Understanding the Utility of Gravity and Gravity Gradiometry for Geothermal Exploration in the Southern Walker Lake Basin, Nevada

J. D. Shoffner[12], Y. Li[1], A. Sabin[2], M. Lazaro[2]

[1]Colorado School of Mines, Department of Geophysics, Golden CO
[2]Geothermal Program Office, Department of the Navy, China Lake CA

Keywords

Hawthorne, Nevada, Walker Lane, exploration, Navy Geothermal Program Office, inversion, gravity, airborne methods, geothermal, gravity gradiometry, faulting, structure

ABSTRACT

Ground gravity has been instrumental in understanding structure at depth for many geothermal targets. An efficient approach to the interpretation of these data is to model a basin using a series of 2D sections. However, the validity of 2D modeling is questionable when highly 3D structures are present. 3D modeling is often needed when the complexity of 3D structure increases. Full 3D inversions require dense data coverage over the basin and beyond, but large-scale data collection can be time consuming and expensive. The difficulties associated with both the cost and coverage of ground gravity data may be overcome by utilizing the newly available airborne gravity gradiometry surveys.

The southern Walker Lake Basin, Nevada, where the Navy Geothermal Program Office is actively exploring, is a complex basin bounded by N-NNW striking normal faults to the west and Walker Lane type dextral faults to the east. Given the structural complexity and rapid variations in both the basin depth and surface topography in this area, it is clear that 3D modeling is required to quantitatively utilize gravity data in the Southern Walker Lake Basin. We examine and compare 2D density sections to 3D surface inversion modeling of the basin. Preliminary results indicate that the basin constructed using a sequence of 2D sections cannot fully match the observed data and also introduces spurious features. We investigate the data density and distribution required to fully image the complex basin. Within this context, we also examine the feasibility of using airborne gravity gradiometry. This method allows efficient acquisition of gravity gradient data with dense data over a large area. We show through synthetic simulations that the improved data coverage and 3D modeling not only improve the characterization of local structures, but also provide an understanding of regional structure surrounding the target area.

Introduction

Land gravity surveys have shown to be beneficial to the understanding of many geothermal systems by delineating fault location, dip and or offset, as well as depths to basement. Microgravity surveys with highly constrained drill hole data can often define these parameters (Smith et al, 2001). However, in areas where there is sparse or no well data, as well as sparse gravity data, large uncertainties can arise. Currently, gravity surveys in geothermal exploration focuses on targeting computed horizontal gradients to

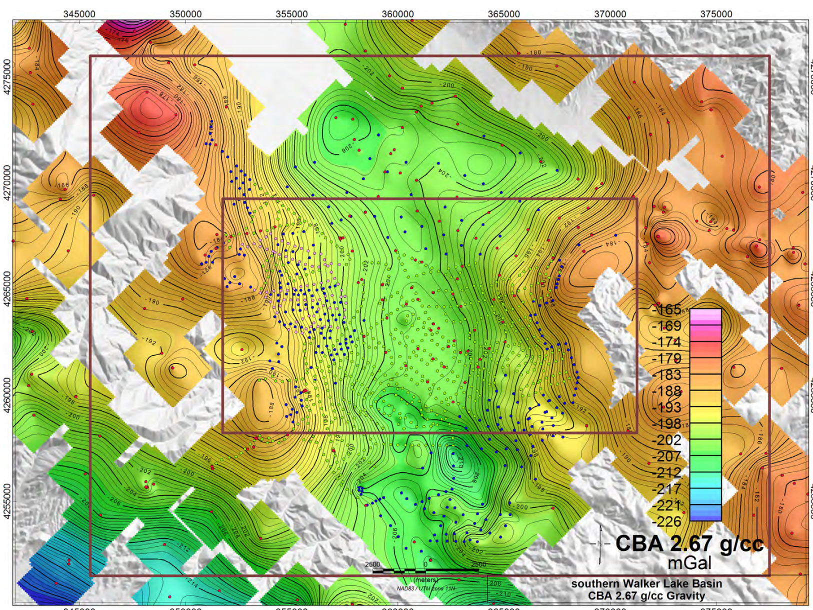

Figure 1. Complete Bouguer Anomaly gravity image. Larger box is the complete inversion area (with padding cells) while smaller box is the focus of the 2D and 3D inversion. Color scale is in mGals and contour interval is 0.5 mGal. Blue dots are Navy stations collected in 2009, pink and green dots are Navy stations collected in 2001, and red dots are stations from the National Gravity and Magnetics Database (GeoNet).

locate faults as well as using 2D cross sections to model basement. However, advances in the mining and petroleum industry show that more information can be derived from standard gravity surveys using 3D inversions that better model complex geologic settings.

A combined total of 1300 gravity stations in the southern Walker Lake Basin were used in this study. The bulk of these stations are located outboard of a right step in a normal fault system in the Wassuk Range where high temperature fluids have been measured in drill holes. The central area of the valley also has dense gravity coverage, but is sparse outside of this area (Figure 1).

2D Methods

Previous work has shown that using geological information coupled with parallel 2D gravity forward modeled cross sections, a 3D view of a basin can be reconstructed (Shoffner, 2010). Using this method, a more rigorous approach was used to create Figure 2 with 12 cross sections over a larger area covering the entire valley. The 3D view shows the depth of the alluvium – basement contact, and was computed by interpolating between the cross section lines with a kriging algorithm. It is apparent that the large offset of normal faulting outboard of the Wassuk Range is modeled well. However, there are large errors associated with the area along the range front where the geothermal exploration is focused. The problem arises due to interpolation between cross sections lines as well as only modeling 2D in a highly complex area. The 2D cross sections model correctly along the profile line, but assume geology and structure are ‘sufficiently linear’ in the lateral direction (Blakely, 1996). However, according to Grant and West (1965), ‘sufficiently linear’ means that the structure must be “at least 20 times longer than it is wide for the two-dimensional assumption to be legitimate.” When assessing the geology in the southern Walker Lake Basin, this assumption is invalid. In order to test the validity of the 2D stitched sections, a forward model was calculated using a surface forward modeling code. Figure 5 shows a difference between the data calculated from the 2D stitched sections and the true data. There is good correlation in the main valley where structures are less complex, but large errors occur on the western edge where geology and topography are complicated and exploration is primarily focused. The large errors observed on the edges of the map show areas of high topography that do not have any surface – basement density contrast, and therefore cannot be correctly forward modeled with this algorithm. In order to account for the issues with 2D modeling, we explore using a 3D surface inversion technique.

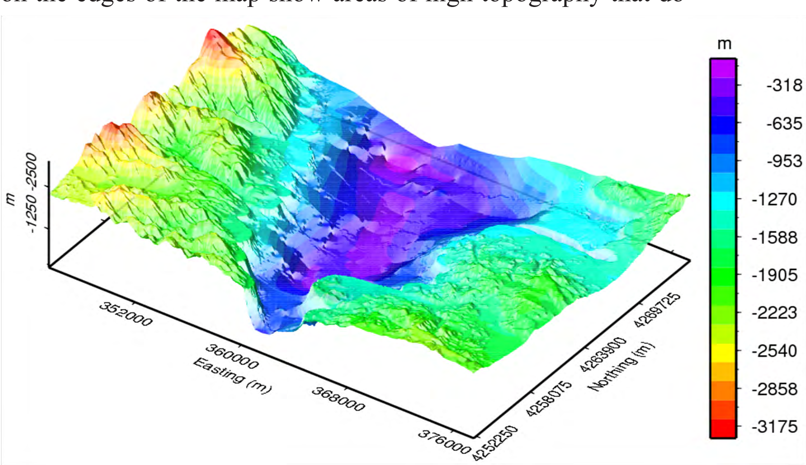

Figure 2. 3D view of the basin obtained by stitching 2D cross sections. Units are in meters.

Gravity Surface Inversion Algorithm

This work uses the gravity modification to the gravity gradiometry surface inversion algorithm developed by Li and Lyrio (2006). This algorithm was originally developed to image top or base of salt in petroleum exploration, when the density contrast is known. This method was adapted for use in imaging a basin where the ‘top boundary’ is surface topography and the ‘base boundary’ is the alluvium – basement contact. The model is found using the inverse solution to the simplified general equation (1),

$$\mathcal{F}\left[h(x,y)\right] = \vec{d} \tag{1}$$

where h is the basin depth, $\vec{d} = \left[d_1, d_2, \ldots, d_n\right]$ is the data vector, and $\mathcal{F}$ is the forward mapping operator. In order to solve the inverse solution, we set up a Tikhonov regularization and minimize the following objective function (Tikhonov and Arsenin, 1977)

$$\min \phi = \phi_d + \mu\phi_m \tag{2}$$

where ϕ_d is the data misfit, ϕ_m is the model objective function, and μ is a regularization parameter that determines a trade-off between the two components. The data misfit is defined as

$$\phi_d = \left\| W_d(\vec{d} - \vec{d}_{obs}) \right\|_2^2, \tag{3}$$

where $\vec{d}$ is the predicted data, $\vec{d}_{obs}$ is the observed data, and $W_d = diag\left\{ 1/\sigma_1, \ldots, 1/\sigma_N \right\}$ is the data weighting matrix. The model objective function ϕ_m is formulated as

$$\begin{aligned} \phi_m &= \alpha_S \int_S (h - h_0)^2 \, dS \\ &+ \alpha_x \int_S \left[\frac{\partial(h - h_0)}{\partial x} \right]^2 dS \\ &+ \alpha_y \int_S \left[\frac{\partial(h - h_0}{\partial y} \right]^2 dS, \end{aligned} \tag{4}$$

where α_x and α_{yy} are coefficients controlling the smoothness of the model in each direction, α_s of the model to the reference model h_0. However, we not only want the basin to be smooth, but also constrained by known bounds as well. The bounds control the range at which the recovered bottom surface could be located, with the highest bound being the surface. While there are different ways to constrain these bounds (Leão et al., 1996; and Barbosa et al., 1997), the logarithm barrier method shown by Nocedal and Wright (1999) is used. Equation (5) shows the final minimization problem.

$$\begin{aligned} \phi &= \left\| W_d(\vec{d} - \vec{d}_0) \right\|_2^2 + \mu \left\| W_m(\vec{h} - \vec{h}_0) \right\|_2^2 \\ &-2\lambda \left[\sum_{j=1}^{M} \left(\frac{h_j - \alpha_j}{b_j - \alpha_j} \right) + \sum_{j=1}^{M} \left(\frac{b_j - h_j}{b_j - \alpha_j} \right) \right], \end{aligned} \tag{5}$$

where λ is the log barrier term, α_j and b_j are minimum and maximum depth, respectively for each cell, M is the number of cells, and $\mathbf{W}_m$ is the discretized matrix representation of the model objective function.

3D Results

Using the 32 km x 25 km area defined in Figure 1, the topography (10 m DEM) was discretized into 100 m x 100 m cells to make the surface, which is also the lower bound of the basin depth. While the area of interest was much smaller (19 km x 12 km, Figure 1), padding cells extending out 6.5 km on each side were used. In practice, cell size increases with distance from the project area, but the size of this problem is small enough (and therefore computationally fast) to keep the same cell discretization for the padding cells as for the model cells. The initial and reference models were set to zero. Bounds were set to -10 m to +5 m in known topographic areas, keeping the inversion focused on only inverting for the surface boundary in the basin. We modeled a single density contrast for the alluvium – basement contact using the same alluvium density as in the 2D modeling (2.20 g/cc), and averaging the basement densities to 2.67 g/cc. This assumes a density contrast of -0.47 g/cc.

Figure 3 show preliminary results of the 3D inversion. In this 3D view of the basin we see a smoother and less subjective model of the basin than the 2D stitch method. Results show that the western area just outboard of the Wassuk Range has steep normal faulting, the eastern side of the valley has a ramp structure up to the Garfield Hills, and the southern area shallows up to the near surface; all correlating with the geologic model. In general, the original area of focus in the center of the valley was recovered very well. Unfortunately, it is clear that the areas that were considered as padding cells were not well defined. Gravity data in these areas were sparse, and not expected to accurately model the basin. The area directly adjacent to the Wassuk range, where gravity data was limited due to steep topography, has difficulties recovering structures. The northern area of the basin is also poorly recovered (as it has the sparsest data); the basin should be deepening in this area. These results confirm that 3D surface inversion is a useful tool, but only in areas with dense gravity coverage. Good results were found where a 300 m x 300 m gravity grid was acquired (Figure 1). Areas near topography were not well recovered because ground gravity is difficult and/or impossible to collect in steep topography such as the Wassuk Range, and can be erroneous when processing terrain corrections with low resolution DEMs. In order to cover the entire area modeled for the southern Walker Lake Basin, a total of 8000 ground gravity stations would need to be acquired if using the 300 m x 300 m station spacing. At \$50 to \$100 a station, this can be very expensive and extremely time consuming. Therefore, we assess the utility of airborne gravity gradiometry.

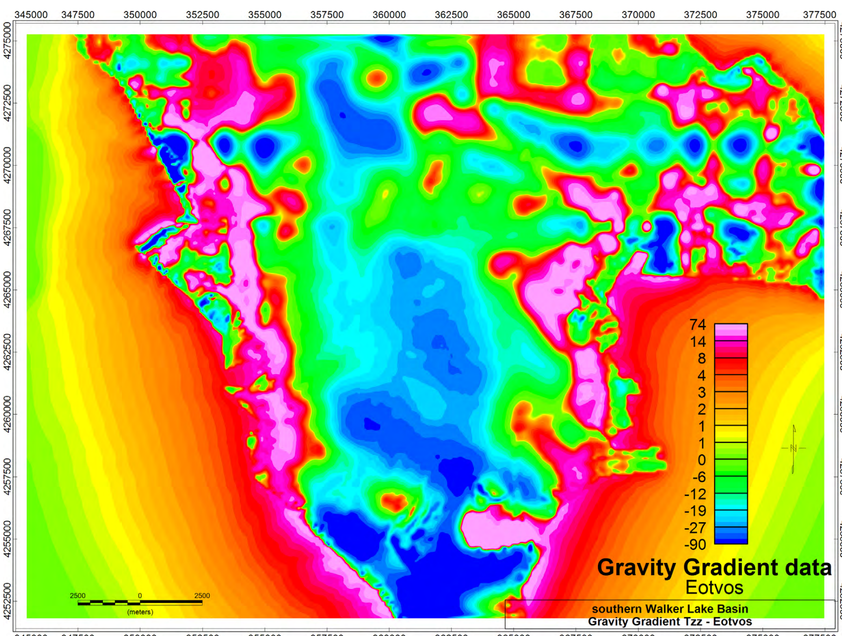

Figure 4. Synthetic Tzz component of gravity gradiometry forward modeling. Color scale in Eötvös.

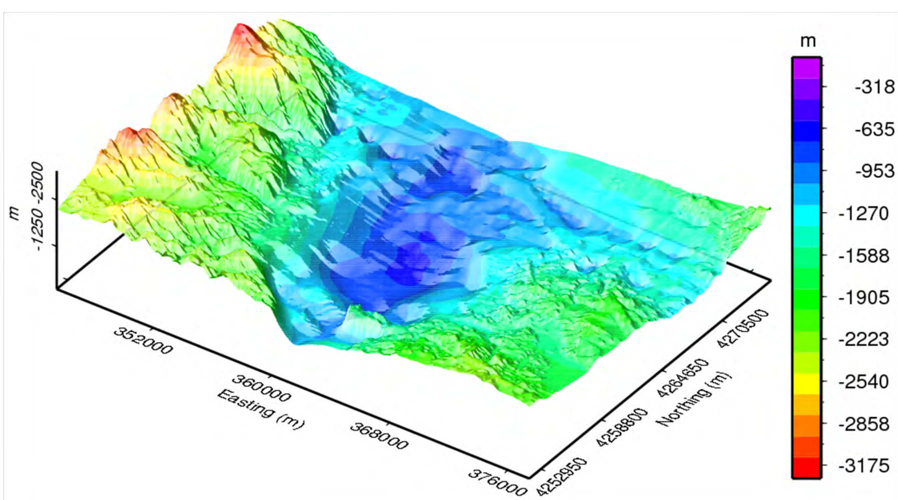

Figure 3. Recovered model using 3D surface inversion. Units are in meters.

Gravity Gradiometry

Airborne gravity gradiometry has been commercially available since the mid 1990s, but has yet to be demonstrated for the geothermal industry. It has been argued that geothermal projects are small scale and the application of airborne methods is expensive. We argue, however, that in order to understand a geothermal prospect, information about the regional geologic setting is critical. Airborne gravity gradiometry has the ability to cover large areas in a short time frame. Furthermore, the method acquires multicomponent gradients of gravity that provide more information than traditional ground or airborne gravity. In order to test the feasibility of the method, we forward model the T_{zz} component of gravity gradient data at 100 m above topography using the recovered model from the 3D inversion. Typical RMS error of gravity gradient data is 5 – 7 Eötvös (0.5 – 0.7 mGal/km). By observing the forward modeled data in Figure 4, we can see that the valley shows a response of -90 to 74 Eötvös, which is well above the resolution of the airborne system at this flight height. There are also more details visible in the center area of the valley. These finer details in the T_{zz} component provide more information that will refine interpretations for the regional and local structural model in geothermal exploration projects.

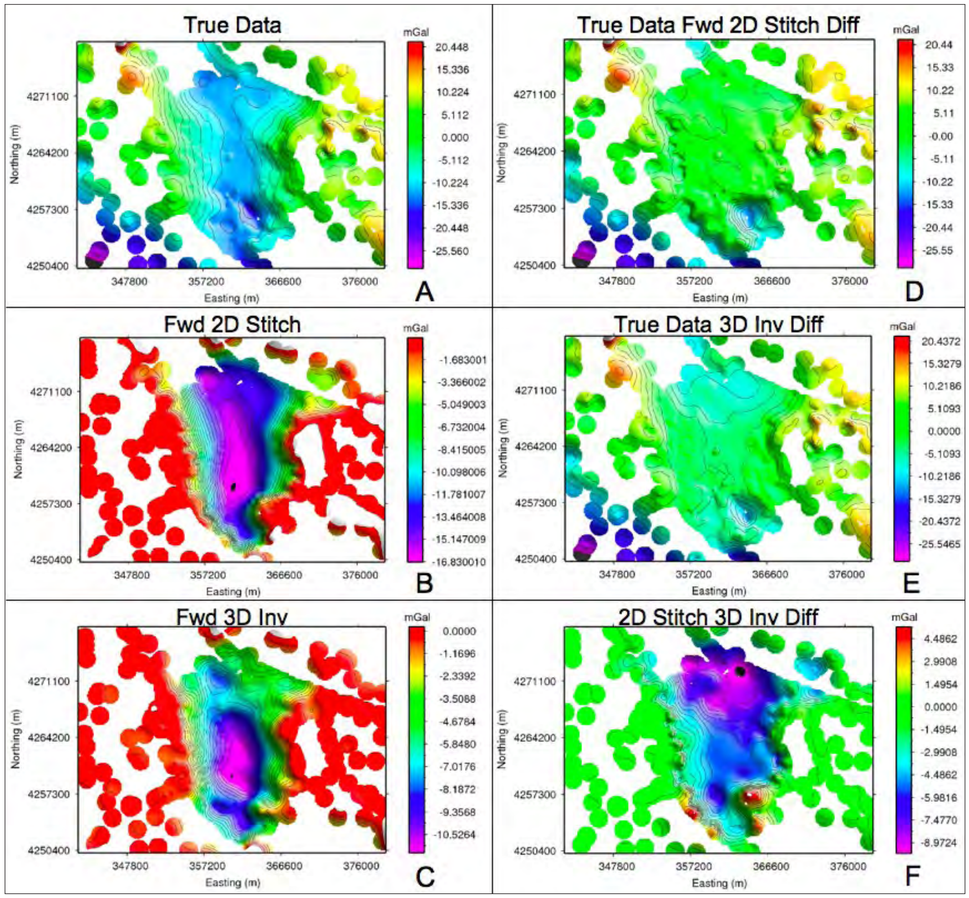

Figure 5. (A-C) Set of forward modeled data from images and (D-E) difference plots. (A) True data with 192.496 mGal value subtracted from data (DC Shift). This value stems from the tie point value of the best-constrained 2D cross section modeled in GM-SYS. (B) Forward model from 2D stitched model. (C) Forward model from 3D inversion recovered model. (D) Difference plot of True data minus 2D stitch data. (E) Difference plot of True data minus 3D inversion data. (F) Difference plot of 2D stitch data and 3D inversion data.

Discussion and Results

When comparing the 2D stitched section (Figure 2) versus the 3D inversion (Figure 3), we see that there is good first order correlation between the two models. However, a major issue with the 2D stitch model is the interpolation between cross section lines. One of the interests of this work is to understand the structure of faulting outboard of the Wassuk Range Front. While along each cross section line there are accurate 2D interpretations, there are no geological or geophysical information between these lines, especially just outboard of the Wassuk Range. The 3D interpretation, however, shows a smoother basement and what could be two major fault displacements along the Wassuk Range Front. This is consistent with geologic interpretations from Hinz et al. (2010). This model will be refined in future work by creating tight bounds from known drill hole data acquired by the Navy GPO. In order to understand the difference in these models, we forward modeled the data of the recovered models and compared them with the true data. What is apparent with the difference map of the true and 2D stitch (Figure 5D) are inconsistencies outboard of the Wassuk Range. While the difference is small, we can see that the difference plot of the true and 3D surface inversion model (Figure 5E) is much smoother and closer to zero in this area. While the 2D stitch model does have a better comparison with the entire valley, since this method can be more subjective, the 3D surface does a better job in the central focus area. This would be improved with better data coverage throughout the rest of the valley.

To understand the data coverage, we investigated the use of airborne gravity gradiometry. While expensive for upfront, small-scale surveys, the method may be very useful and economical for collecting regional data as well as difficult terrain or restricted ground access areas. Regional understanding of geology has become important for geothermal exploration to understand regional stresses and even other nearby potential geothermal sites that would otherwise be undiscovered. This method has gained momentum in the mining and petroleum industry in the past decade, and is becoming increasingly useful as better inversion algorithms take advantage of the multi-component measurements. In this work we forward modeled only the T_{zz} component and have found not only that the simulated data exceeds the noise threshold, but also adds information that may be critical for understanding structures in geothermal systems.

Conclusion

The density sections modeled and stitched into a 3D view show good results for a first order approach to imaging the southern Walker Lake Basin. However, there are obvious errors when looking between line interpolations, as well as errors in assuming that all structures are 2D when modeling the cross sections. In this 3D basin where there are large topographic changes as well as complex geology and fault structures, interpreting any geophysical measurement should be performed in 3D. This led to performing a surface inversion using a 3D algorithm. While we are only modeling a surface contrast of a single density, further work will involve accounting for compaction within the sediments with depth and using tight lithologic bounds from drill hole data for a more accurate solution. Preliminary modeling from the 3D inversion show good results where data density is high, but poor results where data are sparse. This led us to investigating the utility of airborne gravity gradiometry that will decrease time and costs while increasing data density and information. Forward modeling show that higher resolution features can be recovered. Using airborne gravity gradiometry will likely increase knowledge about regional geology as well as local geology while reducing time and costs from large-scale ground gravity surveys.

Acknowledgements

We would like to thank the Navy Geothermal Program Office for support of this work, Dr. Jim Faulds, Nick Hinz and others at the University of Nevada Reno, Bureau of Mines and Geology. I would also like to acknowledge the members at the Center for Gravity, Electrical and Magnetic Studies at the Colorado School of Mines for all supporting discussions and comments.

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