BOUGUER GRAVITY ANOMALY MAP AND DATA OF TIMPANOGOS ROCK GLACIER, UTAH

by

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INTRODUCTION

In arid regions, like much of the American West, alpine ice is a vulnerable buffer against drought, providing freshwater to streams in the summer and fall. Rock glaciers and other periglacial landforms are common in many of Utah's mountain ranges. Yet, despite their abundance, little is known about how much ice is buried beneath their rock carapaces. As a first step to predicting the future water resources stored in Utah rock glaciers we need to document where and how much ice currently exists.

This Data Series publication contains a map and data of the Bouguer gravity anomaly over the Timpanogos Glacier and the adjoining area (Figure 1). This rock glacier is located in the Emerald Lake Cirque east of Mount Timpanogos in the Wasatch Range of Utah. Bouguer gravity anomalies reflect variations in density of subsurface material. Low gravity values indicate lower densities, and for this map we interpret low density anomalies as the presence of subsurface ice. We chose Timpanogos Glacier because of the ease of accessibility for our research team and the CG-6 relative gravimeter device we used to collect data.

Gravitational anomalies have been commonly used to map depth to bedrock in sedimentary basins (e.g., Abbott and Louie, 2000). The mapping of the thickness of alpine glaciers is less common, often due to the difficulty of making gravity measurements across glacier surfaces. The maps and data presented below highlight the data and methods of this effort which was funded by the U.S. Geological Survey EDMAP program.

METHODS

To create this map, we collected gravity and position information at 232 locations on and around the rock glacier (Figure 2). Gravity data were collected in fall 2024 using a Scintrex CG-6 relative gravimeter (uncertainty of ~5 μGal; 1 μGal = 10^{-8}m/s^2). Measurements on the rock glacier were collected in a grid with an approximate spacing of 25 meters, whereas measurements adjacent to the rock glacier were collected where the terrain allowed for the gravimeter to be properly leveled. Measurements taken to the north of the rock glacier were taken in a cross pattern at a spacing of 25 meters to help determine the reduction density used in the gravity corrections. Station locations were measured in NAD83 (2011) datum using Trimble and Emlid real-time kinematic (RTK) GNSS receivers (uncertainty of ~1.5 cm). A base-rover setup was used and measurements were averaged over 15 seconds. An RTK setup was used because of the importance of obtaining accurate elevation measurements to reduce the raw gravity data to Bouguer anomaly.

Relative gravity measurements were corrected for tides (following the methods of Tamura et al., 1991), instrument drift, and were converted to absolute values relative to a base station measurement taken by an FG-5 absolute gravimeter at the University of Utah. These absolute gravity measurements were then reduced to Complete Bouguer anomalies by applying free-air, latitude, slab, curvature, and terrain corrections with the GTeC software package developed by Cella (2015), using a reduction density of 2.67 g/cm^3.

GTeC uses the recorded station elevations for the free-air, normal gravity, and Bullard (A ([slab], B [curvature], and C [terrain]) corrections, and uses the recorded station latitude for the latitude correction. For the terrain correction, we prepared five zones of digital elevation models (DEMs) using publicly available data from the Utah Geospatial Resource Center (UGRC). These zones were all centered on the study site, nested within each other with the highest resolution and smallest extent DEM covering just the area of the Timpanogos Cirque (zone 5) and the largest and coarsest DEM covering nearly the entire state of Utah (zone 1). This progressive coarsening in resolution away from the data points is justified due to the inverse-square relationship between mass-to-sensor distance and the magnitude of the gravitational field. The chosen radius and resolution of each of the five zones is shown in Table 1 below. The outer limit of curvature and terrain corrections was set to the widely accepted standard of 166.735 km (e.g., Nowell, 1999), however, there is no established standard for the radii of the four smaller zones. These radii and resolutions are instead chosen based on the resolution of available digital elevation data as well as feasibility due to computational limits. Gravity studies typically decrease the resolution of the terrain data for points farther away from the measurement location (e.g., Guglielmetti and Moscariello, 2021; Sgattoni and Castellaro, 2021; Saibi et al., 2022), but there is not a standard method for doing so because the calculation is site dependent. For example, in areas with greater topographic relief, higher resolution terrain data may be required. Another consideration in choosing zone resolutions is that the GTeC software requires that each zone's resolution be an integer multiple of the next smaller zone's resolution. We used the highest resolution terrain data that was available for the innermost zone (0.5 m resolution, within 60 m of the gravity station). The 0.5-m resolution data used was bare Earth lidar data (UGRC), which is not available at this resolution throughout the entire study region. From the innermost zone, we successively decreased the resolution of the terrain data. We performed multiple sensitivity tests to determine the radius and resolution of the terrain data for each successive zone outward that

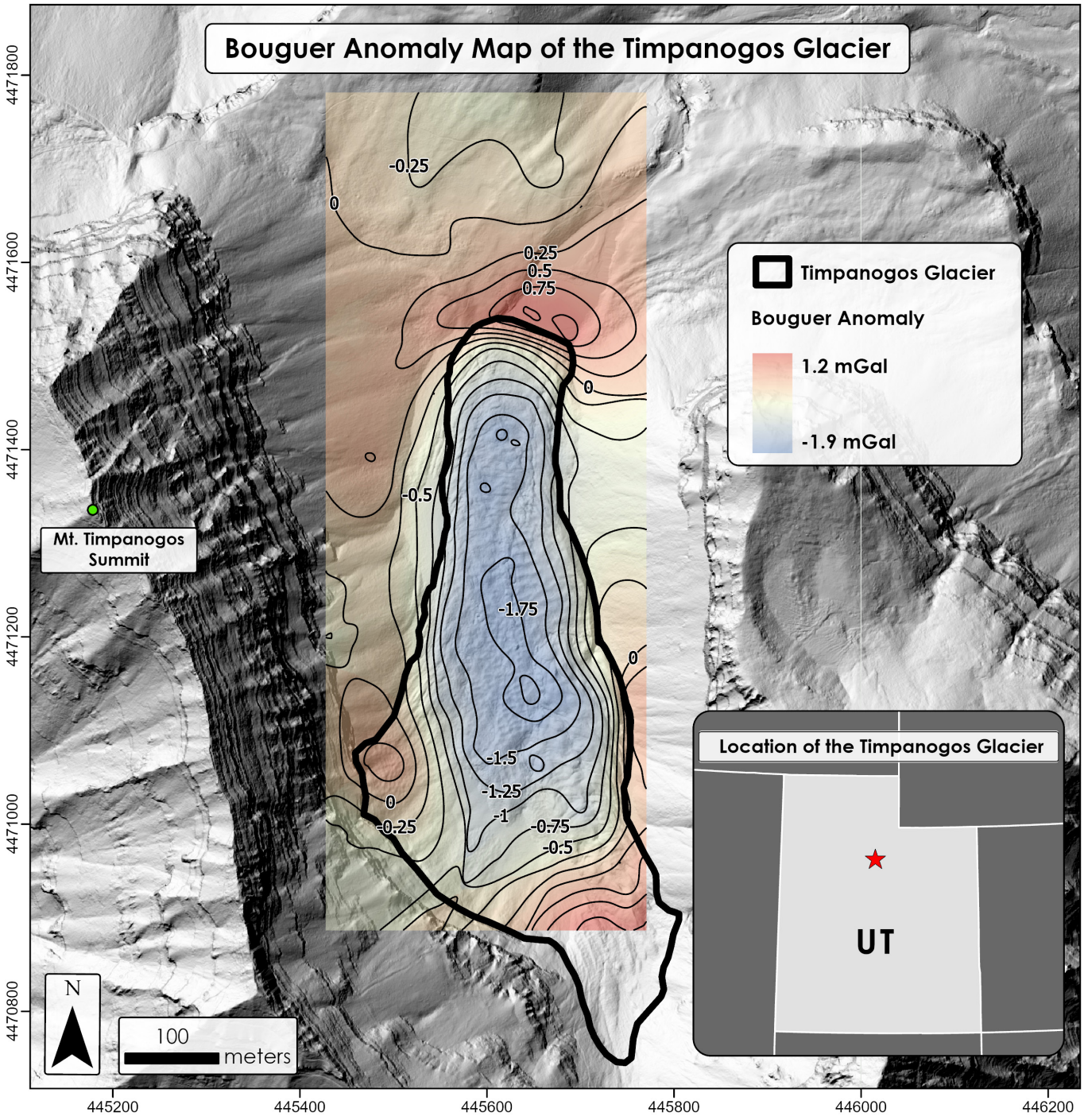

Figure 1. *Bouguer gravity anomaly map of Timpanogos Glacier and adjoining area.*

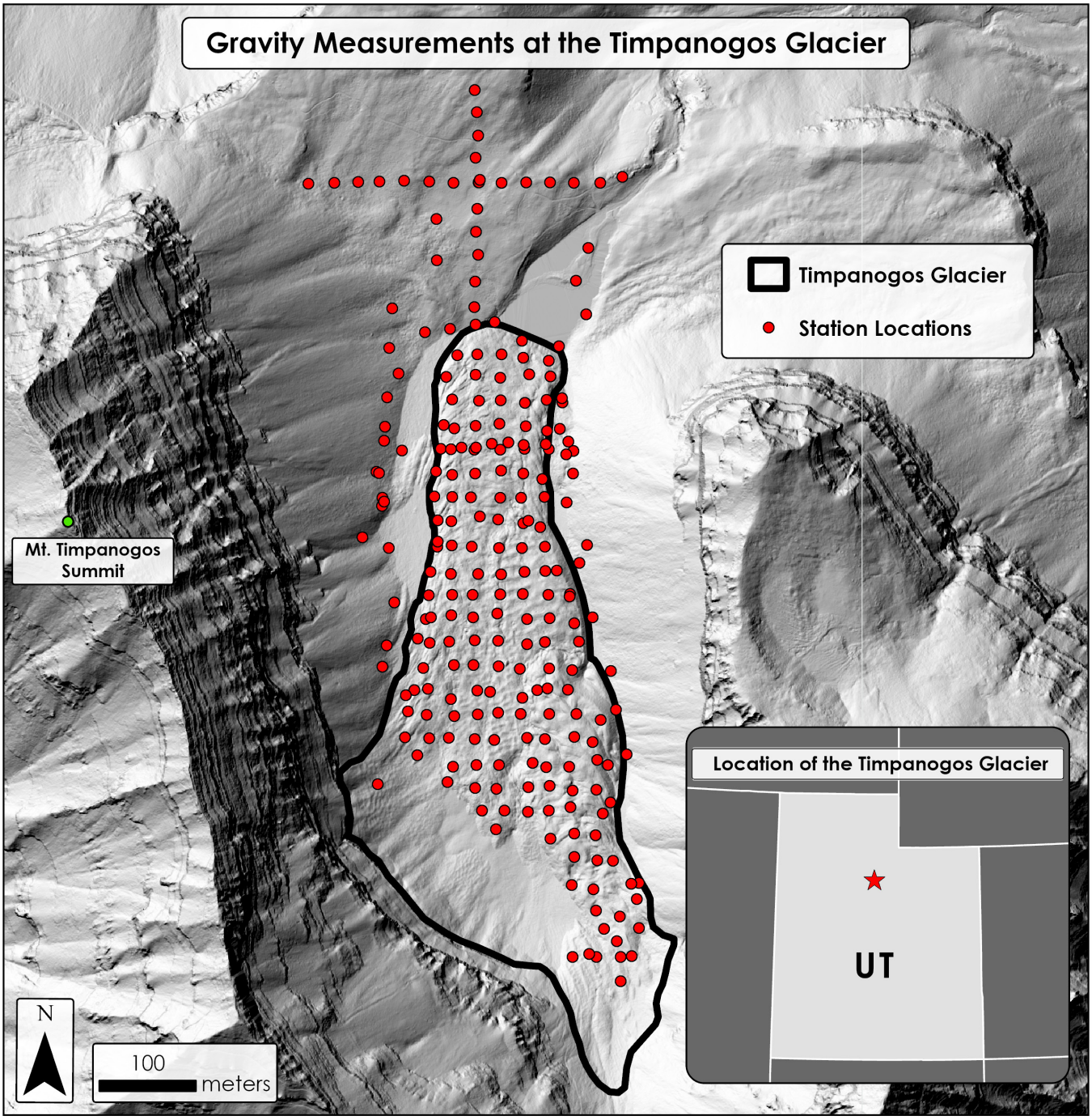

Figure 2. *Gravity measurement locations over the Timpanogos Glacier and adjoining area.*

Table 1. *GTeC Zone Parameters.*

Zone	Radius (m)	Resolution (m)
1	166,735	1,280
2	18,000	80
3	900	10
4	180	5
5	60	0.5

provided an answer without significant change from using the previous zone's resolution. For GTeC's computation of the two innermost zones, we selected the GBOX formula, developed by Blakely (1995), which is used for the three outermost zones by default. More details on how GTeC computes each correction can be found in Cella (2015).

The regional gravity anomaly was computed and removed by fitting a 2-D polynomial of order 2 in both the north-south and east-west directions, which was subtracted from all Bouguer corrected measurements. Finally, these 232 Bouguer anomaly values were interpolated onto a 1-m x 1-m grid by Kriging interpolation using a spherical covariance function in ArcGIS Pro.

BOUGUER GRAVITY RESULTS

Map contours are represented at 0.25 mGal intervals with a semi-transparent colormap overlay, where low gravity anomalies are more blue and high gravity anomalies are more red. The approximate boundary of the rock glacier, created by tracing the boundary of the feature in a DEM hillshade, is outlined in black. The underlying hillshade was made using 0.5-meter resolution elevation data from the UGRC. Around the main body of the rock glacier, the hillshade outline follows the change in steepening at the edges of the landform typical of periglacial features. In the rooting zone of the rock glacier, the hillshade outline reflects the approximate start of deposits that could contain ice based on morphology and field observations.

The map depicts a gravity low that follows the shape of the glacier between roughly 447100 and 447500 meters Northing. This low anomaly ranges from -0.5 to -1.9 mGal and is lowest along the centerline of the glacier. The southwestern and southern parts of the glacier likely show a high gravity anomaly due to the interpolation of sparse data rather than a lack of subsurface ice. These areas of the cirque are composed of steep talus or were covered in snow that persisted from the previous winter, which hindered access for gravity measurements.

DATASET DESCRIPTIONS

The Appendix contains three datasets (A1, A2, A3) which include gravity data for the Timpanogos Glacier at four stages in the gravity reduction process: raw measurements, non-regionally-corrected Bouguer anomaly, regionally-corrected Bouguer anomaly, and Interpolated Bouguer anomaly. The latitudes/northing, longitudes/easting, and elevations in all four datasets are in the NAD83 (2011) datum.

Dataset A1, labeled "A1 – 2024 Timpanogos Relative Gravity Measurements," contains the 309 raw relative gravity measurements taken by the CG-6 gravimeter at the Timpanogos cirque and the University of Utah base station in fall 2024. We provide these raw measurements to allow comparison with newer data collected in future gravity studies of this area.

Dataset A2, labeled "A2 – 2024 Timpanogos Bouguer Anomaly," contains the 232 gravity measurements that have been referenced to absolute gravity, corrected for tides and instrument drift, and reduced to Bouguer anomaly using the GTeC software package. It also contains the measurements that have been corrected for the regional gravity trend.

Dataset A3, labeled "A3 – 2024 Timpanogos Interpolated Bouguer Anomaly," is a spherical Kriging interpolation of the regionally corrected Bouguer anomaly, which was used to create Figure 1. The point data were interpolated onto a grid of 1-m x 1-m resolution that matches the extent of the station locations. The ArcGIS Pro spherical Kriging function used parameters as follows: nugget = 0, partial sill = 0.35, major range = 130. These parameters were determined by calculating a semi-variogram of the data prior to running the interpolation.

EXPLANATION OF DATASET FIELDS

Dataset A1 – 2024 Timpanogos Relative Gravity Measurements

Station Name	Name of measurement location. FASB is University of Utah absolute gravity station. ABGS is a base station at the Aspen Grove trailhead. TGBS is the base station near the glacier used for drift corrections. TGX_Y are measurements made in the Emerald Lake Cirque where X is the survey number and Y is the measurement number of that survey.
Date (UTC)	UTC date of the gravity measurement.
Time (UTC)	UTC time of the gravity measurement.
CorrGrav (mGal)	Two-minute averaged relative gravity measurement (milliGal) that has been corrected for instrument tilt and sensor temperature.
StdDev (mGal)	Standard deviation of the 120 measurements taken over the two-minute period (milliGal). This value is calculated automatically by the gravimeter.
StdErr (mGal)	Standard error of the averaged relative gravity measurement (milliGal). This value is calculated automatically by the gravimeter.
RawGrav (mGal)	Two-minute averaged relative gravity measurement (milliGal) that has not been corrected for instrument tilt and sensor temperature.
X Tilt (arcsec)	Instrument tilt in the X-axis (arcseconds).
Tilt (arcsec)	Instrument tilt in the Y-axis (arcseconds).
SensorTemp	Deviation of the sensor temperature from the set point (milliKelvin).
TiltCorr (mGal)	Tilt correction applied by the instrument (milliGal).
TempCorr (mGal)	Temperature correction applied by the instrument (milliGal).
MeasurDur (s)	Measurement duration (seconds).
Latitude	Latitude of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).
Longitude	Longitude of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).
Elevation (m)	Elevation (meters) of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

Dataset A2 – 2024 Timpanogos Bouguer Anomaly

Name	Name of measurement location. TGX_Y are measurements made in the Emerald Lake Cirque where X is the survey number and Y is the measurement number of that survey.
Lon	Longitude of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

Lat Latitude of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

Elev Elevation (meters) of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

bouguer_anomaly_mgal

Gravity measurement that has been referenced to absolute gravity, corrected for tides and instrument drift, and reduced to Bouguer anomaly (milliGal) using the GTeC software package.

bouguer_anomaly_mgal_regional_correction

Bouguer anomaly (milliGal) with regional gravity trend removed.

Dataset A3 – 2024 Timpanogos Interpolated Bouguer Anomaly

easting Easting (meters) of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

northing Northing (meters) of the measurement location as taken by the RTK GNSS. Spatial reference is NAD83 (2011).

Bouguer_anomaly_mGal

Bouguer anomaly value (milliGal) interpolated from the 232 regionally corrected measurements using a Kriging interpolation with a spherical covariance function.

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APPENDIX

Datasets

https://ugspub.nr.utah.gov/publications/data_series/ds-4/ds-4a.zip