845.82	444	537.660	-63.022	-2.8	31.0	-22.7	21.4	31.1	313
469882.94	5290919.32	460	537.980	-63.082	45.1	1.7	2.3	45.1	45.1	3
469902.32	5290995.23	470	537.630	-62.802	33.4	-24.7	27.6	31.0	41.5	42
469929.58	5291150.18	490	536.590	-62.172	35.8	59.7	-56.2	41.0	69.6	306
469852.56	5291315.31	510	535.550	-61.649	-2.7	69.3	-69.3	3.5	69.4	273

/ end of data

NGA Project #: 382 FILE: SPK_FIGS.dwg (Fig2) DATE: 16-AUG-97 REVISION: C-22-DEC-97



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Trough sediments
Density=1.95 gm/cm 3

FIGURE 2

GRAVITY MODEL: WWD to DAKOTA WELL

NORTH SPOKANE AQUIFER STUDY

NGA Project #: 382 FILE: SPK_FIGS.dwg (Fig3) DATE: 16-AUG-97 REVISION: C-22-DEC-97

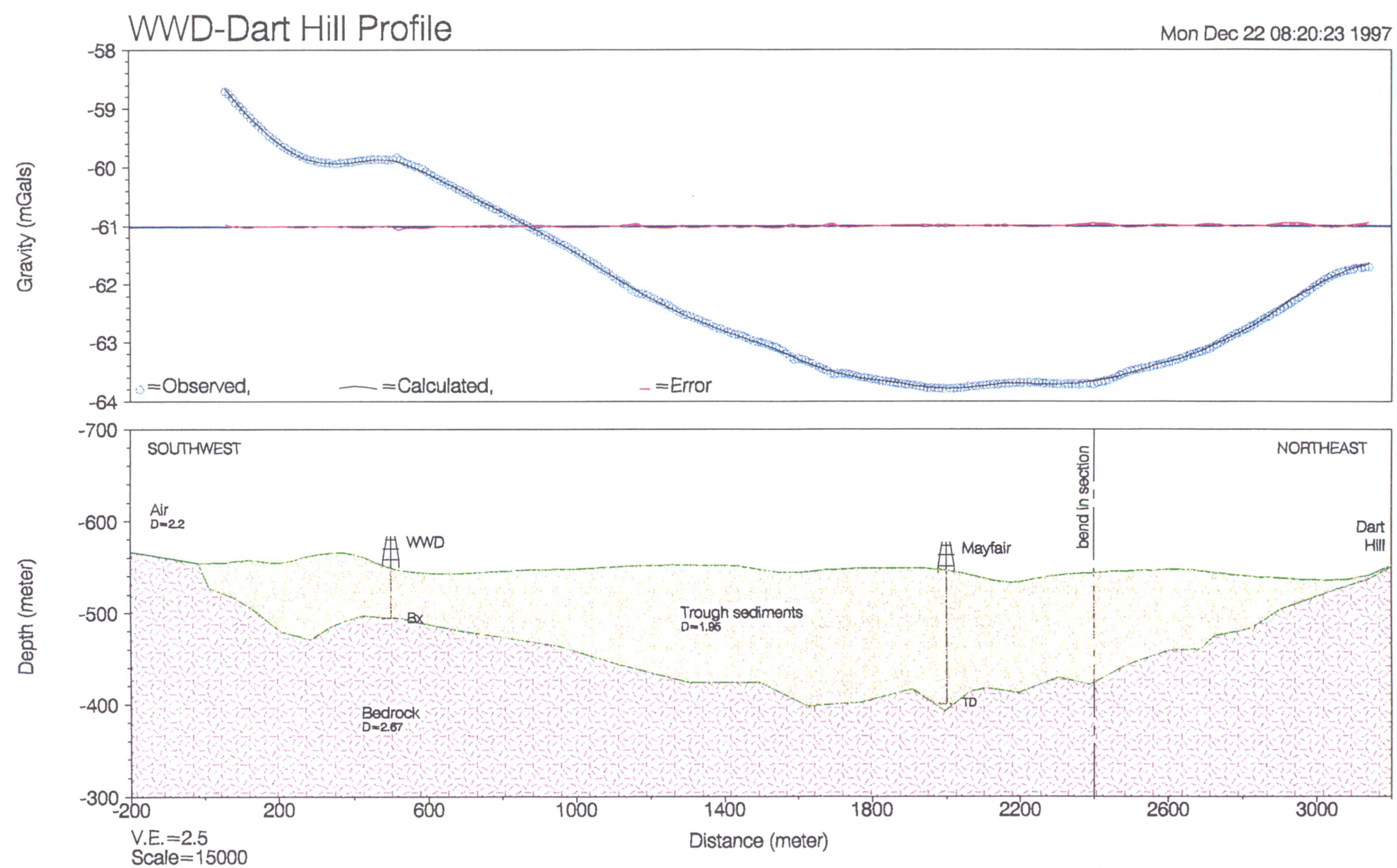

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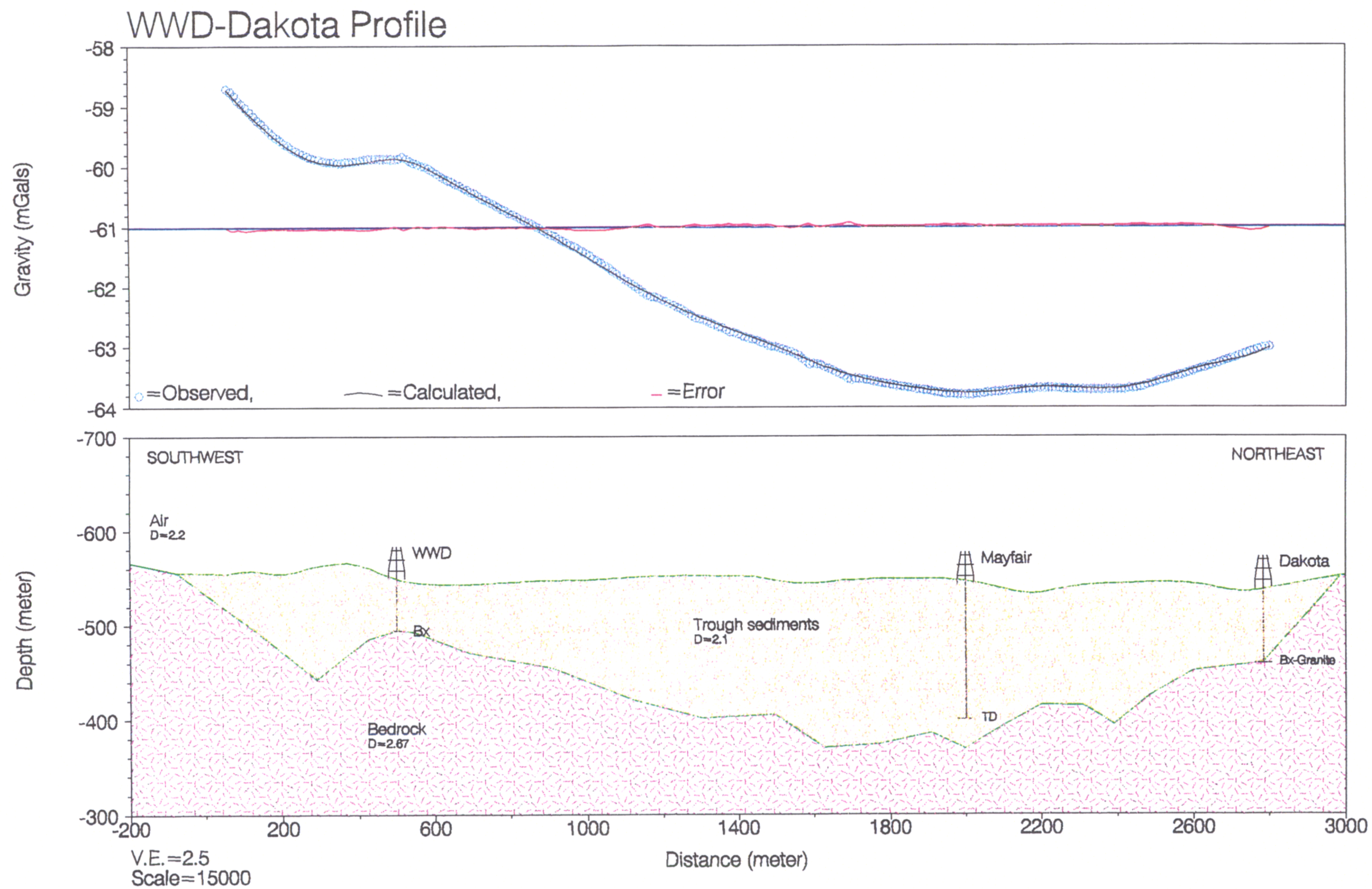
FIGURE 3

GRAVITY MODEL: WWD to DART HILL

NORTH SPOKANE AQUIFER STUDY

NGA Project #: 382 FILE: SPK_FIGS.dwg (Fig 4) DATE: 16-AUG-97 REVISION: C-22-DEC-97



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Trough sediments
Density=2.1 gm/cm ^{3}

GRAVITY MODEL:
ALTERNATE INTERPRETATION
NORTH SPOKANE AQUIFER STUDY

FIGURE 4