Constraints on Subsurface Density from Gravity Surveying In and Around the Salt Lake Tuff Ring Complex, South-Central Oahu

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SUMMARY

We report the outcome of a reconnaissance, on-land gravity survey, in and around the Salt Lake Tuff Complex (SLTRC) of south-central Oahu, Hawaii. The survey spans an area of ~4500 x ~3500 m and comprises 332 measurements with an average spacing of ~200 m. The data were corrected for the effects of measurement elevation (free-air correction) and for the gravitational attraction of topography (complete Bouguer correction) using a LiDAR-derived, digital elevation model (DEM) with 1 m accuracy in all directions. A regional gradient associated with the large-scale structure of the Koolau shield volcano was estimated and removed to isolate the local subsurface variations of interest. The resulting residual Bouguer anomaly (RBA) varies by ±2 mGal. The RBA was then inverted to produce solutions for the 3D density structure that fit the RBA to measurement uncertainty. A wide range of plausible solutions were produced by varying the density used for the topographic correction (2300-2700 kg/m$^3$) as well as parameters of the inversion that influence the depth range of the density heterogeneity in the solutions. The 996 solutions show heterogeneity extending to depths of >2 km bsl, and appreciable differences in detailed 3D structure between models. Despite these differences, the planview patterns of mean density anomaly within the depths (~240 m bsl to ~6 m above sea level) of the fresh water reservoir are all very similar. The planview patterns differ primarily in total variation: the median is ~180 kg/m$^3$, and 180 kg/m$^3$± 30 kg/m$^3$ represent the 10th and 90th percentiles. The most prominent feature is an RBA and mean density high in the northern Aliamanu Tuff Ring and along its southern border near the center of the SLTRC. To the east, the RBA and mean density anomaly decrease to low-amplitude values, and then increase again to positive values near the base Moanalua Ridge. Around the base of Red Hill Ridge and at the mouth of Moanalua Valley just south of Red Hill Ridge, the RBA and mean density anomaly are negative. A base-level interpretation of the gravity data postulates that basaltic rock associated with higher RBA also have lower porosity, and correspondingly lower hydraulic conductivity, whereas basaltic rock having negative RBA and lower density contrast may be more hydraulically conductive. Our findings provide a structural framework that can be used with existing and new data to make improved inferences of groundwater flow, or for the design of future geophysical (e.g., seismic or electrical) investigations targeting more detailed structure.
1. Introduction

We report on findings of a land-based reconnaissance gravity survey in and around the Salt Lake and Aliamanu Craters, between the upland part of the Moanalua Aquifer System and the south-central coast of Oahu (Fig. 1). These craters are coalesced tuff rings, refer to as the Salt Lake Tuff Ring Complex (SLTRC), formed as part of the Honolulu Volcanics series. Knowledge of the subsurface structure of this complex as well as the adjacent area is important for our understanding of groundwater flow around and beneath Navy’s Red Hill Fuel Storage Facility and the associated risk to drinking water sources.

Tuff rings are formed by phreatomagmatic eruptions, the explosive interaction between molten rock and groundwater [e.g., Sohn and Park, 2005; White and Ross, 2011]. During a phreatomagmatic eruption, ash and country rock are ejected from the volcanic vent, and are deposited around the vent forming a tuff ring. The eruption can also create a diatreme, a downward-pointing, cone-shaped excavation within the ring filled with eruption products. The cemented ash and rock fragments of a diatreme can produce poorly permeable structures that can extend a couple hundred meters into the sub-surface [Sohn and Park, 2005]. The magma plumbing system that fed the volcanic vent may be present today as dense intrusive rock formations such as dikes, which are well-known to be barriers to groundwater flow in Hawaii (e.g. Stearns and Vaksvik, 1935; Takasaki and Mink, 1986; Hunt, 1996; Oki, 2005).

![Figure 1. Geologic map of the area around the Salt Lake Tuff Ring Complex (SLTRC). The black box outlines the study area (geology adapted from Sherrod et al. [2007]).](image-url)
pore-space of the material, which can influence hydraulic conductivity [Milsom, 2002]. The materials likely to be present in our survey area include soil, saprolite (clay-rich deposits of weathered basalt), alluvium/colluvium, carbonate rock, basalt (with varying porosity and fracture density), tuff, olivine-rich xenoliths within the tuff formations [e.g., Jackson and Wright 1970; Keshav et al. 2007], and gabbro. Table 1 lists known densities of some of these materials. The density of geologic media depends on the solid rock density and the volume fraction of pore space. The fluid conductivity of the rock tends to decrease with decreasing porosity, and thus the increasing bulk density of a given material. However, there are exceptions; for example, clays with high porosity have poor conductivity due to the tiny size and non-connecting topology of the individual pores. Thus the information gleaned about material type, as well the reference assumption about the inverse correlation between aquifer material density and its ability to transmit water makes knowledge of the subsurface density—as detected by accurate measurements of gravity—useful for understanding the groundwater flow environment.

Table 1. List of relevant geologic materials and various of estimates of the associated properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density Range (kg/m³)</th>
<th>Porosity (volume fraction)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saprolite</td>
<td>Average: 1100 Range: 840-1540 (dry); 1440-2140 (saturated)</td>
<td>Average: 0.60 Range: 0.48-0.71</td>
<td>Miller, 1988; page 22</td>
</tr>
<tr>
<td>Saprolite</td>
<td></td>
<td>Average: 0.51 Range: 0.50-0.51</td>
<td>Finstick, 1999</td>
</tr>
<tr>
<td>Tuff</td>
<td></td>
<td>Average: 0.44 Range: 0.22-0.56</td>
<td>Finstick, 1999</td>
</tr>
<tr>
<td>Welded Tuffs</td>
<td>2180 +/- 230</td>
<td>0.141 +/-0.089</td>
<td>Keller, 1960</td>
</tr>
<tr>
<td>Basalt</td>
<td>Average – 2400 Range: 1600-2900</td>
<td>Average: 0.43 Range: 0.05-0.51</td>
<td>Nichols et al., 1996</td>
</tr>
<tr>
<td>Basalt</td>
<td></td>
<td>Massive basalt: Range: 0.08-0.10 Interconnected: Range: 0.05-0.10</td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>2800</td>
<td></td>
<td>Visher and Mink, 1964; page 95</td>
</tr>
<tr>
<td>Basalt</td>
<td>1360 to 2650</td>
<td></td>
<td>Miller, 1987; page 22</td>
</tr>
<tr>
<td>Olivine Basalt</td>
<td>2000 to 2600</td>
<td></td>
<td>Manghanani &amp; Woolard, 1965; page 292</td>
</tr>
<tr>
<td>Amphibolite dike</td>
<td>Density 3000</td>
<td></td>
<td>Manghanani &amp; Woolard, 1965; page 292</td>
</tr>
<tr>
<td>Olivine cumulates</td>
<td>3300</td>
<td></td>
<td>Flinders et al. (2013)</td>
</tr>
</tbody>
</table>

The objective of this study is to use land-based gravity measurements to map the basic character of sub-surface density in and around the SLTRC. We first describe the acquisition of 332 surface gravity measurements and how the data were processed in order to isolate the signal from the local subsurface. The resulting residual Bouguer gravity anomaly is then inverted to explore a wide range of plausible 3D density structures that fit the anomaly. Finally, we highlight the robust features of the solutions and discuss how the results should be used for an improved understanding of groundwater flow in this important area.
2. Data acquisition and processing

During June through August 2018, 332 relative (not absolute) gravity measurements were made in the ~4500 m x 3500 m study area (Fig. 2) using a G1096 LaCoste and Romberg gravimeter. The survey covered all of the major geologic types in the study area including the volcanic tuffs, Koolau flank lavas, and alluvium (Fig. 1). Each day of surveying began and ended by tying the survey measurements to the benchmark at the Hawaii Institute of Geophysics (HIG) building (University of Hawaii at Manoa). This gravity benchmark was established by the National Geospatial–Intelligence Agency (NGA), measured to have an absolute gravity of 978944.611 ± 0.0012 mGal. Corrections for the tidal deformation of the solid-earth were made using a modified version of the program GravProcess [Cattin et al. 2015]. Corrections for instrument drift were applied by linearly interpolating in time between the two benchmark measurements at the beginning and end of each survey day. The sum of the tidal and linear drift corrections were typically of order 0.1 mGal.
Free-air gravity anomalies were produced by first removing the WGS84 model of the gravitational pull of the Earth’s reference ellipsoid, followed by correcting for the fact that each measurement was made at different elevations above the geoid (i.e., the free-air correction). Elevations for the free-air correction were derived by interpolating our GPS-measured locations (< 1 cm lateral accuracy) to a high-resolution digital elevation model (DEM). The DEM is based on LiDAR surveys conducted by the NGA, and has 1 meter accuracy in all directions (Fig. 2).

As is typical, the resulting free-air gravity anomaly shows a positive correlation with topography, due to the attraction of the topographic mass between the measurement point and the geoid (Fig. 3, top left). In addition, the anomaly reveals a SW to NE regional increase associated with the
large-scale and deep (>2 km bsl) structure of the Koolau shield volcano [Strange et al. 1965, Flinders et al. 2013], the center of which is ~10 km to the NE of the study area. The free-air gravity anomaly spans 205 to 250 mGal, representing a total variation of 45 mGal.

To correct for the gravitational attraction of topography, we produced a 10-meter grid of topography within the study area and extending 500 meters beyond each edge of the area using the high-resolution DEM. Outside of this area, extending 20 km away from the borders of the study region, we used a 50 meter grid of subaerial topography provided by the US Geological Survey (USGS, http://www.pacioos.hawaii.edu/metadata/usgs_dem_10m_oahu.html) as well as submarine bathymetry provided by the Hawaii Research Mapping Group (HMRG, Hawaii multibeam bathymetry synthesis www.soest.hawaii.edu/hmrg/multibeam/). The gravitational attraction of the topography was computed by treating each topography grid as a rectangular prism and summing the contributions of all grids within 20 km of each measurement point. This summed signal was then subtracted from each free air gravity anomaly points.

The resulting complete Bouguer gravity anomaly (Fig. 3, top right) thus reflects subsurface density variations within the local area as well as the regional gradient associated with the Koolau shield. The Bouger anomaly spans 205 to 232 mGal, representing a total variation of ~27 mGal, 40% less than that of the free air gravity anomaly. The standard error at each measurement point is estimated to be ~0.35 mGal. This error is computed as the L2-norm (square-root of the sum of squares as an estimate of the square root of variance) of four sources of uncertainty or error: measurement error (0.1 mGal), the tide and drift correction (0.1 mGal), the free-air correction (0.3086 for the 1-m DEM uncertainty), and the Bouguer correction (0.1 mGal).

The final step in the data reduction is to remove the regional gradient. This was done by fitting a 2D linear function to the Bouguer anomaly and then subtracting this “tilted planar” regional field (Fig 3, lower left). A linear function was chosen because it provides a good representation of the field associated with the Koolau shield volcano [Flinders et al. 2013], which occurs over much greater wavelengths than the dimensions of the study area; and because removing this function, preserves all signal at wavelengths less-than, or equal to the lateral dimensions of the study area. In contrast, removing a regional trend represented with a higher-order polynomial would risk removing potentially important variations internal to the study area. The resulting residual Bouguer gravity anomaly (RBA) therefore isolates the full-wavelength content of lateral variability in subsurface density variations that is contained within the study area (Figs. 3 lower right, Fig. 4). Correspondingly, the RBA shows a much smaller total variation of ±2 mGal than the full Bouguer anomaly. The result shown in Fig. 3 (bottom right) and Fig. 4 was computed using a density of $\rho_t = 2500$ kg/m$^3$ for the topographic correction. The magnitude of variation depends on the assumed density (-2.7 to +1.9 mGal for $\rho_t = 2700$ kg/m$^3$; -1.9 to +1.6 mGal for $\rho_t = 2300$ kg/m$^3$) and therefore $\rho_t$ is varied in the subsequent analysis.

The RBA within the SLTRC spans nearly the entire range of the measured values (~2 to +2 mGal, Figs. 3 and 4). Relatively high RBA values (+1 to +2 mGal in Figs. 3 and 4) occur within the Aliamanu Crater (NW), and on the south flank of this crater. In contrast, the RBA in the Salt Lake Crater (SW) generally range from neutral (~0 mGal) to negative values (-0.5 to -2 mGal), much different than the Aliamanu Crater. The RBA of the tuffs outside of the craters were generally in the neutral range. Just ESE of Aliamanu Crater, the RBA show nearly neutral values, and then increases to
another local high (+0.5 to +1) further east, near the base of Moanalua Ridge, associated with Koolau flank lava. West and south of the Red Hill Ridge, RBA values are relatively low (-2 to -1 mGal). Negative RBA values (−0.5 to −2 mGal) are identified with alluvium in Halawa Valley and near the mouth of Moanalua Valley.

![Inverted residual Bouguer anomaly (RBA) values shown as colored circles superimposed on the geological map (geology adapted from Sherrod et al. [2007]).](image)

**Figure 4.** Residual Bouguer anomaly (RBA) values shown as colored circles superimposed on the geological map (geology adapted from Sherrod et al. [2007]).

### 3. Subsurface density structure

Here we explore geologically plausible solutions for the subsurface density structure that explain the residual Bouguer gravity anomalies. This was done using GRAV3D [GRAV3D, 2015], a suite of software tools for inverting the gravimetric responses to a 3D distribution of density contrasts. The method uses Newton’s law of gravity to solve for the 3D density distribution that fits the RBA to a specified tolerance, while minimizing the deviation from a reference, or prior distribution, subject to constraints on how rapidly densities can vary in space, as well as the depth extent of the structure. We define the misfit tolerance to be met when the sum of squared misfit to each RBA point, normalized by the square of the standard error (0.35 mGal) equals the number of points (\( n =332 \)). Our reference model is the zero density anomaly, which is relevant to a situation in which density is uniform below the surface, or more realistically, varies only vertically, both of which produce a constant gravity field. The solutions therefore are the distributions of density anomalies \( \Delta \rho \) relative to the mean density structure in the area that fit the data to standard error, with minimal 3D variation. The solution space includes the surface topography down to a depth of 3666 m, and spans 5900 m east-west by 4500 m north-south. The volume is discretized with
cells spanning 100 x 100 m horizontally, and 10 m vertically at all levels above sea level, 20 m to a depth of 267 m bsl, and 100 m below that.

The main influence of how deep the inversions place most of the heterogeneity is the weighting function that corrects for the decay of the gravitational signal with depth $z$ from a source,

$$
\Delta w_j = \left[ \frac{1}{\Delta z_j} \int_{\Delta z_j}^{\infty} \frac{dz}{(z + z_0)^\alpha} \right]^{1/2}, \quad j = 1, 2, \ldots, M.
$$

(1)

Here $w_j$ is the weight on the $j$th cell out of a total of $M$ cells composing the 3D model volume; $\Delta z_j$ is the thickness of the cell, also defining the bounds of the above integral; and $z_0$ and $\alpha$ are parameters that control the magnitude and form of the decay, respectively. Details of where this weighting function and its derivatives appear in the equations of the inversion are given in the users manual for GRAV3D [GRAV3D, 2015]. The general behavior is that the more rapidly $w_j$ decays with depth (i.e., with smaller values of $z_0$ and/or larger values of $\alpha$), the deeper density contrasts appear in the solutions. Correspondingly, the more gradual the decay is (i.e., larger values of values of $z_0$, and/or smaller values of $\alpha$), the closer the structure is to the surface.

As with essentially all geophysical inverse problems, the solutions are non-unique. This is caused by the fact that the problem is underdetermined (i.e., in this case there are far fewer observation points than cells in the density model), but more fundamentally with gravity, an inherent non-uniqueness arises due to the direct trade-off between the magnitude of a mass anomaly and its squared distance from an observation point. This nature of the problem requires exploring a large range of solutions that are plausible given geologic constraints as well as the physical conditions of the problem. The key geologic constraint is the range of likely densities associated with the topographic correction used to produce the complete Bouguer anomaly, which (again) we take to be $\rho_t = 2300$ to $2700$ kg/m$^3$. The physical constraints are the aperture of the survey region, for which we require $z_0$ to be a small fraction, hence we examine values of 10 m to 500 m. Finally, the inverse square decay in Newton’s law of gravity motivates values of $\alpha$ near 2, whereby $\alpha$ is varied between 1.5 and 2.5. We thus discretized the 3D parameter space of $\rho_t$, $z_0$, and $\alpha$ over the above ranges and producing 996 solutions, all fitting the data equally well in a statistical sense.

Fig. 5 depicts three example density models from the suite of solutions. Again the solutions are the density contrasts (or anomalies), $\Delta \rho$, relative to the mean structure, whatever that might be. A key quantity for characterizing the structure relevant to groundwater flow is the range of density anomalies $\Delta \rho$ within the depths appropriate for the fresh water reservoir. This depth interval is approximately ~240 m bsl to ~6 m above sea level. Therefore, below each geographic coordinate in the model, we compute the mean density within that depth interval, which we refer to as $\overline{\Delta \rho}$. Each density model therefore produces a map of $\overline{\Delta \rho}$ (maps in Fig. 5). The 996 models display different amplitudes of total variations of $\overline{\Delta \rho}$ across the study region. The top row of Fig. 5 shows the model that is at the lower 10th percentile of the total variation in $\overline{\Delta \rho}$; the middle shows the model at the median of the total variation in $\overline{\Delta \rho}$; and the bottom shows the model at
the higher 90th percentile. These models therefore represent the likely range of $\Delta \rho$ that can optimally fit the RBA.

Figure 5. Plausible solutions for density anomalies produced by GRAV3D inversions. Maps show $\Delta \rho$, the mean density anomaly between 241 m bsl and 3 m above sea level. The three E-W depth sections are along the dashed lines in the map; dashed lines in the cross-sections mark 241 m bsl. Rows show the model at the 10th (top), 50th (middle), and 90th (bottom) percentiles of the total variation in $\Delta \rho$. Colors are saturated so the actual minimum and maximum $\Delta \rho$ extend beyond the range of the color bar. Contour interval is 20 kg/m$^3$ in all panels.
In the central and south parts of Aliamanu Crater, \( \Delta \rho \) is positive, having values of 40–70 kg/m³ in the model with the median variation (middle in Fig. 5), and 30–60 kg/m³ and 60–80 kg/m³ at the 10th and 90th percentiles, respectively. The local negative RBA near the mouth of Moanalua Valley, south of the Red Hill Ridge has \( \Delta \rho = -50 \) to -80 kg/m³ in all three models. Just east of the SLTRC \( \Delta \rho \) decreases and then increases near the base of Moanalua Ridge to positive values of 30–50 kg/m³ (median model) ranging 30–40 kg/m³ to 50–70 kg/m³ in at the 10th and 90th percentiles, respectively.

The depth cross-sections along the three E-W profiles illustrate the appreciable differences between the models. The difference in the depth distribution of the anomalies are especially notable. Thus, the detailed distribution and magnitudes of the density anomalies for any particular model are not robust. However, despite these differences, the maps of \( \Delta \rho \) display a remarkably similar pattern, with relatively subtle differences in the amplitudes. Thus it is these depth-averaged density anomalies that are the robust aspects of the solutions, which should be used for interpretation.

4. Summary and Interpretation

What we most confidently learn about the subsurface density structure from the RBA is the geographic pattern of mean density within the shallowest few hundred meters, here computed between elevations of +6 and -241m, where most of the fresh water is likely to reside. Notable features include the prominent high RBA in the center and southern margin of Aliamanu Crater, which is associated with mean density excess (\( \Delta \rho \)) of +40 to +70 kg/m³. On the eastern side of the crater, very low-amplitude RBA values separate another high (+ 30 to +50 kg/m³) near the base of Moanalua Ridge. The mouth of Moanalua Valley, areas near the base of Red Hill Ridge, shows a RBA low and a negative \( \Delta \rho \) of -50 to -80 kg/m³.

These mapped density contrasts are relative to the average structure of the study region, which likely involves low-densities associated with sediment and saprolite (~1000–2000 kg/m³, Table 1) within a few hundred feet of the surface [Liberty and Clair, 2018] and then increasing densities with depth with increasing basaltic content (1600-2900 kg/m³ Brandes et al. [2011]). The implied range of density contrast between sediment/saprolite and basalt of 0-1900 kg/m³ is large compared to the variations seen in the model \( \Delta \rho \) values of ±80 kg/m³. The negative contrasts near Moanalua Valley and the base of Red Hill Ridge are consistent with the presence of relatively thick layers of less dense material such as colluvium, alluvium, saprolite, or altered basalt. The high \( \Delta \rho \) at the base of Moanalua Ridge is consistent with denser structure such as a shallower basalt basement overlain by thinner sediment/saprolite. The density excess below Aliamanu Crater all but negates the possibility of a deeply protruding diatreme of low-density tuff material. Instead, it is more likely that the tuff material is relatively thin, and is underlain by crust that is slightly denser than the average of the area, perhaps due to the presence of low-porosity basalt, a small amount of intrusive rock, or a combination of the two. Mantle xenoliths present in
tuff material [e.g., Jackson and Wright 1970; Keshav et al. 2007], would also tend to elevated densities. If these higher-than-average densities are associated with lower porosity and is less conductive to groundwater flow, then the rock beneath Aliamanu Crater could inhibit, or be a partial barrier, to groundwater flow. That said, volumetrically sparse fractures in basalt can have a small effect on the average density over length scales of hundreds of meters, but can lead to strong spatial heterogeneity or anisotropy in hydraulic conductivity [Hunt 2004].

5. Future Work

This study demonstrates the utility of using gravity anomaly surveys as a tool in hydrogeologic assessments. We have identified areas underlain by denser geologic features which, due to the greater density, likely represent barriers to groundwater flow along expected inland-to-coastal (mauka-to-makai) pathways. We conclude that the spatial variations found in the RBA and $\Delta \rho$ should be viewed as reference maps of the course-scale material heterogeneity in the region. These results must be integrated with other constraints provided by geological or geophysical observations, as well as water well data for understanding groundwater flow paths. The results of this study may also be used to motivate and design targeted surveys using other geophysical technologies—such as electrical, magnetotelluric, and/or seismic methods—for delineating more detailed structure, especially the variation with depth, and ultimately to improve upon or test quantitative models of groundwater flow.

The survey was prompted by groundwater anomalies in the Red Hill area including a generally flat water table (NAVAC, 2018), unexplained high groundwater elevations, and contrast in groundwater chemistry over very short distances. The gravity and groundwater data all indicate that the current state of knowledge of the hydrogeology around the SLTRC is only preliminary. As part of the Investigation of Groundwater Flow Paths in South-Central and Southeast Oahu (DOH reference number SDWB-18-001-RW), the groundwater data (chemistry and water level) will be spatially correlated with the gravity data to more concisely draw inferences on how the subsurface geology may be affecting groundwater flow paths.

A priority was placed on the area of Salt Lake Tuff Complex due to its proximity to the Red Hill and Moanalua Ridges, Red Hill Bulk Fuel Storage Facility, and the delineated boundary between the Honolulu and Pearl Harbor Aquifer Sectors. Groundwater recharged in the upland recharge areas must also pass beneath other tuff rings including the Makalapa Crater, Akulikuli Vent, and Wiliki Cone (Pankiwsky, 1972) to reach the expected coastal discharge areas along the eastern shores of Pearl Harbor. Future geophysical surveying should expand to include the entire region covered by tuffs in the Kalihi, Moanalua, Red Hill, and Halawa areas; as well as apply other geophysical technologies, such as seismic and/or electrical methods, to validate, refine, and expand upon the conclusions of this study.

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