Open-Source Gravity Reduction Workflows for Geothermal Resource Assessment

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ABSTRACT

Potential-field geophysical data such as gravity can enhance understanding of geothermal resources at all stages of the resource life cycle, including assessment, exploration, development, and monitoring, and at multiple scales, from the reservoir scale to regional scale. However, to make gravity data useful for geothermal resource characterization, several processing steps are required to isolate the effects of density variations in the Earth's crust to enable the identification of structural features associated with geothermal resources. Although this process is well-established, standard computational implementations for processing gravity data that are FAIR (Findable, Accessible, Interoperable, and Reproduceable) are still lacking. This paper details ongoing efforts at the U.S. Geological Survey (USGS) to develop a standard set of open-source Python tools for gravity data reduction that align with the FAIR principles. This workflow makes use of existing open-source tools for geophysical data processing with the goal of maximizing opportunities for rapid improvements, interoperability, and adaptability to other types of geophysical data.

1. INTRODUCTION

Potential-field geophysical data, such as gravity and magnetic data, support understanding of geothermal resources. Gravity data are widely used at the reservoir scale for determining the spatial extent of potential reservoirs, identifying key geologic structures that control reservoir behavior and defining drilling targets (e.g., Omollo and Nishijima, 2023). At the regional scale, variations in the gravity anomaly can be used to identify favorable structural settings where undiscovered geothermal resources may be present (e.g., Guglielmetti and Moscariello, 2021). Additionally, temporal gravity data can be used to monitor changes in reservoir water balances over time, providing reservoir managers with critical information about drawdown and recharge rates, as well as phase changes within the reservoir (e.g., Phelps and others, 2018). Therefore, the acquisition of new gravity data is often motivated by the need for both monitoring and assessing geothermal resources.

However, before it can be used for geothermal resource characterization, gravity data must undergo a series of processing steps that reduce it to an anomaly value that represents the effect of density variations in the Earth's crust. This reduction process removes several effects which influence the raw observed gravity values, such as the mass of the Earth, elevation above sea level, tidal effects, effects of terrain in the vicinity of the measurement, and the effects of isostatic crustal compensation. Although the reduction process is well-established, implementations for computing these data vary widely among practitioners, and there is no standard approach for software implementation, particularly one that is open-source and freely available. The USGS publishes large amounts of publicly accessible gravity data, but developing reproduceable workflows for identifying gravity anomalies remains a challenge. This paper outlines ongoing efforts at USGS to publish open-source Python tools for gravity data reduction that align with the FAIR (Findable, Accessible, Interoperable, and Reusable) guiding principles (Barker and others, 2022). These tools use core scientific Python packages and leverage existing tools from the Fatiando a Terra package (Uieda and others, 2013) for geophysical processing steps. By leveraging existing tools, this modular approach ensures that the workflow can rapidly benefit from improvements to underlying packages as they become available. Additionally, this approach helps ensure interoperability with other software development projects that rely on the same common set of tools (Heagy and others, 2024).

2. BACKGROUND

In recent decades, the amount of computational resources available to geophysicists has rapidly increased, and so has the number of software tools for conducting large scale modeling of geophysical potential field anomalies. Many of these recent tools are being implemented in the Python programming language, which has become widely used throughout the geophysical community (Krieger and Peacock, 2014) and has hosted the development of an ecosystem of open-source geophysical modeling tools (Heagy and others, 2024).

The open-source project Fatiando a Terra (Uieda and others, 2013) provides a common Python API (application programming interface) for students and researchers to use geophysical methods. The Fatiando a Terra project has developed into several sub-projects, including Harmonica (Uieda and others, 2020, 2021), which provide tools for modeling geophysical potential fields. Other sub-projects include Boule (Uieda, 2019), which defines reference ellipsoids for calculating normal gravity of the earth and other planetary bodies, and Verde (Uieda, 2018), which offers spatial data processing, gridding, and interpolation tools. SimPEG (Cockett and others, 2015) is another Python library, separate from Fatiando a Terra, which provides a collection of tools for forward modeling and inversion of many types of geophysical data including gravity, magnetics, and electromagnetics. More recently, collaboration with SimPEG has resulted in an additional sub-project of Fatiando a Terra called Choclo (Soler and Uieda, 2022), which provides a common engine for forward modeling gravitational and magnetic fields of simple geometries and underlies the forward modeling tools available in Harmonica and SimPEG.

Further, standards for data processing have been evolving to help develop global open-source data standards for geophysical data. An example of this is GSpy (Foks and others, 2022; James and others, 2022) which provides scalable data containers for geophysical data of all types.
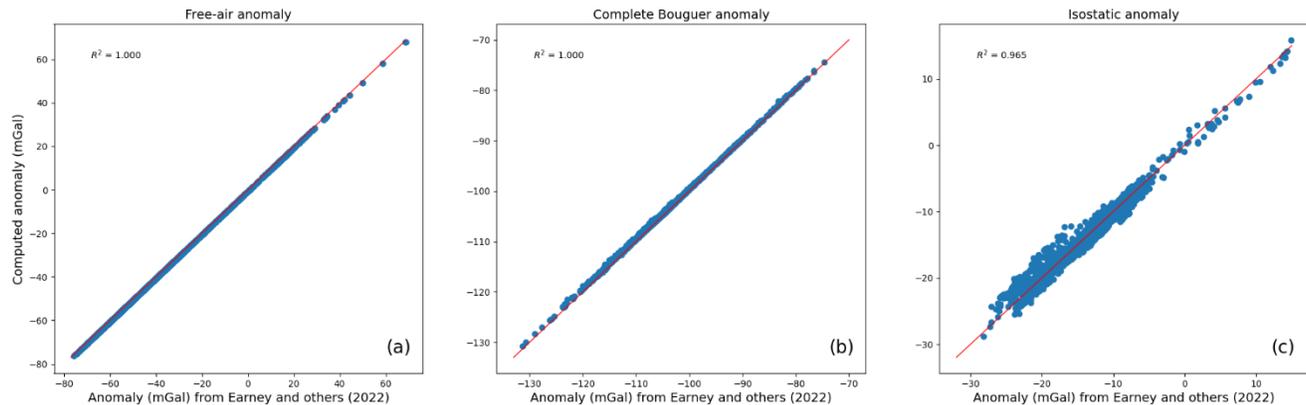

Figure 1: Shows differences in the results between anomalies computed using this workflow and the those published by Earney and others (2022): (a) free-air anomaly; (b) Complete Bouguer anomaly; (c) isostatic anomaly.

3. CASE STUDY

I demonstrate open-source gravity reduction workflows using geophysical data collected on the lands of the Confederated Tribes of the Umatilla Indian Reservation (UIR) in northeast Oregon (Earney and others, 2022). These data were collected in 2017 and 2020 to characterize the structural setting of possible geothermal resources in the UIR and to identify favorable drilling locations. The dataset includes gravity data collected at 1,820 stations located throughout the UIR. The gravity data includes values for observed gravity, field terrain correction, free-air anomaly, total terrain correction, complete Bouguer anomaly, and isostatic anomaly. In this case study, I focus on calculating the isostatic anomaly, because this is the value that Earney and others (2022) use for calculating horizontal gradient maxima in order to identify structural features associated with geothermal resources. Note that I focus on developing workflows that use observed gravity as a starting point; that is, I do not focus on calculating observed gravity from the field measurements.

As noted by Blakely (1995), the first step in gravity reduction is to remove the gravitational attraction of the reference ellipsoid. This attraction is also known as the "normal gravity". The next step is to remove the effect of elevation above sea level or the "free air" correction. Both steps can be computed simultaneously using the Boule library (Uieda, 2019). The next step is to compute the "simple" Bouguer correction, which approximates the effect of all mass between sea level and the observation point assuming the mass is equivalent to an infinitely extensive horizontal slab of homogeneous density. The Harmonica library (Uieda and others, 2020, 2021) can be used directly to compute the simple Bouguer anomaly.

The next step is to compute terrain corrections, which are subtracted from the simple Bouguer anomaly to obtain the complete Bouguer anomaly. This is done at each station using a series of five nested grids: (1) a 1/3 arc-second (approximately 10m) grid extending to 895m from the station; (2) a 1 arc-second (approximately 29m) grid extending from 895m to 2.7km from the station; (3) a 3 arc-second (approximately 88m) grid extending from 2.7km to 5.2km from the station; (4) a 30 arc-second (approximately 730km) grid extending from 5.2km to 28.8km from the station; and (5) a 10km grid extending to 166.7km from the station. All distances refer to radial distances from the station. Terrain corrections were computed by modeling the terrain as a series of vertical prisms extending to sea level. This scheme of nested grids, based loosely on Grand and others (2004), satisfies recommendations for standard gravity data reduction procedures proposed by Hinze and others (2005), which recommend using high-resolution DEM data (e.g., 10m and 30m resolution) to a distance of 895m from the station, and coarser resolution DEMs out to 166.7km from the station.

The calculations were performed in Harmonica which implements the methods for calculating the gravitational attraction of prisms published by Nagy and others (2000, 2002) and Fukushima (2020). Field terrain corrections were added to the computed terrain corrections to capture the effect of topography in the immediate vicinity of the measurement location, although field terrain corrections are not available for all measurements. The 1/3 arc-second DEM was obtained from the USGS National Map (USGS, 2024; USGS 2025) and the 1- and 3 arc-second DEMs were obtained from the void-filled Shuttle Radar Topography Mission (SRTM) elevation datasets (USGS, 2018b). The 30 arc-second DEM was obtained from the Global 30 Arc-Second Elevation Dataset (GTOPO30) (USGS, 2018a), which was also used to obtain the 10km DEM used in the outermost grid by downsampling.

Computing the isostatic anomaly is the final step. This is achieved by estimating the Moho depth from the topography using the Airy hypothesis; that is, isostatic compensation assumes homogeneous crustal density that is compensated by variations in the depth of the crust-mantle interface (Blakely, 1995). Once this Moho depth has been computed, I calculate the gravitational effect of the variations in the crustal density by assuming that the upper mantle has a density of 600 kg/m^3 greater than the crust and that variations in crustal thickness are relative to a reference depth of 30km. Isostatic correction is calculated by first estimating the Moho depth using Harmonica and calculating the gravitational attraction of this density contrast between continental crust and upper mantle to a distance of 166.7km

from the station location. A constant offset of 20 mGal was added to this isostatic correction to approximate the isostatic effects beyond the distance of 166.7km.

A proof-of-concept to test the utility of the workflow for geothermal resource assessment is determining whether this workflow can be used to identify lineations associated with potential structural controls on geothermal resources. Local horizontal gradient maxima points, or "maxspots", are a widely used tool to identify potential structural features, such as faults, contacts, intrusions, or dikes, which may control fluid pathways and favorable features for geothermal resources. To test the outputs of the workflow for this application, I use the Python package pymaxspots (Cronkite-Ratcliff and Athens, 2025) to identify maxspots along the gradients of the interpolated grid.
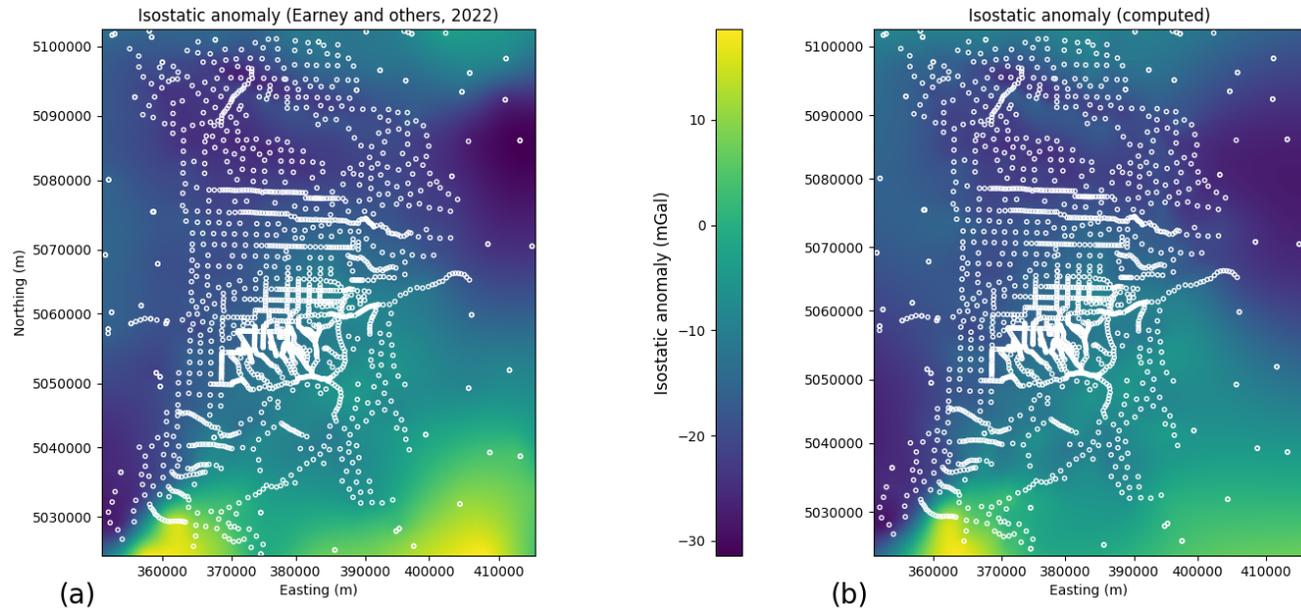

Figure 2: Comparison of gridded isostatic anomaly published by Earney and others (2022) (a) and with the anomaly computed using the open-source workflow (b). White circles show the locations of gravity measurements.

4. RESULTS AND DISCUSSION

Preliminary results obtained with this workflow show that open-source tools can be used to reproduce the gravity anomaly values from Earney and others (2022). Using the methods described above, the free-air anomaly can be reproduced almost exactly with an R-squared of over 0.9999 (Fig. 1a). The complete Bouguer anomaly can be reproduced closely with an R-squared of over 0.9996 (Fig. 1b). The differences between the CBA computed from the workflow and that from Earney and others (2022) include a constant offset of < 1 mGal, leaving a total standard deviation of differences of approximately 0.16 mGal. This may represent the differences between the approach of Earney and others, who used the terrain correction method of Plouff (1977), and the one implemented herein. It should be noted that Earney and others relied solely on field terrain corrections to represent terrain effects near each station, but field terrain corrections were not available at all stations.

The isostatic anomaly can be reproduced with an R-squared of approximately 0.965 (Fig. 1c) and a total standard deviation of differences of approximately 1.15 mGal. However, the method employed in this workflow does not include a more detailed representation of isostatic effects beyond 166.7km from the stations, including bathymetry and the ellipticity of the earth out to the maximum range of 180 degrees as recommended by Hinze and others (2005). The resolution of 10km used to calculate the Moho depth may also be a source of error in the computation of the isostatic anomaly for this case.

A comparison between the isostatic anomaly as estimated by the open-source workflows and those published by Earney and others (2022) are shown in Fig. 2. This figure shows that the overall anomaly looks qualitatively similar to the published grids for complete Bouguer anomaly and isostatic anomaly. Gridding was performed using the 2D spline method of Sandwell (1987) implemented in Verde.

Fig. 3 shows results from computing the maxspots on the gridded anomaly, comparing results from the workflow presented herein (Fig. 2a) to that published by Earney and others (2022) (Fig. 2b). Note that the maxspots shown in Fig. 3 were computed from the gridded isostatic anomaly published by Earney and others (2022) using the pymaxspots package. Although the maxspots shown in Fig. 3 may differ slightly from the maxspots published by Earney and others (2022), they provide a more direct comparison to the results from the workflow presented herein; because the same software tool is used to compute the maxspots on each gridded isostatic anomaly, the difference in the results shows the effects of differences between the processed anomalies. Maxspots from both gridded anomalies show that many of the same linear features are automatically identified in both instances, especially in areas of high data density. Where differences in the computed maxspots exist, they are mainly located in areas of low data density.
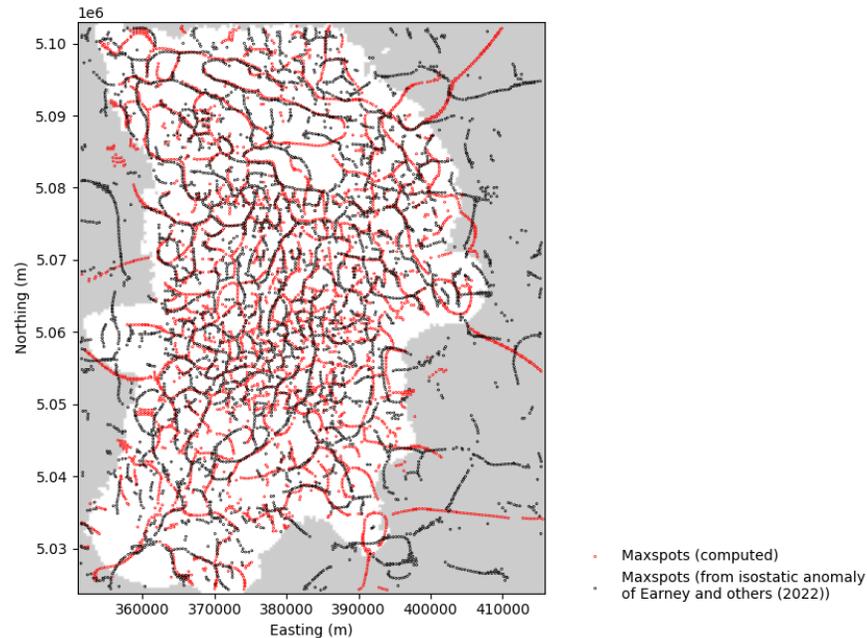
Figure 3: Comparison of maxspots locations computed from the gridded isostatic anomaly using the open-source workflow (red points) with those computed from the gridded isostatic anomaly published by Earney and others (2022) (black points). Areas with high station density (defined as having at least 10 stations within 5km) are located in the white portion of the figure, whereas areas with fewer than 10 stations within 5km are overlain with gray.

5. CONCLUSION

This paper highlights ongoing work at the USGS to develop workflows for gravity data processing that use existing open-source tools to align with FAIR standards. The case study in this paper demonstrates that by using existing tools, workflows can be constructed that produce similar results to published datasets and can be used to identify structural features of interest for geothermal resource assessment. The modular approach presented herein can be adapted for other types of geophysical data, such as magnetic data, which is often used together with gravity data for geothermal resources assessment. Feasibility of adapting the workflow for magnetics is aided by the fact that the Fatiando a Terra package already includes tools for processing magnetic data.

Despite recent growth in the availability of open-source tools for geophysical data processing, there remain several challenges to achieving the goal of FAIR compliant workflows for gravity data reduction: (1) existing tools often do not have comprehensive coverage of datasets required by all users, such as vertical datums and reference ellipsoids; (2) existing tools currently lack standard procedures for the most complex computational steps in the gravity data reduction process, particularly terrain corrections and isostatic corrections; (3) in addition to gravity reduction steps themselves, gravity data processing involves steps which are empirical in nature but nevertheless have a substantial outcome on geologic interpretations. These challenges indicate areas where future software development could focus to maximize adoption among the geophysics community and best align with FAIR principles.

Although the current focus of these efforts is on development, planning software development efforts can ensure that end users' needs are met. Compared to developers, end users prioritize having a consistent and user-friendly interface, interoperability, technical support and training, and a user community to share experiences (McGaughey and others, 2025). Making software easy to use can therefore maximize adoption among potential end users.

DISCLAIMER

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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