Regional Gravity Survey of Silver Spurs Ranch Revisited

Wes Wilson

Sangre Geophysics

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History

In June 2006 a regional gravity survey was conducted along all access roads on Silver Spurs Ranch at a 100m spacing resulting in 357 gravity measurements spanning the ranch. The motivation behind the survey was to try to understand the near surface structure accompanying the dike structure related to the emplacement of the Spanish Peaks and its impact on groundwater flow. This was a single man bootstrap survey meant to investigate proof of concept. As such, survey locations were measured using a hand held Garmin GPS receiver to reduce the expense of surveying. The lateral latitude-longitude accuracy of the Garmin is advertised to be within 15 m and can be as accurate as 5 to 10 m. However, the vertical elevation accuracy can be as poor as 30 m. The vertical error translates into significant uncertainty errors for the final gravity maps. As of 2022, the USGS published digital elevation maps (DEM) of the region which currently have a vertical accuracy of 1/3 arc second or 0.82 m. The improved vertical accuracy translates into improved accuracy of the final gravity maps and subsequent interpretations. This was the motivation behind reprocessing the original gravity survey with elevations from the USGS DEM. These maps replace those described in the original document.

Gravity survey

The survey instrument and procedure are detailed in the previous document. The locations and station numbering is shown in Figure 1.

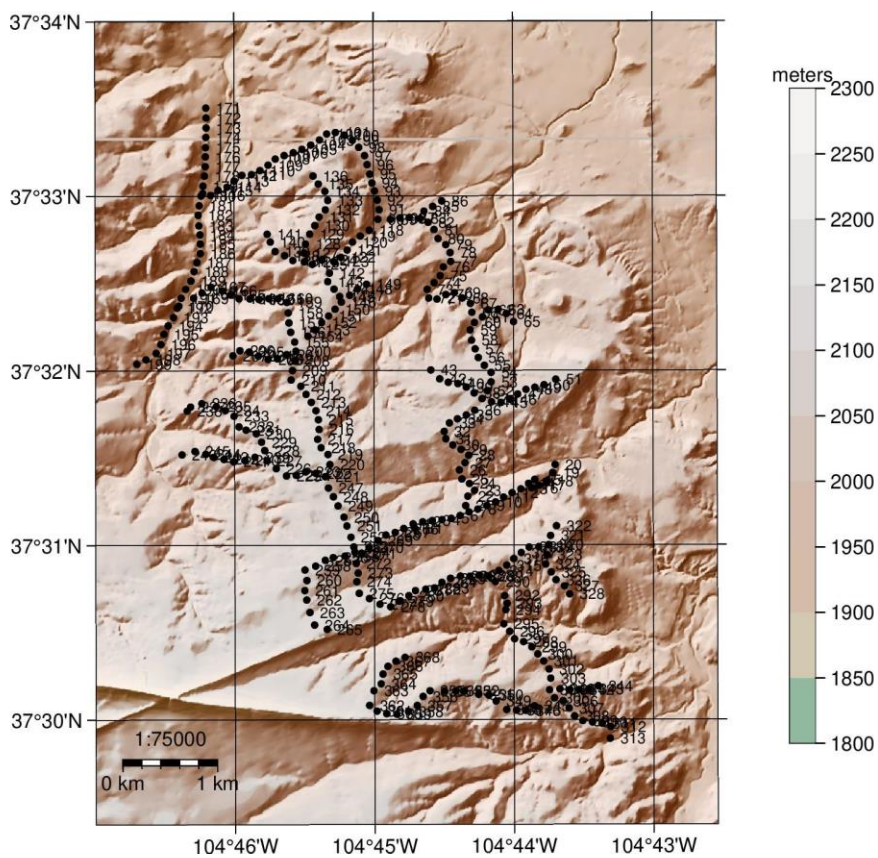

Figure 1 Gravity locations and station numbers shown on a topographic map of the region. Station numbers identify individual measurements in the gravity tables which are available on request.

The topographic map in Figure 1 is derived from USGS DEM file n38w105.tif. Station elevations are extracted from the DEM grid by using a nearest neighbor bilinear interpolation. The station elevation difference between the original survey and the reprocessed survey is shown below.

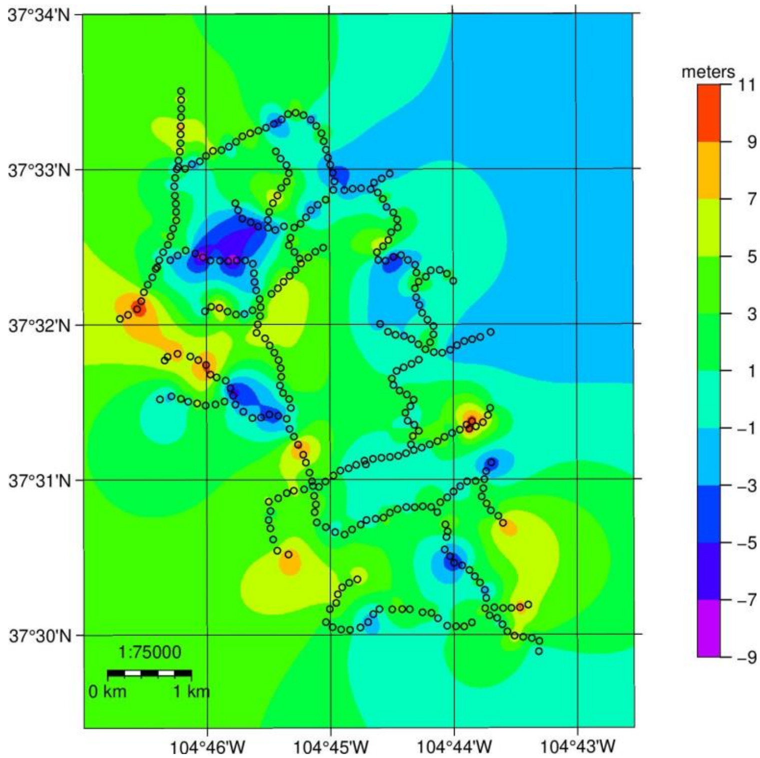

Figure 2 Survey elevation differences between the original survey and the new reprocessed survey

Most of the original survey elevations are within ± 3 m of the USGS DEM elevations. However, there are spotty elevation differences along the east side of the survey and larger differences along the north entrance to Silver Spur Road, Cantel Road and Boot Court.

As discussed in the previous treatise, there are a number of factors which cause variations in the gravity measurements:

- electronic instrument drift during the course of the survey
- tidal variation caused by the sun and moon
- latitude variations caused by the shape of the earth
- elevation differences along the survey profile
- density difference beneath a corrected datum elevation
- elevation differences in the surrounding terrain

Formulas for these corrections are found in Appendix A.

The goal of interpretation is to correct for all these effects and then model any remaining density variations. The free air anomaly map corrects for the first four, the simple Bouguer anomaly includes the correction to an elevation datum and the complete Bouguer corrects for all contributions from the surrounding terrain. The final anomaly map contains only the effect of near surface density anomalies in the earth and the interpretation of these anomalies can lead to insights into subsurface structure.

The impact of the elevation errors can be seen by comparing the Bouguer anomalies from the previous survey with the Bouguer anomaly using the new elevations.

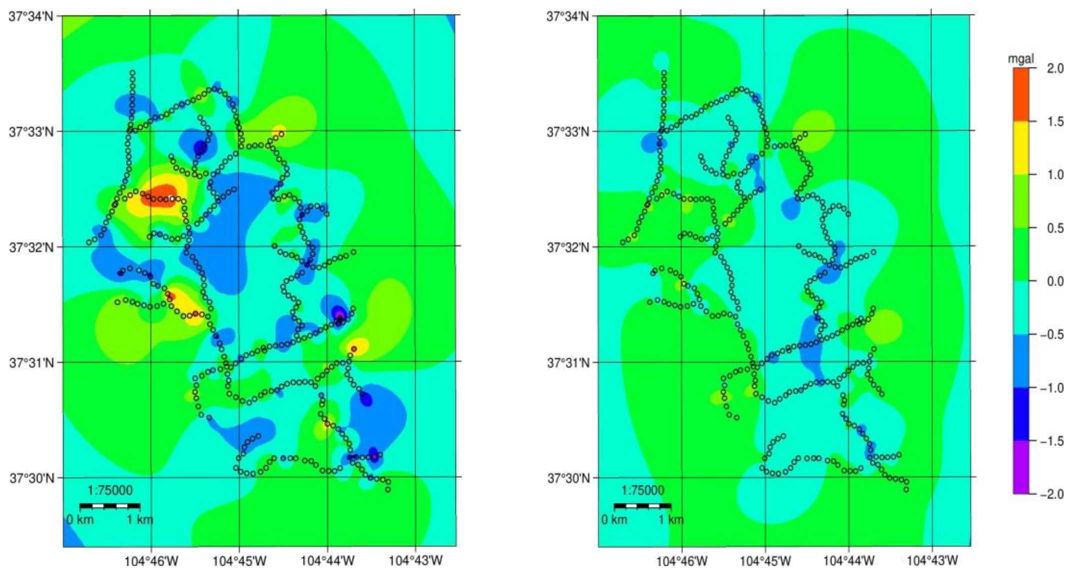

Figure 3 Bouguer anomaly map for the original survey elevations on the left and the corresponding Bouguer anomaly using the new USGS DEM elevations on the right

The overall features between the two are similar, but the new map is much smoother without elevation related spikes. If the elevation difference map is compared with the Bouguer difference map, an almost one to one correlation between elevation error and gravity anomaly error is seen.

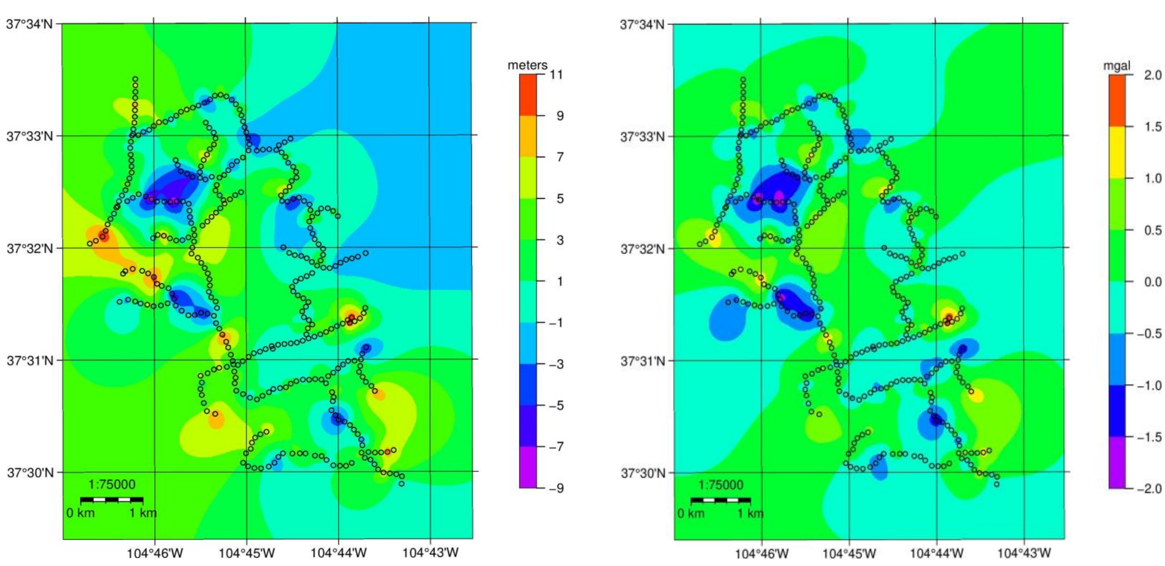

Figure 4 Elevations difference map on the left and Bouguer anomaly difference on the right

Complete Bouguer anomaly

The complete Bouguer anomaly map includes a correction for variations attributed to the surrounding topography. For this study, the simple Bouguer and complete Bouguer corrections are applied using a vertical prism model generated in the Geoscience Analyst application developed at the University of British Colombia and now maintained by Mira Geoscience.

To apply the corrections, a vertical prism model is built where the individual prisms match the surface topography on the top and extend to a planar base at an elevation of 1000 m with cell sizes of 10 m in the x and y directions. The density value assigned to the prism is 2.67 g/cc. This gives both a simple Bouguer correction and a terrain correction at the same time. The terrain correction for the earlier survey was corrected manually using circular Hammer templates. The 3D model correction is more robust.

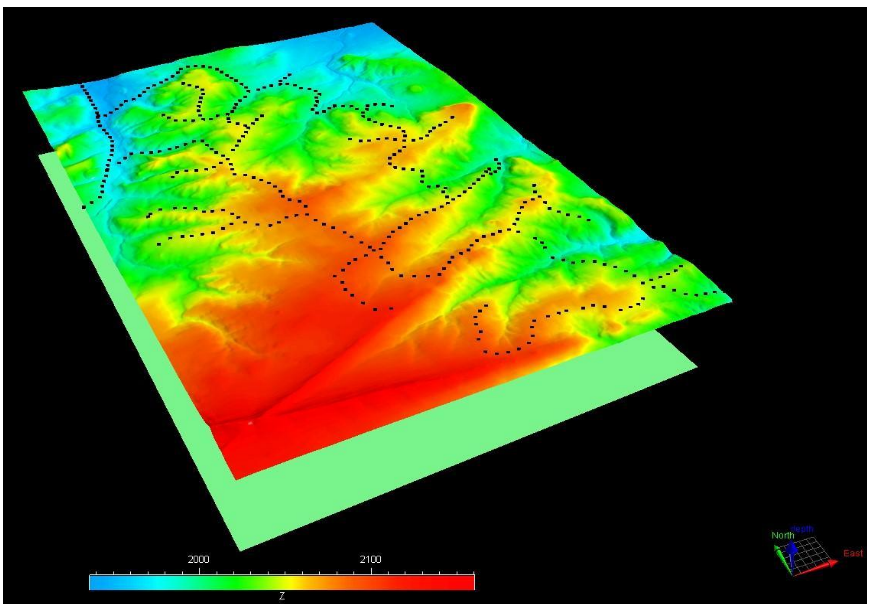

Figure 5 Vertical prism model used to apply terrain corrections to the Bouguer anomaly map. Elevations are in meters. Big Dike and Small Dike appear in red at the bottom of the model.

The final reprocessed complete Bouguer anomaly map is shown below.

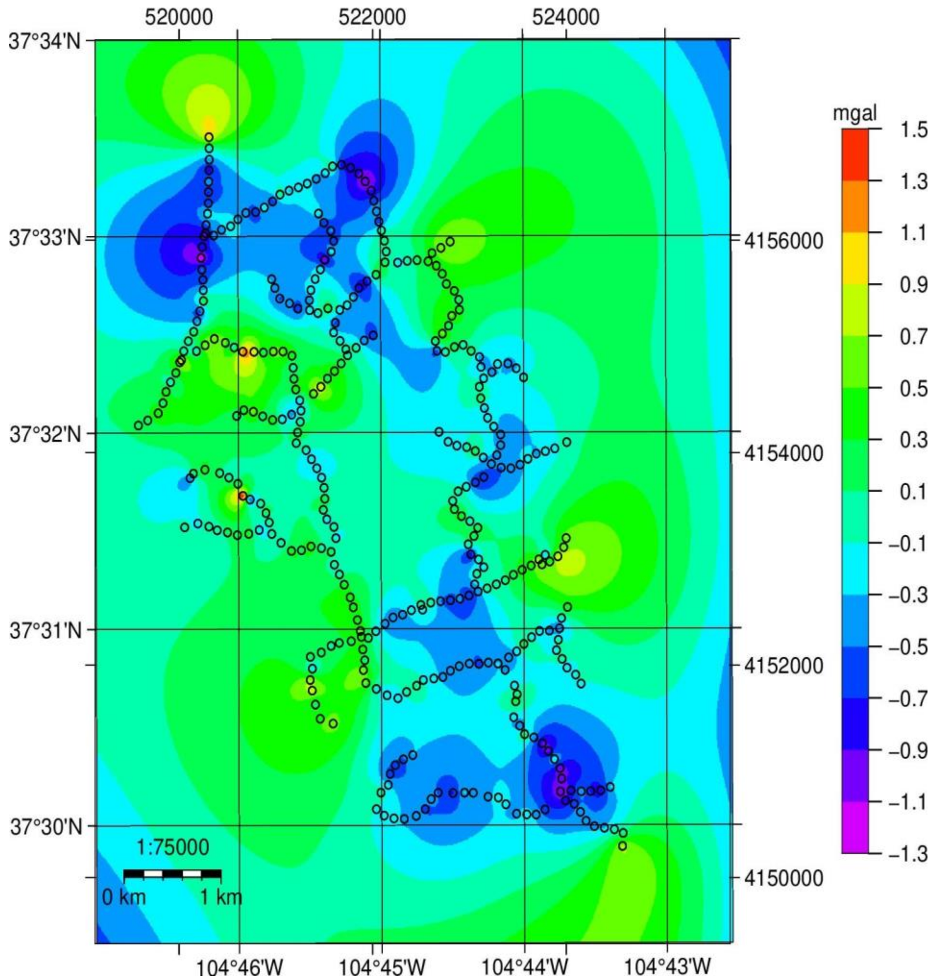

Figure 6 Final complete Bouguer anomaly map. Locations are shown in both latitude-longitude coordinates and Universal Transverse Mercator (UTM) coordinates.

Gravity modeling

The complete Bouguer anomaly map shows remaining gravity variations after all corrections are made and is the basis for the interpretation. Anomalies associated with the near subsurface geology are interpreted by matching a computed gravity field to the observed gravity anomaly. The models can be simple geometries like spheres and cylinders or more complicated structures built from sums of cubes. The gravity field associated with a cube of constant density can be computed rapidly. The parameterization for an arbitrarily oriented cube is :

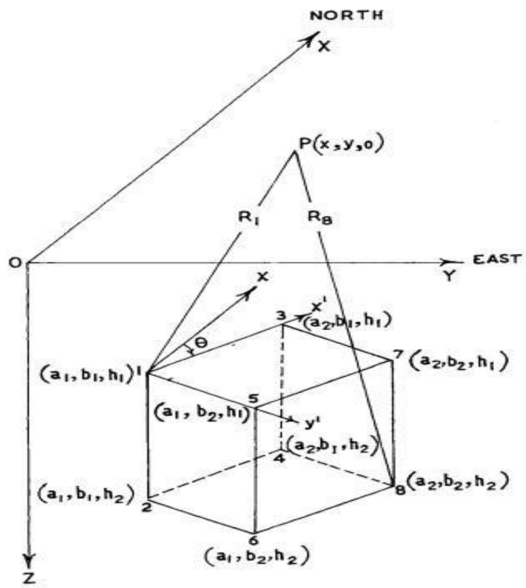

Figure 7 Parameterization for an arbitrarily oriented cube (Rao and Babu, 1991).

The gravity anomaly ΔT for this parameterization at point P for a cube of constant density with an arbitrary orientation can be written as (Kunaratnum, 1981)

$$\Delta T(x, y, 0) = \sum_{k=1}^{2} \sum_{\ell=1}^{2} \sum_{m=1}^{2} S\Bigg[G_1 \ln (R_{k\ell m} + \alpha_k) + G_2 \ln (R_{k\ell m} + \beta_\ell) + G_3 \ln (R_{k\ell m} + h_m) + G_4 \arctan \frac{\alpha_k h_m}{R_{k\ell m}\beta_\ell} + G_5 \arctan \frac{\beta_\ell h_m}{R_{k\ell m}\alpha_k}\Bigg],$$

It looks complicated but it's a simple fast computation for the computer. By building up a model from a number of cubes, the gravity anomaly for arbitrary structures can be computed. The problem lies in how to arrange the cubes to match the surface gravity. This requires solving an inverse problem. The cubes get arranged mathematically in such a way as to minimize the difference between the observed gravity field and the computed gravity field. There are a number of different inversion methods. As a first pass on a 3D interpretation, an application in the Geoscience Analyst software package is used to compute an unconstrained inversion. A constrained inversion uses the known geology to create the structure of the model and the densities in these structures are modified to match the observed gravity field. Since we know little about the subsurface structure, an unconstrained inversion is used to move individual cubes and adjust their internal density to match the gravity anomaly. The final model does not necessarily reflect geology, but gives a sense of the density distribution.

As a starting point, a block model is constructed with cubes of constant density.

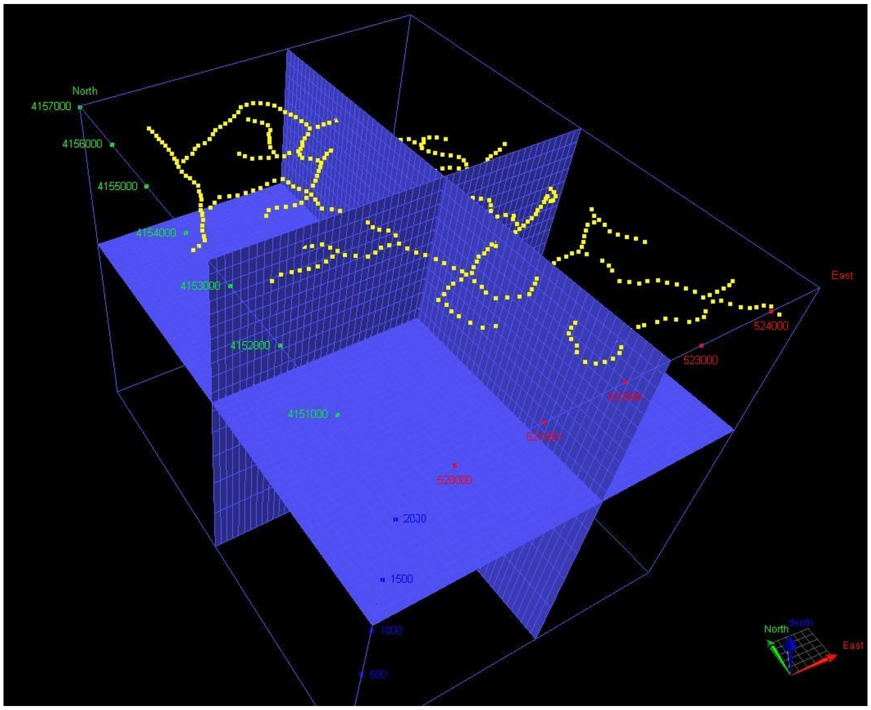

Figure 8 Starting model for the unconstrained inversion. Lateral cell sizes are 100m x 100m. Vertical cell size increases with depth. Initial densities are set to 2.67 g/cc.

The inverted model is shown in Figure 9. The response color spectrum represents relative densities above and below the background density of 2.67 g/cc. The blue cube objects are isosurfaces near -.03 g/cc or regions where the density is less than the background value.

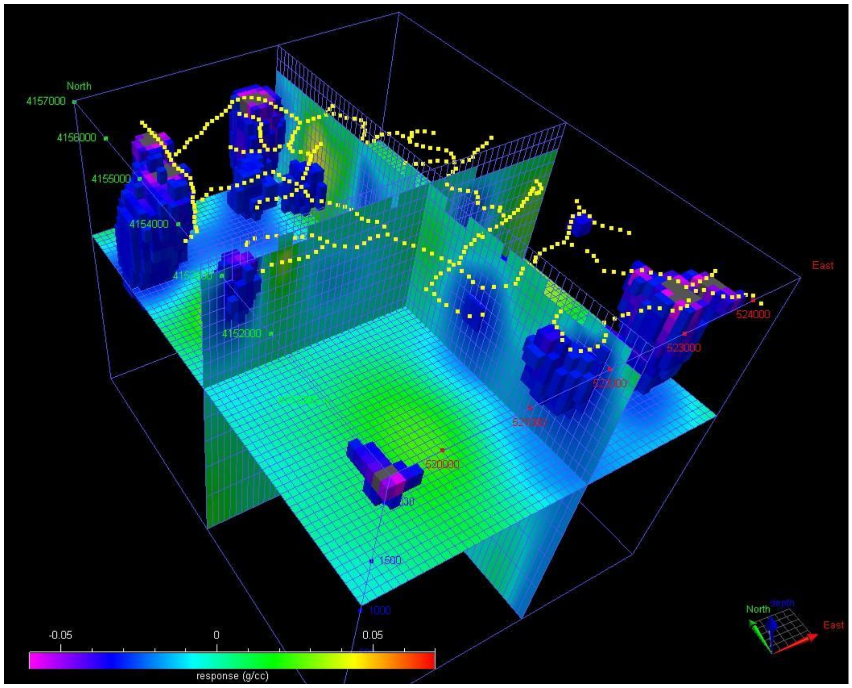

Figure 9 Block model inversion which is the best match to the gravity values at the yellow locations.

Horizontal and vertical slices exist at each of the grid locations. Removing the block model grid, the density anomalies are more apparent.

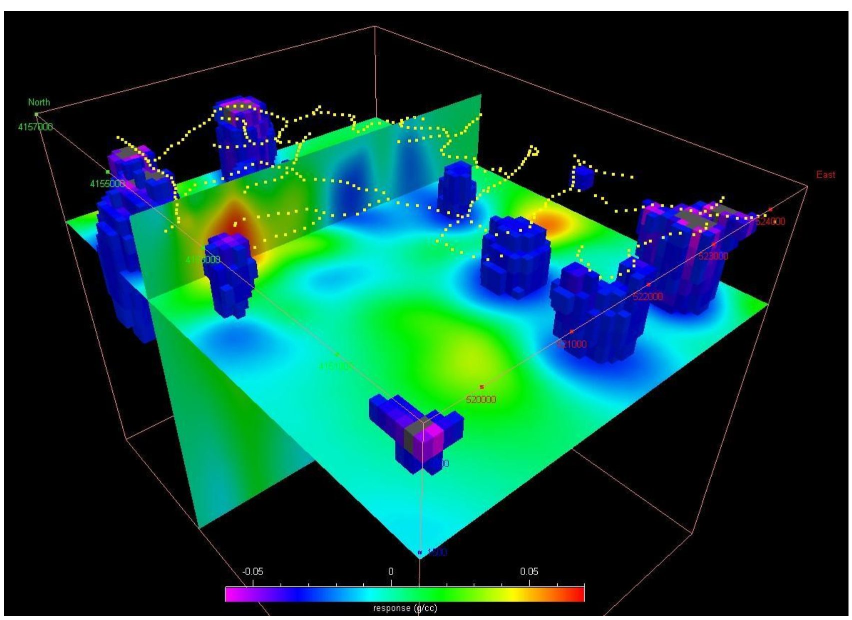

Figure 10 Unconstrained inversion for a horizontal depth slice of 800m and a vertical slice which transects the north end of Silver Spur Rd.

A depth slice at 800 m is extracted and plotted in map view for comparison with the surface complete Bouguer anomaly. The negative anomalies in the depth slice are smoother and more pronounced as expected for a potential field like gravity.

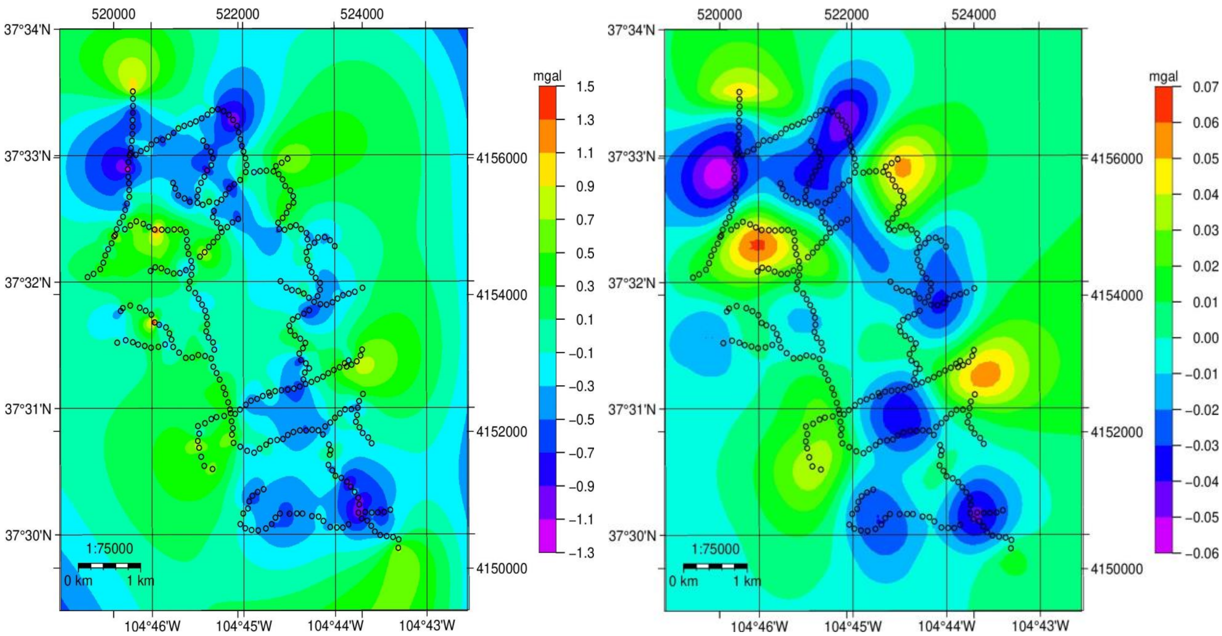

Figure 11 Surface Bouguer anomaly on the left and inverted depth slice at 800m on the right.

The Bouguer anomaly map is reminiscent of a map of existing coal mines in the area. A collection of maps showing the extent of the coal mining is found at ideal-colorado.com. One map shows the coverage for Silver Spurs Ranch.

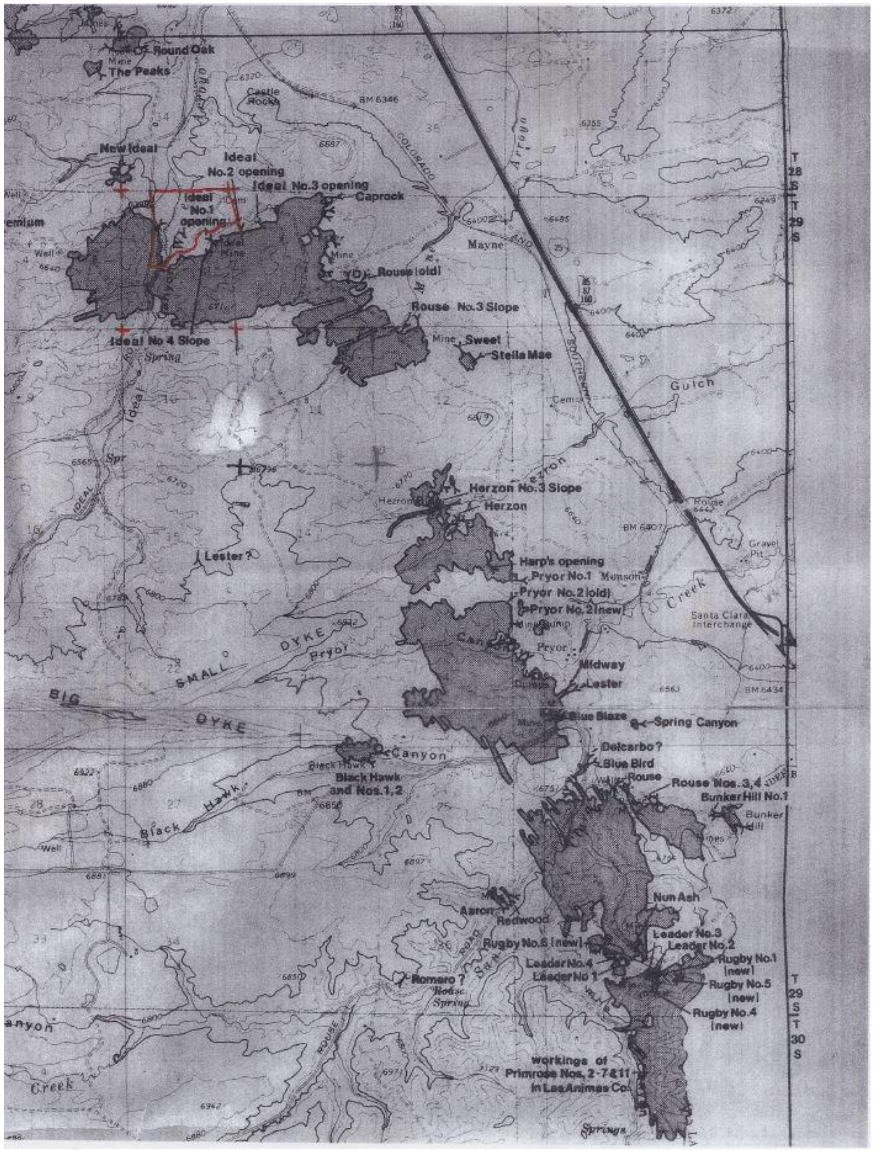

Figure 12 Coal mining activity in the area that encompasses Silver Spurs Ranch. Ideal mine appears at the top, Hezron in the middle and Pryor at the bottom.

If the borders of the Ideal, Hezron and Pryor mines are digitized and overlaid on the Bouguer map, a similarity between coal mines activity and the negative Bouguer anomaly appears.

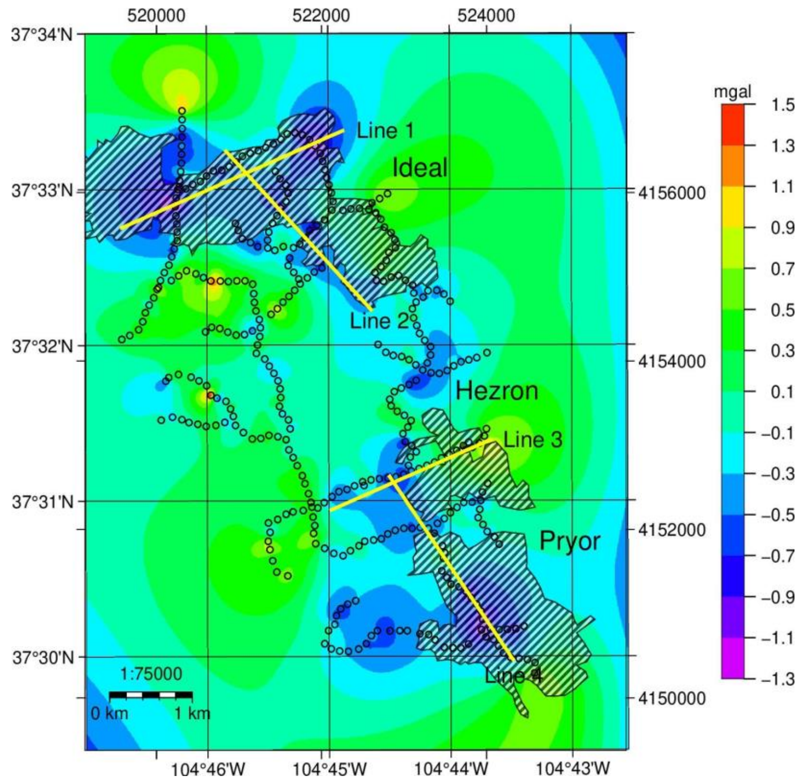

Figure 13 Boundaries of the Ideal, Hezron and Pryor mining works overlaid on the complete Bouguer anomaly map. Yellow lines indicate locations for 2.5D cross section models.

The Ideal and Pryor mines are a reasonable match to the gravity anomalies, but the Hezron mine appears to be slightly offset. To investigate the possibility that the anomalies are mine works related, a series of 2.5D prism models are constructed. The 2.5D models are approximations that are infinite perpendicular to the prism axis and help quantify extent and relative densities.

In the initial study, density values were measured for dike rock samples taken from the road cut in Walsenburg and sedimentary rock samples taken from various locations on the ranch. The average dike rock density is 3.85 g/cc and the average sedimentary rock density is 2.42 g/cc. One surface sample of bituminous coal yielded a density of 1.5 g/cc. These values are used to establish prism densities.

The Bouguer correction assumes a standard country rock density of 2.67 g/cc. This is slightly higher than measured values, so additional prisms are added to approximate the effect of the country rock. The earth, of course, is much more complicated. Well control in the area is sparse, but there is an older Geological Survey Bulletin (Johnson, 1958) that addresses geology and coal resources in the area. Figure 14, taken from plate 48 of the report, shows typical stratigraphic columns for several wells in an area trending from Pryor to the Huerfano River along the range front. As an example, Column D is found near the Morning Glory mine about 5 km northwest of Walsenburg. Assuming that the average coal seam is on the order of 1 m thick and there may be up to 15-20 of these seams, the Bouguer anomaly is approximated by a rectangular prismatic body 20 m thick with the density of coal, 1.5 g/cc. This is a gross simplification, but allows the computation of expected anomaly magnitudes.

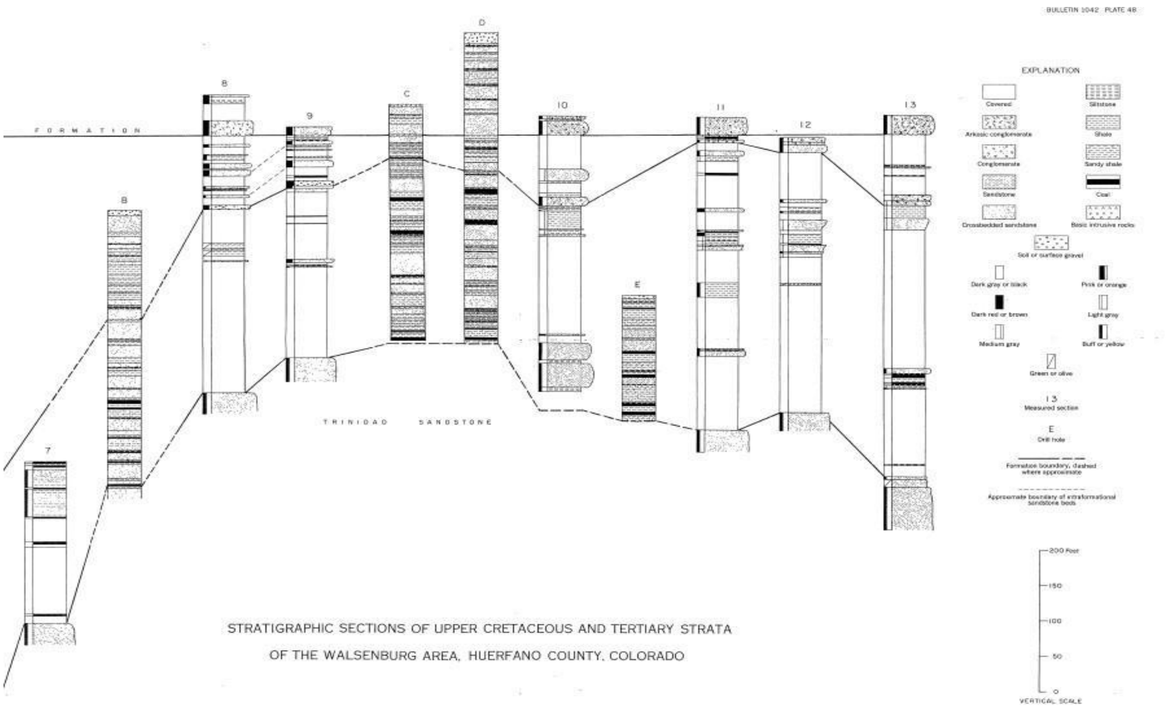

Figure 14 Well control along the range front from Walsenburg to the Huerfano River. Coal beds are shown in black. Scale is shown in the lower right corner (GS Bulletin 1042-O Plate 48).

FastGrav is a freeware 2.5D gravity modeling application that allows interactive editing of mass objects to match the observed gravity values. Rectangular prisms are added with FastGrav to approximate coal beds and surrounding country rock for the four cross sections shown in yellow in Figure 13.

Line 1 in Figure 15 is a west to east trending line along the northern border of the Ideal mine. Observed gravity values are extracted from the surface Bouguer anomaly at 100 m intervals along the profile. Prisms are added to the model in an attempt to match the observed gravity. The prisms are annotated with the corresponding density value in g/cc attached to the name. The rectangular prisms vary in density and extent. The thickness is kept constant at 20 m and the density value is varied to match the observed values. The x1,y1 and x2, y2 coordinates in the cross section profiles are the endpoints locations of the profile in UTM coordinates. The blue profile line is the gravity value computed by summing all contributions from each prism and the black profile line is the observed gravity values.

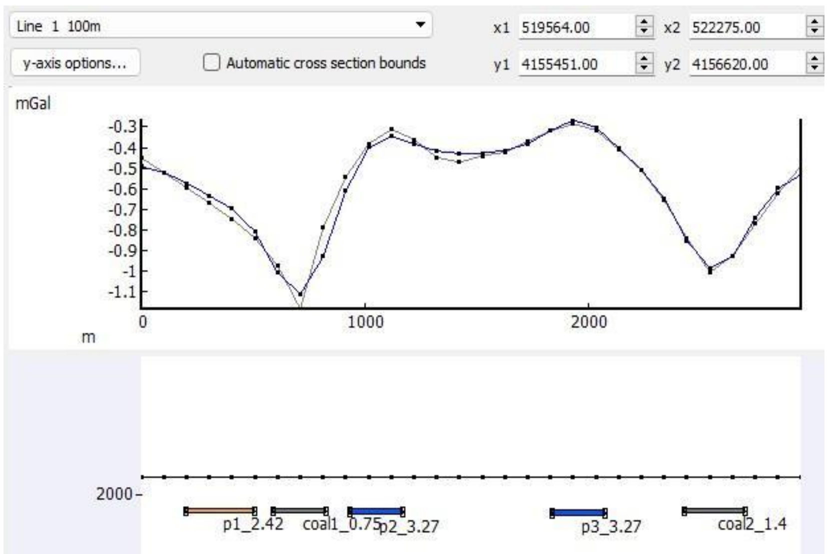

Figure 15 Line 1 profile trending west to east along the northern boundary of the Ideal mine works. The blue curve is computed from the model prism. Black points are field observations. Coal is colored in grey and country rock is brown or blue depending on the relative density.

The surface elevation at the center of the coal1 negative anomaly is 1960 m. The mine floor at this location taken from a map of the Ideal mine is 1921 m. The base of the coal1 prism is set to this same depth. The coal1 prism gives the best fit for a density of .75 g/cc which is quite a bit lower than a coal density of 1.5 g/cc and may reflect the effect of honeycombing created by the access shafts in the mine. A value of .75 g/cc corresponds to an extraction percentage of 50%.

The coal2 prism is placed at the same depth. The density that fits the observations the best is 1.4 g/cc. This may indicate that the amount of coal produced was less than at the coal1 location or some other variation. No attempt was made to account for regional dip of the beds. Prisms of higher density are added to match the observations and represent country rock. The mean density value of sandstone measurements is 2.42 g/cc and the harder volcanic rocks have a higher average density around 3.27 g/cc.

Line 2 in Figure 16 is a northwest to southeast traverse across the Ideal mine. Prism thicknesses are again taken to be 20 m for both coal and country rock. The southern most extent of the coal 2 prism is about half way down the traverse. The best fit above the coal 1 prism is for a density of 1.5 g/cc and 1.4 g/cc for the coal 2 prism. Additional country rock prisms are added to match the observations.

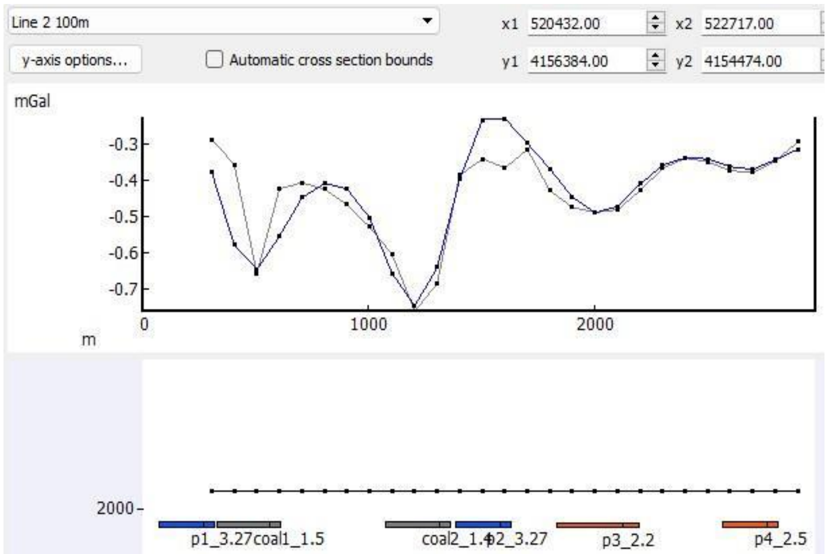

Figure 16 Line 2 along a northwest to southeast traverse across Ideal mine.

Line 3 in Figure 17 follows Leather Drive starting just east of Silver Spur Road and ending at the Hezron mine works. The center of the gravity anomaly is offset to the southwest from the mine works. This is an exception to what is seen for the Ideal and Pryor mine anomalies. Modeling of the anomaly requires a density of 1.0 g/cc to match the observations on the eastern half of the traverse. This corresponds to the density of water. If correctly modeled, it is possible that it reflects flooded coal tunnels. The elevation at the base of the water and coal model prisms is 1945 m. Lot 107 is along the traverse and has a water well that extends to a depth of 1941 m. There is water, but no show of coal in the drilling log. Water quality is poor and requires treatment for drinking. It is consistent with a possible mine shaft source, but not conclusive. A water isotope or similar study is necessary to confirm. The anomaly above the Hezron mine is more complicated than modeled. The negative spike at an offset of 2000 m may also be coal related.

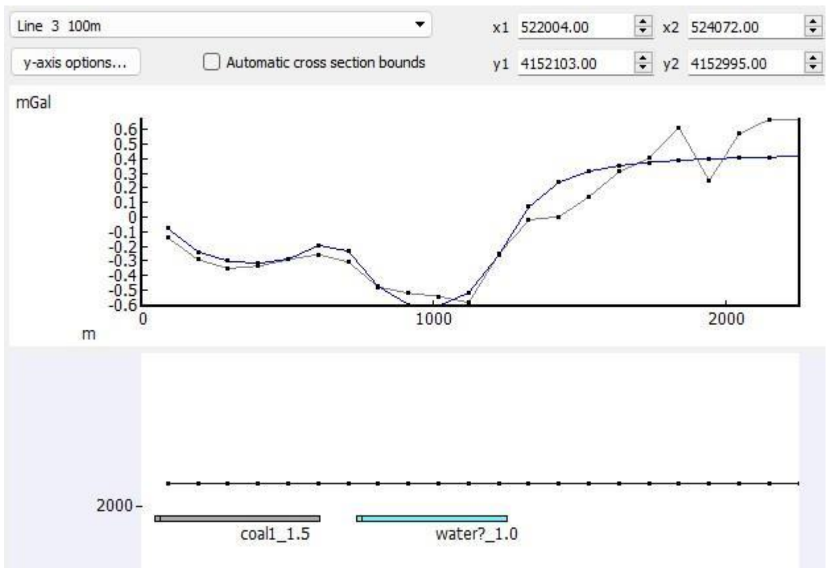

Figure 17 Line 3 along Leather Dr starting just east of Silver Spur Rd and extending to the Hezron mine works.

Line 4 in Figure 18 is a northwest to southeast trending profile starting at Leather Drive and ending at the south end of Silver Spurs Ranch. The southern half of the line is above the Pryor mine works. The best fit density of 1.5 g/cc for the coal1 prism is consistent with a possible coal source. Prisms representing country rock are added to match the remaining anomaly. The surface elevation at the center of coal1 prism is 2042 m and the depth at the top of the coal1 anomaly is 1905 m for a depth from surface of 137 m. The peak of the p2 high density prism coincides with the intersection of Small Dike along the traverse.

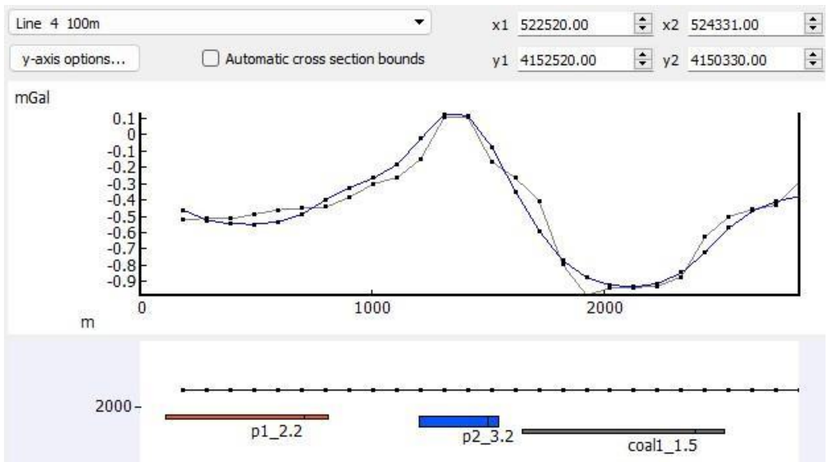

Figure 18 Line 4 along a northwest to southeast trending line that traverses the Pryor mine works.

The interpretations are consistent with a possible coal source for the negative Bouguer anomaly values seen in Figure 6. However, gravity models that match observed values are not unique. There may be alternative interpretations. For this study, using the density of coal gives a plausible match to the observed values and the extent of the anomalies show a general correlation to known mine locations.

Conclusions

Free air and Bouguer anomaly corrections rely on an accurate measurement of surface elevation. Comparison of surface elevations measured during the original survey in 2006 and a recent digital elevation map shows deviations of as much as 11 m. The error propagated to the gravity anomaly can be as much as 3.4 mgal for the free air anomaly and as much as 2.1 mgal for the Bouguer anomaly. The Bouguer anomaly ranges from -1.3 to 1.5 mgal, so the error in spots in the original survey is larger than the anomaly. No bueno. The anomalies in the original survey show a similar trend to the ones in the reprocessed survey, but in the northwest region of the survey there are significant differences.

After correcting the station elevations, the gravity map shows a correlation with coal mine extents in the area. Simple 2.5D models suggest that a viable interpretation is that the negative Bouguer values in Figure 6 correspond to possible coal deposits and coal mining activities.

References

Kunaratnam, K., 1981 Simplified expressions for the magnetic anomalies due to vertical rectangular prisms: Geophys. Prosp., 29, 883-890.

Rao, D. Bhaskara and Babu, N. Rames, 1991 A rapid method for three-dimensional modeling on magnetic anomalies: Geophysics, vol. 56, no. 11, 1729-1737.

Johnson, R, 1958 Geology and coal resources of the Walsenburg area, Huerfano County, Colorado: Geological Survey Bulletin 1042-O.

Acknowledgments

The 3d unconstrained inversion was computed using the Geoscience ANALYST Pro Geophysics application supported by Mira Geoscience (mirageoscience.com).

The 2.5D forward modeling profiles were accomplished using the FastGrav (fastgrav.com) shareware application.

All gravity maps were constructed using the freeware Generic Mapping Tool (GMT) application which is supported by the School of Ocean and Earth Science and Technologyof the University of Hawai'i at Mānoa and grants from the National Science Foundation (www.soest.hawaii.edu).

The original 2006 survey was partially funded by Silver Spurs Property Owners Association.

Special thanks go to my very patient wife, Lanie, who supported me during the study.

Appendix A

Gravity correction formulas

Drift correction:

$$g_{dc} = g_{obs} – [(g_{base2} - g_{base1})/(t_{base2} – t_{base1})]X(t_{obs} – t_{base1})$$

g_{obs} = observed gravity
g_{base} = gravity at base station
t_{obs} = time of gravity observation
t_{base} = time of observation at base station

Latitude correction:

$$g_{IGF} = 9.78032[(1 + 0.00193185138\sin^2 \lambda)/(1 - .006694379\sin^2 \lambda)^{1/2}]$$

λ = geographic latitude in radians

Free air correction:

g_{FA} = 0.3086*(surface elevation – datum elevation) elevation in meters

Bouguer correction:

g_B = g_{FA} - 0.04193*density*(surface elevation – datum elevation)

for an average density of 2.67 g/cc

g_B = g_{FA} - 0.112*(surface elevation – datum elevation)

g_B = 0.1966*(surface elevation – datum elevation) elevation in meters

Complete Bouguer correction:

$g_{CB} = g_{dc} – g_{IGF} + g_B$ + terrain correction