Innovate Geothermal Ltd.
104-445 West 2nd Avenue
Vancouver, British Columbia
V5Y 0E8 Canada

Mobile#: (604) 349-8040
Email: jeff@innovategeothermal.com

3D Geophysical Modelling of Gravity Data at the Utah FORGE site

Prepared for: Utah Geological Survey

Project #0011

May 2019

innovate Geothermal

Table of Contents

1. Introduction 1

2. Modelling Parameters 3

2.1. Model Coordinate System and Datum 3

2.2. 3D Model Extents and 3D Model Mesh 3

2.3. Topographic Data 4

2.4. Gravity Data 5

2.5. Density Data 6

2.6. Geologic Boundary Constraints 7

3. 3D Density Model Results 9

3.1. Density Model Misfit 9

3.2. Density Model #1: Original Top-of-Basement Surface Boundary Constraint 11

3.3. Density Model #2: Modified Top-of-Basement Surface Boundary Constraint 13

4. Summary 18

References 20

Appendix 1: List of Deliverables 21

List of Figures

Figure 1. Perspective view of the 3D gravity model volume. 4

Figure 2. Misfit maps for Density Model #1 and Density Model #2 10

Figure 3. Slices through Density Models #1 and #2 that pass through well 58-32. 16

Figure 4. Slices through Density Models #1 and #2 that pass through the southern portion of the model volume. 17

1. Introduction

This report describes the 3D geophysical inversion modelling of gravity data at the FORGE site near Milford, Utah. FORGE is the Frontier Observatory for Research in Geothermal Energy and the site in Utah has been selected by the U.S. Dept. of Energy for a 5-year R&D program to test technologies for the development of Engineered Geothermal Systems (EGS).

The overall goal of 3D modelling of gravity data at the FORGE site is to help characterize the subsurface geologic framework. Specifically, modelling of gravity data in 3D, used in conjunction with rock density measurements and other subsurface geologic information can provide an independent test of an existing 3D geologic model (e.g. Witter et al., 2018). Such an exercise can be useful for reducing uncertainty in 3D geologic models (Witter et al, 2019).

This report provides details regarding the model parameters, data used, and geologic constraints applied to the 3D gravity modelling effort. Two different 3D density models constitute the output of the gravity modelling effort and each are discussed in this report. Modelling parameters and input data used to generate each of the two density models are the same; however, the geologic boundary constraints used for the two models are different. For density model #1, an initial or “original” top-of-basement surface was used as a fixed boundary constraint. Based upon observations of density model #1, the top-of-basement surface was modified to test whether a modified top-of-basement surface would be more geologically reasonable yet still provide a good fit to the measured gravity data. In density model #2, the modified top-of-basement surface is used as the geologic boundary constraint to test this hypothesis.

Background on 3D geophysical modelling of gravity data

The purpose of geophysical inversion modelling of gravity data is to create a model of the subsurface depicting the distribution of rock density that is quantitatively consistent with the variations in the gravity signal measured at the land surface. This is valuable because, in many cases, rock density is a good proxy for lithology and, therefore, a subsurface 3D density can be useful for predicting 3D geologic relationships.

Geophysical inversion modelling of gravity data in three dimensions is not new. One of the first 3D gravity inversion codes was developed at the University of British Columbia by Li and Oldenburg (1998). 3D gravity inversion modelling that is simultaneously constrained by geologic surfaces and rock density measurements was pioneered in Australia by Fullagar & Pears (2007) and Fullagar et al. (2008). Commercial software packages have been developed that perform geologically-constrained inversion modelling of gravity data in 3D (e.g. Geomodeller, GOCAD Mining Suite and VPmg). Such software packages have been used in the mineral exploration industry to better understand subsurface geology and structure for over 15 years (for examples see Witter, 2015; Burney & Sumpton, 2013). Recent development of the open source SimPEG code (Cockett et al., 2015) has greatly facilitated 3D geophysical inversion modelling that is independent of the existing commercial codes. In this study, we have used the SimPEG geophysical code in conjunction with a low-cost 3D design software (Rhino3D; www.rhino3d.com) for all modelling tasks. Using this approach, we have succeeded in constructing spatially-accurate 3D geological constraints for use in the 3D geophysical inversion modelling.

2. Modelling Parameters

2.1. Model Coordinate System and Datum

All 3D modelling and analysis for this project were performed in UTM NAD83 zone 12 coordinate system and datum. NAVD88 was used as the vertical datum.

2.2. 3D Model Extents and 3D Model Mesh

The 3D volume used here for the geophysical modelling is 8.25 km long (E-W) x 5.25 km wide (N-S) x 3.69 km (thick) and shown in Figure 1. Specifically, the vertical extent of the model volume spans a range in elevation from -1200 masl to +2490 masl. On average, the bottom of the model lies at ~3 km below the ground surface. The footprint of the Utah FORGE site is centered in the western portion of the model area. We chose to extend the model volume further to the east, beyond the edge of the FORGE site, in order to overlap the model area with regions where granitoid basement rocks are exposed at the land surface.

This model volume was initially discretized into a rectilinear mesh made up of individual cells 50 m (X) x 50 m (Y) x 30 m (Z) in size. This resulted in a total of ~2.1 million cells for the entire model volume. This is a large number of cells which would be computationally intensive for any geophysical inversion modelling algorithm. In order to make the geophysical inversion problem more tractable, we used the SimPEG code to re-discretize the model volume using an Octree mesh which, in our case, effectively reduced the total number of cells by increasing the thickness of the cells deeper in the model volume. For depths 0-300 m, the model cells are 30 m thick; from 300-1200 m depth, the model cells are 60 m thick; and at even greater depths, the model cells are 120 m thick. This reduced the total number of cells in the output density model to less than 300,000 cells.

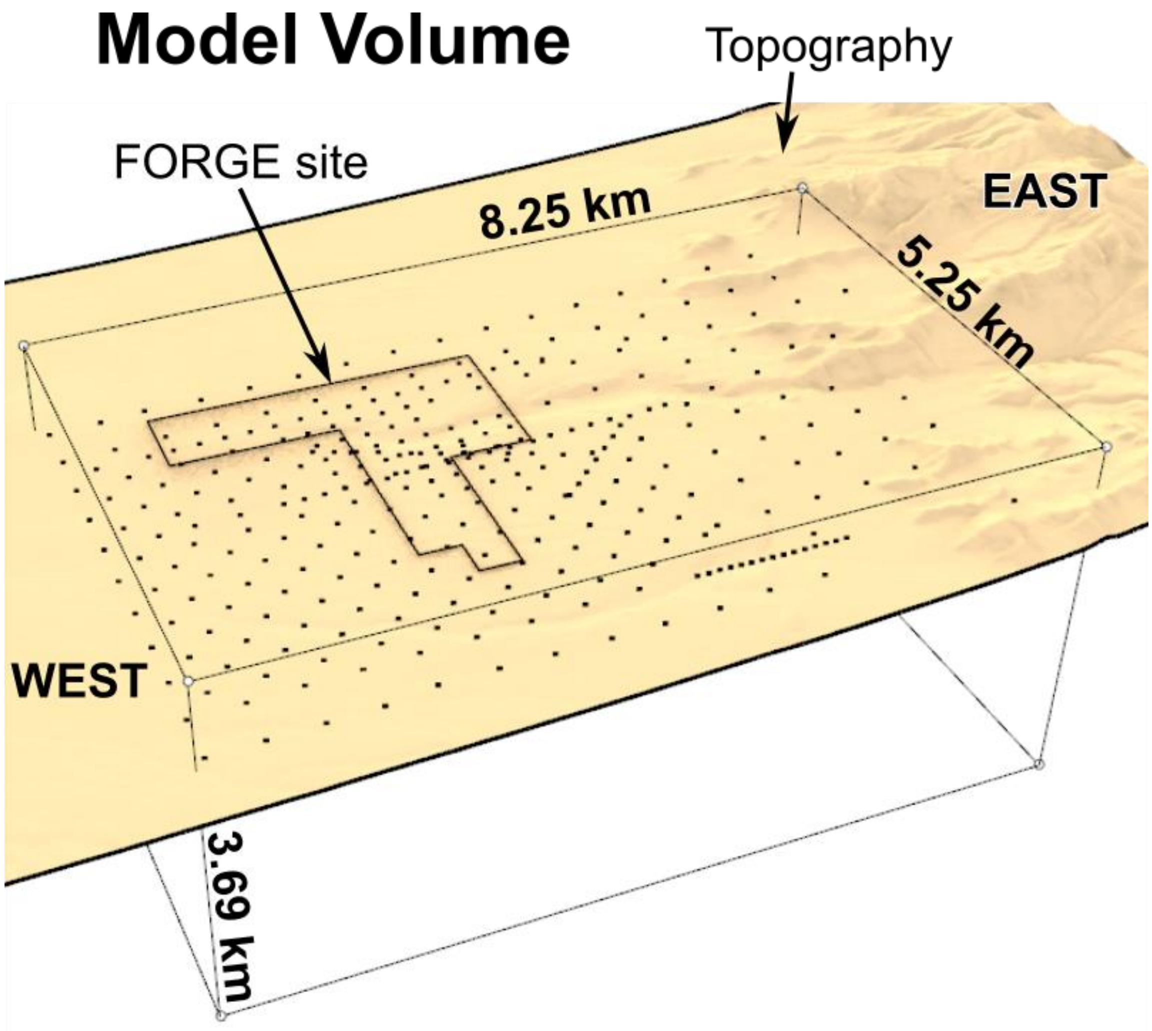


Figure 1. Perspective view looking to the NE of the 3D gravity model volume. The footprint of the FORGE site is shown by the black polygon. Locations of the gravity stations used in this study are shown by the black dots.

2.3. Topographic Data

Topographic data used to constrain the land surface for the 3D gravity modelling exercise consisted of a 25 m digital elevation model (DEM) generated from land surface vertices downloaded from the Utah FORGE website (https://utahforge.com/project/earth-model/). These DEM data were supplemented by 323 additional ground surface elevation datapoints which coincide with the locations of the gravity survey measurements.

2.4. Gravity Data

All gravity data used in this study were collected by the Utah Geological Survey (UGS) as part of the FORGE project (Figure 1). In the 3D geophysical inversion modelling effort, we used gravity data collected at 323 separate measurement stations spread across the 8.25 km x 5.25 km model area footprint. Gravity station spacing varies from 250 m to 350 m in and around the FORGE site while station spacing increases to ~500 m in the eastern portion of the model area on the edge of the Mineral Mountains. Overall, the gravity station coverage is broadly uniform across the entire model area with gaps in coverage only existing in the SE corner and along the easternmost edge of the model area (Figure 1).

UGS performed standard gravity data reduction and terrain correction on the acquired gravity measurements and delivered Complete Bouguer Anomaly gravity data of the project area for use in the 3D gravity modelling. Average gravity data measurement error is ~0.03 mGal according to the UGS.

Methods described in Nettleton (1939) and Parasnis (1966) are commonly used to select the appropriate terrain correction density for data reduction. These methods are most useful in areas with appreciable topographic relief. Since the area around the FORGE site is largely flat, these two methods proved ineffective. To contend with this issue, we performed a number of forward and inverse modelling tests, assuming different terrain correction densities from 2.50 g/cm^3 to 2.67 g/cm^3. The results of these tests suggest that a terrain correction density of 2.55 g/cm^3 is a good approximation of the average density of the model volume. Thus, Complete Bouguer Anomaly gravity data with a terrain correction density of 2.55 g/cm^3 has been used for all subsequent 3D gravity modelling in this study.

For the purposes of the 3D gravity inversion modelling, we assumed that the gravimeter measurement sensor is situated ~20 cm above the ground surface.

No regional gravity trend was removed from the data prior to 3D geophysical modelling. Visual assessment of the gravity data in the FORGE project area suggests that any regional gravity signal is weak and would likely have little to no effect on the gravity modelling results. If a strong regional gravity signal was present in the data and it was not removed prior to 3D gravity modelling, there is a risk that the regional gravity signal could generate density variations in the model output that are not real.

Prior to 3D geophysical modelling, the FORGE gravity data were upward continued by 20 m in order to suppress short wavelength features in the data that likely arise from near surface (i.e. 10's of meters) density variations. Upward continuation of the gravity data by such a small amount has little to no effect on density variations in the model at deeper levels (i.e. 100's of meters). This is because the amount of upward continuation (20 m) is small compared to the gravity station spacing (250 – 500 m).

2.5. Density Data

Rock density measurements from the project area are required in order to help guide the geophysical inversion modelling towards a geologically meaningful result. Fortunately, a wireline geophysical log was available for well 58-32, located at the FORGE site. This geophysical log included a neutron density log which extends from a depth of 0.66 to 2.3 km. These density data were downloaded from https://utahforge.com/project/earth-model/. Density data were also available for the nearby Acord-1 well, however, these data were not used in this study since they lay outside of the 3D model volume.

Neutron density log data for well 58-32, suggest that ~300 m interval of the basin fill material (660 – 960 m deep) that immediately overlies the granitoid basement has an average density of 2.42 g/cm^3. The density of the basin fill at shallower levels (i.e. 0 – 660 m deep) was not measured by the geophysical log. However, density data derived from well cuttings from 58-32 suggest that basin fill density decreases from ~2.4 g/cm^3 at 660 m deep to ~2.0 g/cm^3 in the near surface (Gwynn et al., 2018).

Within the granitoid basement, the neutron density log reveals values of 2.7 – 2.9 g/cm^3 for dioritic rocks and ~2.6 g/cm^3 for granitic rocks with the granitic rocks appearing to be the more volumetrically dominant of the two (Gwynn et al., 2018).

For the purposes of the 3D geophysical modelling, we selected 2.42 g/cm^3 as the average starting density of the basin fill materials and 2.65 g/cm^3 as the average starting density of the granitoid basement rocks. A value of 2.42 g/cm^3 is a useful median value since the basin fill in the deeper portions of the basin, to the west of well 58-32, likely have higher density and evidence from measurements on well cuttings shows that basin fill density in the shallower portions of the basin is lower than 2.42 g/cm^3. Similarly, 2.65 g/cm^3 is a reasonable starting value for the granitoid basement density as it falls between the measured values for granitic and dioritic rocks observed in well 58-32. These starting density values are important because the geophysical inversion modelling results tend to reveal two features: 1) which portions of the 3D model volume require rock density values that differ from the starting values and 2) how much the modelled density values differ from the starting values. These two features help us interpret the subsurface geologic framework and how it may differ from the existing 3D geologic model.

It should be noted that we are aware that the assumption of a uniform density of 2.42 g/cm^3 in the basin fill is a gross simplification. In reality, the spatial variations in density in the basin fill are more complex. In the future, if more subsurface density data are available for the basin fill materials over a wider area, it would help to better evaluate the magnitude and spatial distribution of basin fill density.

2.6. Geologic Boundary Constraints

Geologic boundary constraints are also important for guiding 3D geophysical inversion models towards geologically reasonable outcomes. At the FORGE site, a 3D seismic reflection survey (Miller et al., 2018) was conducted to help map the topography of the top of the granitoid basement rocks in the subsurface. This 3D seismic survey covers an area ~5.5 km (E-W) x ~4.5 km (N-S) which lies within the footprint of the 3D gravity model volume. One of the outcomes of the seismic study is a 3D surface which demarcates the geologic boundary between the lower-density basin fill materials above and the higher-density granitoid rocks below. This top-of-basement geologic horizon was downloaded from the Utah FORGE website (https://utahforge.com/project/earth-model/). For the geophysical inversion modelling, we utilized this top-of-basement geologic horizon as a fixed constraint. In other words, we assumed that the 3D topography of the top-of-basement is actually at the location predicted by the 3D seismic reflection data. One of the purposes of the 3D inversion modelling in this study is to show where the gravity data may or may not support this assumption.

To accomplish this, we ran two different versions of the 3D gravity inversion modelling. In the first version (Model #1), we used the original top-of-basement surface (downloaded from the Utah FORGE website) as the fixed geologic boundary constraint. We found that this top-of-basement surface is in agreement with the gravity data in some portions of the model volume, but not all. As a result, we modified the top-of-basement surface in a few locations, where the density model mismatch was greatest, to try and improve the geophysical inversion model output. Therefore, the second version (Model #2) of the 3D gravity modelling used a modified top-of-basement surface as the fixed geologic boundary constraint. Two different density models were obtained using these two different geologic boundary constraints. Both model results are described below.

As mentioned earlier, density data from 58-32 well cuttings provide evidence for a decrease in density in basin fill materials at shallower and shallower levels. We attempted to mimic this in a “test” inversion scenario by creating additional, subhorizontal geologic boundaries within the basin fill to use as fixed constraints in the 3D gravity inversion modelling. Specifically, we built laterally extensive geologic boundaries (above the granitoid basement) at 200 m, 400 m and 600 m depth to demarcate hypothetical boundaries between 2.1 g/cm^3, 2.2 g/cm^3, and 2.3 g/cm^3 basin fill materials. It was hoped that these depths and density values would approximate the actual subsurface density variations in the basin fill. When we ran this geophysical inversion “test” using these more complex geologic constraints within the basin fill, the density model result was non-geological (e.g. a near surface sediment layer with a density of 2.75 g/cm^3). This outcome highlights the importance of using as much measured data as possible as the basis for geologic boundary constraints. Using geologically reasonable “guesses” as fixed geologic boundary constraints instead (as described here) can lead to gravity inversion model results which are geologically unsatisfying and undoubtedly incorrect.

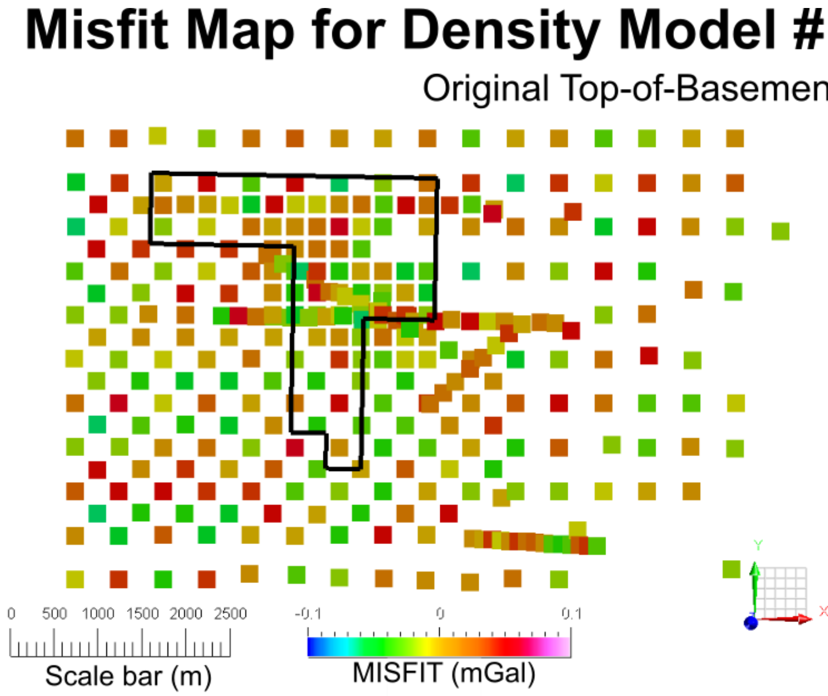
3. 3D Density Model Results

3.1. Density Model Misfit

Density model misfit is an important measure of how well the output density model matches the measured gravity data. How this works is the 3D geophysical inversion algorithm first outputs a 3D density model. The rock volume depicted in the 3D density model generates a gravity response at the land surface which is then calculated at each of the 323 stations where actual gravity measurements were obtained in the field. The difference between the model gravity response and the actual gravity measurements is called the misfit. Ideally, we would want the misfit to be on par with the average measurement error of the gravity data. If this occurs, it means that the density model generates a gravity response which is essentially the same as and within the error of the measured gravity data.

The average error for the measured gravity data is 0.03 mGal. Maps showing the misfit at all gravity stations for the two density models generated in this study are shown in Figure 2. The level of misfit for both models is virtually identical. Both density models achieve a level of misfit which is less than 0.05 mGal at ~95% of all gravity stations and less than 0.03 mGal at ~66% of all gravity stations. An alternative way to assess the overall misfit is to calculate the root mean square (RMS) of the misfit for all gravity stations combined. Using this approach, the RMS misfit is 0.0298 mGal for Model #1 and 0.0295 mGal for Model #2.

These results show that the density models generate a gravity response which is largely within error of the measured gravity data. This does not imply, necessarily, that the density models are “geologically right”. Instead, it only means that the density models generated from the geophysical inversion are quantitatively consistent with the gravity data measured in the field. Non-uniqueness is an unavoidable problem in geophysical modelling, so no model is a 100% correct representation of reality. All models have portions which are wrong. All we can hope to accomplish is to create a model which is consistent with existing data and be the least wrong possible. Achieving an acceptable



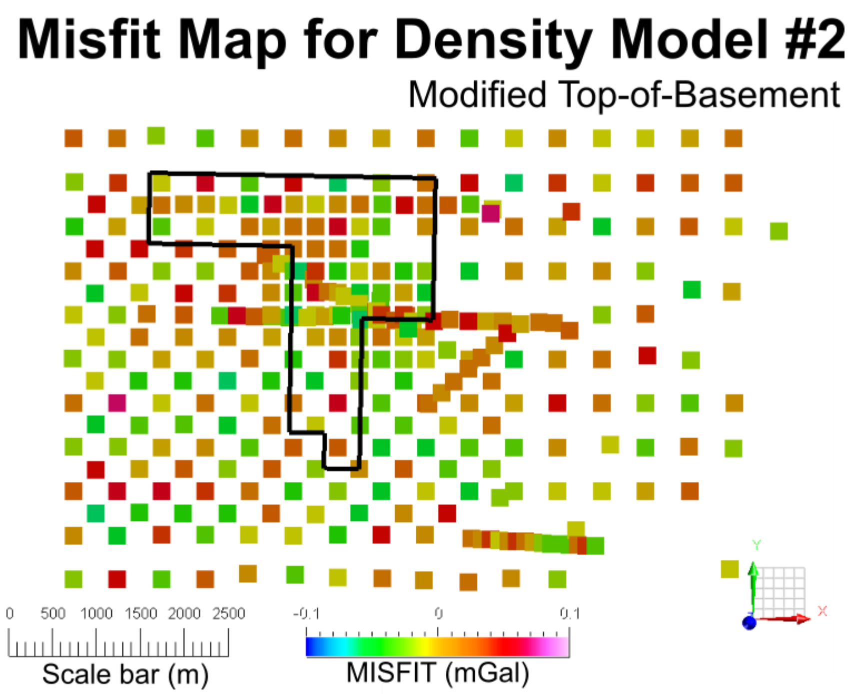


Figure 2. Maps of the misfit between: (measured gravity data) and (the gravity response calculated from the 3D density model derived from geophysical inversion). MISFIT = (Measured gravity data – calculated gravity response). FORGE site footprint is the black polygon. Locations of gravity measurement stations across the project area shown as colored squares with colors representing the amount of misfit in mGal for each individual station. Most stations have a misfit between -0.03 and +0.03 mGal (light green – yellow – orange). **Upper panel:** misfit map for Density Model #1. **Lower panel:** misfit map for Density Model #2.

level of misfit is an important first step and the resulting density model is one which can then be geologically interpreted with more confidence.

3.2. Density Model #1: Original Top-of-Basement Surface Boundary Constraint

The initial geophysical inversion modelling effort generated density model #1 and used the original top-of-basement surface as a geologic boundary constraint. Two E-W slices through density model #1 are depicted in Figures 3a & 4a.

Density model #1 profile at well 58-32

A model slice that cuts E-W through well 58-32 (Figure 3a) shows a density distribution which largely consists of two relatively uniform rock bodies: granitoid basement at ~2.65 g/cm^3 and overlying basin fill materials at ~2.42 g/cm^3 which are separated by the original top-of-basement surface.

A zone of anomalously high density in the model is observed to the east of the FORGE site where the inversion algorithm has placed higher density materials in both the basin fill and granitoid basement in order to achieve a good fit with the measured gravity data. This zone of anomalously high density in the model could be explained in two ways: a) the top-of-basement is actually shallower than assumed and/or b) the zone of high density is actually occupied by higher density (~2.8 g/cm^3) dioritic rocks.

On the west side of the model volume a small zone of anomalously low density is observed. We have run various tests on this anomalous area and interpret it to be a model artifact (i.e. not real) which has arisen due to the inversion algorithm attempting to model short-wavelength density variations in the near surface.

Overall, beneath the FORGE site itself and in the vicinity of well 58-32, the density model #1 results show that a two-layer geologic model with relatively uniform 2.42 g/cm^3 density basin fill and 2.65 g/cm^3 granitoid basement which are separated by the original top-of-basement surface is quantitatively consistent with the measured gravity data (Figure 3a). A cross-section through the southern portion of the density model, however, tells a different story.

Density model #1 profile through the southern part of the model volume

Figure 4a shows an E-W slice through density model #1 in the southern portion of the model volume (at UTM NAD83 zone 12 Northing 4260200 m). The 3D seismic survey does not extend this far south, so the original top-of-basement surface has been extrapolated from the north in this area, and its exact location is thus, more uncertain. Density model #1 reveals zones with anomalously high and low densities in this southern portion of the model. A large low density zone exists in the SW quadrant of the model volume and lies at an elevation below about 1000 masl, on both sides of the original top-of-basement surface. This zone of anomalously low density could suggest two things: a) the top-of-basement surface is deeper than has been assumed and/or b) a large quantity of sedimentary materials with a density significantly less than 2.42 g/cm^3 exist within the basin fill in the SW quadrant.

On the eastern side of Figure 4a, a zone of anomalously high density is present within the basin fill materials. Three options could explain this observation: a) the top-of-basement surface should be shallower than has been assumed, b) a small body of higher density dioritic rocks is present in the basement in this region, and/or c) rock material in the basin fill is denser than 2.42 g/cm^3 in this zone. This part of the model which exhibits high density could, potentially, also be explained by silicification of the basin fill, a process which could densify the sedimentary material. However, this zone of high density lies ~300 m west of the Opal Mound fault, a fault which is thought to be an impermeable barrier to geothermal fluid flow. Thus, the other two options mentioned may be more likely.

On the far eastern edge of Figure 4a is a zone of anomalously low density located in the granitoid basement which we interpret here as a possible inversion modelling artifact. This SE corner of the model volume has only one nearby gravity station for the inversion modelling algorithm to use (see Figure 1). Without gravity data points to guide the inversion algorithm, the density model output appears to have diverged significantly. Additional gravity data in this area may be able to rectify this problem. Alternatively, there may be real variations in subsurface density in this region which are poorly resolved in the density model.

Similar to Figure 3a, small, shallow, and scattered zones of low (and high) density seen in Figure 4a are interpreted here as near surface model artifacts.

Overall, apart from the noted regions of anomalously high and low density, this southern portion of the density model largely consists of a fairly uniform granitoid basement of ~2.65 g/cm^3 and a basin fill with density of ~2.42 g/cm^3. However, the large zones of anomalous density observed in this area call into question the exact location of the top-of-basement boundary in the southern part of the model volume.

3.3. Density Model #2: Modified Top-of-Basement Surface Boundary Constraint

A second geophysical inversion modelling effort pursued as part of this project generated density model #2. This second effort used a modified top-of-basement surface as the geologic boundary constraint. The modified top-of-basement surface was generated by manually adjusting in 3D the shape of the original top-of-basement surface either up or down. The decisions of where and how much to modify the original top-of-basement surface were guided by the results of density model #1 described previously. Specifically, for zones in density model #1 which showed anomalously high density, the original top-of-basement surface was moved upwards, and it was moved downwards for zones of anomalous low density. In sum, the original top-of-basement surface was modified upwards in four areas, all of which lie east of the FORGE site in zones with either poor or no seismic interpretation. In all four of these locations, the original top-of-basement was made shallower (vertically) by several tens to a few hundreds of meters over areas that covered less than ~1 km^2. In contrast, in only one area was the original top-of-basement surface modified by deepening the surface (i.e. in the SW quadrant of the model volume). In this area, the surface was deepened by up to ~650 m over an area ~2 km x ~4 km. Two E-W slices through density model #2, which show examples of these modifications, are depicted in Figures 3b & 4b.

Density model #2 profile at well 58-32

Figure 3b shows an E-W slice of density model #2 that goes through well 58-32. By comparison with density model #1 (Figure 3a) we can see the effect of raising the top-of-basement surface in the vicinity of the anomalously high density region on the east side of the model. By making the top-of-basement surface shallower, the high density region in the basin fill has gone away. However, the anomalous high density in the granitoid basement remains (Figure 3b). This suggests that in order to match the gravity measurements, the top-of-basement would need to be even shallower (which may be geologically unreasonable) or the granitoid basement would need to contain higher density rocks (such as diorite) which is, arguably, more geologically likely for this location.

Density model #2 profile through the southern part of the model volume

Figure 4b shows an E-W slice of density model #2 that passes through the southern portion of the model volume. Here, we can see the effects of raising the top-of-basement surface on the east-central side of the model and deepening the top-of-basement surface in the SW quadrant.

Raising the top-of-basement in the region that exhibits anomalously high density in model #1 (shown in Figure 4a) has almost completely removed the high density anomaly from the basin fill material (Figure 4b). The shape of the modified top-of-basement that achieved this, however, is a flat-topped horst with a few hundred meters of offset. This shape is likely to be geologically incompatible with what is currently understood about the area. Thus, a small zone of higher density dioritic rocks in the basement may be more likely than raising the top-of-basement surface to explain this anomalous zone of high density.

In the SW quadrant of Figure 4b, the original top-of-basement surface has been lowered substantially to test the impact on the anomalously low density zone observed in this region. Would lowering the granite surface make the low density zone disappear? In this instance, the answer is no. In fact, the low density zone in the SW quadrant appears not to have changed much between density models #1 and #2 (compare Figures 4a and 4b). This means that further deepening of the top-of-basement surface would be required to increase the model density in the basin fill to values closer to ~2.42 g/cm^3. Such a substantial deepening of the granite surface is, arguably, geologically unlikely. Thus, we must seek an alternative scenario to explain the low density zone that appears to be required by the measured gravity data. A geologically-likely explanation is that the basin fill sediments in the SW quadrant of the model volume house sedimentary packages with significantly lower density than 2.42 g/cm^3. One geologically plausible possibility could be low density clays deposited from Lake Bonneville in the near surface. Unfortunately, we have no data on the thickness, extent, geometry, and depth of such low density sediment packages that, according to the gravity data, are likely to be present in the SW quadrant. Similarly, the presence of such low density sediments tend to mask the top-of-basement surface in this area making it more difficult to accurately test the location of the top-of-basement in the SW quadrant.

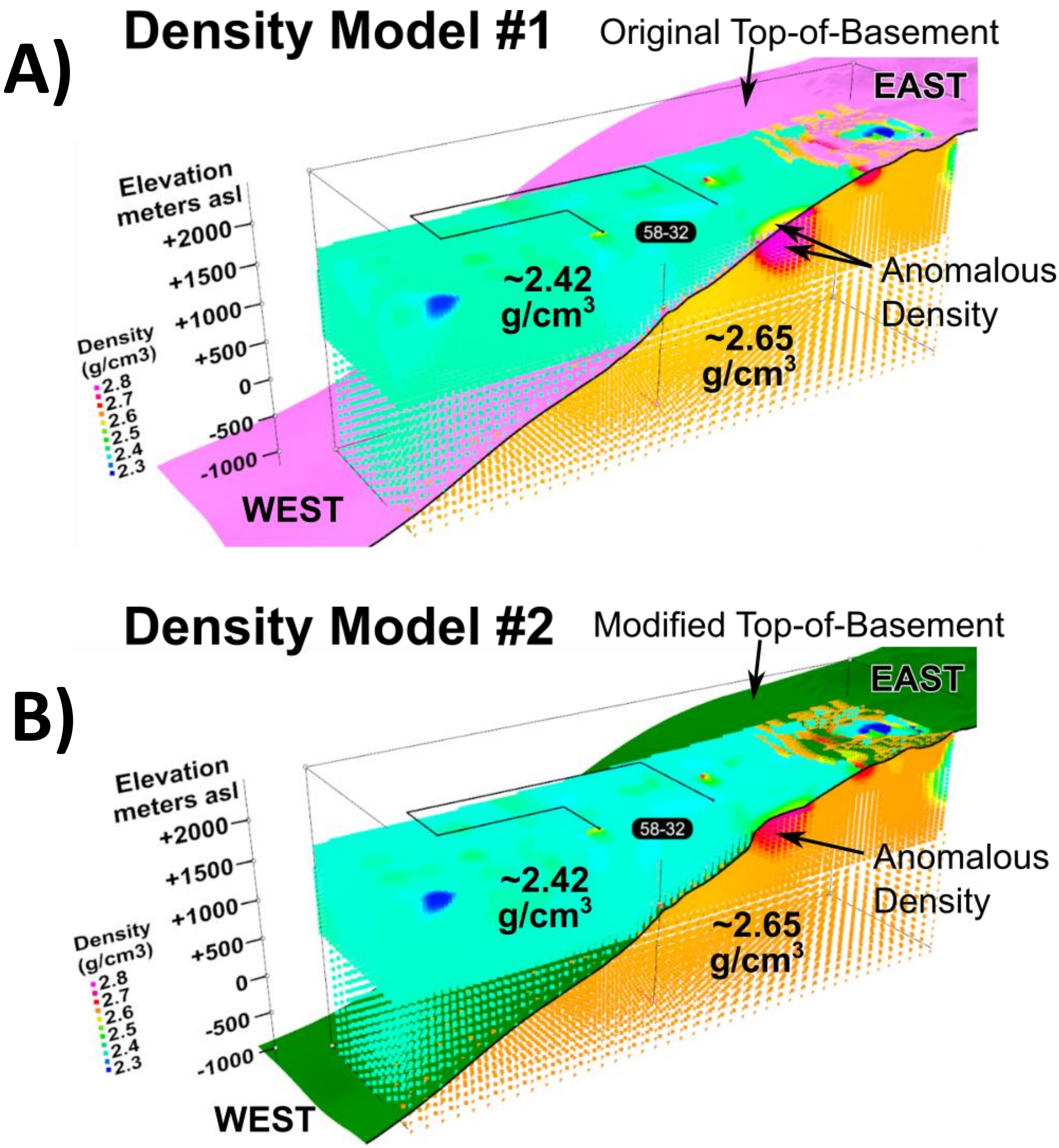


Figure 3. Perspective view looking to the NE of the 3D density models. **Upper panel A):** Density Model #1. **Lower panel B):** Density Model #2. Shown are E-W slices through the models that pass through well 58-32. The top-of-basement is shown as the colored surfaces in each model. The 3D geologic model assumes basin fill lies above the top-of-basement surface and granitoid basement lies below. Model densities are shown by colored cubes with warm colors representing high density and cool colors representing low density (color bar shown on left). Basin fill starting density = 2.42 g/cm^3 and granitoid basement starting density = 2.65 g/cm^3. Zones of anomalous density also shown.

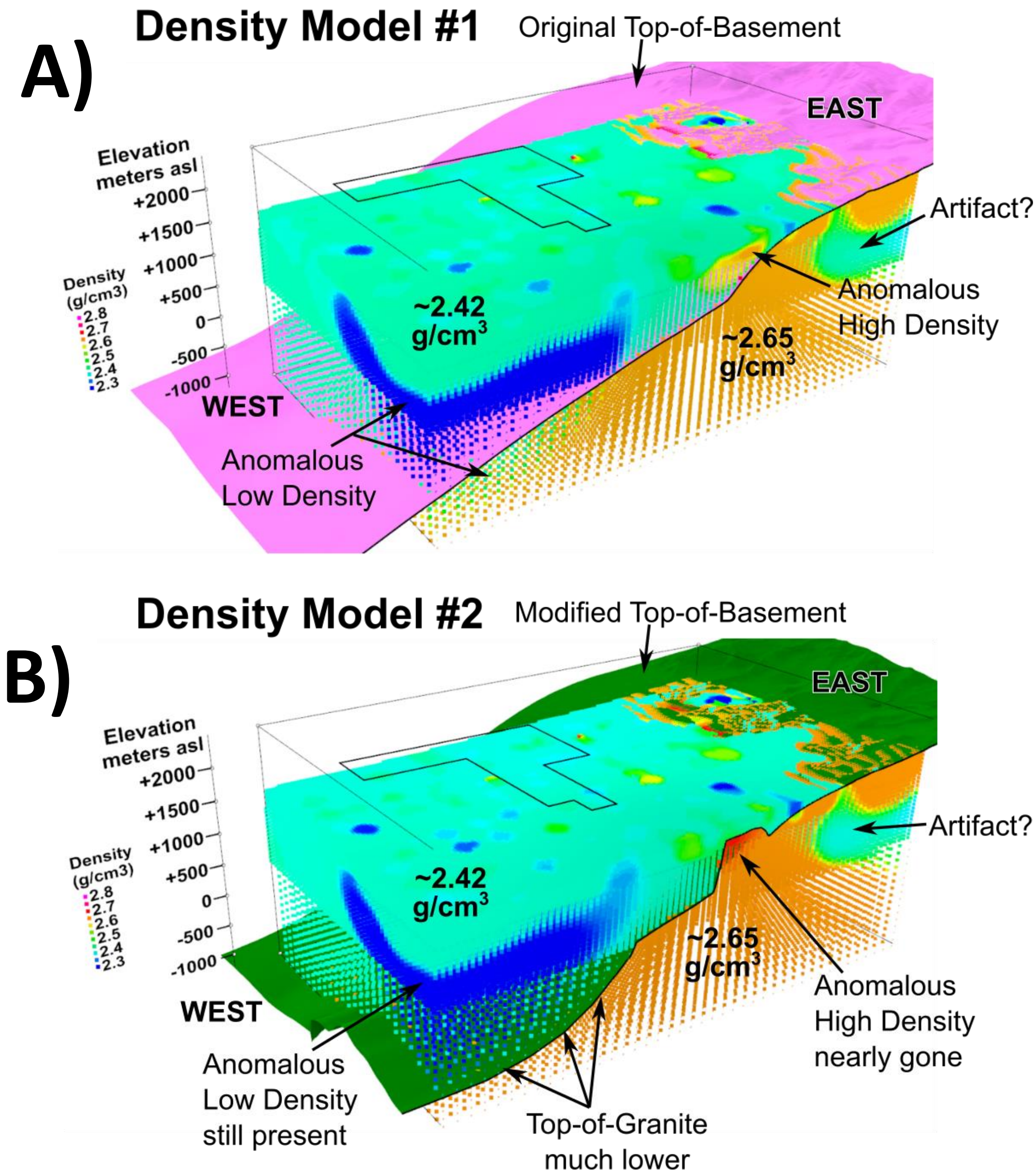


Figure 4. Perspective view looking to the NE of the 3D density models. **Upper panel:** Density Model #1. **Lower panel:** Density Model #2. Shown are E-W slices through the models that pass through the southern portion of the model volume (at UTM NAD83 zone 12 Northing 4260200 m). The top-of-basement is shown as the colored surfaces in each model. The 3D geologic model assumes basin fill lies above the top-of-basement surface and granitoid basement lies below. Model densities are shown by colored cubes with warm colors representing high density and cool colors representing low density (color bar shown on left). Basin fill starting density = 2.42 g/cm^3 and granitoid basement starting density = 2.65 g/cm^3. Zones of anomalous density also shown.

4. Summary

In this study, 3D geophysical inversion modelling of gravity data was performed using data from the FORGE site near Milford, Utah. The purpose of this exercise was to test the existing 3D geologic model and provide additional geologic information about the subsurface at the FORGE site. The model volume in this exercise covered an area 8.25 km x 5.25 km and extended to a depth of ~3 km below the ground surface. Data utilized to help guide the inversion modelling toward a geologically-reasonable outcome include: land surface topography, 323 measured gravity data points, a downhole neutron density log from well 58-32, and a 3D "top-of-basement" surface derived from a seismic reflection interpretation.

The 3D gravity modelling effort here succeeded at generating geologically reasonable density models of the subsurface. The output density models generate a gravity response that is within the measurement error of the field-acquired gravity data. In addition, the output 3D density models are dominated by rock density values that are consistent with average density measurements from the neutron density log in well 58-32. These two conclusions mean that the density model results are consistent with available measurements, geophysically-viable, and suitable for geological interpretation. Overall, the density models generated suggest that the field-acquired gravity data are largely consistent with a simple, 2-layer geologic model that consists of basin fill materials (~2.42 g/cm3) underlain by granitoid basement (~2.65 g/cm3) that are separated by the "top-of-basement" surface derived from the seismic interpretation.

This simple geologic model, however, does not explain the gravity data everywhere. In the SW quadrant of the model volume, the gravity data suggests that: 1) a significant section of low density materials are present in the basin fill stratigraphy and/or 2) the "top-of-basement" surface needs to be significantly deeper than currently assumed. We believe that the former is the more likely explanation. But the exact geometry, thickness, extent, and depth of such low density sediments are not precisely constrained by the 3D density modelling. In addition, four locations have been identified where the gravity data suggest higher density rocks are required in the 3D geologic model. These higher density rocks could be: 1) a shallower “top-of-basement” that extends higher density basement rocks up into the lower density basin fill, 2) higher density diorite rocks within the predominantly granitic basement, or 3) possibly, basin fill materials that have been made denser due to silicification. All four of these identified locations lie outside of the footprint of the “top-of-basement” seismic interpretation so any modifications to the current “top-of-basement” interpretation would not be in conflict with other datasets.

The 3D density models generated in this study contribute to a refined understanding of the variations in subsurface geology at the FORGE site. As additional geoscience data are gathered at FORGE, subsequent rounds of 3D gravity inversion modelling that incorporate more geologic constraints could further refine the subsurface geologic framework at FORGE.

References

Burney C, Sumpton J (2013) 3D Modelling of the Merlinleigh Sub-basin. Company Case Study, Intrepid Geophysics, https://www.intrepid-geophysics.com/ig/uploads/casehistories/Case%20study%20Merlinleigh3.pdf; Accessed December 4, 2018.

Cockett R, Kang S, Heagy LJ, Pidlisecky A, Oldenburg DW (2015) SimPEG, An open source framework for simulation and gradient based parameter estimation in geophysical applications. Computers & Geosciences, v. 85, p. 142-154.

Fullagar PK, Pears GA (2007) Towards geologically realistic inversion. *in*: Milkereit B, editor. Proceedings of exploration 07: fifth decennial international conference on mineral exploration, Toronto; 2007.

Fullagar PK, Pears GA, McMonnies B (2008) Constrained inversion of geologic surfaces—pushing the boundaries. The Leading Edge, v. 27, p. 98–105.

Gwynn M, Allis R, Hardwick C, Jones C, Nielsen P, Hurlbut W (2018) Rock Properties of FORGE Well 58-32, Milford, Utah. Geothermal Resources Council Transactions, v. 42, 24 pages.

Li Y, Oldenburg DW (1998) 3-D inversion of gravity data. Geophysics. v. 63, p. 109-19.

Miller J, Allis R, Hardwick C (2018) Seismic Reflection Profiling at the FORGE Utah EGS Site. Geothermal Resources Council Transactions, v. 42, 13 pages.

Nettleton LL (1939) Determination of density for reduction of gravimeter observations. Geophysics, v. 4, p. 176-183. doi:10.1190/1.1437088

Parasnis D (1966) Mining Geophysics. Elsevier, Amsterdam-London-New York, 356 pages.

Witter JB (2015) GOCAD® Mining Suite Software as a Tool for Improved Geothermal Exploration. Proceedings World Geothermal Congress, Melbourne, Australia, 19-25 April 2015, 5 pages.

Witter JB, Glen JMG, Siler DL, Fournier D (2018) 2D and 3D Potential Field Mapping and Modelling at the Fallon FORGE site, Nevada, USA. Geothermal Resources Council Transactions, v. 42, p. 1194-1214.

Witter JB, Trainor-Guitton WJ, Siler DL (2019) Uncertainty and risk evaluation during the exploration stage of geothermal development: A review. Geothermics, v. 78, p. 233-242.

Appendix 1: List of Deliverables

Two .csv files (density model and misfit) for Utah FORGE 3D gravity model #1 which uses the original top-of-basement surface as a geologic constraint (downloaded from the Utah FORGE website).

UtahFORGE#1_Original_Top_Granite_Density_Model.csv

UtahFORGE#1_Original_Top_Granite_Density_Model_MISFIT.csv

Two .csv files (density model and misfit) for Utah FORGE 3D gravity model #2 which uses a slightly modified top-of-basement surface as a geologic constraint (the modifications to the top-of-basement surface were made in this study based upon the results of model #1).

UtahFORGE#2_Modified_Top_Granite_Density_Model.csv

UtahFORGE#2_Modified_Top_Granite_Density_Model_MISFIT.csv

One .dxf file and one .csv file that represent the Modified Top-of-basement surface.

UtahFORGE#2_Modified_Top_Granite_Surface.dxf

UtahFORGE#2_Modified_Top_Granite_Surface_Pts.csv

One Geoscience Analyst file with both of the density models, top-of-basement surfaces, and model misfits so they can be visualized in 3D.

UtahFORGE_3D_Gravity_Models_May2019.geoh5

All data in the deliverables are in UTM NAD83 zone 12.