Gravimetric Survey in the VIDAL quadrangle

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Abstract

Knowledge of local gravity fields allows for the interpretation of structures beneath the earth. Faults, bedrock depths, subsurface voids and other crustal anomalies can be detected by interpreting the local gravity. In this paper we summarize a gravity survey done on the Riverside mountains in California. We show that the gravity data is consistent with the geologic structure proposed.

1 Introduction

1.1 Goal of gravity measurements

Geophysics is the study of the earth through the measurement of physical properties. Out of Newton's universal law of gravitation we can derive

$$g(r) = \frac{mG}{r^2} \tag{1}$$

G is a known constant and g and r can be measured in the field. From this m can be calculated, which is the mass underneath the place where gravity is being measured. If the mass is known, the density

$$\rho = \frac{m}{V} = \frac{m}{Ah} \tag{2}$$

of a certain rock type can be calculated by changing elevation h locally. From the knowledge of the change in rock density multiple observations of subsurface structures can be made.

Knowledge of local gravity fields allows for the interpretation of structures beneath the earth. Faults, bedrock depths, subsurface voids and other crustal anomalies can all be detected by interpreting the local gravity. It is impossible to understand local geology completely by merely observing surface rocks and structures. Putting together geology and local gravity can lead to a better understanding of crustal bedrock structures. Measuring gravity is one way in the field of observing deep structures and density differences below the surface. Other techniques, like seismology, are available but were not used in this field exercise.

1.2 Method

Gravity changes very little in a given region, thus highly sensitive equipment must be used and time must be taken at each point to obtain an accurate reading. Other considerations must be taken into account and corrections to measurements must be applied. Corrections for drift, changes in latitude, tides, elevation and terrain effects must be accounted for. Most of the corrections are simple calculations. The terrain effects correction, however, needed to be converted from its original state into a form which we could use.

Despite these difficulties, local gravity must be known to better understand local geology. As per equations (1) and (2), observed gravity is proportional to rock density. Therefore an area of high gravity implies a higher density rock underneath and low gravity implies low density. If a higher density rock, like igneous, is observed at the surface next to a low density rock, like sedimentary, and the local gravity indicates a gradient of high to low density under the sedimentary portion it might be concluded that the igneous dips under the sedimentary rocks.

1.3 Location

Location of basecamp:
$34°3.7548'$ N, $114°32.6438'$ W (in WGS84 coordinates)

Elevation: 234.448 m ellipsoidal height
Geoidal height in that area[a]: -31.57 m

[a] http://www.ngs.noaa.gov/cgi-bin/datasheet.prl

The Riverside Mountains are located around 34 degrees north and 114.5 degrees west. The most recent geologic map of the area is two and a half decades old. The southeastern part of California is being slowly deformed by the active faulting to the west. The area is essentially being dragged along with the fault and moves slightly every year. Ever since the Farallon Plate started being subducted under North America, a subduction and strike slip fault zone has existed along the western edge of California. Most of the motion today is the result of the pacific plate moving north and the North American plate moving south relative to each other. This motion can be detected through static GPS.

Our survey area is located west of Palm Springs and north of Blythe. Most of the structures in this area have a northwesterly trend. Most of the relief is tectonic in origin due to faulting. The San Andreas fault runs NW-SE to the west of Palm Springs. Multiple smaller faults exist perpendicular and parallel to the San Andreas. The general topography of the area is rugged mountains with alluviated valleys in between in multiple stages of desert erosion.

The geology of our specific area is quite complicated. In general, a Precambrian basement is exposed in the north which is up against thrust fault with Cretateous, Miocene and Permain areas to its south. These two areas have a fault between them and to the southwest lies Quaternerary deposits. The Triassic areas are mostly black shale, the Miocene is red conglomerate and alluvial deposits fill up the riverbeds.

1.4 Regional gravity data

Very few large area gravity surveys of the Riverside Mountains have been done in the past. The gravity points from these surveys were too sparsely scattered to be useful for what we wanted to accomplish. Ideally, as we traverse different formations, multiple gravity measurements can be taken to identify the subsurface structure. This is hard to do with kilometers between data points as in the previous gravity surveys. To understand the geology in the area we are interested in, a much more intensive local survey was needed to be done.

1.5 Objectives

Our main goal in the survey was to compile local gravity measurements such that when interpreted with the observed surface geology a better understanding of the rocks below the crust could be obtained. The area we surveyed contained various geologic features such as faults and various rock types including conglomerates and metamorphic rocks. We set out with that data to measure gravity in the area to compile a better model for the contacts and rocks below the surface. We also wanted to measure the density of the rocks in the area. To do this we, while staying within a formation, took measurements at the top and bottom of canyons and hills.

We went into the area with only a rough geologic map and basic sketches of possible cross sections of the area. Each day, after collecting and processing the data we modified our plan for the next day's area of study. Measurements of elevation and gravity were taken every 100 meters along the paths we chose. Sometimes more frequent measurements were made in valleys and on hilltops in hope of obtaining an accurate density reading. As with most data collections, the number of points taken are enough to draw basic conclusions but more points would have been better.

1.6 Equipment

With a gravimeter and a GPS antenna we were able to get data points containing heights, latitude, longitude and gravity. The GPS antenna is used to get accurate height measurements of the elevation of the gravimeter, taking into account the height difference between the antenna and the gravimeter itself. Using this data and multiple corrections we were able to compile a gravity field map of the area we were studying.

1.7 Map material

The terrain in our area of study consists of multiple different rock types. In the north there are the Precambrian basement rocks. To the southwest there is Pleistocene silt and sand. To the southeast there is Permian dolomite. To the west there is Triassic and Permian shale and siltstone. In the northwest corner there is a small patch of Cretaceous gneissic granite. South of this is a larger patch of Miocene breccia.

Rock type	Classification	Density $[\frac{g}{cm^3}]$
Granite	Igneous	2.5 - 2.8
Basalt	Igneous	2.7 - 3.3
Andesite	Igneous	2.4 - 2.8
Peridotite	Igneous	2.78 - 3.37
Quartzite	Metamorphic	2.5 - 2.7
Granulite	Metamorphic	2.52 - 2.73
Sandstone	Sedimentary	1.6 - 2.7
Air		≈ 0
Water		1
Sediments		1.7 - 2.3
Sandstone		2.0 - 2.6
Shale		2.0 - 2.7
Limestone		2.5 - 2.8
Granite		2.5 - 2.8
Basalts		2.7 - 3.1
Metamorphic Rocks		2.6 - 3.0

Table 1: Rock types and their density

1.8 DEM data of the region

DEM stands for digital elevation model. It's a standard[1] introduced by the U.S. Geological Survey (USGS) for datafiles that are entered into the National Digital Cartographic Data Base (NDCDB).

The datafile we were using was of type 1, which means it is a 7.5 x 7.5' quadrangle with a 30 m grid spacing. So the height information of this model is presumably only the average height over a square of 30 x 30 m.

Our survey area was located within the quadrangle VIDAL (see figure 2), whose lower right (SE) corner has the NAD27 coordinates 34°0′ N 114°30′ W.

In figure 3 we zoomed into the DEM and plotted the locations of our gravity measurements. The size of the circles is proportional to the Bouguer-corrected gravity in that location. The raw data can be found in Appendix A.

[1] The details can be looked up under `http://rockyweb.cr.usgs.gov/nmpstds/acrodocs/dem/1DEM0897.PDF` and `2DEM0198.PDF`.

To check the accuracy of the DEM heights, we compared them to the GPS measurements. Figure 4 shows the difference between those two heights. Surprisingly, the DEM is quite accurate, the two height values differ mostly by less than 10 meters. The few data points where the difference is up to 18 m were either hilltops or ravines, where it's clear that the averaging effect over 30 x 30 m blocks has the biggest effect.

1.9 Local and regional gravity

The gravitational data that we had beforehand came from two sources: a data file that was contributed to the Southern California Earthquake Center by Dr.Shawn Biehler of University of California at Riverside on December 14, 1998[2] and a paper by Thomas B. Gage and Robert W. Simpson from 1980[3]. We used all the data from the first but only about 20 data points (the closest ones to our survey area) of the latter, as we had to manually enter them into the computer.

In the following figures the pre-existing gravity data points are marked with white dots (for the data file) or black asterisks respectively (for the manually transcribed data), whereas our own measurements are marked with black circles of different size (proportional to the local raw gravity).

In the figures that show a bigger area than our survey area, the latter is marked with a white rectangle.

We plotted the raw g values as well as the Bouguer corrected values to demonstrate the effect of the correction: In the raw data you can still recognize part of the topography, while in the corrected data such traces have been eliminated.

[2] `http://www-gpsg.mit.edu/~tah/12.221/CA_gravity.txt`

[3] Principal Facts for Gravity Stations in the Big Maria, Riverside, and Whipple Mountains, California; by Thomas B. Gage and Robert W. Simpson; data obtained in March and April of 1980

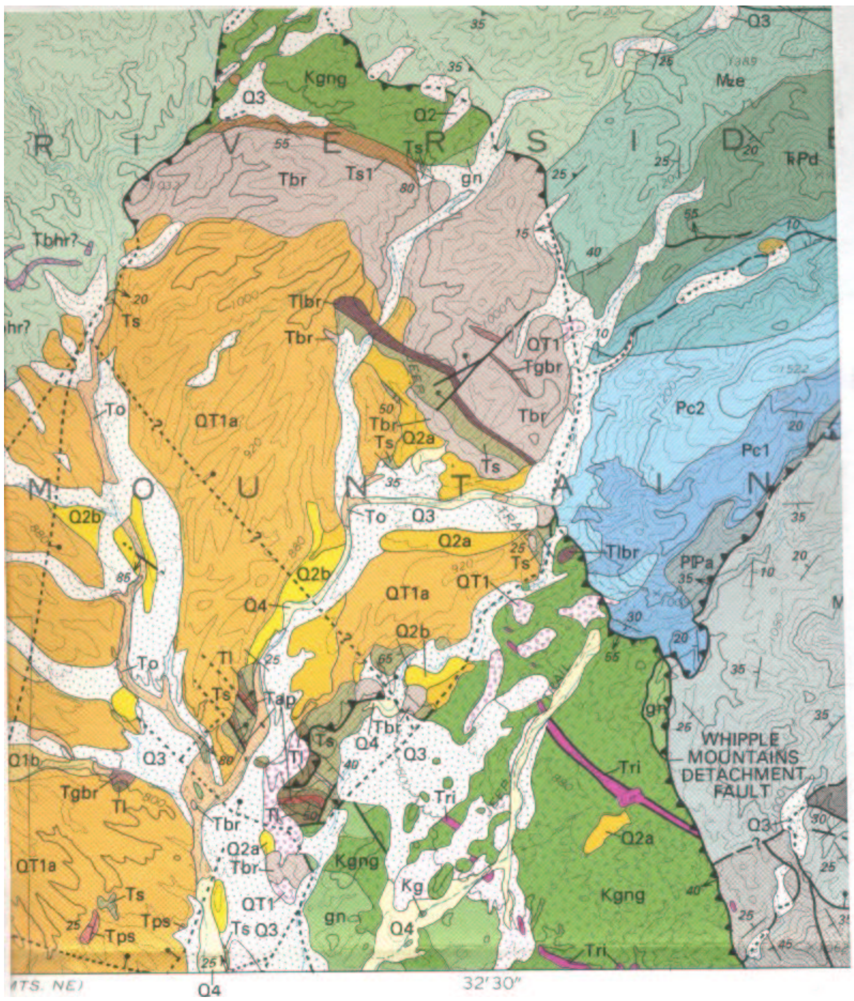

Figure 1: Geological map of survey area

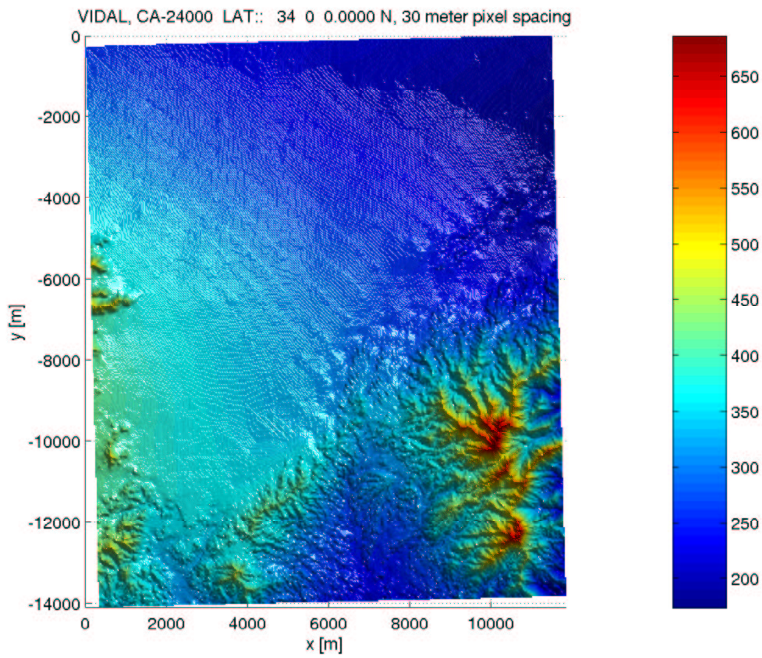

Figure 2: DEM: whole VIDAL quadrangle

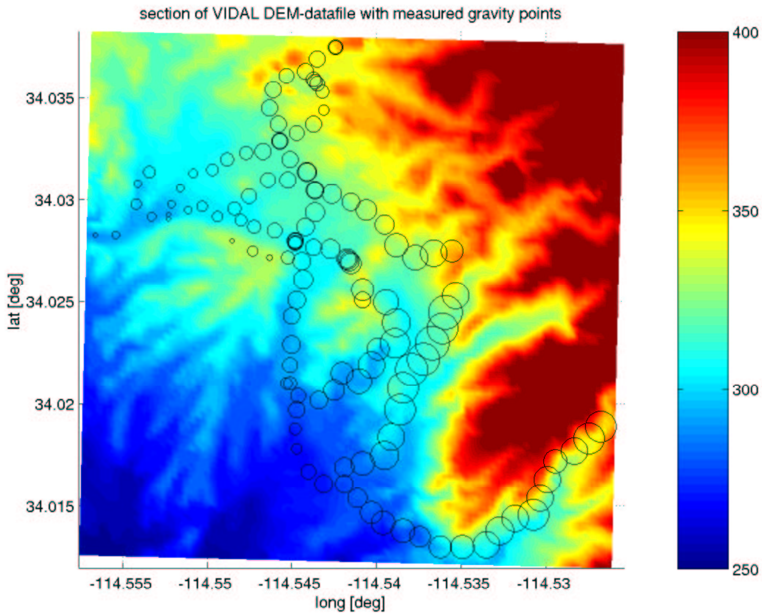

Figure 3: Zoom into DEM: Our survey area with location and magnitude of gravity measurements

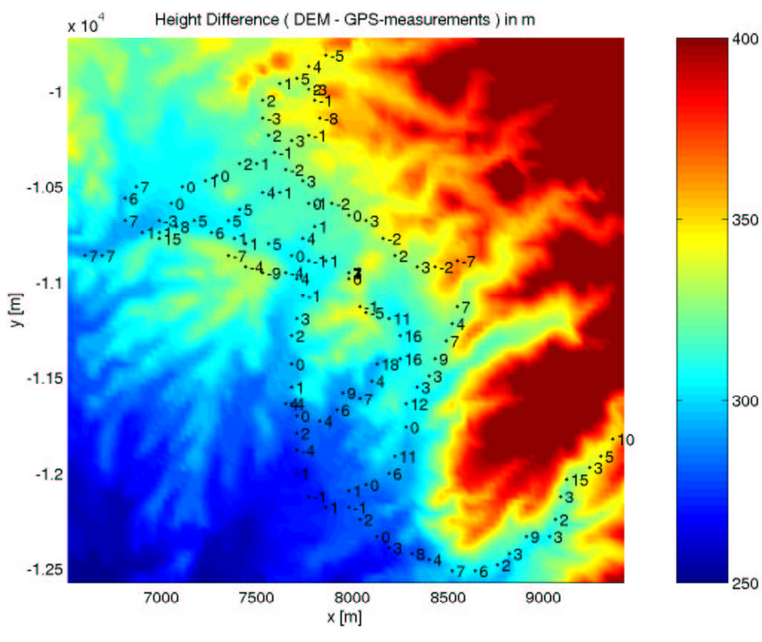

Figure 4: Difference between DEM heights and our GPS data

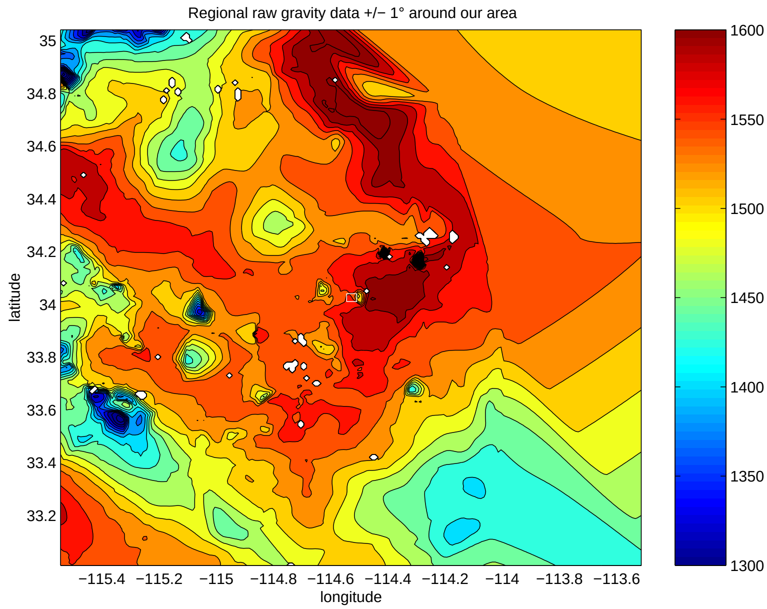

Figure 5: Regional raw gravity data $\pm 1^{\circ}$ around our survey area

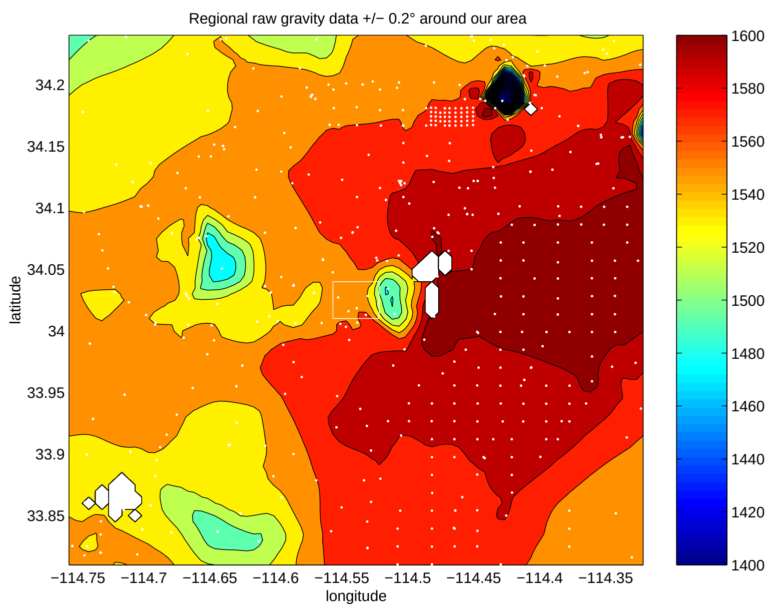

Figure 6: Raw gravity data $\pm 0.2^{\circ}$ around our survey area, with pre-existing measurement locations

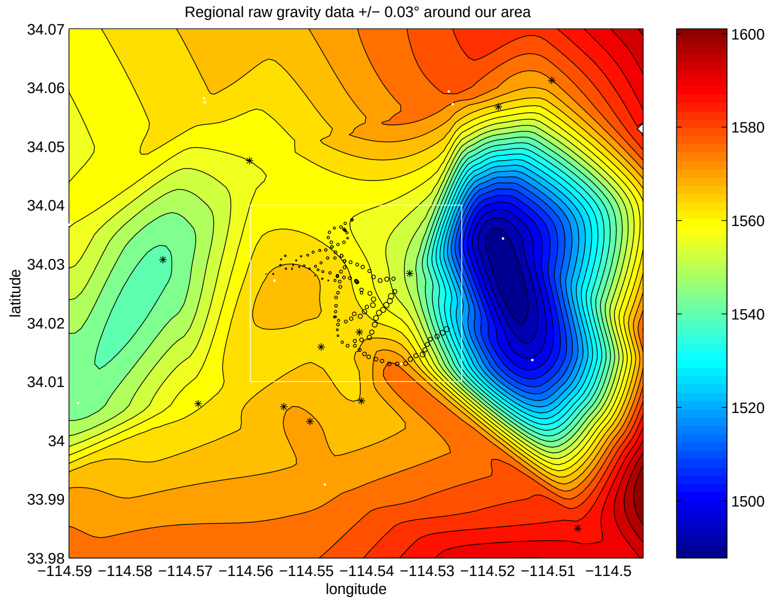

Figure 7: Raw gravity data $\pm 0.03^{\circ}$ around our survey area, with pre-existing measurements and our own gravity measurement locations

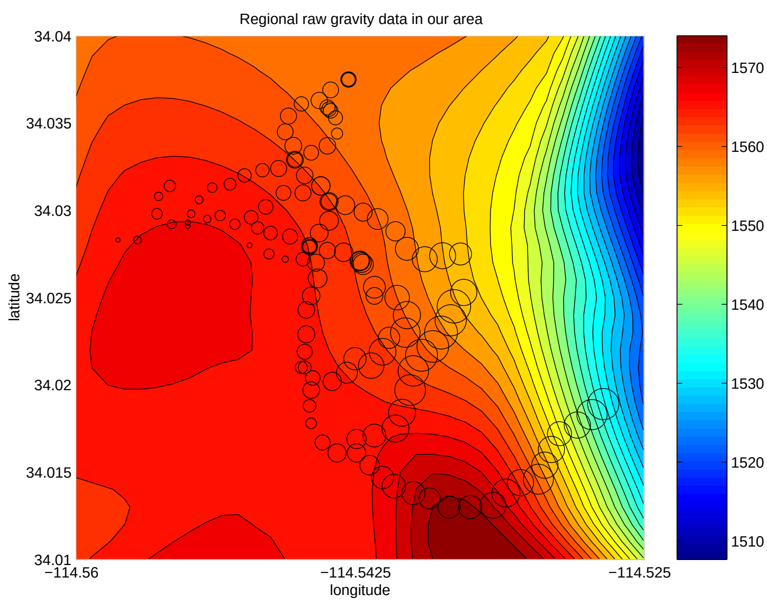

Figure 8: Raw gravity data of our survey area, with the sites of our own gravity measurements

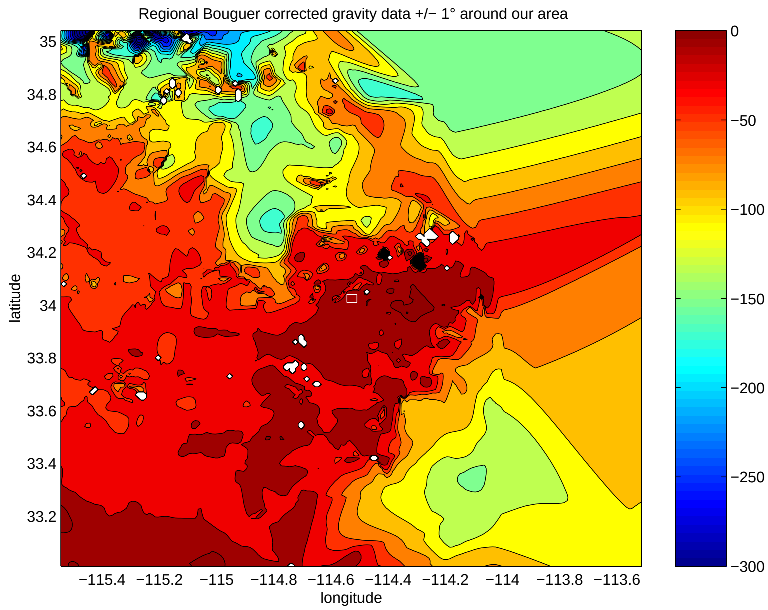

Figure 9: Regional Bouguer corrected gravity data ±1° around our survey area

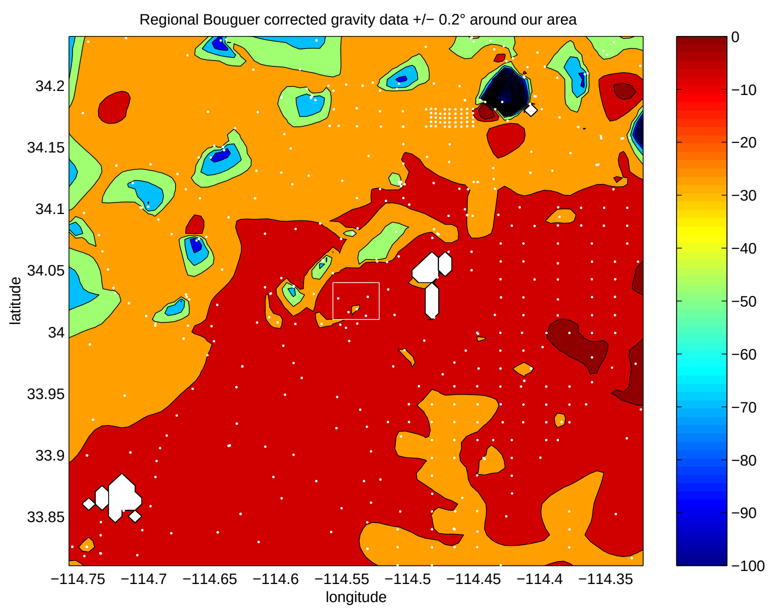

Figure 10: Bouguer corrected gravity data ±0.2° around our survey area, with pre-existing measurement locations

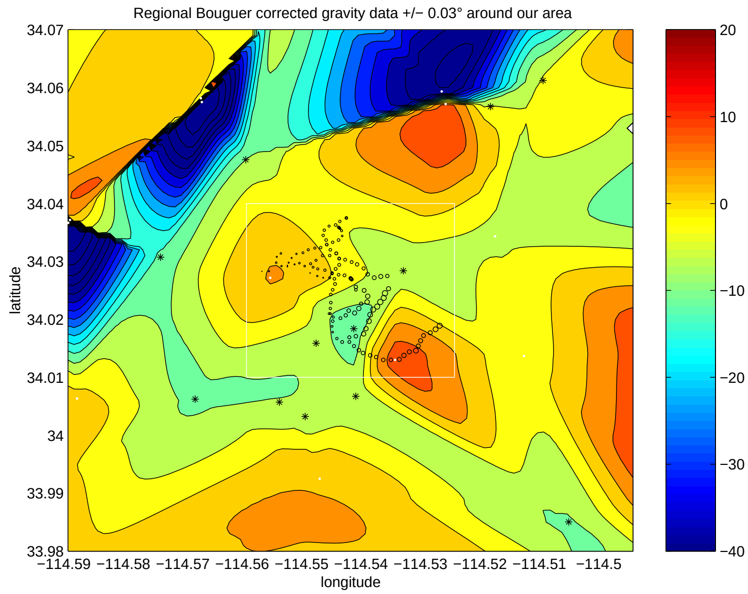

Figure 11: Bouguer corrected gravity data ±0.03° around our survey area, with pre-existing measurements and our own gravity measurement locations

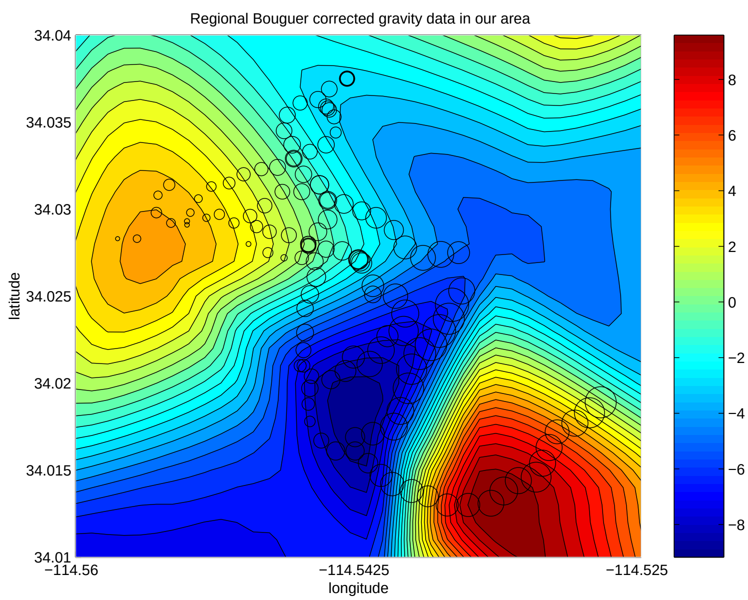

Figure 12: Bouguer corrected gravity data of our survey area, with the sites of our own gravity measurements

2 Procedures

2.1 Gravimeter

A LaCoste and Romberg gravimeter, such as the one used in this field study, measures the local force of gravity using a mass and spring. A mass and a spring each be connected to a lever in such a way that the torque on the lever due to the mass and the spring are each proportional to the sine of the angle of the lever from horizontal. In this case, if the torque due to the spring and the torque due to the mass cancel, they will do so at all angles of the lever, and the lever will be subject to no restoring force. A Lacoste and Romberg gravimeter approximates this situation, so that the angle of the lever is subject to an extremely small restoring force, thus making the angle of the lever extremely sensitive to variations in the local gravitational field.

To ensure accuracy, the mechanism of the gravimeter must be carefully isolated from sources of error. The gravimeter is maintained at a constant temperature through the use of a small battery powered heater. In addition, the gravimeter is hermetically sealed so that there will be no variation in air pressure,and hence the buoyancy of the parts of the gravimeter's mechanism.

Mechanical gravimeters typically have a small drift in their calibration due to effects such as creep deformation of their parts. To compensate for this, we started and ended each day of measurements by measuring the gravitational acceleration at our base camp. After applying the tidal correction to these measurements, we were able to discern the drift and approximately correct for it by linear interpolation.

In three instances, measurements were found to be in obvious disagreement with other nearby measurements, possibly because of transcription errors, and these data points were discarded.

2.2 GPS

The latitude, longitude, and elevation of our gravitational measurements was accomplished using GPS (Global Positioning System). GPS recievers compute their location by measuring the distance to a subset of the 28 GPS satellites which orbit the earth with a period of 12 hours. The distances to the satellites is calculated based on the time it takes for radio signals to propagate from the satellites to the receiver. The satellites themselves behave independently of the action of the receivers, passively emitting signals at 1.575 GHz and 1.227 GHz at all times.

The signals from the satellites are sine waves with periodic sign reversal according to a pseudorandom binary sequence. The sign re-

Figure 13: Typical position for the gravimeter operator

versals occur at 10.23 and 1.023 MHz. The pseudorandom binary sequence is generated as a function of the time, as kept by atomic clocks on the GPS satellites. The GPS receiver can judge the time of flight of the radio signal based on the discrepancy between the time according to its own clock, and the time deduced from the binary sequence it is receiving from the satellite. By using signals from two satellites plus estimated elevation, or by using signals from more than three satellites, the GPS reciever can correct errors in its internal clock.

The binary sequences are distinct for each satellite and allow the GPS reciever to distinguish and tune in to specific satellites without requiring the satellites to transmit at different frequencies. Also, a much slower sign reversal is used to transmit data from the satellites to the gps recievers at a rate of 15 bits per second.

We took GPS measurements with three different levels of accuracy. For navigation, i.e. measuring the distance to the next point or finding data points of past days, we used handheld GPS, with an accuracy of approximately ± 20 m. To measure the locations of our gravity measurements we used a GPS receiver attached to a tripod mounted antenna. We approximately levelled the antenna at each location by eye to increase the precision of the readings. We measured the height of the antenna relative to the gravimeter using a height stick.

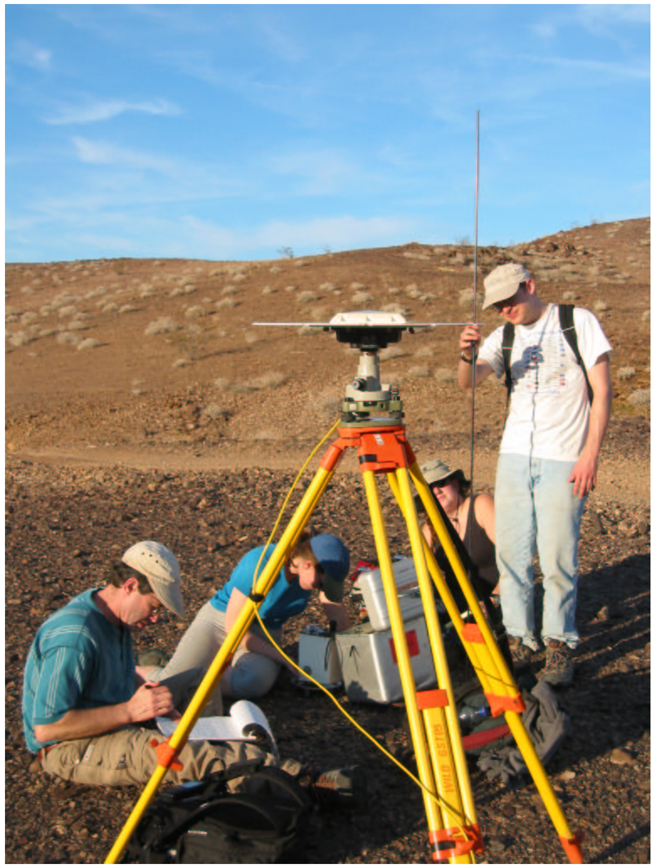

Figure 14: GPS setup, including magic height stick

The height stick readings are probably accurate to about ±5 cm. The latitude and longitude of the gravimeter is less important and it was only necessary to place the gravimeter within a meter or two of the GPS antenna. The GPS readings were taken over a period of several minutes, and resulting data downloaded to a computer. By averaging over the data points from a given gravimetry site, the latitude, longitude, and elevation could be measured with sufficient accuracy that the uncertainties are small compared to those in the gravimeter readings.

Our highest precision GPS readings were taken over the course of a day at a pair of geodetic markers separated from each other by a few hundred meters. For this measurement we aligned the GPS antenna with the geodetic marker using a telescope with crosshairs which was attached to the tripod. The antenna was carefully levelled using bubbles. Also, the antennas were oriented relative to true north using a magnetic compass. The height of the antenna was measured relative to the geodetic marker using a height stick to millimeter accuracy, taking advantage of the fact that the height stick was designed to fit into the geodetic marker and the antenna.

Figure 15: 100 m Journey from one site to the next

2.3 Coordinate systems

Perhaps the most obvious way of representing locations on the earth is in spherical coordinates. However, this suffers from some drawbacks. Most importantly, the centrifugal force due to daily rotation causes the earth to more closely resemble an oblate ellipsoid than a sphere. The distance from the Earth's center of mass to its surface varies between the poles and the equator by approximately 20 km due to this effect. Because of this, ellipsoidal coordinate systems have been devised. For historical reasons, there exist a number of different ellipsoidal coordinate systems for the earth. Commonly seen are NAD27, NAD83, and WGS84. The last two digits in the names of these coordinate systems represent the year in which they were introduced. WGS84 is especially suited for use with GPS, and it is the coordinate system that we used.

An even more sophisticated coordinate system for the Earth is the geoid. The geoid is a shape which is defined by the equipotential surface, taking into account Earth's locally varying gravitational field and its rotation. Anyone defining horizontal based on the perpendicular to a plumbline will in effect be using the geoid. In practice, the geoid is usually expressed in a series of spherical harmonics, and typically only the first several terms are of interest.

Often it is desirable to represent the earth on a flat surface such as a piece of paper or a computer screen. For this purpose the Earth's features must be projected onto a plane. Some of the maps in this report, especially those based on Digital Elevation Models (DEMs) are of this type and use a Universal Transverse Mercator (UTM) projection. UTM projections come in different varieties such as NAD27 and WGS84 just like coordinate systems. The DEM files that we have used are in NAD27 format.

2.4 Measurement points and planning of cross-sections

The measurements were taken either along the existing roads, into inviting ravines or sometimes along a straight line on a cross-country walk. Succeeding different data points have a surface distance of approximately 100 meters.

The measurement paths were designed so that we would cross the contacts between various rock types as observed on the surface. We aimed to make cross-sections in directions perpendicular to the inferred dips of the assumed underground structures and to cover the area with a grid of data points to make computer interpolation possible.

The measurements taken on the last day of the field camp were meant to extend the boundaries of the area studied by the geologist group, as the data points of the day before showed a local peak of gravity at the corner of our map. It was necessary to determine how this gravity high was bordered on the other side. As expected, due to the lower density rock present on the other side of the mountain, the gravity values there were lower.

3 Data Processing

3.1 Drift Correction

The dial reading of the gravimeter is subject to a small drift, due to mechanical deformations.[4] To correct for this, we took a measurement at the GPS antenna at base camp on the morning and evening of every day.

The daily drift (which we assume to be linear) can then be eliminated by the following formula:

$$g_{\text{dial}}^{\text{drift-corr}} = g_{\text{dial}} + \frac{g_{\text{dial}}^{\text{morning}} - g_{\text{dial}}^{\text{evening}}}{t^{\text{evening}} - t^{\text{morning}}} \cdot \left(t - t^{\text{morning}}\right) \qquad (3)$$

where t is the time when the measurement g_{dial} was taken.

3.2 Correction for different days

Next we have to take into account the variation between different days, by adding the difference of two morning readings to the drift-corrected value:

$$g_{\text{dial}}^{\text{day-corr}} = g_{\text{dial}}^{\text{drift-corr}} + g_{\text{dial}}^{\text{1stmorning}} - g_{\text{dial}}^{n\text{thmorning}} \qquad (4)$$

3.3 Conversion from dial reading into g value

The Lacoste and Romberg gravimeter was calibrated by the manufacturer. We used the resulting table to calculate gravitational accelerations from dial readings by linearly interpolating between calibration points.

The obtained g value is called 'raw g' and plotted in figure 16.

3.4 Tidal Correction

In addition to the gravitational attraction of earth, a gravimeter reading will depend on the tidal forces due to the moon and sun. In this survey, we are interested in geological features, so theoretical values of the tidal forces were calculated using the TSoft software package[5] and subtracted from our measured values. The gravitational acceleration due to tidal forces was less than 0.1 milligal, and is plotted in figure 17.

[4] and tidal effects, but we dealt with that seperately

[5] `http://www.astro.oma.be/SEISMO/TSOFT/tsoft.html`

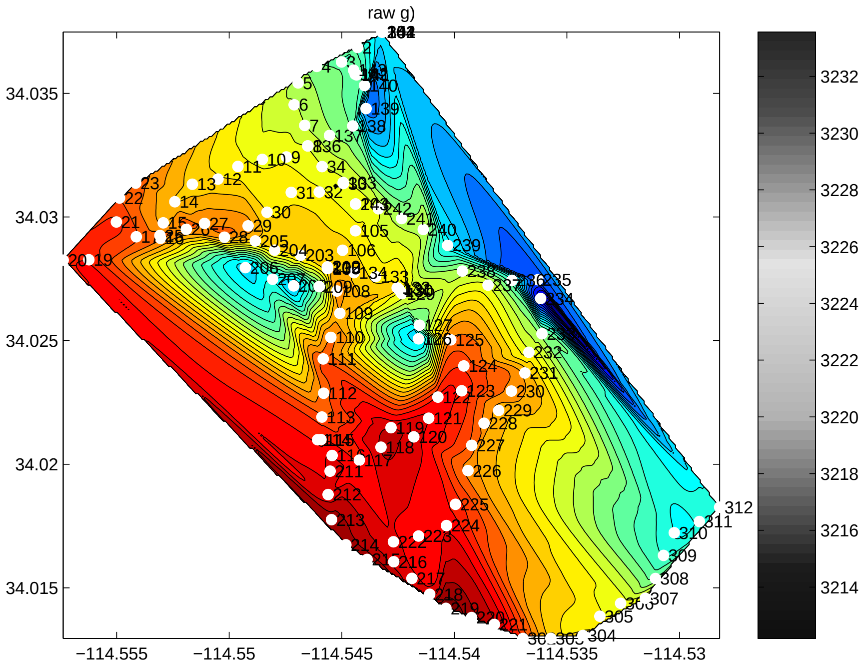

Figure 16: Raw g

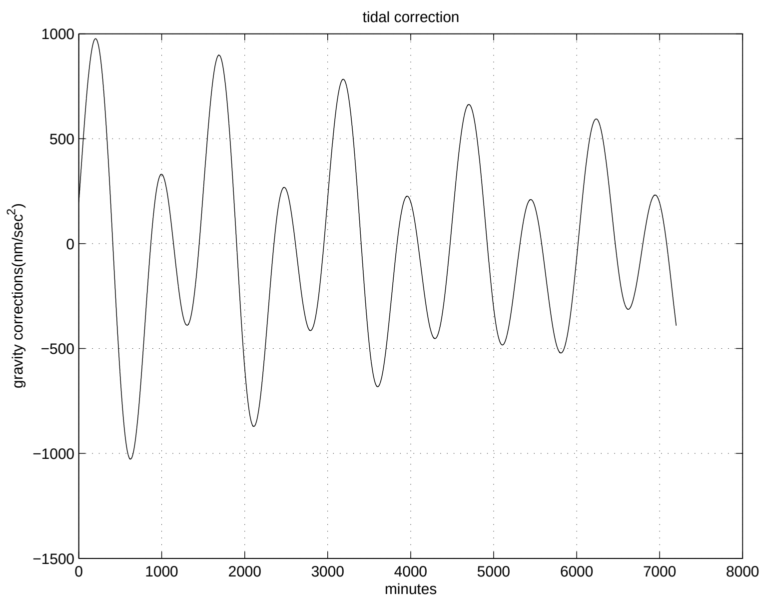

Figure 17: Tidal corrections

3.5 Latitude Correction

The earth is not a perfect sphere, but rather an ellipsoid, with a bulge around the equator and flat top and bottom at the poles, due to the earth's rotation. The rotation also produces centrifugal forces. Both effects reduce the gravity when you move towards the equator. The effect can be approximated by the first two terms of an expansion in latitude:

$$g^{\text{theory}} = 978032\left(1 + 5.2789 \cdot 10^{-3}\sin(\varphi)^2 - 2.35 \cdot 10^{-6}\sin(\varphi)^4\right) \quad (5)$$

We are usually only interested in the aberration of our observed g from this theoretical value, so we look at the difference $g^{\text{observed}} - g^{\text{theory}}$.

The latitude corrected g can be admired in figure 18.

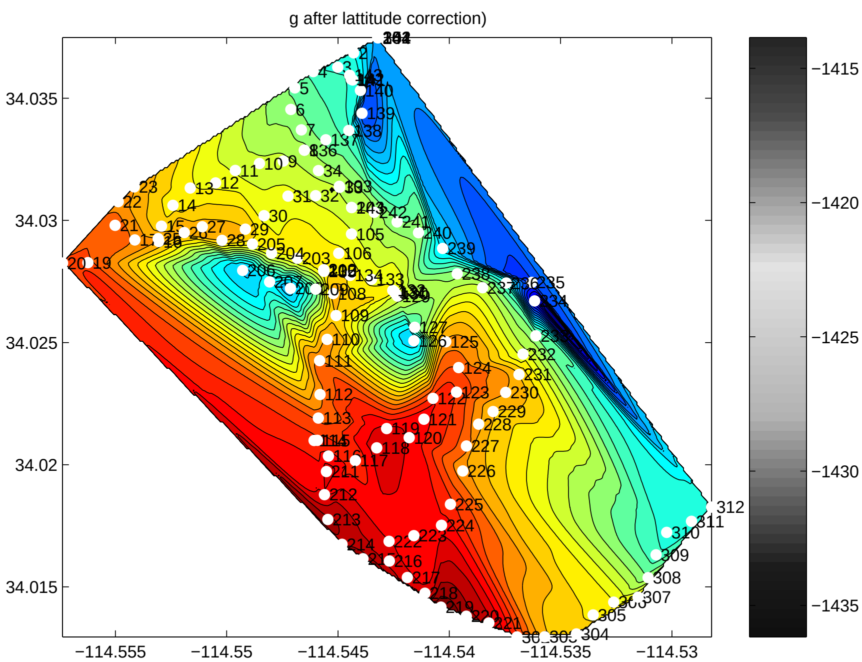

Figure 18: g after latitude correction

3.6 Free Air Correction

As we know, gravity varies with the distance to the earth's center of mass. We are only interested in gravity anomalies due to varying rock densities, so we want to correct for the effect of different elevation. The GPS measurements provide us with the height of our gravity data points. We use the following 1st order approximation of Newton's Law[6]:

$$g^{\text{free-air}} = g^{\text{raw}} - 0.307 \frac{\text{mgal}}{\text{m}} \cdot h \tag{6}$$

where h is the elevation relative to a reference point (in our case, the base camp). The factor 0.307 is $2\,GM_{\text{E}}$.

The free air corrected g is plotted in figure 19.

As each correction is added, the range between maximal and minimal g value on the map becomes smaller and smaller, because the dominating disturbing factors like elevation are taken out.

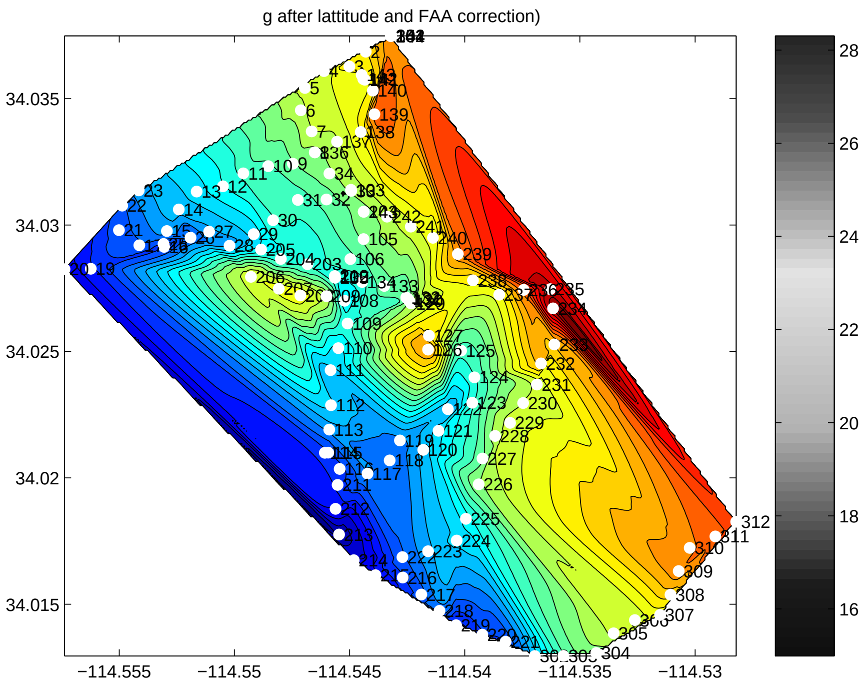

Figure 19: g after latitude and free air correction

[6] $g(r) = \frac{GM_{\text{E}}}{r^2} \quad \rightarrow \quad g(r+h) \approx g(r) + \frac{\partial g}{\partial r} \cdot h = g(r) - 2\,GM_{\text{E}} \cdot h$

3.7 Bouguer Correction

If we only apply the free air correction, we assume that our data point is floating[7] above a flat earth surface (with the height of base camp). Hence the name "free air" correction. In reality there's rock between us and the elevation 0 surface, with an average density of 2.67 $\frac{\mathrm{g}}{\mathrm{cm}^3}$. This additional rock layer exerts an additional gravitational force that has to be taken into account by the Bouguer Correction:

$$g^{\text{bouguer}} = g^{\text{free-air}} + 2\pi\rho G \cdot h \approx g^{\text{free-air}} + 0.112\frac{\text{mgal}}{\text{m}} \cdot h \qquad (7)$$

Figure 20 shows g^{bouguer} in our survey area.

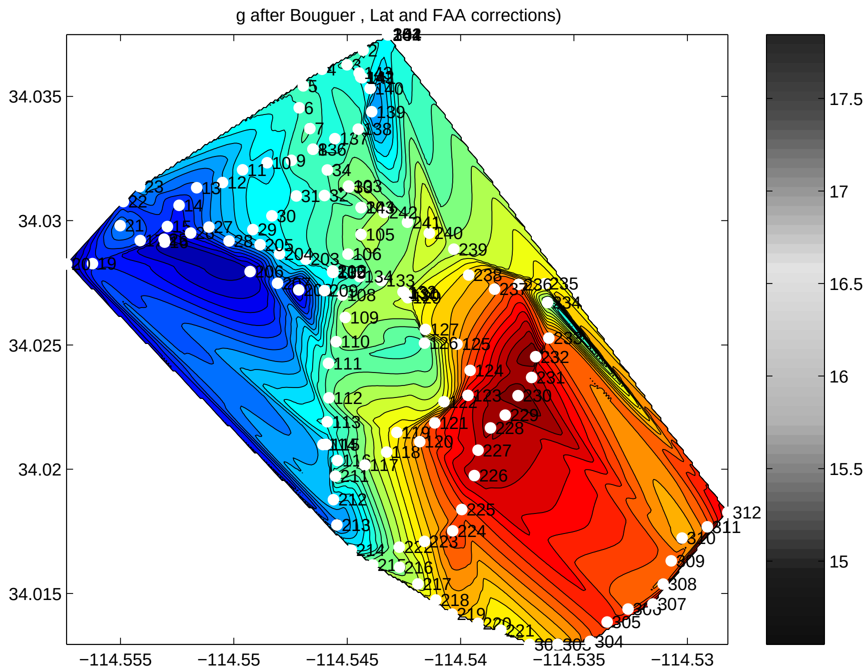

Figure 20: g after latitude, free air and Bouguer correction

Comparing figures 20 with 12 we find that there is fair agreement in the southeast corner of the survey region between our measurements and pre-existing gravity data in that it is a region of high gravity. However, it looks like the maximums are shifted, which is probably only an artifact due to the low spatial resolution of the regional dataset.

[7] as all our measurements took place at higher elevation than base camp

They disagree elsewhere, in particular in the northwest corner there's a significant discrepancy. As our dataset contains many datapoints close to each other in mutual agreement, this is probably the more credible result.

3.8 Terrain Correction

The Bouguer correction is a positive gravity correction that accounts for the deviation of the topography from the infinite horizontal slab. The terrain correction has to account for two complementary effects of topography, both decreasing the observed gravity comparing to the one predicted after the Bouguer correction. First is the pulling upwards due to elevated topography surrounding the observation point, and second is the smaller downwards attraction when the observation point is on a hilltop with sloping finite planes (see figure 21).

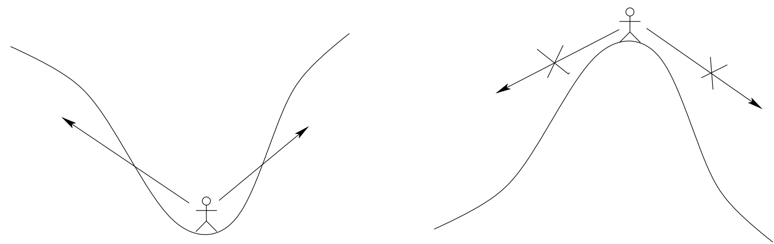

Figure 21: Effects of topography

There are several methods for calculating the terrain correction for measured gravity data. We have tried to use the method suggested by Singh & Guptasarma[8], and calculating the gravitational attraction due to rectangular vertical blocks of different heights. The method is based on integrating the attraction due to a fictitious surface density along the surfaces of the bodies in question. The field area, a square of 3x3 km was divided to $30\,m^2$ blocks, each represented by an average height. The data was adopted from the DEM file of the VIDAL USGS quadrangle. The method gave us correct results for a very small number of points. Its main disadvantage: due to the large number of blocks used ($\approx$ 10,000), the calculation time for each observation point was impractically long.

We think that the method is basically a very useful one, and can be used for calculating the terrain correction after the code is made more efficient or can be run on parallel machines. Since the code used is written in Matlab, a careful vectorization of it would probably yield quicker runs with a relatively small effort. Another important improvement for the way the program is being used is to change the resolution of the DEM cells taken into account. Since remote topography has a smaller effect on the local gravity, a lower sample rate for areas further away from the station can be used.

[8]B. Singh, D. Goptasarma, "New method for fast computation of gravity and magnetic anomalies from arbitrary polyhedra", Geophysics, Vol. 66, No. 22, p. 521-526

A popular method for the terrain correction is based on calculating the terrain correction in a radius range $R_{\min} \rightarrow R_{\max}$ around the station only, using a multiquadratic surface fit to the topography in this range. The methodology for dividing the area was formalized by Hammer[9] in 1939 and had been used since. The outer range correction is usually calculated by the method of Plouff[10]. However, the complexity of the multiquadratic method is also proportional to N^2, N being the number of elevation points (i.e. DEM blocks) in the range. An implementation of the Plouff[11] method in Fortran can be used with not a very large effort by downloading the Fortran code provided on the USGS website. A much faster method of terrain correction calculation exploits the regular gridded nature of the DEM and the fact that he classical terrain correction formula, given under a linear and planar approximation by Moritz (1968)[12], is a convolution integral.

While a space-domain integration performs $\mathcal{O}(N^2)$ operations given N data points, the 2D-FFT only performs $\mathcal{O}(N \ln N)$ operations, thus greatly reducing the computation time. The basis of the 2D-FFT terrain-correction software is based on the paper of Li & Sideris (1994)[13]. An example for the use of this method can be found in Kirby & Featherson[14]

[9] Hammer, Sigmund, 1939, Terrain corrections for gravimeter stations, Geophysics, 4, 184-194.

[10] Plouff, Donald (1966) Digital terrain corrections based upon geographic coordinates [abstract], Geophysics, 31, 1208.

[11] Plouff, Donald, 2000, Field estimates of gravity terrain corrections and Y2K-compatible method to convert from gravity readings with multiple base stations to tide- and long-term drift-corrected observations: U.S. Geological Survey Open-File Report 00-140, 35 p.

[12] Moritz H. 1968. On the use of the terrain correction in solving Molodensky's problem. Department of Geodetic Science and Surveying, Ohio State University Report 108.

[13] Sideris M. G. 1985. A fast Fourier transform method for computing terrain corrections. manuscripta geodaetica 46, 66-73.

[14] Kirby, J. F. & Featherstone, W. E. (1999), Terrain correcting Australian gravity observations using the national digital elevation model and the fast Fourier transform, Australian Journal of Earth Sciences, 46, (4), 555-562.

4 Interpretation

4.1 Calculating Densities of various rock types

Gravity can be a powerful tool for estimating the density of a rock formation. By measuring the difference in gravity and in elevation between two adjacent stations, we can evaluate the density of the rock captured between them (see figure 22).

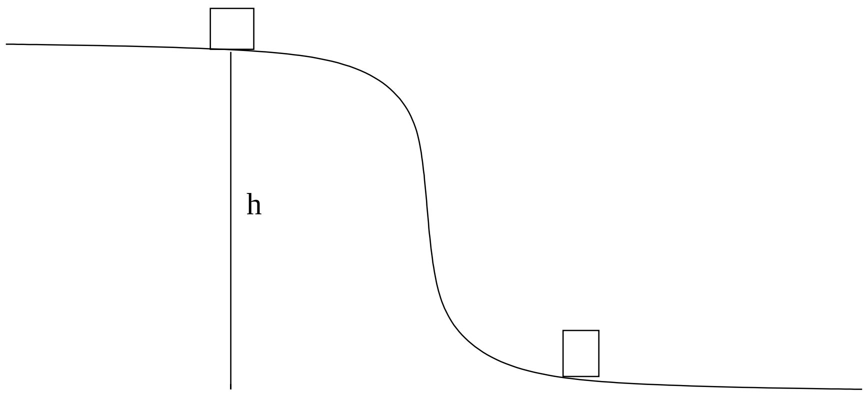

Figure 22: estimating the density of a rcok

$$\Delta g = 2\pi \rho G \cdot \Delta h$$

where $G = 6.67 \cdot 10^{-11} \frac{\mathrm{m}^3}{\mathrm{kg\,s}^2}$

The gravity used for the calculation should include the free-air correction due to the elevation difference, but not the Bouguer correction, which is in fact a hidden assumption about densities.

We have tried to estimate the densities of the three major rock formations seen in the field area: the dense Mesozoic rocks, the amorphous Tertiary conglomerate, and the Quaternary alluvium coverage.

Results:

formation	stations	Δh [m]	Δg [mgal]	density [$\frac{\mathrm{g}}{\mathrm{cm}^3}$]
Basement	V230-V232	17.108	1.9728	2.7515
Mz/PC	V224-V225	4.5170	2.7350	2.5948
Tertiary	V205-V206	31.8290	2.7350	2.0504
	V208-V203	31.1590	2.5090	1.9214
	V206-V16	46.2400	5.9810	1.8447
Alluvium??	V15-V26	4.9070	0.6801	3.3070

We can see in the results the significant differences in densities between the three formations. The Mesozoic/Precambrian rocks ("Basement") have density which is very close to that of metamorphose rock types, like Quartzite and Granulite. The Tertiary, being a conglomerate combined of many types of rocks, clust sizes and porosities, has a mean density that is lower than that of a more uniform rock. The alluvium coverage, which is very sporadic, should have result in a very low mean density, due to the high percentage of air still contained in its structure. However, this is not shown in our result, probably due to lack of sufficient measurements of thick alluvium beds.

4.2 Proposed Model

The gravity data suggests a region of high gravity in the southeast corner tapering off to low gravity in the west. It also tapers off, but more slowly, in the southeast direction. There is an apparent line of change from high to low gravity horizontally across the upper mid portion of our data. Many of the points for the mountaintops are have lower gravity than we expected but we think that is because we need an appropriate terrain correction for those places. Despite these few low points the gravity data is very smooth across the region.

When looking at both the gravity and geology sets there are several interpretations to be made. The first is the contact between the Precambrian basement and the Cretaceous gneissic granite. Both of the maps show the difference in rock type and gravity along that line. The second is that Triassic and Permian rock seem to be more dense than the Miocene and Cretaceous rock. Given this and the gradients between the two it can be hypothesized that the Permian and Triassic rock lie at an angle underneath the Miocene and Cretaceous rock. These rocks probably dip at a shallow angle beneath the surface to the northwest.

Assuming those two conjectures are correct, we can assume more. By putting those two observations together we can also conclude that the contact between the Precambrian and the Cretaceous continues to the southeast into the Perimian and Triassic area. Perhaps the fault boundary between the Precambrian and the Cretaceous extends further than the maps say it does.

Perhaps it is not the Triassic and Permian rocks that are causing a large gravity anomaly underneath the Miocene. Dolomite and shale aren't extremely dense rocks and the difference in density between those and the breccia might not be able to account for the change in gravity. It is possible there is a heavy mass underneath the area that is causing the gravity anomaly. It is possible for an intrusion of metamorphic or igneous rock to be lying underneath the Permian and Triassic area, but from our data it is impossible for us to tell.

For calculating the density of the different rock types, most of the results turned out as we expected. Multiple calculations of the density were made for each rock type and the calculations for each rock type were similar. Because each rock came out to the density that was expected this implies that the heavier rocks that are causing the gravity gradient are not close to the surface in our sample areas. Because the density of each surface rock type is known perhaps later more accurate speculation of the angle of the dense rock underneath the area can be made using this data. If the model of one rock layer lying under the other doesn't make sense at that point, then it is possible that the density of the heavy mass below the surface could be calculated, if that model is correct.

4.2.1 Simplified mathematical model

The proposed geologic structure - a dense slab going underneath a lighter slab - can be modeled as two simple polyhedrons, shaped like wedges, with oposing slopes. See figure 23.

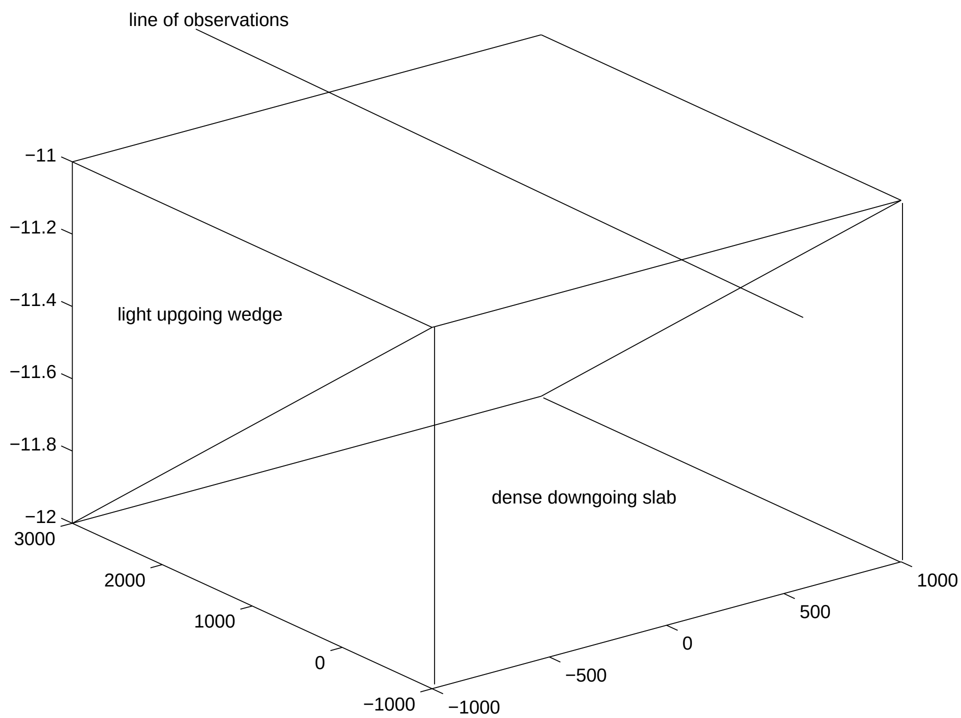

Figure 23: Model of the proposed geologic structure

The resulting gravity that would be observed along a line on the surface would be the sum of the gravities resulting of each of the bodies. See figure 24.

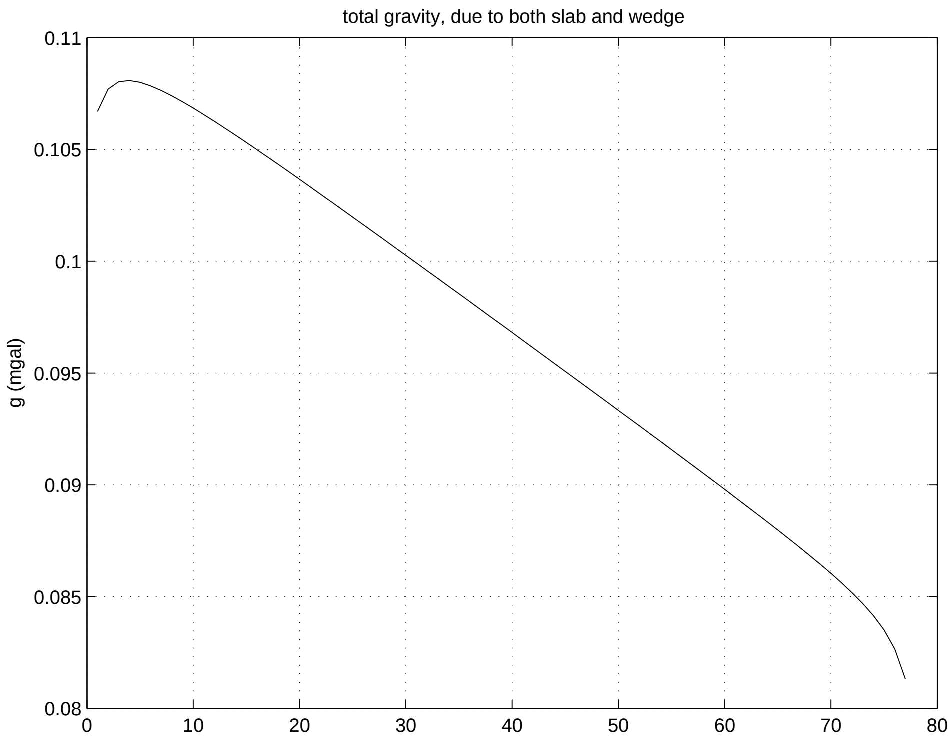

Figure 24: Modeled gravity for wedge

The values presented were calculated using the `grvmag3d.m` Matlab program, with the files `slope.m` and `down_slope.m` as model input.

A Raw datafiles

A.1 data_all

The columns refer to the following attributes:
Name of datapoint / dial reading / hour / minute (Pacific Time of dial reading) / latitude degree / decimal minutes / longitude degree (W) / minutes / height of GPS antenna above base camp / height of GPS antenna above gravimeter / daily drift correction in dial reading per minute / hour / minute (time of first dial reading of the day) / daily offset of dial reading

001	3052.72	10	56	34	2.2493	114	32.5918	81.433	1.44	1.2077e-4	10	13	0
002	3054.86	11	07	34	2.2116	114	32.6580	70.256	1.47	1.2077e-4	10	13	0
003	3054.99	11	17	34	2.1764	114	32.7007	69.677	1.48	1.2077e-4	10	13	0
004	3056.03	11	28	34	2.1654	114	32.7667	62.892	1.52	1.2077e-4	10	13	0
005	3056.73	11	38	34	2.1255	114	32.8165	59.809	1.53	1.2077e-4	10	13	0
006	3057.13	11	49	34	2.0725	114	32.8271	56.999	1.49	1.2077e-4	10	13	0
007	3057.08	11	55	34	2.0222	114	32.7987	57.436	1.47	1.2077e-4	10	13	0
008	3057.76	12	01	34	1.9726	114	32.7905	53.522	1.52	1.2077e-4	10	13	0
009	3058.25	12	15	34	1.9456	114	32.8476	50.184	1.53	1.2077e-4	10	13	0
010	3058.24	12	22	34	1.9399	114	32.9118	48.701	1.54	1.2077e-4	10	13	0
011	3058.67	12	30	34	1.9227	114	32.9767	46.265	1.54	1.2077e-4	10	13	0
012	3059.15	12	43	34	1.8921	114	33.0298	42.618	1.56	1.2077e-4	10	13	0
013	3059.52	12	52	34	1.8795	114	33.0982	39.087	1.48	1.2077e-4	10	13	0
014	3059.77	12	59	34	1.8370	114	33.1451	36.470	1.50	1.2077e-4	10	13	0
015	3060.26	13	07	34	1.7859	114	33.1757	33.343	1.51	1.2077e-4	10	13	0
016	3061.27	13	24	34	1.7481	114	33.1833	25.912	1.51	1.2077e-4	10	13	0
017	3061.87	13	54	34	1.7520	114	33.2475	25.072	1.58	1.2077e-4	10	13	0
019	3062.94	14	07	34	1.6962	114	33.3743	18.391	1.77	1.2077e-4	10	13	0
020	3062.85	14	12	34	1.6954	114	33.4427	16.667	1.53	1.2077e-4	10	13	0
021	3062.54	14	24	34	1.7880	114	33.3009	22.59	1.52	1.2077e-4	10	13	0
022	3061.75	14	29	34	1.8461	114	33.2922	25.934	1.45	1.2077e-4	10	13	0
023	3061.51	14	38	34	1.8824	114	33.2492	29.289	1.49	1.2077e-4	10	13	0
025	3061.33	15	05	34	1.7553	114	33.1847	25.710	1.49	1.2077e-4	10	13	0
026	3061.10	15	12	34	1.7701	114	33.1145	28.486	1.56	1.2077e-4	10	13	0
027	3060.95	15	18	34	1.7846	114	33.0659	31.056	1.49	1.2077e-4	10	13	0
028	3060.61	15	23	34	1.7511	114	33.0129	32.658	1.56	1.2077e-4	10	13	0
029	3060.65	15	32	34	1.7785	114	32.9498	34.522	1.50	1.2077e-4	10	13	0
030	3059.05	15	39	34	1.8117	114	32.8993	43.9307	1.57	1.2077e-4	10	13	0
031	3058.84	15	46	34	1.8597	114	32.8349	45.663	1.56	1.2077e-4	10	13	0
032	3058.48	15	51	34	1.8608	114	32.7604	48.244	1.51	1.2077e-4	10	13	0
033	3057.89	15	59	34	1.8813	114	32.6957	52.807	1.46	1.2077e-4	10	13	0
034	3057.74	16	07	34	1.9223	114	32.7525	53.021	1.54	1.2077e-4	10	13	0
035	3052.77	16	32	34	2.2493	114	32.5918	81.433	1.44	1.2077e-4	10	13	0
102	3052.90	09	33	34	2.2492	114	32.5924	81.321	1.55	-1.9737e-4	8	55	-0.11
103	3058.04	09	55	34	1.8838	114	32.6964	52.721	1.21	-1.9737e-4	8	55	-0.11
104	3058.18	10	05	34	1.8319	114	32.6634	51.237	1.13	-1.9737e-4	8	55	-0.11
105	3058.79	10	11	34	1.7667	114	32.6636	48.007	1.18	-1.9737e-4	8	55	-0.11
106	3059.49	10	21	34	1.7194	114	32.6981	43.342	1.19	-1.9737e-4	8	55	-0.11
107	3059.77	10	31	34	1.6751	114	32.7376	40.165	1.23	-1.9737e-4	8	55	-0.11
108	3060.87	10	41	34	1.6205	114	32.7128	34.821	1.21	-1.9737e-4	8	55	-0.11
109	3060.45	10	48	34	1.5663	114	32.7053	37.738	1.24	-1.9737e-4	8	55	-0.11
110	3061.22	10	56	34	1.5077	114	32.7293	32.363	1.22	-1.9737e-4	8	55	-0.11
111	3061.74	11	02	34	1.4557	114	32.7494	28.540	1.21	-1.9737e-4	8	55	-0.11
112	3061.52	11	12	34	1.3723	114	32.7484	29.475	1.21	-1.9737e-4	8	55	-0.11
113	3062.11	11	19	34	1.3145	114	32.7531	24.796	1.31	-1.9737e-4	8	55	-0.11
114	3063.06	11	26	34	1.2594	114	32.7646	17.476	1.16	-1.9737e-4	8	55	-0.11
115	3063.11	11	32	34	1.2598	114	32.7557	17.691	1.19	-1.9737e-4	8	55	-0.11
116	3063.88	11	40	34	1.2212	114	32.7257	14.255	1.25	-1.9737e-4	8	55	-0.11
117	3063.22	11	48	34	1.2099	114	32.6533	19.872	1.17	-1.9737e-4	8	55	-0.11
118	3064.67	11	58	34	1.2412	114	32.5956	13.896	1.25	-1.9737e-4	8	55	-0.11
119	3064.59	12	08	34	1.2889	114	32.5690	15.278	1.21	-1.9737e-4	8	55	-0.11
120	3064.28	12	16	34	1.2666	114	32.5083	18.732	1.23	-1.9737e-4	8	55	-0.11
121	3063.97	12	22	34	1.3116	114	32.4685	21.487	1.21	-1.9737e-4	8	55	-0.11
122	3063.44	13	05	34	1.3629	114	32.4441	21.680	1.28	-1.9737e-4	8	55	-0.11
123	3063.10	13	12	34	1.3782	114	32.3805	28.132	1.17	-1.9737e-4	8	55	-0.11
124	3062.44	13	19	34	1.4384	114	32.3749	30.994	1.29	-1.9737e-4	8	55	-0.11
125	3061.33	13	26	34	1.5020	114	32.4097	35.827	1.23	-1.9737e-4	8	55	-0.11
126	3052.90	13	41	34	1.5043	114	32.4957	77.068	1.18	-1.9737e-4	8	55	-0.11
127	3055.77	13	51	34	1.5375	114	32.4931	64.784	1.24	-1.9737e-4	8	55	-0.11
129	3058.25	14	11	34	1.6142	114	32.5400	50.966	1.24	-1.9737e-4	8	55	-0.11

130	3058.82	14	18	34	1.6206	114	32.5450	47.481	1.18	-1.9737e-4	8	55	-0.11
131	3059.76	14	24	34	1.6254	114	32.5487	41.597	1.08	-1.9737e-4	8	55	-0.11
132	3059.15	14	30	34	1.6280	114	32.5525	45.893	1.12	-1.9737e-4	8	55	-0.11
133	3059.06	14	36	34	1.6554	114	32.6097	45.779	1.13	-1.9737e-4	8	55	-0.11
134	3059.72	14	43	34	1.6648	114	32.6675	41.098	1.19	-1.9737e-4	8	55	-0.11
135	3059.64	14	52	34	1.6755	114	32.7383	40.078	1.15	-1.9737e-4	8	55	-0.11
136	3057.77	15	08	34	1.9725	114	32.7908	53.042	1.18	-1.9737e-4	8	55	-0.11
137	3056.74	15	14	34	1.9978	114	32.7328	58.736	1.10	-1.9737e-4	8	55	-0.11
138	3055.69	15	21	34	2.0211	114	32.6707	65.711	1.19	-1.9737e-4	8	55	-0.11
139	3050.99	15	28	34	2.0631	114	32.6354	88.243	1.18	-1.9737e-4	8	55	-0.11
140	3054.66	15	38	34	2.1192	114	32.6395	70.354	1.07	-1.9737e-4	8	55	-0.11
141	3056.10	15	44	34	2.1449	114	32.6605	63.137	1.17	-1.9737e-4	8	55	-0.11
142	3055.24	15	51	34	2.1467	114	32.6642	67.815	1.16	-1.9737e-4	8	55	-0.11
143	3055.34	15	58	34	2.1563	114	32.6684	67.580	1.09	-1.9737e-4	8	55	-0.11
144	3052.87	16	09	34	2.2484	114	32.5925	81.518	1.67	-1.9737e-4	8	55	-0.11
201	3052.90	08	53	34	2.2492	114	32.5924	81.294	1.43	-4.4346e-5	8	29	-0.19
202	3059.84	09	10	34	1.6779	114	32.7386	40.764	1.77	-4.4346e-5	8	29	-0.19
203	3059.37	09	22	34	1.7071	114	32.8097	42.927	1.47	-4.4346e-5	8	29	-0.19
204	3059.20	09	29	34	1.7198	114	32.8790	43.066	1.49	-4.4346e-5	8	29	-0.19
205	3059.62	09	35	34	1.7419	114	32.9308	40.104	1.29	-4.4346e-5	8	29	-0.19
206	3052.87	09	42	34	1.6772	114	32.9569	72.043	1.40	-4.4346e-5	8	29	-0.19
207	3053.89	10	09	34	1.6491	114	32.8844	69.176	1.33	-4.4346e-5	8	29	-0.19
208	3052.59	10	12	34	1.6328	114	32.8281	74.106	1.49	-4.4346e-5	8	29	-0.19
209	3056.26	10	20	34	1.6311	114	32.7601	58.511	1.56	-4.4346e-5	8	29	-0.19
210	3059.80	10	27	34	1.6789	114	32.7386	40.913	1.78	-4.4346e-5	8	29	-0.19
211	3064.62	10	40	34	1.1832	114	32.7311	11.882	1.75	-4.4346e-5	8	29	-0.19
212	3064.33	10	47	34	1.1263	114	32.7365	10.740	1.66	-4.4346e-5	8	29	-0.19
213	3065.73	10	53	34	1.0656	114	32.7275	1.732	1.75	-4.4346e-5	8	29	-0.19
214	3065.41	11	00	34	1.0046	114	32.6892	5.568	1.71	-4.4346e-5	8	29	-0.19
215	3066.23	11	06	34	0.9688	114	32.6327	2.706	1.78	-4.4346e-5	8	29	-0.19
216	3064.46	11	12	34	0.9635	114	32.5617	12.183	1.65	-4.4346e-5	8	29	-0.19
217	3064.26	11	19	34	0.9231	114	32.5131	13.591	1.57	-4.4346e-5	8	29	-0.19
218	3064.42	11	25	34	0.8842	114	32.4658	13.638	1.18	-4.4346e-5	8	29	-0.19
219	3066.74	11	32	34	0.8501	114	32.4224	2.034	1.76	-4.4346e-5	8	29	-0.19
220	3065.63	11	39	34	0.8278	114	32.3543	7.427	1.57	-4.4346e-5	8	29	-0.19
221	3064.85	11	46	34	0.8112	114	32.2933	10.421	1.50	-4.4346e-5	8	29	-0.19
222	3064.13	11	57	34	1.0118	114	32.5625	14.936	1.74	-4.4346e-5	8	29	-0.19
223	3063.73	12	04	34	1.0256	114	32.4957	19.047	1.63	-4.4346e-5	8	29	-0.19
224	3063.82	12	09	34	1.0513	114	32.4209	21.397	1.77	-4.4346e-5	8	29	-0.19
225	3063.04	12	13	34	1.1029	114	32.3968	25.714	1.57	-4.4346e-5	8	29	-0.19
226	3061.10	12	18	34	1.1847	114	32.3636	38.979	1.59	-4.4346e-5	8	29	-0.19
227	3061.79	12	23	34	1.2458	114	32.3536	35.531	1.50	-4.4346e-5	8	29	-0.19
228	3061.11	12	27	34	1.2995	114	32.3211	40.438	1.56	-4.4346e-5	8	29	-0.19
229	3060.40	12	34	34	1.3306	114	32.2821	44.325	1.57	-4.4346e-5	8	29	-0.19
230	3061.06	12	41	34	1.3774	114	32.2481	41.936	1.70	-4.4346e-5	8	29	-0.19
231	3060.39	13	18	34	1.4213	114	32.2120	45.018	1.77	-4.4346e-5	8	29	-0.19
232	3058.08	13	29	34	1.4715	114	32.2014	58.774	1.43	-4.4346e-5	8	29	-0.19
233	3056.31	13	36	34	1.5165	114	32.1667	64.547	1.44	-4.4346e-5	8	29	-0.19
235	3050.09	13	53	34	1.6480	114	32.1774	96.792	1.37	-4.4346e-5	8	29	-0.19
236	3054.61	14	07	34	1.6461	114	32.2466	74.622	1.43	-4.4346e-5	8	29	-0.19
237	3057.91	14	12	34	1.6345	114	32.3104	56.095	1.41	-4.4346e-5	8	29	-0.19
238	3056.88	14	23	34	1.6689	114	32.3785	60.671	1.35	-4.4346e-5	8	29	-0.19
239	3053.54	14	31	34	1.7310	114	32.4181	76.916	1.26	-4.4346e-5	8	29	-0.19
240	3056.98	14	42	34	1.7699	114	32.4828	59.545	1.30	-4.4346e-5	8	29	-0.19
241	3056.84	14	50	34	1.7964	114	32.5407	59.150	1.57	-4.4346e-5	8	29	-0.19
242	3057.80	14	56	34	1.8198	114	32.6024	54.502	1.48	-4.4346e-5	8	29	-0.19
243	3058.00	15	04	34	1.8313	114	32.6631	51.723	1.38	-4.4346e-5	8	29	-0.19
244	3052.83	15	21	34	2.2492	114	32.5924	81.294	1.43	-4.4346e-5	8	29	-0.19
302	3062.35	09	24	34	0.7772	114	32.2174	24.3463	1.73	0	7	48	-0.14
303	3059.72	09	31	34	0.7774	114	32.1429	39.2424	1.85	0	7	48	-0.14
304	3059.49	09	39	34	0.7843	114	32.0573	41.9231	1.66	0	7	48	-0.14
305	3058.64	09	44	34	0.8310	114	32.0121	47.9867	1.72	0	7	48	-0.14
306	3058.25	09	50	34	0.8624	114	31.9570	48.7978	1.16	0	7	48	-0.14
307	3058.65	09	54	34	0.8746	114	31.8912	49.3188	1.61	0	7	48	-0.14
308	3056.03	10	01	34	0.9227	114	31.8640	61.7494	1.66	0	7	48	-0.14
309	3054.41	10	07	34	0.9787	114	31.8427	70.9421	1.74	0	7	48	-0.14
310	3053.81	10	14	34	1.0338	114	31.8140	73.3533	1.68	0	7	48	-0.14
311	3053.92	10	21	34	1.0608	114	31.7471	74.0928	1.64	0	7	48	-0.14
312	3054.49	10	26	34	1.0958	114	31.6931	73.5076	1.62	0	7	48	-0.14
313	3053.08	10	33	34	1.1347	114	31.6483	82.0944	1.74	0	7	48	-0.14
314	3064.89	12	05	34	3.7546	114	32.6430	0	1.36	0	7	48	-0.14
300	3064.89	07	48	34	3.7546	114	32.6430	0	1.36	0	7	48	-0.14
301	3054.79	09	13	34	0.8096	114	32.2920	10.5057	1.71	0	7	48	-0.14
128	3052.26	14	02	34	1.5886	114	32.4945	79.356	1.28	-1.9737e-4	8	55	-0.11
234	3048.02	13	47	34	1.6024	114	32.1700	105.151	1.36	-4.4346e-5	8	29	-0.19

B Matlab scripts

B.1 grav_over_dem.m

```
clear all;
close all;

%%%%%%%%%%%%%%%%%%%%%%%%%
%%  Declare variables  %%
%%%%%%%%%%%%%%%%%%%%%%%%%
h_basecamp = 234.448;  %% height of basecamp; must be added to height in gravity_data file
h_geoid = -31.57;  %% geoidal height at the closest survey points
                   %% (R160 & Riverside2: -31.57 / P160: -31.58)

xmin = 218;
xmax = 315;
ymin = 325;
ymax = 420;
xrange = xmin:xmax;
yrange = ymin:ymax;

latmin  = 34.01;
latmax  = 34.04;
longmin = -114.56;
longmax = -114.525;

topo_file_name = 'VIDAL_CA-24000.dem';
sample_frequency = 1;
pixel_spacing = 30;
pixel_width = 30;

%%%%%%%%%%%%%%%%%%%%%%%%
%%  Read in the data  %%
%%%%%%%%%%%%%%%%%%%%%%%%
[latgrat, longgrat, topo_mat, dem_info] = usgs24kdem(topo_file_name, sample_frequency);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  Announce the internal name of the DEM that we just read in  %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp(sprintf('Read DEM file: %s', getfield(dem_info, 'Quadranglename')))

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  Build some position matrices assuming the pixel spacing, %%
%%  flipping the y axis                                      %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
[topo_mat_rows, topo_mat_cols] = size(topo_mat);
x_vec = sample_frequency * pixel_spacing * linspace(0, topo_mat_cols - 1, topo_mat_cols);
y_vec = -sample_frequency * pixel_spacing * linspace(0, topo_mat_rows - 1, topo_mat_rows);
[x_mat, y_mat] = meshgrid(x_vec, y_vec);

%%%%%%%%%%%%%%%%%%%%%%%%
%%  Plot the results  %%
%%%%%%%%%%%%%%%%%%%%%%%%
%surf(longgrat(325:392,218:277), latgrat(325:392,218:277), topo_mat(325:392,218:277))  %% days 1&2
surf(longgrat(325:420,218:315), latgrat(325:420,218:315), topo_mat(325:420,218:315))  %% all data
%surf(longgrat, latgrat, topo_mat)   %% complete quadrant
axis tight
shading interp
daspect([1 0.8285 1/5])
material shiny
%camlight
xlabel('long [deg]')
ylabel('lat [deg]')
zlabel('z [m]')
title('section of VIDAL DEM-datafile with measured gravity points')
view(0, 90)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  Add gravity measurement locations  %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
load gravity_data;
longs_wgs=gravity_data(:,1);
lats_wgs=gravity_data(:,2);
```

```
heights=gravity_data(:,3);
g_boug=gravity_data(:,4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%  convert WGS84 into NAD27  %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
longs=longs_wgs+7.899917e-4;
lats=lats_wgs-1.606944e-5;
%% only valid near base camp

hold on
for i=1:length(g_boug)
        plot3(longs(i),lats(i),heights(i)+500,'ok','markersize',(g_boug(i)-14.2)*6);
        %% the numbers are chosen such that all points are visible (above 3d surface)
        %% and the circles have a reasonable size range
end;
caxis([250,400])
colorbar
hold off


%%%%%%%%%%%%%%%

figure;

% surf(x_mat, y_mat, topo_mat)  %% whole quadrangle
surf(x_mat(yrange,xrange), y_mat(yrange,xrange), topo_mat(yrange,xrange))  %% only our area
shading interp
daspect([1 1 1/5])
material shiny
xlabel('x [m]')
ylabel('y [m]')
zlabel('z [m]')
title('Height Difference ( DEM - GPS-measurements ) in m')
axis tight
view(0, 90)
caxis([250,400])
colorbar

hold on
for i=1:length(lats)
    j = (longgrat-longs(i)).^2+(latgrat-lats(i)).^2;
        [y_nearest,x_nearest]=find(j == min(min(j)));
        plot3(x_nearest*30,-y_nearest*30,500,'k.');
    h_text = sprintf(' %d',round(topo_mat(y_nearest,x_nearest)-heights(i)-h_basecamp+h_geoid));
        text(x_nearest*30,-y_nearest*30,500,h_text);
end;
hold off


%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%  gravity plots  %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%

load lat.ca;
load long.ca;
load g.ca;
load elev.ca;
load grav_1980mwgs;

%% join the two gravity data sets
lat = [lat', grav_1980mwgs(:,1)'+grav_1980mwgs(:,2)'/60]';
long = [long', grav_1980mwgs(:,3)'+grav_1980mwgs(:,4)'/60]';
g = [g', grav_1980mwgs(:,6)']';
elev = [elev', grav_1980mwgs(:,5)']';

gtheo = 978032*(1+(5.2789e-3).*((sin(lat/180*pi)).^2)-(2.35e-6).*((sin(lat/180*pi)).^4));
gtheo = gtheo + elev*(0.112-0.307);  %% latitude, free air and Bouguer correction

ganom = g - gtheo + 978024;  %% addition of mean value to have the colorbar centered around 0

%%%%%%%%%%%%%%%%%%%
%% very far away %%
```

```
%%%%%%%%%%%%%%%%%%%
figure;
axis([longmin-1,longmax+1,latmin-1,latmax+1]);
[x,y]=meshgrid((longmin-1):0.01:(longmax+1), (latmin-1):0.01:(latmax+1));
z_g=griddata(long,lat,ganom,x,y,'cubic');
contourf(x,y,z_g,30);
xlabel('longitude')
ylabel('latitude')
title('Regional gravity data +/- 1 around our area');

hold on
%% draws a box around our data area
plot([longmin,longmin,longmax,longmax,longmin],[latmin,latmax,latmax,latmin,latmin],'w-');

hold off
%caxis([1300,1600]);
colorbar

%%%%%%%%%%%%%%
%% far away %%
%%%%%%%%%%%%%%
figure;
axis([longmin-0.2,longmax+0.2,latmin-0.2,latmax+0.2]);
[x,y]=meshgrid((longmin-0.2):0.005:(longmax+0.2), (latmin-0.2):0.005:(latmax+0.2));
z_g=griddata(long,lat,ganom,x,y,'cubic');
contourf(x,y,z_g,30);
xlabel('longitude')
ylabel('latitude')
title('Regional gravity data +/- 0.2 around our area');

hold on
%% plot the (alien) gravity measurement points
for i=1:length(g)
        plot3(long(i),lat(i),350,'.w','markersize',5);
end;

%% draws a box around our data area
plot([longmin,longmin,longmax,longmax,longmin],[latmin,latmax,latmax,latmin,latmin],'w-');

hold off
%caxis([1400,1600]);
colorbar

%%%%%%%%%%
%% zoom %%
%%%%%%%%%%
figure;
axis([longmin-0.03,longmax+0.03,latmin-0.03,latmax+0.03]);
[x,y]=meshgrid((longmin-0.03):0.001:(longmax+0.03), (latmin-0.03):0.001:(latmax+0.03));
z_g=griddata(long,lat,ganom,x,y,'cubic');
contourf(x,y,z_g,30);
xlabel('longitude')
ylabel('latitude')
title('Regional gravity data +/- 0.03 around our area');

hold on
%% plot the (alien) gravity measurement points
for i=1:(length(g)-length(grav_1980mwgs))
        plot3(long(i),lat(i),350,'.w','markersize',5);
end;
for i=(length(g)-length(grav_1980mwgs)):length(g)
        plot3(long(i),lat(i),350,'*k','markersize',5);
end;

%% plot our gravity measurement points
for i=1:length(g_boug)
        plot3(longs_wgs(i),lats_wgs(i),heights(i)+350,'ok','markersize',(g_boug(i)-14.2));
end;

%% draws a box around our data area
plot([longmin,longmin,longmax,longmax,longmin],[latmin,latmax,latmax,latmin,latmin],'w-');

hold off
colorbar
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% final zoom to data point location %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure;
axis([longmin,longmax,latmin,latmax]);
[x,y]=meshgrid(longmin:0.001:longmax, latmin:0.001:latmax);
z_g=griddata(long,lat,ganom,x,y,'cubic');
contourf(x,y,z_g,30);
xlabel('longitude')
ylabel('latitude')
title('Regional gravity data in our area');

hold on
%% plot our gravity measurement points
for i=1:length(g_boug)
        plot3(longs_wgs(i),lats_wgs(i),heights(i)+350,'ok','markersize',(g_boug(i)-14.2)*6);
end;

%% draws a box around our data area
plot([longmin,longmin,longmax,longmax,longmin],[latmin,latmax,latmax,latmin,latmin],'w-');

hold off
colorbar
```

B.2 gravity.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%Program file: grvmag3d.m
%Comments: Program for simultaneous computation of gravity
%& magnetic fields from a 3-D polyhedron. With all distances
%in meters, model density in g/cm3, ambient magnetic induction
%and remnant magnetization in gamma, and the magnetic susceptibility
%in SI, it gives gravity fields in milligals and magnetic
%fields in gamma.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
Gc = 6.6732e-3; % Universal Gravitational constant.
%preparedem3
%down_slope
slope
%prepdemeinat
%threebricks

for i=1:2,close(figure(i)),end %clear old figures if present

Nedges=sum(Face(1:Nf,1)); Edge=zeros(Nedges,8);
% Get edgelengths
for f=1:Nf
        indx=[Face(f,2:Face(f,1)+1) Face(f,2)];
        for t=1:Face(f,1)
                edgeno=sum(Face(1:f-1,1))+t;
                ends=indx(t:t+1); p1=Corner(ends(1),:);
                p2=Corner(ends(2),:);
                V=p2-p1; L=norm(V);Edge(edgeno,1:3)=V;
                Edge(edgeno,4) =L;
                Edge(edgeno,7:8)=ends;
        end
end

for t=1:Nf
        ss=zeros(1,3);
        for t1=2:Face(t,1) - 1;
                v1=Corner(Face(t,t1+2),:) - Corner(Face(t,2),:);
                v2=Corner(Face(t,t1+1),:) - Corner(Face(t,2),:);
                ss=ss+cross(v2,v1);
        end
        Un(t,:)=ss./norm(ss);
end

[X,Y]=meshgrid([s_end:stn_spcng:n_end],[w_end:prof_spcng:e_end]);
[npro nstn]=size(X);

if calgrv,Gx=zeros(size(X)); Gy=Gx; Gz=Gx;end

if calmag
        Hin=Hincl*pi/180;
        Dec=Decl*pi/180;
        cx=cos(Hin)*cos(Dec);
        cy=cos(Hin)*sin(Dec);
        cz = sin(Hin);
        Uh=[cx cy cz];
        H=Hintn .* Uh; % The ambient magnetic field
        Ind_magn=Susc.*H/(4*pi); % Induced magnetization
        Min=Mincl*pi/180; Mdec=Mdecl*pi/180;
        mcx=cos(Min) *cos(Mdec);
        mcy=cos(Min)*sin(Mdec); mcz=sin(Min);
        Um=[mcx mcy mcz];
        Rem_magn=Mstrength .* Um; % Remnant magnetization
        Net_magn=Rem_magn+Ind_magn; % Net magnetization
        Pd=(Un * Net_magn')'; % Pole densities
        Hx=zeros(size(X)); Hy=Hx; Hz=Hx;
end
%Comments: Now, for each observation point do the following:
%For each face find solid angle; for each side find p,q,r, and
%add p,q,r of sides to get P,Q,R for the face; if calmagD1, find
%hx,hy,hz; if calgrvD1, find gx,gy,gz. Add the components from
%all the faces to get Hx,Hy,Hz and Gx,Gy,Gz at the station.
for pr=1:npro
    curr_pr = pr
        for st=1:nstn
                opt=[X(pr,st) Y(pr,st) 0];
```

```
                fsign=zeros(1,Nf); Omega=zeros(1,Nf);
                for t=1:Ncor
                        cor(t,:) = Corner(t,:) -opt;
                end % shift origin

                for f=1:Nf
                        nsides=Face(f,1);
                        cors=Face(f,2:nsides+1);
                        Edge(:,5:6)=zeros(Nedges,2); % Clear record of integration
                        indx=[1:nsides 1 2];
                        for t=1:nsides
                                crs(t,:)=cor(cors(t),:);
                        end
                %Find if the face is seen from inside
                        fsign(f)=sign(dot(Un(f,:),crs(1,:)));
                % Find solid angle W subtended by face f at opt
                        dp1=dot(crs(indx(1),:),Un(f,:));
                        dp=abs(dp1);
                        if dp==0
                                Omega(f)=0;
                        end
                        if dp~=0, W=0;
                                for t=1:nsides
                                        p1=crs(indx(t),:); p2=crs(indx(t+1),:); p3=crs(indx(t+2),:);
                                        W=W + angle(p1,p2,p3,Un(f,:));
                                end
                                W=W-(nsides-2).*pi; Omega(f)=-fsign(f)*W;
                        end
                        indx=[1:nsides 1 2];
                        for t=1:nsides
                                crs(t,:)=cor(cors(t),:);
                        end
% Integrate over each side, if not done, and save result
                        PQR=[0 0 0];
                        for t=1:nsides
                                p1=crs(indx(t),:);
                                p2=crs(indx(t+1),:);
                                Eno=sum(Face(1:f-1,1))+t; % Edge number
                                if Edge(Eno,6)==1
                                        I=Edge(Eno,5);
                                        V=Edge(Eno,1:3);
                                        pqr=I .* V; PQR=PQR+pqr;
                                end
                                if Edge(Eno,6) ~=1  %might be a bug?
                                        chsgn=1; % if origin,p1 & p2 are on a st line
                                        if dot(p1,p2)./(norm(p1)*norm(p2))==1
                                                if norm(p1)>norm(p2) % and p1 farther than p2
                                                        chsgn=-1; psave=p1; p1=p2; p2=psave;%interchange p1,p2
                                                end
                                        end
                                        V=Edge(Eno,1:3); L=Edge(Eno,4); L2=L*L;
                                        b=2* (dot(V,p1));
                                        r1=norm(p1); r12=r1*r1; b2=b/L/2;
                                        if r1+b2 == 0
                                                V=-Edge(Eno,1:3);b=2*(dot(V,p1));b2=b/L/2;
                                        end
                                        if r1+b2 ~= 0
                                                I = (1/L).* log ((sqrt(L2 + b + r12) + L + b2)./(r1 + b2));
                                        end
                                        s=find(Edge(:,7)== Edge(Eno,8) & Edge(:,8) ...
                                        == Edge(Eno,7));
                                        I=I*chsgn; % change sign of I if p1,p2 were interchanged
                                        Edge(Eno,5)=I;Edge(s,5)=I;Edge(Eno,6)=1;Edge(s,6)=1;
                                        pqr=I .* V; PQR=PQR+pqr;
                                end
                        end
                        %From Omega,l,m,n,PQR, get components of field due to face f
                        l=Un(f,1);m=Un(f,2);n=Un(f,3);p=PQR(1,1);
                        q=PQR(1,2);r=PQR(1,3);
                        if calmag== 1
                                hx=Pd(f)*(l*Omega(f)+n*q-m*r); Hx(pr,st)=Hx(pr,st)+hx;
                                hy=Pd(f)*(m*Omega(f)+l*r-n*p); Hy(pr,st)=Hy(pr,st)+hy;
                                hz=Pd(f)*(n*Omega(f)+m*p-l*q); Hz(pr,st)=Hz(pr,st)+hz;
                        end
                        if calgrv== 1
                                if dp~=0 %if distance to face is non-zero
```

```
                                        gx=-dens*Gc*dp1*(l*Omega(f)+n*q-m* r);
                                        Gx(pr,st)=Gx(pr,st)+ gx;
                                        gy=-dens*Gc*dp1*(m*Omega(f)+l*r-n* p);
                                        Gy(pr,st)=Gy(pr,st)+ gy;
                                        gz=-dens*Gc*dp1*(n*Omega(f)+m*p-l* q);
                                        Gz(pr,st)=Gz(pr,st)+ gz;
                                end
                        end
                end,
        end
end % end of faces, stns, profiles

if calmag== 1
        Htot=sqrt((Hx+H(1,1)).^2 + (Hy+H(1,2)).^2 + (Hz+H(1,3)).^2);
        Dt=Htot-Hintn; % Correct change in Total field
        % Approx. change in Total field
        Dta=Hx.*cx+Hy.*cy+Hz.*cz;
end

%result_g(station_num) = result_g(station_num)+Gz

%plotting (optional)
%GZ = griddata ( w_end:prof_spcng:e_end, s_end:stn_spcng:n_end,Gz',Y, X);
%contourf (X, Y, GZ);
%colorbar;
%plot (w_end:prof_spcng:e_end, Gz);

%figure;
%[A, B] = meshgrid ( x_vec, y_vec );
%H = griddata (x_vec, y_vec, topo_mat', A, B);
%contourf (A, B, H);
%colorbar;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%prepare_local_block_model.m
%This file prepares a model of a brick to be used by grvmag3d.m and terrain.m
%its purpose is to compensate for the infinite slab added to the terrrain correction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear Corner L2 X dp1 m b Decl Mdecl Y n q Edge edgeno r t Eno Mstrength b2 ends npro r1 t1
clear Face Ncor calgrv f nsides r12 v1 Gc Nedges calmag fht nstn v2 Gx Nf chsgn fsign opt s
clear Gy Omega cor gx p Gz PQR cors gy p1 ss Hincl Susc crs gz p2 st Hintn Un curr_pr i p3 I
clear V dens indx pqr L W dp 1 pr

%calculate average heights
local_block_avg=mean(mean(topo_mat));
total_block_avg=mean(mean(big_topo_mat((ymin-20):(ymax+20), (xmin-20):(xmax+20))));
outer_block_avg = (total_block_avg*(xmax-xmin+40)*(ymax-ymin+40) - local_block_avg*(xmax-xmin)*(ymax-ymin) )
                                        / ( (xmax-xmin+40)*(ymax-ymin+40)- (xmax-xmin)*(ymax-ymin));

calgrv=1; % Change to zero if gravity field is not required
calmag=0; % Change to zero if magnetic field is not required
Ncor=8; Hintn=50000; Hincl=50; Decl=0; Susc=0.01;
Mstrength=0; Mincl=0; Mdecl=0;

%Comments: Corner is an array of x, y, z coordinates of corners
%in meters, one in each row, in a right-handed system with
%x-axis northward, y-axis eastward, and z-axis downward. Corners
%may be given in any order.
Corner = [0 0 0; 0 (ymax-ymin)*30 0; (xmax-xmin)*30 (ymax-ymin)*30 0; (xmax-xmin)*30 0 0;
          0 0 -outer_block_avg; 0 (ymax-ymin)*30 -outer_block_avg;
          (xmax-xmin)*30 (ymax-ymin)*30 -outer_block_avg;
          (xmax-xmin)*30 0 -outer_block_avg;];
%
%negative density for the 'compensation'
%
dens=-2.67;

% Add fht to depths of all corners
Corner(:,3)=Corner(:,3)+fhtz;

%Comments: In each row of Face, the first number is the number
%of corners forming a face; the following are row numbers of the
%Corner array with coordinates of the corners which form that
%face, seen in ccw order from outside the object. The faces may
```

```
%have any orientation and may be given in any order, but all
%faces must be included.
Nf = 6;
Face=zeros([6,5]); % Initialize a sufficiently large array
Face(1,1:5)=[4  1 2 3 4]; Face(2,1:5)=[4  8 7 6 5];
Face(3,1:5)=[4  2 6 7 3]; Face(4,1:5)=[4  1 4 8 5];
Face(5,1:5)=[4  4 3 7 8]; Face(6,1:5)=[4  5 6 2 1];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
% prepdemmodel.m
% This file is preparing an input model to be used by grvmag3d.m
%The input for this file is a DEM file for the local area of the field
%camp.
%The output is a stack of variables, including the definition of Corner and
%Face, to be used by grvmag3d
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5

%clear all existing variables
clear Corner L2 X dp1 m prof_spcng b Decl Mdecl Y e_end n q stn_spcng Edge edgeno n_end
clear r t Eno Mstrength b2 ends npro r1 t1 Face Ncor calgrv f nsides r12 v1 Gc Nedges
clear calmag fht nstn v2 Gx Nf chsgn fsign opt s w_end Gy Omega cor gx p s_end Gz PQR
clear cors gy p1 ss Hincl Susc crs gz p2 st Hintn Un curr_pr i p3 I V dens indx pqr L
clear W dp l pr

%
%define terrain limits
%
xmin=218;
xmax=315;
ymin=325;
ymax=420;

%load data
topo_file_name = 'VIDAL_CA-24000.dem'
[latgrat, longgrat, big_topo_mat, dem_info]   = usgs24kdem(topo_file_name, 1);
topo_mat=big_topo_mat(ymin:ymax, xmin:xmax);

% test model: a downgoing slab
%topo_mat = [
%    [ [120] [100] [80] [60] [40] [20] ];
%    [ [120] [100] [80] [60] [40] [20] ];
%    [ [120] [100] [80] [60] [40] [20] ];
%    [ [120] [100] [80] [60] [40] [20] ];
%    [ [120] [100] [80] [60] [40] [20] ];
%    [ [120] [100] [80] [60] [40] [20] ];
%] ./10;

[topo_mat_rows, topo_mat_cols]            = size(topo_mat);
x_vec                                     = 30 * linspace(0, xmax-xmin, xmax-xmin+1);
y_vec                                     = 30 * linspace(0, ymax-ymin, ymax-ymin+1);
[x_mat, y_mat]                            = meshgrid(x_vec, y_vec);
Corner = zeros(8*length(y_vec)*length(x_vec),3);
Face = zeros(6*length(y_vec)*length(x_vec),5);

%create corners and faces of the terrain's prism discretization. each prism
%has 8 corners and 6 faces, not shared by any other prism.

for y=1:length(y_vec)
    for x=1:length(x_vec)
        blocknum=length(x_vec)*(y-1)+x-1;
        Corner(8*blocknum+1,:) = [y_vec(y)-15,x_vec(x)-15,0];
        Corner(8*blocknum+2,:) = [y_vec(y)-15,x_vec(x)+15,0];
        Corner(8*blocknum+3,:) = [y_vec(y)+15,x_vec(x)+15,0];
        Corner(8*blocknum+4,:) = [y_vec(y)+15,x_vec(x)-15,0];
        Corner(8*blocknum+5,:) = [y_vec(y)-15,x_vec(x)-15,-topo_mat(y, x)];
        Corner(8*blocknum+6,:) = [y_vec(y)-15,x_vec(x)+15,-topo_mat(y, x)];
        Corner(8*blocknum+7,:) = [y_vec(y)+15,x_vec(x)+15,-topo_mat(y, x)];
        Corner(8*blocknum+8,:) = [y_vec(y)+15,x_vec(x)-15,-topo_mat(y, x)];


        Face(6*blocknum+1,:) = [4,1,2,3,4]+8*blocknum.*[0,1,1,1,1];
        Face(6*blocknum+2,:) = [4,8,7,6,5]+8*blocknum.*[0,1,1,1,1];
        Face(6*blocknum+3,:) = [4,2,6,7,3]+8*blocknum.*[0,1,1,1,1];
        Face(6*blocknum+4,:) = [4,1,4,8,5]+8*blocknum.*[0,1,1,1,1];
        Face(6*blocknum+5,:) = [4,4,3,7,8]+8*blocknum.*[0,1,1,1,1];
        Face(6*blocknum+6,:) = [4,5,6,2,1]+8*blocknum.*[0,1,1,1,1];
```

```
    end
end

calgrv=1;
calmag=0;
Ncor=8*length(y_vec)*length(x_vec);
Nf=6*length(y_vec)*length(x_vec);
Hintn=50000; Hincl=50; Decl=0; Susc=0.01;
Mstrength=0; Mincl=0; Mdecl=0;
dens=2.67;

%
%define the height of observation above the bottom of model
%
fhtz = topo_mat (station_x./30, station_y./30) + 1
Corner(:,3)=Corner(:,3)+fhtz; %shift down because measurements are at zero

%Comments: Rectangular grid of stations for computing fields.
%Profiles are along the x-axis (north-south direction). All values
%are in meters.

%
%define lines of observations
%
s_end = station_x;% Starting value of x; south end of profiles
stn_spcng = 30;  % Stepsize in north direction; stn interval
n_end= s_end;  %(xmax-xmin)*30-15;%  Last x; maximum north coordinate

w_end= station_y; % y value for westernmost profile
prof_spcng= 30; % Profile spacing
e_end= w_end;%(ymax-ymin)*30 - 15; % y value for easternmost profile



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%Model file: down_slope.m
% The variables are Ncor = number
% of corners of the model; Hintn = total intensity of
%ambient magnetic induction, gamma; Hincl = inclination of
%Hintn, degrees, downward from horizontal; Decl=declination
%of Hintn, clockwise from north; Susc = magnetic volume susceptibility
%in units SI, a dimensionlessnumberequal to ((c)r  -1),
%where (c)^r = magnetic permeability of the model relative to
%free space; Mstrength, Mincl, Mdecl = magnitude (gamma),
%inclination and declination (degrees), respectively, of remnant
%magnetic induction; Nf = number of faces; Fht D height of observation
%plane above origin, meters; and dens = density of
%model, g/cm3.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%
%This file creates a model of a downgoing slab, to be used as input to
%grvmag3d.m
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5%
calgrv=1; % Change to zero if gravity field is not required
calmag=0; % Change to zero if magnetic field is not required
Ncor=8; Hintn=50000; Hincl=50; Decl=0; Susc=0.01;
Mstrength=0; Mincl=0; Mdecl=0;

%Comments: Corner is an array of x, y, z coordinates of corners
%in meters, one in each row, in a right-handed system with
%x-axis northward, y-axis eastward, and z-axis downward. Corners
%may be given in any order.
Corner = [-1000 -1000 1; -1000 3000 1.999; 1000 3000 1.999; 1000 -1000 1;
    -1000 -1000 2; -1000 3000 2; 1000 3000 2; 1000 -1000 2];
fht=10; dens=2.67;
Nf = 6;

% Add fht to depths of all corners
Corner(:,3)=Corner(:,3)+fht;

%Comments: In each row of Face, the first number is the number
%of corners forming a face; the following are row numbers of the
%Corner array with coordinates of the corners which form that
%face, seen in ccw order from outside the object. The faces may
%have any orientation and may be given in any order, but all
%faces must be included.
```

```
Face=zeros([6,5]); % Initialize a sufficiently large array
Face(1,1:5)=[4 1 2 3 4]; Face(2,1:5)=[4 8 7 6 5];
Face(3,1:5)=[4 2 6 7 3]; Face(4,1:5)=[4 1 4 8 5];
Face(5,1:5)=[4 4 3 7 8]; Face(6,1:5)=[4 5 6 2 1];

%Comments: Rectangular grid of stations for computing fields.
%Profiles are along the x-axis (north-south direction). All values
%are in meters.
s_end= 0;%-320; % Starting value of x; south end of profiles
stn_spcng = 1;%40; % Stepsize in north direction; stn interval
n_end= 0% 320; % Last x; maximum north coordinate
w_end= -900; % y value for westernmost profile
prof_spcng=50; % Profile spacing
e_end= 2900; % y value for easternmost profile

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5
%Model file: slope.m
%Comments:
%This files creates a model of a upgoing wedge, to be used as input to
%grvmag3d.m
%The variables are Ncor = number
% of corners of the model; Hintn = total intensity of
%ambient magnetic induction, gamma; Hincl = inclination of
%Hintn, degrees, downward from horizontal; Decl=declination
%of Hintn, clockwise from north; Susc = magnetic volume susceptibility
%in units SI, a dimensionlessnumberequal to ((c)r  -1),
%where (c)^r = magnetic permeability of the model relative to
%free space; Mstrength, Mincl, Mdecl = magnitude (gamma),
%inclination and declination (degrees), respectively, of remnant
%magnetic induction; Nf = number of faces; Fht D height of observation
%plane above origin, meters; and dens = density of
%model, g/cm3.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%5

calgrv=1; % Change to zero if gravity field is not required
calmag=0; % Change to zero if magnetic field is not required
Ncor=8; Hintn=50000; Hincl=50; Decl=0; Susc=0.01;
Mstrength=0; Mincl=0; Mdecl=0;

%Comments: Corner is an array of x, y, z coordinates of corners
%in meters, one in each row, in a right-handed system with
%x-axis northward, y-axis eastward, and z-axis downward. Corners
%may be given in any order.
Corner = [-1000 -1000 1; -1000 3000 1; 1000 3000 1; 1000 -1000 1; -1000 -1000 1.0001;
-1000 3000 2; 1000 3000 2; 1000 -1000 1.0001];
fht=10; dens=2.0;
Nf = 6;

% Add fht to depths of all corners
Corner(:,3)=Corner(:,3)+fht;

%Comments: In each row of Face, the first number is the number
%of corners forming a face; the following are row numbers of the
%Corner array with coordinates of the corners which form that
%face, seen in ccw order from outside the object. The faces may
%have any orientation and may be given in any order, but all
%faces must be included.
Face=zeros([6,5]); % Initialize a sufficiently large array
Face(1,1:5)=[4 1 2 3 4]; Face(2,1:5)=[4 8 7 6 5];
Face(3,1:5)=[4 2 6 7 3]; Face(4,1:5)=[4 1 4 8 5];
Face(5,1:5)=[4 4 3 7 8]; Face(6,1:5)=[4 5 6 2 1];

%Comments: Rectangular grid of stations for computing fields.
%Profiles are along the x-axis (north-south direction). All values
%are in meters.
s_end= 0;%-320; % Starting value of x; south end of profiles
stn_spcng = 1;%40; % Stepsize in north direction; stn interval
n_end= 0% 320; % Last x; maximum north coordinate
w_end= -900; % y value for westernmost profile
prof_spcng=50; % Profile spacing
e_end= 2900; % y value for easternmost profile
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%Gravity Data Reduction Functions%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%bouguer_corr.m
%this function calculates the Bouguer corerction for given gravity values
%and heights.
%output: the corrected values.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function boug = bouguer_corr(g, h)
        boug = g - 0.112.*h;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%dial2gravity.m
% this function converts gravimeter dial readings to gravity,
% using the part of the data sheet relevant to our field area.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function gravity = dial2gravity (dial_reading)

%gravimeter data
datasheet = [   [2900 3000 3100 3200 ]
                        [3058.5 3164.06 3269.63 3375.22]
                        [1.05562 1.05574 1.05587 1.005598]];

%loop over readings
for j=1:length(dial_reading)
        dial = dial_reading(j);

        if ((dial < 2900) | (dial > 3299))
                continue;
        %find Milligal and interval values
        end

        for i=1:4
                if (floor( dial_reading(j)/100) == datasheet(1, i)/100 )
                        datasheetvalue = datasheet(1, i);
                        intervalvalue= datasheet(3, i);
                        millgalvalue = datasheet(2, i);
                tableline =i;
                break;
                end
        end

        %calculate offset (reading - table)
        offset = dial - datasheet(1,tableline);

        %multiply by interval value
        offset = offset * intervalvalue;

        %add to reading
        gravity(j) = millgalvalue + offset;
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%drift_corr.m
%This function calculates the drift in the gravimeter from day to day and
%from morning to evening, and returns corrected gravity values.
%input: gravity values, times (day, hour, minute), and data matrix of
%measurements done in the basecamp in each day's morning and evening.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function g_drift_corr = drift_corr (g, day, hour, min, base_camp_data_matrix)

base_camp_g = base_camp_data_matrix(:, 2);
base_camp_hour = base_camp_data_matrix(:, 3);
base_camp_min = base_camp_data_matrix(:, 4) + base_camp_hour.*60;
day = day + abs(sign(day-5)) - 1; %make the day=5 to day=4

%
%calculate the drift per minute within each day and the drift between days
%
for d= 1:(length(base_camp_data_matrix(:,1)))/2
    day_corr(d) = base_camp_g(d*2-1) - base_camp_g(1);
    slope(d) = (base_camp_g(d*2) - base_camp_g(d*2-1)) ./ ( (base_camp_min(d*2)-base_camp_min(d*2-1)));
end

%
```

```
%calculate the minute within a day from each station
%
minute_on_day = (hour.*60 + min) - base_camp_min(day.*2-1);

%
%calculate the corrected gravity using the day's slope and day-to-day change
%
g_drift_corr = g - slope(day)'.*minute_on_day + day_corr(day)';



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%freeair.m
%this function calculates the free air corerction to the given gravity
%values, using the given heights
%output: the "corrected" gravity values
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function faa=freeair(g, h)
        faa = g + h.*0.307;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%lat_correction.m
%this function deucts the gravity value computed by the latitude from the
%given gravity values.
%input: gravity values, latitudes (in radians)
%output: corrected gravity values
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

function lat_g = lat_correction (g, rad_latitudes)
        theory = 978032.* (1 + (5.2789e-3).*((sin(rad_latitudes)).^2) - (2.35e-6).*((sin(rad_latitudes)).^4));
        temp = g - theory';
        temp = temp + 975000;
        lat_g = temp;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%tidal_corrections.m
%this functions deducts the tidal gravity corrections from the given
% gravity values.
% input: gravity values, times (days, hours, minutes), and an input file of
% the tidal_corrections per minute, starting at the time of the first
% gravity measurement.
%output: corrected gravity values
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


function g_after_tidal = tidal_correction (input_g, days, hours, minutes)

%load tidal correction matrix
load tidal_corrections;

%translate times into minutes-since-t=0
minutes_times = (days-1).*60.*24 + hours.*60 + minutes;

%add
g_after_tidal = input_g - tidal_corrections(minutes_times)./10000;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%gravity.m
%this is the main function for data reduction of the gravity survey.
%its main steps:
%               1)gain data from the givem global data matrix.
%               2) corrections: (a) tides (b)drift (c) latitude
%                 (d) free-air (e) Bouguer
%               3) plots: anomalies vs. heights; contour map of resulting gravity anomalies
%
%input: loaded data matrix, and a range (number of last matrix line to use)
%
%output: lonitudes, latitudes, heights, resulting gravity
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
function [longs, lats, heights, result] = gravity (data_matrix, range)

%get columns from the data matrix
l%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

at_degrees = data_matrix (1:range, 5);
lat_minutes = data_matrix (1:range, 6)./60;
longs = -114 - data_matrix(1:range, 8)./60;
lats = lat_degrees + lat_minutes;
days = data_matrix (1:range, 15);
hours = data_matrix(1:range, 3);
minutes = data_matrix (1:range,4 );
dial_readings = data_matrix(1:range, 2);
heights = data_matrix(1:range, 9) - data_matrix(1:range, 10) + 1.293;


%data reduction steps
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

g_after_tidal = tidal_correction (dial_readings, days, hours, minutes);
dial_after_corr = drift_corr(g_after_tidal, days, hours, minutes, data_matrix((range+1):length(data_matrix(:,1)), :));
raw_g = dial2gravity (dial_after_corr);
lat_radians = ((lat_degrees + lat_minutes).*pi)./180;
g_after_lat = lat_correction (raw_g, lat_radians);
g_after_car= g_after_lat - g_after_lat(1);
g_after_faa = g_after_car + 0.307.*heights';
g_after_bouguer = bouguer_corr (g_after_faa, heights');
result = g_after_bouguer;

mean_g = mean(result);


%plotting of results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


figure;
plot (heights, result-mean_g, 'ks');
title ('after bouguer');
grid on;
hold on;
for i=1:range
        plot(heights(i), result(i)-mean_g, '.w', 'markersize', 20);
        text( heights(i), result(i)-mean_g, sprintf(' %d',data_matrix(i,1)));
end;
%%%%%%%
figure;
plot (heights, g_after_faa, 'ks', 'markersize', 14);;
title ('after faa');
grid on;
hold on;
for i=1:range
        plot(heights(i), g_after_faa(i), '.w', 'markersize', 20);
        text( heights(i),g_after_faa(i),sprintf(' %d',data_matrix(i,1)));
end;
%%%%%%%%5
figure;
plot (heights, g_after_tidal-mean(g_after_tidal), 'ks');
title ('tidal correction');
grid on;
hold on;
for i=1:range
        plot(heights(i), g_after_lat(i)-mean(g_after_lat)  , '.w', 'markersize', 20);
        text( heights(i), g_after_lat(i)-mean(g_after_lat) , sprintf(' %d',data_matrix(i,1)));
end;
%%%%%%%%%%%

figure;
plot (heights, g_after_lat-mean(g_after_lat), 'ks');
title ('lat corr');
grid on;
hold on;
for i=1:range
        plot(heights(i), g_after_lat(i)-mean(g_after_lat)  , '.w', 'markersize', 20);
        text( heights(i), g_after_lat(i)-mean(g_after_lat) , sprintf(' %d',data_matrix(i,1)));
end;
```

```
%%%%%%%%%%%%


[x,y] = meshgrid(min(longs):0.0001:max(longs), min(lat_degrees+lat_minutes):0.0001:max(lat_degrees+lat_minutes));

z = griddata (longs, lat_degrees + lat_minutes, g_after_bouguer', x, y,'cubic');
figure;
%contourf (x,y,z,30);
pcolor (x, y, z);
colorbar;
shading  interp;
title 'g after Bouguer , Lat and FAA corrections');
grid on;
hold on;
for i=1:range
        plot(longs(i), lat_degrees(i)+lat_minutes(i), '.w', 'markersize', 20);
        text(longs(i), lat_degrees(i)+lat_minutes(i), sprintf(' %d',data_matrix(i,1)));
end;
axis tight
%%%%%%%%%%%%

figure;
contourf(x,y,z,30);
title 'g after Bouguer , Lat and FAA corrections');
colorbar;
hold on;
for i=1:range
        plot(longs(i), lat_degrees(i)+lat_minutes(i), '.w', 'markersize', 20);
        text(longs(i), lat_degrees(i)+lat_minutes(i), sprintf(' %d',data_matrix(i,1)));
end;
axis tight
%%%%%%%%%%%%


figure;
plot3(longs, lat_degrees+lat_minutes, heights,'.-k');
hold on;
grid on;

for i=1:range
        plot3(longs(i), lat_degrees(i)+lat_minutes(i), heights(i),'.w', 'markersize', 20);
        text(longs(i), lat_degrees(i)+lat_minutes(i), heights(i), sprintf(' %d',data_matrix(i,1)));
end;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%density.m
%this function calculates the density of various rock formation using
%hard-coded pairs of measurement points. the density is calculated as
%delta_g / (delta_h * 2 pi G)
%output: the calculated densities, and the station numbers
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


clear g_diffs h_diffs

%stations pairs (line number. not station number!!
pairs = [ [105 107] ; [99 100]; [80 81] ; [78 83]; [16 81 ]; [25 26] ; [15 24]; [13 27] ; [11 10]];

for i=1:length(pairs)
    g_diffs(i) = no_bg(pairs(i, 2)) - no_bg(pairs (i, 1));
    locations(i,1) = grav_all(pairs(i,2), 1);
    locations(i, 2) = grav_all(pairs(i,1), 1);
    h_diffs(i) = h(pairs(i, 2)) - h(pairs (i, 1));
end

densities = (g_diffs ./ h_diffs) ./ (2*pi*6.67e-11)
locations
```