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Enhancing interpretation of geophysical models using petrophysical logging

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SUMMARY

Direct petrophysical measurements, such as density and magnetic susceptibility, may prove useful in improving the interpretability of geophysical models. With measurements becoming more abundant and the capability to measure petrophysical properties across the entirety of drill core, there is a need to explore to what extent such measurements may enhance or improve physical property models derived from geophysical inversion.

Towards that goal, we seek to explore and develop a workflow for using petrophysical data in 3D potential-field inversion. The Stavely Arc region is selected as a study area where drill core petrophysics and regional potential-field data are available. We apply 3D gravity inversion to a subset of the region and use the available density measurements as constraints in the inversion. Results indicate that using petrophysical measurements in inversion may help to further constrain the recovered physical property values in areas away from the borehole locations.

Key words: density, petrophysics, geophysics, gravity, inversion

INTRODUCTION

Utilising drill hole petrophysical data for mineral exploration applications has the potential to improve our understanding of the subsurface and assist with clarifying interpretations from other geoscientific methods. We aim to demonstrate how interpretation of geophysical models derived from potential field data may benefit from having petrophysical data measured along core. While there are various ways to integrate petrophysical and geophysical measurements, a common way is to use the petrophysical data to identify a reasonable range of density and susceptibility values to use in forward modelling.

The use of petrophysical knowledge to interpret physical property models from geophysical inversion has been performed in various ways. Williams and Dipple (2007) use measured physical properties on drill core to map mineral abundance using 3D density and susceptibility models from geophysical inversion. Measured petrophysical properties have been used to understand the nuance of geophysical anomalies associated with alteration patterns via 3D forward modelling (Chopping, 2008). Goodwin and Skirrow (2019) use recovered models from physical property inversion as a proxy for alteration zones in mapping IOCG alteration.

We seek to develop a workflow that uses the spatially located full extent of logged petrophysical data in conjunction with 3D physical property inversion. Physical property inversion provides a way to highlight the benefit of using petrophysics, as the petrophysical values are direct measurements of the physical properties we seek to recover through geophysical inversion. By comparing 3D physical property inversion with and without constraints from petrophysical data, we hope to show how petrophysical data can be utilized to enhance and improve the interpretation potential of geophysical physical property models.

To explore and develop this workflow, we invert gravity data within a subset of the Stavely region and use available measurements of density along drill core to perform constrained inversion. We use the petrophysics as logged along the core in 3D physical property inversion.

STUDY AREA

The Stavely region in western Victoria is selected as a study area, shown in Figure 1, as both petrophysical data along drill core and geophysical data are readily available from previous collaborative projects (Skladzien et al., 2016). Through the Stavely Project a 3D geological model has been produced where statistical petrophysical data is used as prior information in potential-field forward modelling to constrain structural boundaries (Cayley et al., 2018). The petrophysical data has been used to statistically identify realistic constant density estimates for geologic units to forward model 2D gravity profiles along multiple transects. Similarly, statistics of magnetic susceptibility measurements were used to identify an acceptable range of constant values to be used in forward modelling of isolated magnetic anomalies for intrusive bodies.

Within the Stavely Project area, there are 13 boreholes (labelled in Figure 1) with petrophysical measurements along core acquired using a Geotek MSCL-S system (Skladzien et al., 2016). The density measurements along the borehole core range from 0 to 35+ samples per meter depending on the quality of the core. The interval extent of the density measurements along each drill core vary for each borehole ranging from 26 m in STAVELY10 to 469 m in STAVELY07.

The ground gravity data used (Figure 1), are a compilation of data available through GADDS (Wynn and Bacchin, 2009). There are 7246 ground gravity data locations within the study area. There is topographic relief in the south-east portion of the study area, as seen in Figure 1. The change in elevation is approximately 1 km from the south-east to the north-west region of the study area.

METHODS

UBC Grav3D software (Li and Oldenburg 1998) is used to perform 3D physical property inversion of the publicly available gravity data. The study area within the Stavely region covers approximately 160 km by 176 km.

The mesh defining the subsurface is discretised into 500 m cells in the easting and northing directions, and 25 m in the depth direction for the top 2 km followed by increasing cell sizes to a depth of 45 km. The smaller cell size in the depth direction serves two purposes. The first is to allow for representing the topographic relief in the model and the second is to allow for representation of small intervals of the borehole in the model. The boreholes are assumed to be vertical, rendering the lateral cell discretisation less important.

Within the study area used here, there are 8 boreholes (STAVELY04 through STAVELY12, excluding STAVELY08) within the core subsurface mesh and 3 boreholes in the padding cells of the subsurface mesh. In some cases, such as for STAVELY05 and STAVELY10, one or two subsurface cells represents the entirety of the measured density for a borehole. To aggregate the measured density data to a coarser resolution for use in gravity inversion, the minimum, maximum, and mean value of all density measurements within a subsurface voxel is taken to be representative of the density variations. While the lithologic units may vary within each cell, the mean value model is taken to be representative of the bulk density of the subsurface rock volume. The minimum value model is taken to be the lowest expected density value in the subsurface cell volumes and can be used as a lower bound for the expected recovered density. Similar for the maximum value model which can be used as an upper bound for the expected recovered density.

Three sets of inversions are performed. The first gravity inversion is unconstrained by the petrophysical data and is intended to serve as the baseline model for comparison to constrained gravity inversion. The second inversion uses the borehole mean value model as a reference and initial model for gravity inversion. The third inversion uses the minimum value model as a lower bound and the maximum value model as the upper bound in addition to the mean value model for the reference and initial model.

RESULTS

The gravity data are first inverted with no constraints. The unconstrained inversion allows for recovered density contrast ranging from -5 g/cm^3 to 5 g/cm^3. The recovered density contrast models, in all cases, are selected according to an L-curve criterion (Hansen, 1992). A cross section is shown through the recovered density model from unconstrained inversion in Figure 2. The cross section is selected to intersect borehole STAVELY07.

Two constrained inversion are carried out using the density measurements along the drill core at the location of the boreholes. The first uses the mean density model as both the reference and initial model. The same inversion parameters as the unconstrained inversion are used including allowing all recovered contrasts to range from -5 g/cm^3 to 5 g/cm^3.

The second constrained inversion similarly uses the mean value model from the drill core density measurements as the reference and initial model. Additionally, the minimum and maximum density values along the drill core associated with the borehole locations are used as bound constraints. This means that along the borehole, the recovered density contrast from inversion must be between the minimum and maximum density contrast values measured. Cells that do not have a borehole passing through have lower and upper bounds consistent with the previous two sets of inversions, where the recovered contrasts are allowed to range from -5 g/cm^3 to 5 g/cm^3.

Visually, there does not appear to be significant differences between the unconstrained and constrained recovered density contrast models along the cross section extracted and so are not shown. However, there are quantitative differences across the models.

The differences between these three sets of recovered density contrast models can be highlighted by subtracting the recovered density models from each other. The unconstrained density contrast model (Figure 2) is taken as the base level of information that can be extracted from the gravity data via inversion. The recovered models from constrained inversion are differenced from the unconstrained model to visualize any changes that may be present in the recovered density models arising from using the density measurements as constraints in the inversion. The differences in recovered density contrast values are shown in the panels of Figure 3.

The differences between the constrained and unconstrained recovered models are more obvious for the reference constraint (top panel of Figure 3) than for the bound constraint (bottom panel of Figure 3). Although difficult to discern in the cross section, the bound constraint model does contain a difference to the unconstrained model beneath the location of the borehole. Figure 4 shows vertical profiles from the difference models of Figure 3 along the location of the borehole where the differences in density contrast are more readily noticeable.

Figure 5 shows only the shallow values where core density measurements are available, further highlighting the difference across the three recovered density contrast models. The measured minimum, mean, and maximum values from petrophysical measurements are shown using grey lines. The mean measured density line shows the reference and initial model imposed on inversion, while the minimum and maximum density values were used in the bound constrained inversion. The unconstrained and reference constrained values are similar along the region with core constraints while the bounds constrained model is limited by the maximum measured density value. In the following section, a discussion of the implications of the differences between these models is discussed.

DISCUSSION

Comparison of recovered models from unconstrained and constrained inversion show differences in areas beneath the boreholes in both cases, and across the section in one case (Figure 3). The drill core density measurements help to constrain the near surface density contrast when used as a reference and initial model. This similarly occurs in the case where drill core density measurements are used as bound constraints (Figure 4).

The density contrast is altered to account for the constraining of the density contrast in the shallow portion of the model. As a non-unique problem, having better constraints on the near surface density contrast may assist in better resolving the density contrasts in deeper regions of the model. This could have implications for further interpretation of the physical property model in cases where, for example, the geologic features of interest lie below the borehole and direct observations of petrophysical properties are not available.

The differences here indicate that developing a workflow to incorporate petrophysical measurements with geophysical physical property inversion may be fruitful. As a first step towards that goal, this work identifies aspects that need to be further explored.

The recovered density contrast values from inversion in all three cases align most with the maximum density measurements along the core. The nature of UBC-style 3D physical property inversion relies on smoothing. Where recovery of the physical properties from geophysical inversion may be a good relative representation of the subsurface contrasts, the values may not be comparable to the directly measured petrophysical values in an absolute sense. Further, the instrument that measures the density along the drill core is calibrated and presumed to provide representative density measurements, however whether or not there is an offset between the measured density and true density, as identified in work by Chopping (2008), could also play a role in relating petrophysical measurements and geophysical physical property models.

Lastly, while the results do indicate there is a change when petrophysical constraints are used further work should be done to understand the degree to which this is important for geologic interpretation. With the extensive knowledge about the geology of the Stavely region and previous modelling efforts, further development of the workflow through comparison to existing geologic models may yield further insight into the value that petrophysical data may hold in enabling more productive use of geophysical physical property models.

CONCLUSIONS

3D physical property inversion of gravity data within the Stavely region has been performed with constraints from petrophysical measurements. Use of direct petrophysical density measurements along drill core is shown to alter the recovered density model from gravity inversion when measured density values are used as constraints in the physical property inversion. Constraining the shallow portion of a model may improve the interpretability of the physical property model as regions beneath the boreholes are better constrained.

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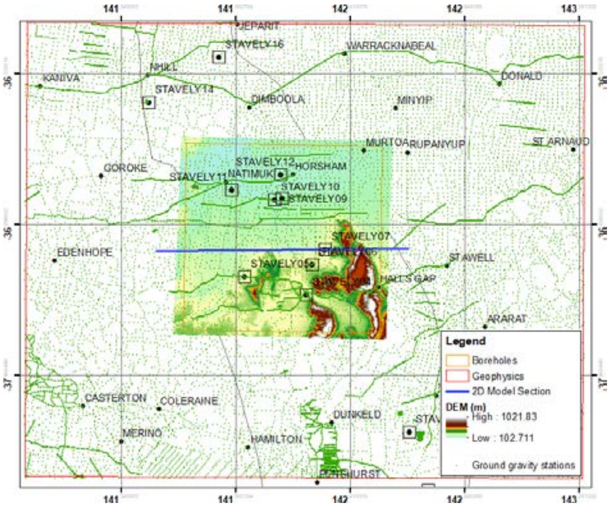


Figure 1. Location map of study area in Stavely region showing ground gravity stations used for gravity inversion (green dots), elevation, and borehole locations containing density measurements along drill core.

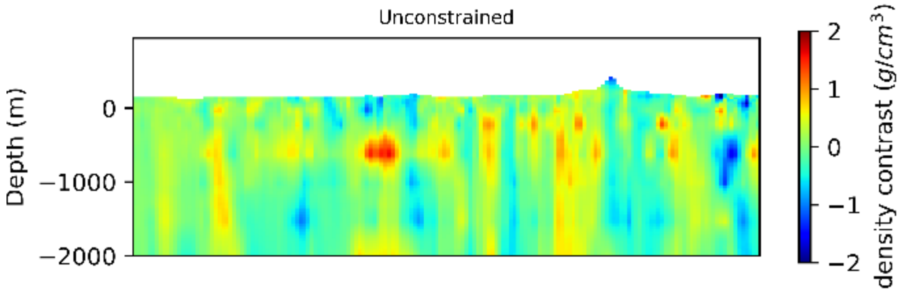


Figure 3. Cross section through recovered model from unconstrained inversion.

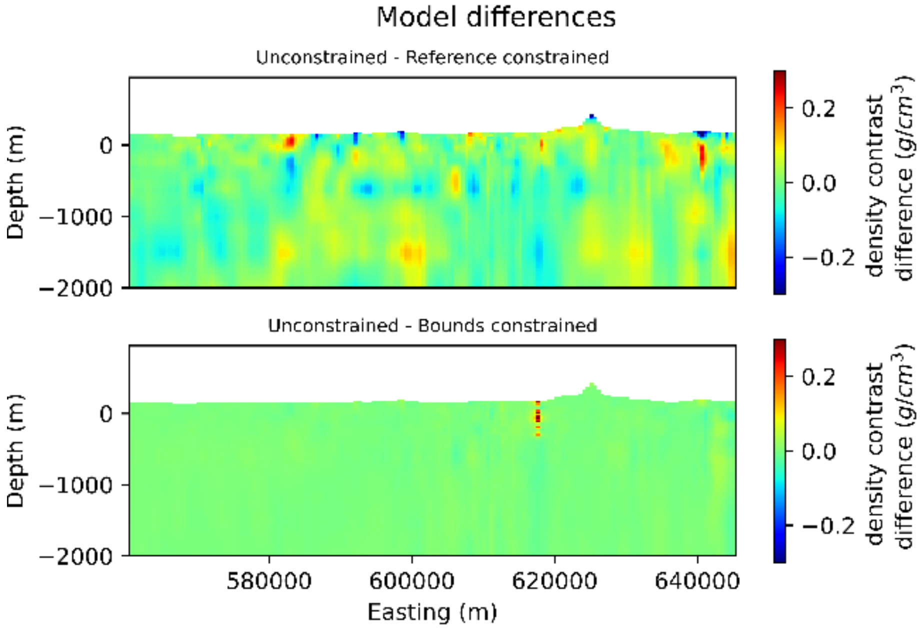
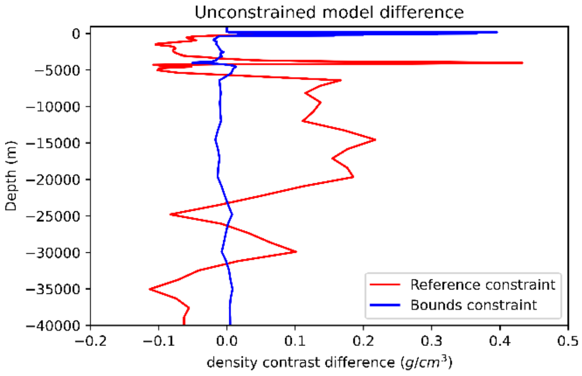


Figure 2. Cross sections through (top) difference between recovered models from unconstrained inversion and inversion using reference model constraint; (bottom) difference between recovered models from unconstrained inversion and inversion using bounds constraint in addition to reference constraint.



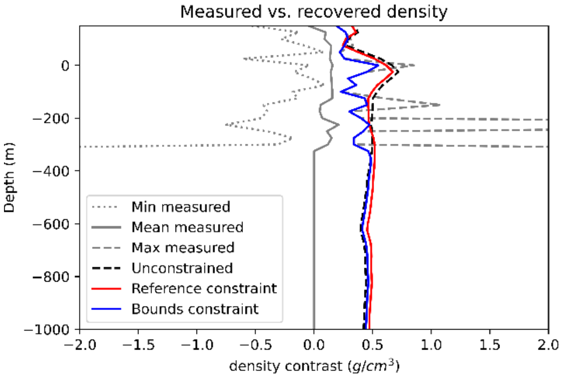


Figure 4. Vertical profile through cross section extent in Figure 3 and through entirety of modelled depth extent beneath the borehole location showing difference in density contrast values between constrained and unconstrained inversion.

Figure 5. Density contrast values along borehole from three recovered models along with minimum, mean, and maximum measured values from core (converted to density contrast using 2.67 g/cm^3).