

3D Geophysical Inversion Modelling of Gravity Data as a Subsurface Geothermal Exploration Tool With an Example From Akutan (Alaska, USA)

Jeffrey B. Witter¹, Pete Stelling², Paige Knapp², and Nicholas H. Hinz³

¹Mira Geoscience Ltd., Vancouver, British Columbia, Canada

²Western Washington University, Bellingham, Washington, USA

³Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV, USA

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ABSTRACT

Three dimensional geophysical modelling was performed using gravity data collected from the Hot Springs Bay Valley geothermal area on Akutan Island, Alaska. The aim of this effort was to assist an ongoing subsurface exploration program. The geophysical modelling performed included four techniques: apparent density inversion modelling, 3D forward modelling, 3D depth-to-basement inversion modelling, and 3D unconstrained, heterogeneous inversion modelling. Density measurements on rock from drill core and surface samples were analyzed and used to ground-truth the geophysical model results. Apparent density modelling produced a map showing geologically-reasonable lateral variations in density across the project area. Forward modelling was performed on an existing 3D pseudo-basement model and was found to have a poor fit to the observed gravity data. A new depth-to-basement model derived from 3D inversion modelling was generated. This new model fit the observed gravity data better, but overall, a simple two-layer geological model was deemed inappropriate for Akutan. The 3D heterogeneous inversion model result fits the gravity data well, matches observed density measurements from geothermal wells, and appears to be consistent with observed surface geology and structural trends. The 3D density model created from heterogeneous inversion modelling serves as a good, initial 3D geological model for Akutan but it should be updated and improved with more geological constraints as additional drilling and geoscience data are collected.

Introduction

Three-dimensional geophysical inversion modelling of potential field data (i.e. gravity and magnetics) is not common practice in the geothermal exploration industry (IFC, 2014). The use of gravity and magnetic data in geothermal exploration is often limited to interpretation of geologic structure using 2D plan maps of Bouguer gravity or Total Magnetic Intensity data (e.g. Grauch, 2002). In other cases, profiles of gravity and magnetic data in combination with geologically-reasonable rock property values are used to help construct 2D geologic cross-sections via an iterative geophysical modelling approach (Watt et al., 2007; Glen et al., 2008; Egger et al., 2010; Ponce et al., 2010; Santos and Rivas, 2009). Analysis of potential field data using a 2D approach can be useful for the development of geothermal conceptual models. However, a more rigorous interpretation of the subsurface can be gained through geophysical inversion modelling of potential field data in three dimensions. Such an approach aids in the development and testing of improved 3D conceptual models of geothermal systems.

Commercial software algorithms, developed for the mineral exploration industry, enable routine inversion modelling of gravity and magnetic data in 3D (Oldenburg and Pratt, 2007; Fullagar et al., 2007; Fullagar et al., 2008). In this paper, we describe four different techniques for 3D geophysical modelling of gravity data that are applicable to geothermal exploration:

1. Apparent Density Inversion Modelling
2. 3D Forward Modelling
3. 3D Depth-to-Basement Inversion Modelling
4. 3D Unconstrained, Heterogeneous Density Inversion Modelling

Similar techniques for geophysical modelling of magnetic data are also available but are not discussed here. The geophysical modelling techniques listed above have their own advantages and limitations; however, when used in combination they are useful for exploring the possible 3D distribution of rock density in the subsurface. Such information can be helpful as part of a geothermal exploration program. Examples of these geophysical modelling techniques are presented for the Hot Springs Bay Valley geothermal area on Akutan Island (Alaska, USA). Overall, geophysical modelling of gravity data in 3D is a valuable geothermal exploration tool for the following reasons:

- A) With adequate coverage, gravity data modelled in 3D provides subsurface geoscience information between wells
- B) Modelling of gravity data delivers values of rock density which is more geologically-relevant than anomalies measured in milligals on 2D gravity maps
- C) 3D characterization of density contrasts can be useful for identifying faults, lithologic contacts, and/or zones of hydrothermal alteration
- D) Results of 3D modelling of gravity data are useful to test hypotheses about the 3D distribution of major lithologic blocks prior to drilling and can also be used to construct initial 3D geological models based upon density

Gravity Modelling Techniques

Background

The software used to perform the modelling presented in this paper includes GOCAD Mining Suite (for 3D visualization and geological model management) linked to VPmg software (for the geophysical modelling) and is described in Witter (2015). To perform the geophysical modelling, the subsurface is discretized into vertical, close-packed, rectangular prisms that have a user-defined horizontal dimension and extend the full vertical extent of the model. Each vertical prism can be subdivided into different geological units with rock types and physical properties specifically assigned to each cell in the model. By performing geophysical inversion modelling on a geological model, the physical property values of the model cells or the geometry of the geological contacts in the model are adjusted until an acceptable level of fit with the observed gravity data is achieved. Following completion of the inversion modelling, a comparison between the observed gravity data and the gravity response calculated from the geological model can be made to visually examine the degree of fit between the model and the data. For more information on the geophysical inversion modelling methods applied in this study, see Li and Oldenburg (1998), Oldenburg and Pratt (2007), Fullagar et al. (2007), and Fullagar et al. (2008).

Geophysical modelling of any type suffers from the problem of non-uniqueness. In other words, a geophysical model result may be acceptable mathematically, while at the same time be incorrect geologically. We propose an approach which uses a variety of geophysical modelling techniques to explore the density model space and help facilitate a geophysical model output which is geologically relevant. Incorporating density measurements from the field into the geophysical modelling process is a valuable way to tie the geophysical model results to geological reality, particularly when there is no 3D geological model available.

Apparent Density Inversion Modelling

Apparent density modelling is a technique which converts map-based gravity data (measured in milligals) into a 2D map showing lateral variations in density (measured in kg/m^3). The method assumes that the density value within each rectangular prism in the model is the same in the vertical direction down to a depth of 25 km. Apparent density modelling is a simple technique that can quickly assess the magnitude of lateral variations in density across a study area that are consistent with the gravity data. Apparent density maps are useful for comparison with geologic maps to see if expected rock density values and rock unit spatial distribution are in agreement with those determined from geologic mapping. Apparent density modelling is an important first step in the analysis and interpretation of gravity data because it: 1) produces an initial estimate of the magnitude of rock density variations and 2) demarcates the locations of significant density contrasts. This approach is limited, however, by the assumption that density is uniform in the vertical direction and no geologic information is incorporated as constraints.

3D Forward Modelling

When a 3D geological model is already available (no matter how simple), geophysical forward modelling of that model is useful to test the relationship between the geological model and the geophysical data. Different rock units in the geological model need to be assigned density values. Then, geophysical forward modelling is performed on the 3D geologic model to calculate its geophysical response and, in turn, determine how well the observed gravity measurements match the gravity values calculated from the 3D geologic model. This is called the level of misfit and is evaluated in two ways: 1) as a map showing the difference between the observed gravity measurements and the calculated gravity values and 2) an overall root mean square (RMS) misfit value for the entire model (in mGal). The misfit map is useful for showing which portions of the 3D geologic model match well with the gravity data and which portions do not. The RMS misfit value is useful because the goal of the geophysical modelling exercise is to reduce the RMS misfit to a level which is equivalent to the error in the gravity measurements.

3D Depth-to-Basement Inversion Modelling

Depth-to-basement inversion modelling is a simple technique which attempts to divide the Earth into a two-layer geologic model consisting of lower density cover rocks (overburden) and higher density basement rocks. The inversion modelling process determines the geometric shape of the lithologic contact between these two layers that best matches the gravity data. The overburden and basement rocks are assumed to have homogeneous densities. In many geologic environments, a simple two layer model can serve as an adequate approximation. For example, the overburden layer may represent basin fill sediments, clastic sedimentary rocks, or young pyroclastic successions. Such lower density rocks would have a marked density contrast with dense basement rocks such as plutonic (e.g. granite, gabbro) and metamorphic rocks (e.g. gneiss, marble). Depth-to-basement modelling can be useful to demarcate the approximate shape of a basement contact provided that the overburden and basement have a strong and consistent density contrast. This approach is limited, however, by the assumption that the geologic framework can be approximated by a two-layer model with uniform density in each rock layer. Lithologic complexity is common in many geologic environments, and such variations can result in substantial misfit in the model output.

3D Unconstrained, Heterogeneous Density Inversion Modelling

In the absence of a 3D geological model, gravity data can be modelled using geophysical inversion techniques to determine a 3D heterogeneous distribution of density in the subsurface that best matches the gravity measurements (Li and Oldenburg, 1998). No geological information is included in the geophysical modelling process. Density contrasts are distributed at depth using a standard depth weighting scheme (Li and Oldenburg, 1998). The purpose of performing this type of unconstrained geophysical modelling is three-fold: 1) obtain a general understanding of the range of rock density values expected in the subsurface, 2) obtain a general understanding of the potential spatial distribution of density in the subsurface, and 3) generate one possible density distribution that is unbiased by geological information. Such an unconstrained density model, generated from gravity data alone, can be interpreted geologically. However, doing so can be risky due to the problem of non-uniqueness in geophysical model results. 3D unconstrained model results are useful as a comparison with other geophysical model results that are constrained by prior geological knowledge. Ultimately, in order to increase the geological-relevance of geophysical model results, geological information must be incorporated into the geophysical modelling process to guide it towards a result which is consistent with the observed geology.

Example From the Hot Springs Bay Valley Geothermal Area on Akutan Island

Background

The volcanic island of Akutan is located in the Aleutian archipelago ~1300 km SW of Anchorage, Alaska (Figure 1). Hot springs and active volcanism on the island suggest the presence of geothermal energy resources to power the city of Akutan and fish processing plant located there. Since 2009, a concerted geothermal exploration effort has been undertaken by the city of Akutan at the Hot Springs Bay Valley geothermal area. This effort has included geological mapping, geophysical surveys, geochemical sampling, and the drilling of two shallow temperature gradient wells (Kolker et al., 2010; Kolker et al., 2012; Ohren et al., 2013; Stelling and Kent, 2011; Stelling et al., 2015). Like other volcanic geothermal areas, subsurface exploration is challenging on Akutan because the surface is covered by young lavas, pyroclastic units, debris flow deposits, and glacial sediments. The heterogeneous volcanic pile does not have a predictable stratigraphy to facilitate confident extrapolation of geologic units into the subsurface. As a result, construction of a starting geologic model at Akutan is difficult and subsurface geoscience exploration prior to drilling requires a stronger dependence on the interpretation of geophysical data and models compared to less stratigraphically complex sites.

Gravity Data Acquisition

In 2012, a gravity survey was performed at Akutan in which 217 measurements were made across the project area (Zonge, 2012). The measurements have an irregular spatial distribution (due to the rugged topography) with gravity station spacing varying from ~150 m to ~300 m or more (Figure 2). The gravity data were processed by the geophysical contractor using industry-standard methods (e.g. Gravity and Terrain Correction software, Geosoft Oasis Montaj v 7.1) and all elevations are referenced to the Geoid using the GEOID 09 model and NAVD88 datum. Complete Bouguer Anomaly gravity maps were produced at terrain density values ranging from 1.50 to 3.00 g/cm³ (Zonge, 2012).

Terrain Density Analysis

Prior to geophysical modelling, we needed to determine the optimal, average terrain density value for the Akutan area. An estimate of the terrain density is required for terrain-correction calculations that yield Complete Bouguer Anomaly data (which is used as input for the geophysical modelling). To estimate the terrain density, we used the Nettleton method. This simple method finds the optimal terrain density by identifying which terrain-correction density yields the least correlation between the Complete Bouguer Anomaly data and the gravity station elevations (Nettleton, 1971). We found that 2.45 g/cm³ is the best estimate of the average terrain density for the Akutan project area. Therefore, Complete Bouguer gravity data, referenced to a density of 2.45 g/cm³, were used for the geophysical modelling in this study. The gravity data points were then gridded over the 7.5 km x 4.5 km project area using a horizontal cell size of 100 m.

Density Measurements From Rock Core and Surface Samples

Rock density was measured on samples of rock core recovered from the two geothermal gradient wells drilled within the project area in 2010 and surface rock samples collected during a 2012 geologic mapping campaign. In total, 32 and 48 density measurements were made on core from wells TG2 and TG4, respectively. These density measurements were made on the four main rock types encountered in the wells: basalt lava, andesite lava, ashfall tuff, and mass wasting deposits identified as “debris flow” (alternatively referred to as “lithic basalt” in Stelling and Kent,

Figure 2. 3D perspective view towards the southwest over the City of Akutan geothermal project area. Topography ranges from sea level to ~800 m and is draped with the geologic/structural map of Hinz and Dering (2012). Spheres on the land surface show the locations of gravity stations and are colored according to the Complete Bouguer Anomaly value in mGal shown on the color bar (2.45 g/cm³ reference density).

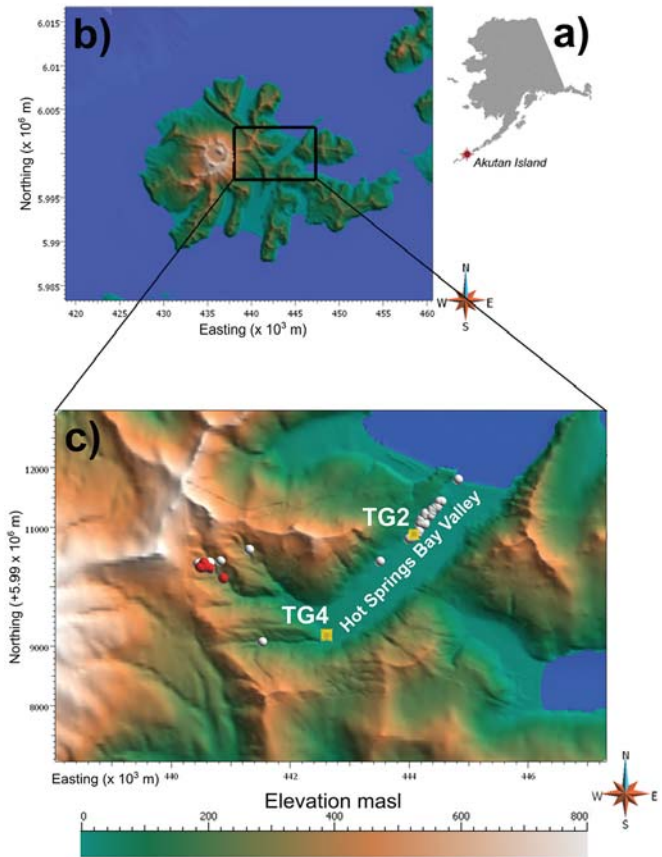
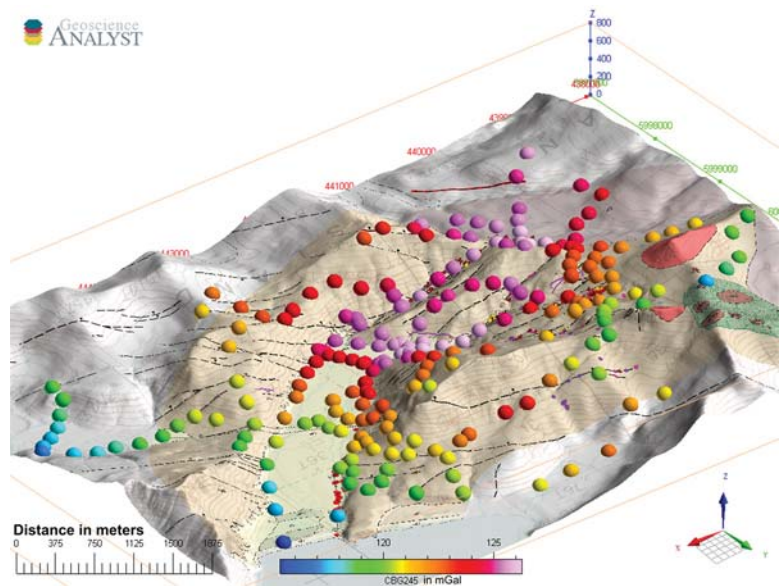


Figure 1. Location maps for the City of Akutan geothermal project. a) Location of Akutan in Alaska. b) Akutan Island with the project area shown as a black box. c) Topography within the project area. Temperature gradient wells, TG2 and TG4, are shown as yellow symbols. Fumaroles and hot springs are denoted by red and white spheres, respectively. All coordinates are in WGS84 UTM zone 3N.



2011). The depths of each of these core samples is well below that of modern surficial deposits, and, although these deposits have not been

dated, are likely to be >0.5 Ma and possibly >1 Ma (Richter et al., 1998; Coombs and Jicha, 2013). The densities of six surface rock samples were also measured. Nearly all of the surface samples were obtained northwest of the fumarole field and are unaltered. The densities of the surface samples fall within the range of similar rock types found in TG2 and TG4. The range of measured densities for all the rock samples is 2.26 g/cm^3 to 2.90 g/cm^3 with an average density of $2.55 \pm 0.14 \text{ g/cm}^3$. A summary of the measured density values is shown in Figure 3.

Rock density variations were analyzed vs. depth in the two wells (Figure 4). Rock density values vary significantly but do not show any particular relationship with depth. This is likely due to the complex stratigraphy that changes rapidly with depth as can be seen on the composite well logs (Figure 4). The average subsurface densities of core measured at well sites TG2 and TG4 are indistinguishable. Average density of the 32 rock samples measured at TG2 is $2.53 \pm 0.09 \text{ g/cm}^3$ and the average for the 48 rock samples from TG4 is $2.54 \pm 0.16 \text{ g/cm}^3$. In addition, the range in density values obtained for each rock type have considerable overlap and are difficult to uniquely distinguish from one another. Thus it is not possible to assign distinct density values to each individual rock type which would be useful for building a 3D geological model. The rock density data, however, is still useful as a means to ground-truth the results of the 3D geophysical inversion modelling effort, as will be discussed below.

Apparent Density Inversion Modelling

The apparent density inversion modelling used the Complete Bouguer Anomaly gravity data (2.45 g/cm^3 reference density) gridded at 100 m and digital topography with a spatial resolution of 30 m as input data. The resulting model consists of vertical prisms of constant density that have a horizontal cell size of 100 m. The tops of the prisms terminate at the topographic surface and extend to a depth of 25 km. Since the density in each prism is constant in the vertical direction, the results can be visualized by projection onto topography (Figure 5). The majority of the density values returned in the apparent density model result lie in the range $2.3 - 2.6 \text{ g/cm}^3$. The spatial relationships of high and low density rocks shown in Figure 5 are similar to that which would be observed in Bouguer gravity maps, however, apparent density models show values of rock density instead of anomalies measured in milligals.

To test how well the apparent density model matches the gravity data, we calculated gravity values generated from the apparent density model and compared them with the observed gravity measurements to create a map showing the difference between these datasets (i.e. misfit, Figure 6). The apparent density model result is acceptable because the misfit varies by $\pm 0.5 \text{ mGal}$ ($<5\%$ of the range in observed gravity) over the majority of the model area. The RMS misfit calculated for the

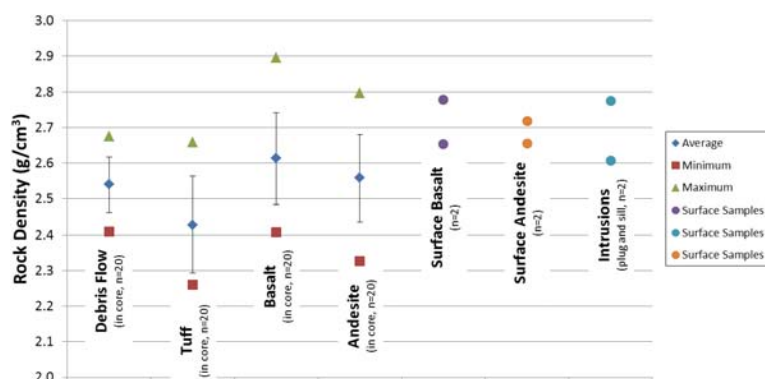


Figure 3. Results of rock density measurements. Density values measured on rock core from TG2 and TG4 are shown on the left, grouped into the four major rock types encountered downhole (the error bars show 1σ standard deviation). Density values measured on six surface samples are shown on the right and labeled by rock type.

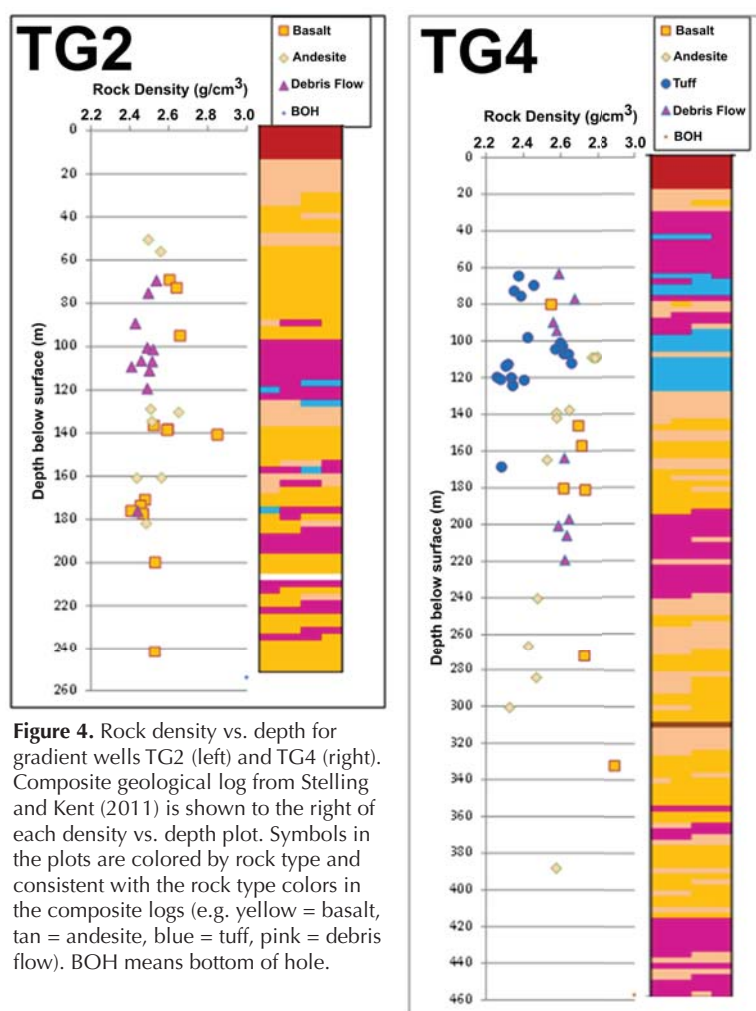


Figure 4. Rock density vs. depth for gradient wells TG2 (left) and TG4 (right). Composite geological log from Stelling and Kent (2011) is shown to the right of each density vs. depth plot. Symbols in the plots are colored by rock type and consistent with the rock type colors in the composite logs (e.g. yellow = basalt, tan = andesite, blue = tuff, pink = debris flow). BOH means bottom of hole.

entire apparent density model is 0.12 mGal. This value is less than the error in the measured gravity data (0.24 mGal), which was estimated by calculating 10% of the standard deviation of the amplitude of the gravity data.

3D Depth-to-Basement Modelling

A pseudo-basement interface calculated from the Akutan gravity data using the USGS horizontal-density-sheet edge solution methodology has been generated for the project area by other workers (Ohren et al., 2013; Stelling et al., 2015). Here, we test how well this model result matches the gravity measurements using a 3D geophysical forward modelling approach. Then, we compare the pseudo-basement surface with a new top-of-basement surface generated for the project area from 3D geophysical inversion modelling.

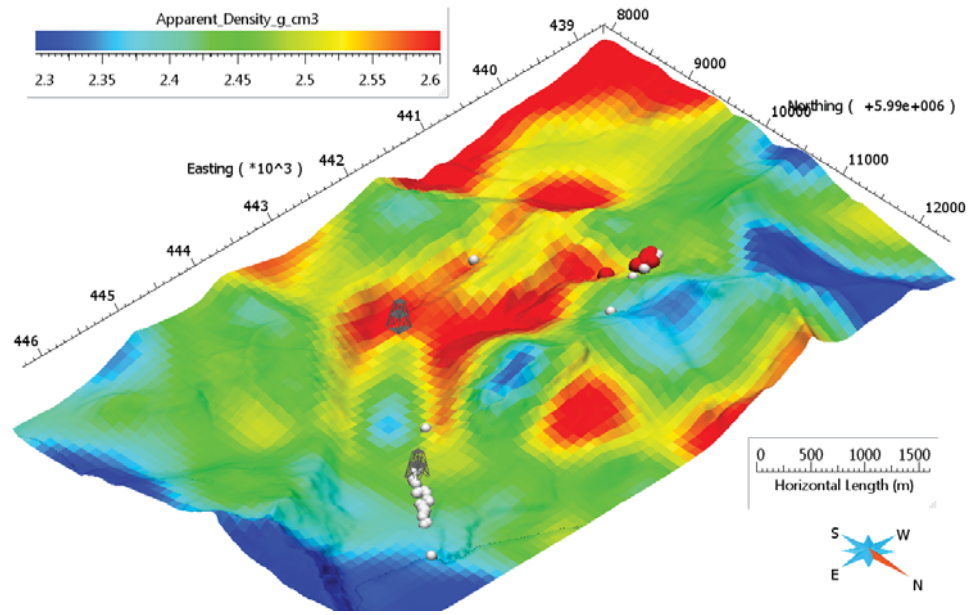


Figure 5. 3D perspective view towards the southwest looking up Hot Springs Bay Valley across the project area. The apparent density map has been overlain on topography highlighting areas of expected higher and lower density rocks in the subsurface. The color bar shows the expected density values. The locations of the two exploration wells (grey) are shown in addition to fumaroles (red spheres) and hot springs (white spheres).

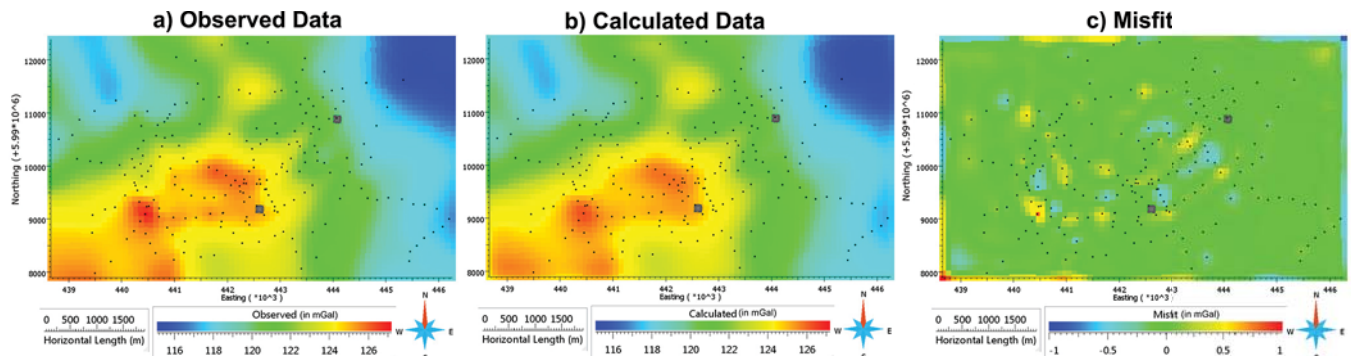


Figure 6. a) Map of the observed gravity data (Complete Bouguer with 2.45 g/cm³ reference density) gridded with a 100 m cell size. b) Map of the gravity response calculated from the apparent density model. c) Map showing the observed gravity minus the calculated gravity (i.e. the misfit). The majority of the misfit across the model area is near zero (green) and indicates good fit (RMS misfit = 0.12 mGal). Units on the color bars are mGal. Gravity station locations and wells are shown by small black dots and larger grey squares, respectively.

The pseudo-basement interface consists of a 2D contour map showing the elevation of the top of the pseudo-basement. The associated pseudo-basement model for Akutan consists of two geologic layers with assumed density values: cover at 2.30 g/cm³ and basement at 2.445 g/cm³. We digitized the contours from the 2D pseudo-basement map and then built a surface in 3D that represents this surface (Figure 7). Next, we created a 3D block model with 100 m x 100 m x 100 m cells that extends from 1 km above sea level to 3 km below sea level. Each of the cells in the block model was assigned a constant density of 2.30 g/cm³ above the pseudo-basement surface and 2.445 g/cm³ below the surface. Lastly, 3D geophysical forward modelling was performed on the 3D block model to test how well this pseudo-basement model representation matches the observed gravity data. We used Complete Bouguer gravity data with a 2.30 g/cm³ reference density as the observed data to match the density of the upper layer of rocks in the model. A comparison between the observed gravity data and the gravity response calculated from the 3D pseudo-basement model is shown in Figure 8. The overall misfit for the pseudo-basement model is 2.49 mGal which is ~25% of the range in the observed gravity data and significantly higher than the error in the gravity data (0.24 mGal).

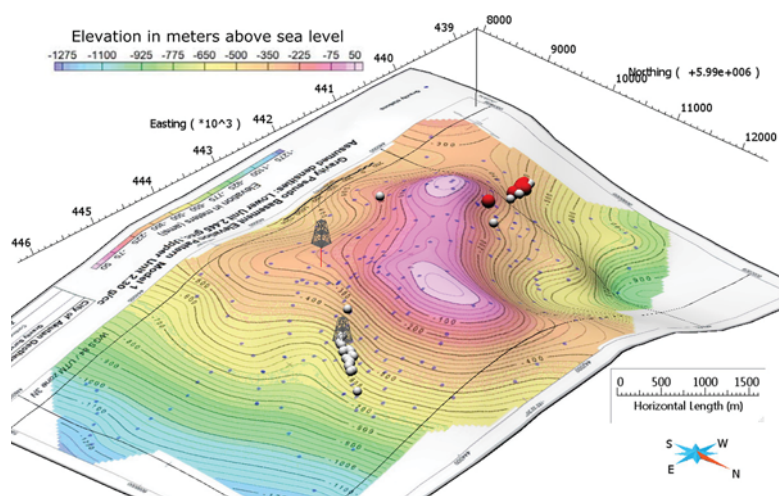


Figure 7. 3D perspective view towards the southwest up Hot Springs Bay Valley showing the pseudo-basement surface. The elevation of this surface is defined by the color bar. The locations of the two exploration wells (grey) are shown in addition to fumaroles (red spheres) and hot springs (white spheres). Adapted from Ohren et al., 2013 and Stelling et al., 2015.

For this study, we also performed 3D depth-to-basement geophysical inversion modelling to see if we could generate a new two-layer basement model that has an improved fit to the observed gravity data. The input data for the 3D basement inversion modelling includes: Complete Bouguer Anomaly gravity data (2.45 g/cm^3 reference density) gridded at 100 m, a digital elevation model with a spatial resolution of 30 m, and a horizontal

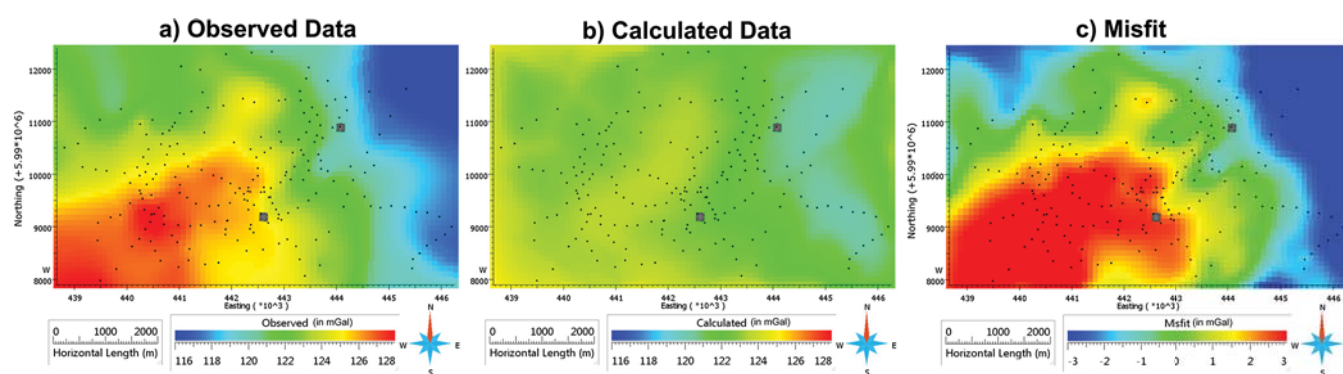


Figure 8. a) Map of the observed gravity data (Complete Bouguer with 2.30 g/cm^3 reference density) gridded with a 100 m cell size. b) Map of the gravity response calculated from the pseudo-basement density model. c) Map showing the observed gravity minus the calculated gravity (i.e. the misfit). The majority of the misfit across the model area is non-zero (i.e. not green) and indicates poor fit (RMS misfit = 2.49 mGal). Units on the color bars are mGal.

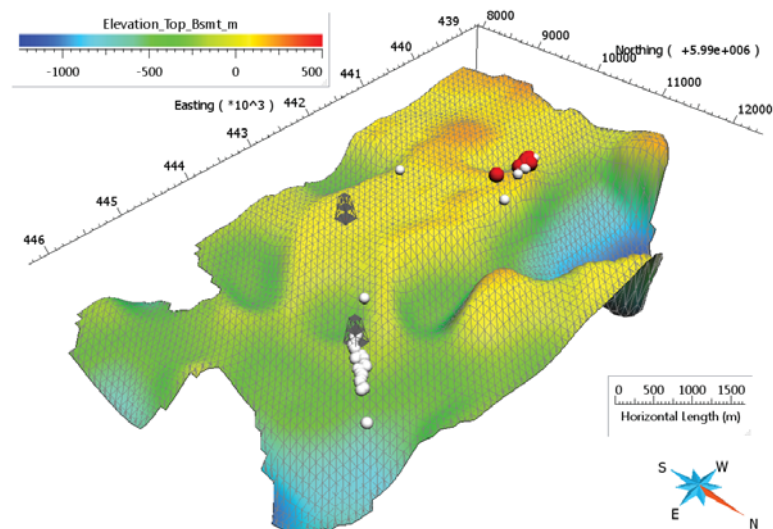


Figure 9. 3D perspective view towards the southwest up Hot Springs Bay Valley showing the new top-of-basement surface generated in this study. The basement surface is painted by the elevation of the top of basement (shown by the color bar) in metres above sea level. The locations of the two exploration wells (grey) in addition to fumaroles (red spheres) and hot springs (white spheres) are shown. The shape of this new basement surface differs significantly from the pseudo-basement surface shown in Figure 7, yet it has a better fit to the observed gravity data.

starting basement surface placed at 1.2 km below sea level. We assume that this new model consists of two geologic layers with fixed densities: cover at 2.45 g/cm^3 and basement at 2.8 g/cm^3 . We chose a cover density of 2.45 g/cm^3 to coincide with the results of the terrain density analysis using Nettleton's method. We chose to use the Complete Bouguer gravity data with 2.45 g/cm^3 reference density as input data for similar reasons. A basement density of 2.8 g/cm^3 was selected to represent intrusions of gabbroic composition which might lie at depth at this dominantly mafic volcanic island. The dimensions of the cells in the inversion model are $100 \text{ m} \times 100 \text{ m} \times 100 \text{ m}$ and the model extends from 1 km above sea level to 3 km below sea level. The inversion modelling algorithm adjusted the shape and elevation of the starting basement surface until it achieved the best possible fit to the gravity data, generating a new depth-to-basement model.

The output of the new basement inversion modelling effort is shown in Figure 9. A comparison between the observed gravity data

and the gravity response calculated from the 3D block model built from the new basement inversion effort is shown in Figure 10. The overall misfit for this new model derived from 3D basement inversion modelling is 0.57 mGal – a significant improvement to the fit compared to the pseudo-basement model, but not as low as the target misfit (i.e. 0.24 mGal).

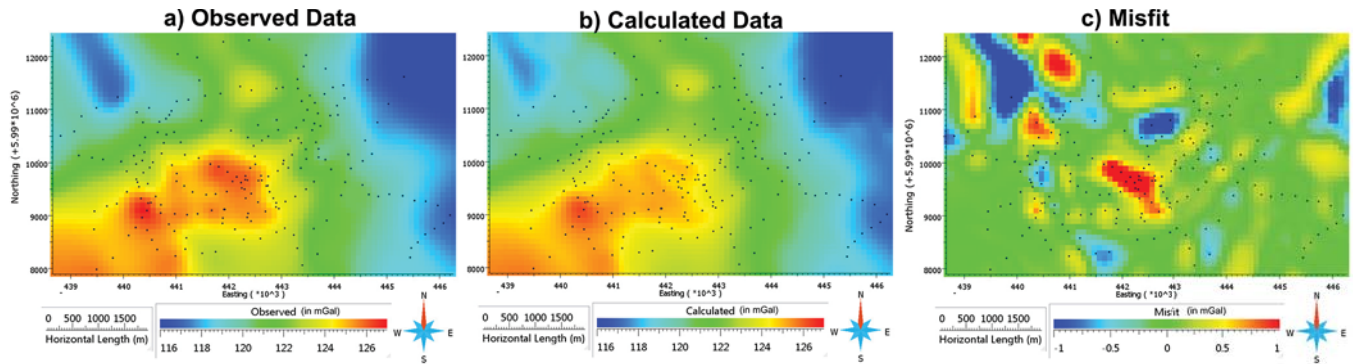
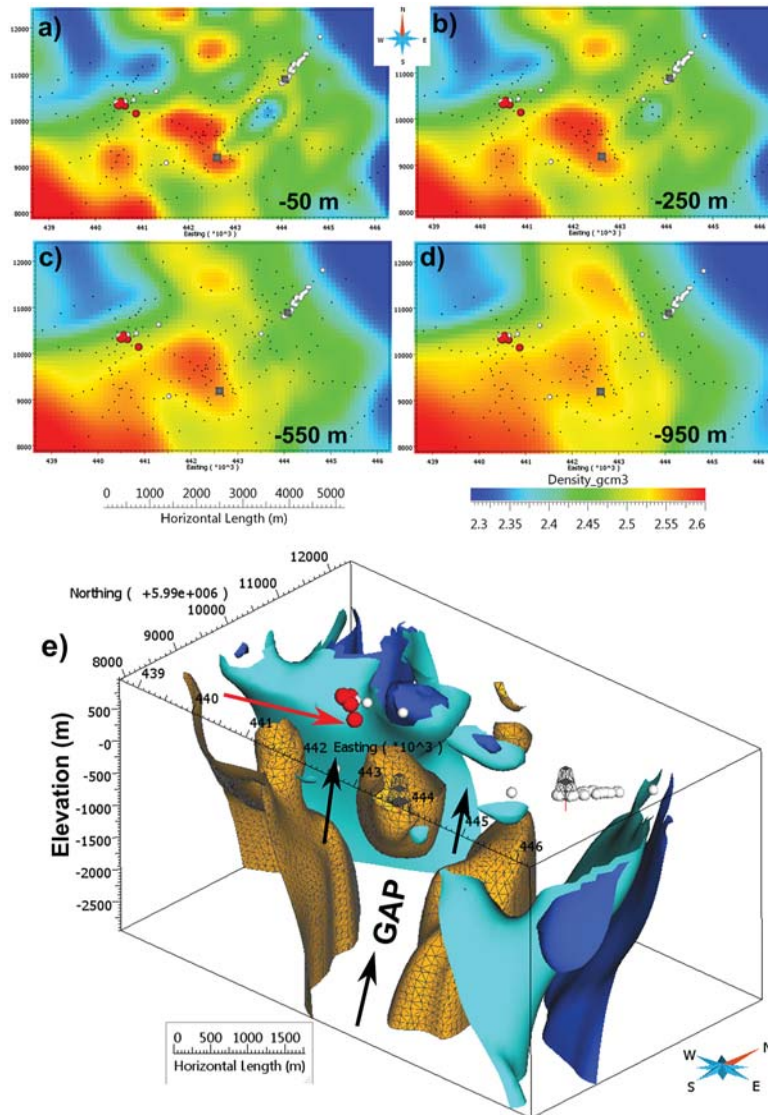


Figure 10. a) Map of the observed gravity data (Complete Bouguer with 2.45 g/cm³ reference density) gridded with a 100 m cell size. b) Map of the gravity response calculated from the new 3D top-of-basement inversion model from this study. c) Map showing the observed gravity minus the calculated gravity (i.e. the misfit). The misfit across the model area is highly variable but mostly lies between ±0.5 mGal (i.e. yellow-green-light blue) which indicates a mediocre fit (RMS misfit = 0.57 mGal). Units on the color bars are mGal.



3D Unconstrained, Heterogeneous Density Modelling

Depth-to-basement modelling has its limitations because we are restricted to a two-layer geologic model with fixed densities. To further explore possible density variations in the subsurface, we performed 3D geophysical inversion modelling again but used a different approach which allows for a fully heterogeneous distribution of density in the model. This approach does not utilize any geological or physical property constraints, but instead it creates a model with an unrestricted density distribution that best fits the observed gravity data. The input data for the 3D unconstrained, heterogeneous inversion modelling includes the Complete Bouguer Anomaly gravity data (2.45 g/cm³ reference density) gridded at 100 m, a digital elevation model with a spatial resolution of 30 m, and a constant starting model density of 2.45 g/cm³. The dimensions of

Figure 11. Different views of the 3D unconstrained, heterogeneous density model result. Locations of fumaroles (red dots) and hot springs (white dots) are shown for reference. Upper panel: horizontal slices through the 3D unconstrained model at depths of a) -50 m, b) -250 m, c) -550 m, and d) -950 m. Model density values vary according to the color bar. Gravity station locations and wells are shown by small black dots and larger grey squares, respectively. Lower panel: e) 3D perspective view of the unconstrained model looking towards the northwest showing only the density iso-surfaces with values 2.55 g/cm³ (orange), 2.40 g/cm³ (light blue), and 2.35 g/cm³ (dark blue). This view reveals a gap which parallels the NW-trending portion of the upper reaches of Hot Springs Bay Valley. Northwest and northeast structural trends are shown by black and red arrows, respectively.

the cells in the inversion model are 100 m x 100 m x 100 m and the model again extends from 1 km above sea level to 3 km below sea level. The inversion modelling algorithm adjusts the density values of the cells in the starting 3D block model until the best possible fit to the gravity data is achieved. The output of the 3D heterogeneous inversion modelling is shown in Figure 11. A comparison between the observed gravity data and the gravity response calculated from the 3D block model generated from the heterogeneous inversion effort is shown in Figure 12. The overall misfit for this new model derived from 3D inversion modelling is acceptable at 0.28 mGal, which is quite similar to the error in the gravity data (0.24 mGal).

Discussion

Geophysical inversion modelling is hampered by non-uniqueness, which means that a model result generated by an inversion modelling algorithm is one of many which can explain the data. In other words, a geophysical model result may be acceptable mathematically, but at the same time be incorrect geologically. Thus, for geophysical modelling to be robust, geologically-relevant, and useful to geothermal exploration, three aspects are required: a) geophysical modelling needs to be performed in three dimensions to account for 3D variations in the subsurface, b) to properly explore the multitude of possibilities in the model space, the same data should be modelled multiple times using different modelling techniques to facilitate an improved geological interpretation, and c) incorporating geoscience data (such as a geological model and/or rock property values) as explicit constraints in the modelling process is critical to help guide the geophysical model output towards a geologically-reasonable result.

At Akutan, we employed multiple techniques to model gravity data in three dimensions. The absence of a 3D geological model for Akutan combined with the small amount of drilling and rock property data, meant that our ability to perform geophysical inversion modelling with geological and rock property constraints was limited. Therefore, the task at hand was to build a 3D geologically-reasonable understanding of the subsurface which is consistent from one dataset to another.

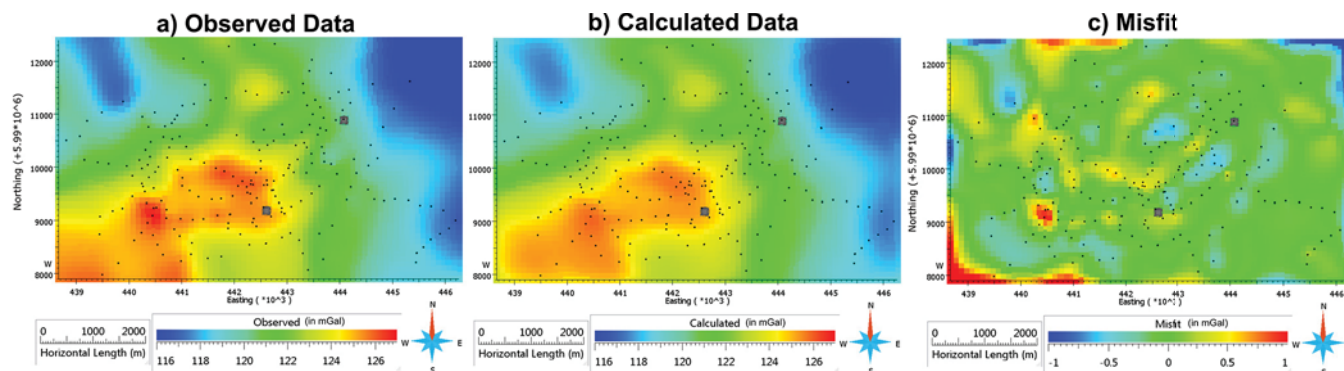


Figure 12. a) Map of the observed gravity data (Complete Bouguer with 2.45 g/cm³ reference density) gridded with a 100 m cell size. b) Map of the gravity response calculated from the 3D unconstrained, heterogeneous inversion model from this study. c) Map showing the observed gravity minus the calculated gravity (i.e. the misfit). Nearly all of the misfit across the model area is low (i.e. green) which indicates a good fit (RMS misfit = 0.28 mGal). Units on the color bars are mGal.

The apparent density model that we generated (Figure 5) is a simple representation of the subsurface density distribution for the Hot Springs Bay Valley geothermal area. The low misfit for this model shows that it is mathematically consistent with the gravity data (Figure 6). Unfortunately, the apparent density model is geologically unreasonable since we know that, as a 3D representation of the subsurface, the assumption of constant density in each vertical prism is unrealistic. What the apparent density model tells us though is that the observed gravity *can* be explained well by a geological model that is dominated by lateral variations in density. Thus, the locations of the density contrasts in the apparent density map are likely to be accurate representations of the edges of lithologic blocks of different density in the subsurface. Such regions of rapid density change in 3D space may represent lithologic contacts or faults, both of which could represent zones of permeability. Furthermore, the apparent density model returned a range of density values that are reasonable for the geologic environment of Akutan.

The 3D basement inversion model generated in this study is also a very simple 3D geological representation of the subsurface (Figure 9). Without doing any modelling, most workers would agree that a two-layer model with fixed density values is not likely to be an accurate representation of the complex and heterogeneous Akutan volcanic pile. Indeed, the fit of the 3D basement inversion model to the gravity data is good in some portions of the model but poor in others (Figure 10). We also tested lower values for basement density but the misfit was worse than the 2.8 g/cm³ value used here. Basement densities higher than 2.8 g/cm³ were judged geologically-unreasonable due to the lack of any evidence for such high density rocks at Akutan. Importantly, the density measurements from the core samples from the two wells do not match

the 3D basement inversion model. According to the 3D basement inversion model, TG4 should encounter a transition from low density cover rocks (2.45 g/cm^3) to high density basement rocks (2.80 g/cm^3) at a depth of $\sim 22 \text{ m}$ below the ground surface. This is inconsistent with the measured densities for 48 rock samples from TG4 that lie deeper than 22 m depth and have an average density of only 2.54 g/cm^3 (Figure 4). Similarly, the model predicts a transition to basement rocks in well TG2 at a depth of 248 m. The geologic log for TG2 does not record any significant change in lithology at that depth and the average density of core from TG2 (2.53 g/cm^3) does not match the cover rock density from the model (2.45 g/cm^3 ; Figure 4). Overall, we conclude that: a) 3D depth-to-basement inversion modelling is an impractical geophysical modelling approach for Akutan considering the geological environment and b) the results are not particularly informative.

The 3D heterogeneous inversion model generated in this study (Figure 11) fits the gravity data well (Figure 12). However, this model contains no geological information and is simply an idealized density distribution output by the inversion algorithm. The primary question with this model is how well it represents geologic reality. To address this question, we can first compare the model densities with those measured in the field. The five 100 m model cells which coincide with the 457 m deep TG4 have the range $2.56 - 2.58 \text{ g/cm}^3$ which compares favorably with the average rock core density for this well of 2.54 g/cm^3 . Similarly, the three model cells which coincide with the 254 m deep TG2 have the range $2.48 - 2.50 \text{ g/cm}^3$. The average measured density for core from well TG2 is 2.53 g/cm^3 . This suggests that the 3D heterogeneous inversion model does recover geologically-reasonable density values in the uppermost several hundred metres despite the lack of geological constraints in the model. A comparison of the model results with the densities of the six surface samples does not yield a similar agreement. We believe this is due to an insufficient number of surface rock samples and the unaltered nature of the surface samples are likely imparting a high density bias to these samples. Second, we can compare the 3D heterogeneous inversion model results to the mapped surface geology. Work by Hinz and Dering (2012) identified a fossil geothermal system in the upper reaches of Long Valley in the northwest corner of the project area. The ancestral Long Valley geothermal system is characterized by extensive argillic alteration which is consistent with the low densities predicted in the northwest portion of the 3D density model. Furthermore, the active fumarole field lies near the contact between the lower density ancestral Long Valley geothermal system to the north and the higher density Hot Springs Bay Valley geothermal system to the south. This marked density contrast may represent a major lithologic boundary that is responsible for the permeability that gives rise to the fumaroles. Third, NW and NE structural trends can be inferred from the 3D heterogeneous inversion model (Figure 11). These trends are in close agreement with the orientations of 2 out of 3 principal structural trends mapped in the field by Hinz and Dering (2012). Of particular interest is that ground cracks formed on Akutan during a 1996 earthquake swarm in a WNW orientation (Waythomas et al., 1998). Earthquake epicenters triggered on Akutan by a M 8.2 earthquake in the Kurile Islands (Russia) in 2007 lie along the same WNW trend (McGimsey et al., 2007). Thus, structural trends mapped using geophysical inversion modelling of gravity data are in relatively good agreement with structural trends that may be indicative of permeability on Akutan.

The recommended next steps for the Akutan geothermal exploration program are to use the 3D heterogeneous density model as a starting 3D geological model in which the different density compartments represent different rock units. Then, add all existing geoscience data and models into a single 3D visualization environment, and continually update the 3D geological model as new drilling, geological, geophysical, and rock property data become available. Additional geophysical inversion modelling of the gravity data, constrained by growing amounts of geoscience information will be an effective approach to further refine the 3D geological model and test ideas about structure and distribution of rock types in the Hot Springs Bay Valley geothermal area.

Conclusions

Geophysical modelling was performed with four different modelling techniques using gravity data from the City of Akutan geothermal project area, Alaska. These techniques include three inversion modelling methods: apparent density modelling, 3D depth-to-basement modelling, and 3D unconstrained, heterogeneous density modelling. In addition, 3D geophysical forward modelling was performed in order to test how well an existing basement model fits the observed gravity data. The apparent density model has a good fit to the gravity data and the lateral contrasts shown in this model likely represent important rock unit boundaries in the subsurface. Forward modelling of the pseudo-basement model showed that it does not honor the gravity data very well. A new 3D basement inversion modelling effort improved the fit to the data; however, a two-layer geologic model with fixed densities is inappropriate for a volcanic environment such as Akutan. The 3D heterogeneous inversion model also has a good fit to the gravity data and matches well with the measured density values from wells TG2 and TG4. Low density values predicted in the northwest portion of the project area coincide with a strongly altered region mapped in the same area that is expected to be characterized by low density rock. Structural trends inferred from the geophysical models in this study also agree well with those inferred from geologic mapping and seismicity.

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