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Incorporating Geological Constraints into Geophysical Forward Models: A Case Study from Ohaaki Geothermal Field, New Zealand

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ABSTRACT

Geophysics plays a vital role in geothermal exploration, mapping and monitoring. Gravity data are used to reveal deep geological structure and provide rock property information that help locate and characterize geothermal systems. However, the inherent ambiguity of gravity data adds uncertainty that makes modelling and interpretation more challenging. In this paper we present a workflow that reduces modelling uncertainty by incorporating geological information that constrains the gravity modelling toward a geologically interpretable result. A case study from the Ohaaki Geothermal Field, New Zealand, is presented that demonstrates how the non-uniqueness of gravity modelling is reduced by use of a geologic reference model. The workflow works seamlessly through Seequent's Leapfrog, Oasis montaj and GM-SYS™ and is applicable to potential field geophysical data from any geothermal field that has a drilling derived geological model.

1. INTRODUCTION

Using a geological model to constrain geophysical modelling helps reduce uncertainty. The geological model in turn must be robust, reflecting real data, such as those from drilling. However, borehole data are at times limited due to the high costs associated with drilling. Geologic models of areas with complex geology are often simplified based on information gathered from limited number of boreholes.

This case study shows how the confidence of the geological model can be increased by integrating ground gravity data with information from borehole lithology logs. This is be done by forward modeling the existing geological model and comparing its predicted geophysical response with the observed response in gravity data. This identifies areas of good fit and areas of poor fit. From this, updates to the geological model and further work that could decrease the model misfit and increase confidence can be proposed. To test this workflow, we focused our work on the area around the Ohaaki Geothermal Field (Figure 1).

Many studies define the Ohaaki Geothermal Field (Mroczek et al., 2016 and references therein), this study however, uses open-source data and mimics the understanding and typical uncertainty found at exploration stage. The geology of the Ohaaki area is represented by a sequence of lacustrine deposits (Huka Falls Formation), rhyolite lavas and breccias, reworked sediments, variably welded pyroclastic formations along with airfall tuffs, pumice breccias and andesites that have a more limited distribution. These volcanic and volcaniclastic units overly the Mesozoic greywacke basement (Mroczek et al., 2016).

Gravity data used in this study are from the compilation of Stagpoole et al. (2020) which were tied to New Zealand Reference Gravity Stations (https://doi.org/10.21420/96Q5-8581) and referenced to the IGSN71 gravity datum (Morelli et al., 1972) for New Zealand. Stagpoole et al. (2020) used a density of 2670 kg/m^3 for Bouguer and terrain corrections out to a radius of 120 km from each gravity observation point. The correction density represents the density of the Mesozoic greywacke basement encountered in some deep boreholes in the eastern Taupo Volcanic Zone (Wood, 1996; Wood et al., 2001; Chambefort et al., 2016; Milicich et al., 2020).

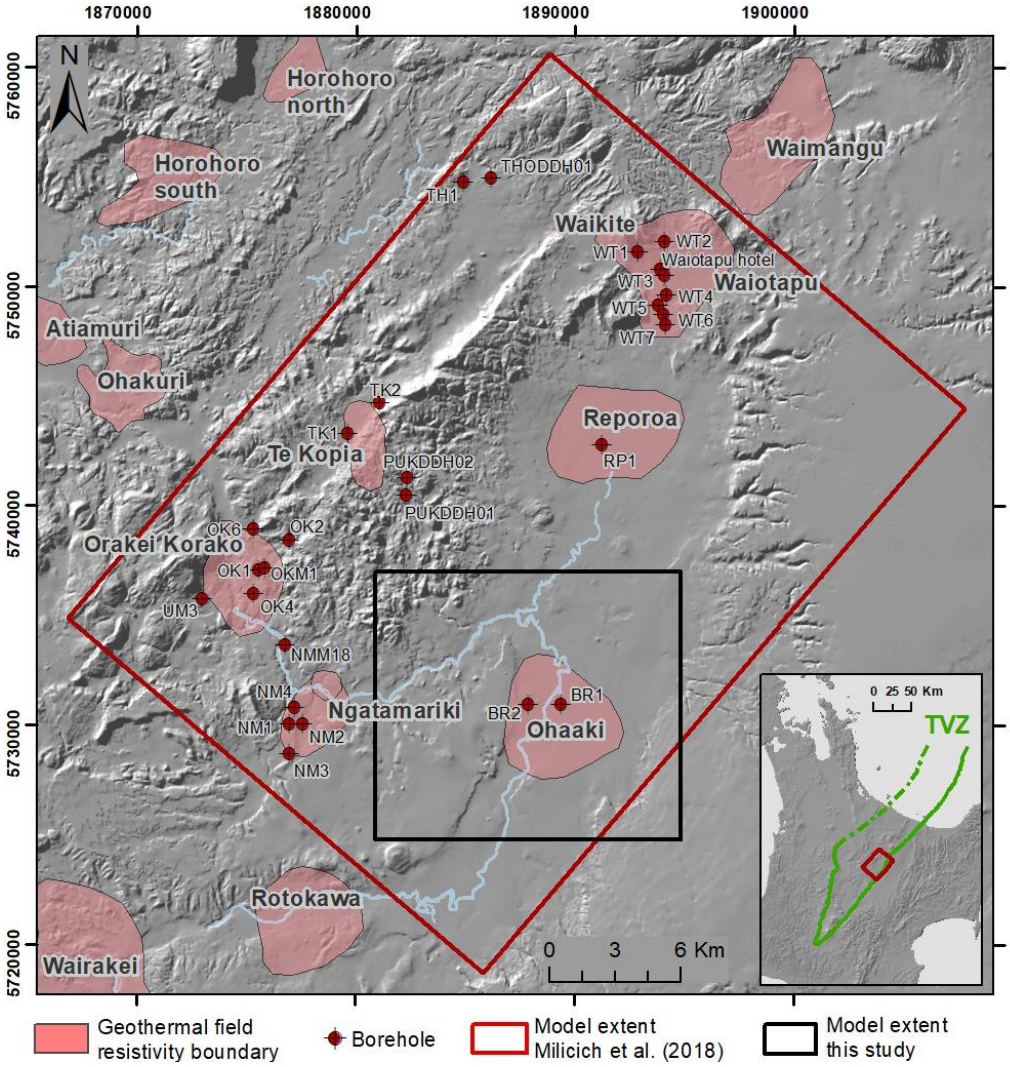


Figure 1: Map of the model extent of Milicich et al. (2018) and the model extent of this study focused on the area around the Ohaaki Geothermal Field. The location of boreholes used for subsurface information and resistivity boundaries of the geothermal fields are shown. Inset map: North Island, New Zealand, showing the Milicich et al. (2018) model extent in relation to the Taupo Volcanic Zone (TVZ).

2. METHOD

Forward modelling is the process of creating a geologic model with associated physical properties and calculating the geophysical response of that model. Results are compared with the observed geophysical response and updates are iteratively applied until a good fit within an error tolerance is reached (Figure 2).

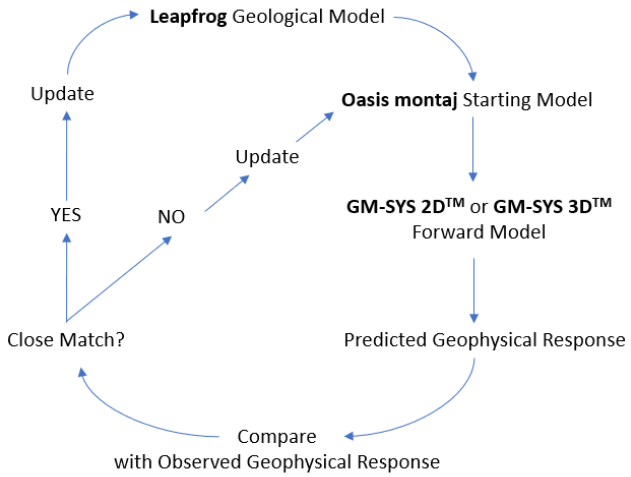


Figure 2: Flow diagram illustrating the iterative forward modelling method.

2.1 The Geological Model

The geological model used in this case study is the Ohaaki area extracted from a modified version of the hydrogeological model of the Taupo Volcanic Zone presented in Milicich et al. (2018) (Figure 3). Built in Leapfrog Geothermal, it is a simplified geological model of the area, focusing on groups of rock types with similar hydrogeological properties. The model is akin to an exploration stage project in that input data is limited and hydrogeological units have been shaped by the regional structural setting. The model was built using publicly available borehole data, surface geology and geological cross sections (Milicich et al., 2018). The Ohaaki area was extracted by modifying the extents of the 2018 hydrogeological model to the area of the black box shown in Figure 3. The hydrogeological groupings within this area consist of sediments and pyroclastics, fine-grained sediments, lava domes and intrusions, post-Whakamaru pyroclastics, Whakamaru group, pre-Whakamaru pyroclastics and greywacke.

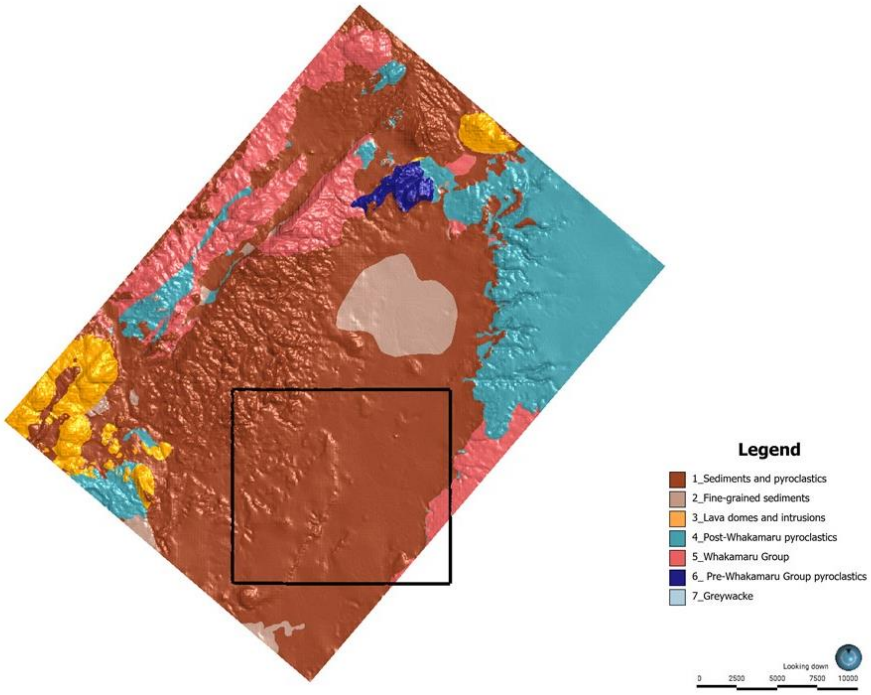


Figure 3: Regional hydrogeological model from (Milicich et al. 2018) with the extent for this study shown by the black box built with Leapfrog Geothermal.

2.2 Build a Starting Model

A forward model calculation requires a starting model. For this the geological model was exported from Leapfrog Geothermal and brought directly into Oasis montaj as a geosurface; a surface comprised of the individual geological layers.

The geosurface was reprojected and clipped to the Ohaaki area of interest (Figure 4). The uppermost boundary of each geological layer was sampled onto a surface elevation grid. GM-SYS 3D™ an Oasis montaj extension was used to model the geophysical response in 3D. A GM-SYS 3D™ depth model was constructed by stacking these surface grids to create geological interfaces. The surface grids could be coincident but may never intersect. Satellite derived topographical data was downloaded using Oasis montaj's Seeker, gridded, and used to define the uppermost layer. The geometry (cell size in X and Y and coordinate system), and extent of the model was defined by this uppermost surface grid. The base of the model was set to a depth of 6000 m to match the geological model. The outer surface of the discrete closed body of the subsurface domes and intrusions was also incorporated into the GM-SYS 3D™ model.

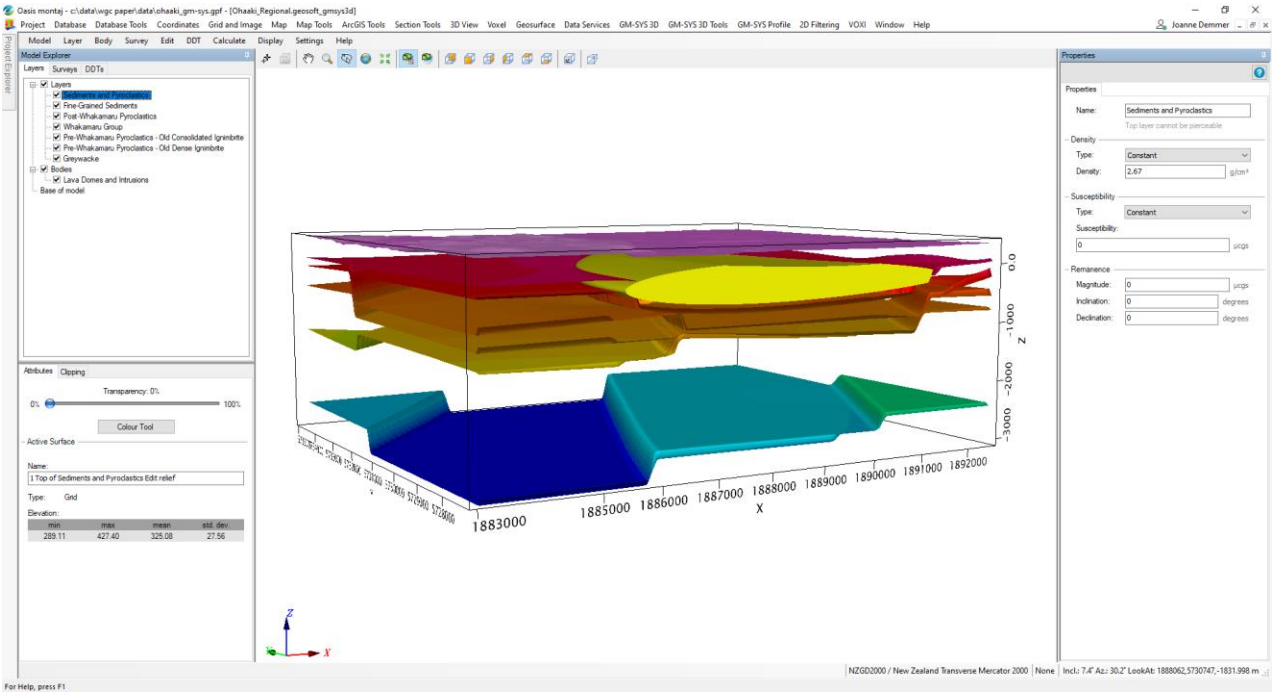


Figure 4: A screenshot of the Ohaaki area's GM-SYS 3D™ depth model in Oasis montaj, constructed from surfaces that define the uppermost elevation of each geological unit. Elevation surfaces are displayed on a linear color stretch.

2.3 Assign Rock Properties

Physical rock property information was assigned for each geological unit. In GM-SYS 3D™, density, magnetic susceptibility, and remanent magnetization can be assigned along with property distribution type: constant, lateral variation or voxel variation.

Average bulk densities were derived from published rock property data (Milicich et al. 2018). The average dry bulk densities used in the forward model calculation are listed in Table 1. The density of the Whakamaru Group was unknown, therefore an initial estimate of 2.00 g/cm^3 was used. The density distribution was set to be constant, assumed to be homogeneous.

Table 1: Average bulk densities used in the GM-SYS 3D™ forward model

Geological Unit	Dry Bulk Density (g/cm^3)
Sediments and Pyroclastics	2.67
Fine-Grained Sediments	1.55
Post-Whakamaru Pyroclastics	1.75
Whakamaru Group	2.00
Pre-Whakamaru Pyroclastics:	
Old Consolidated Ignimbrite	2.35
Old Dense Ignibrite	2.15
Greywacke	2.65
Lava Domes and Intrusions	1.8

2.4 Incorporate Observed Geophysical Data

The complete Bouguer anomaly ground gravity data was gridded using the minimum curvature method (Figure 5A). The Bouguer anomaly grid should be filtered to only contain wavelengths that correlate to feature(s) of interests. Depending on the depth of investigation, the regional trend or residual anomaly could be used. In GM-SYS 3D™, if a wavelength filter is applied to the observed gravity response, the same filter should be applied to forward modelled response. The regional anomaly grid (Figure 5B) was created by upward continuation of the complete Bouguer anomaly grid to 1000 m. The residual anomaly grid (Figure 5C) was created by applying a Gaussian high pass filter with a 10 km cut-off wavelength to the complete Bouguer anomaly grid. The terrain correction density of 2.67 g/cm^3 was used as the background density.

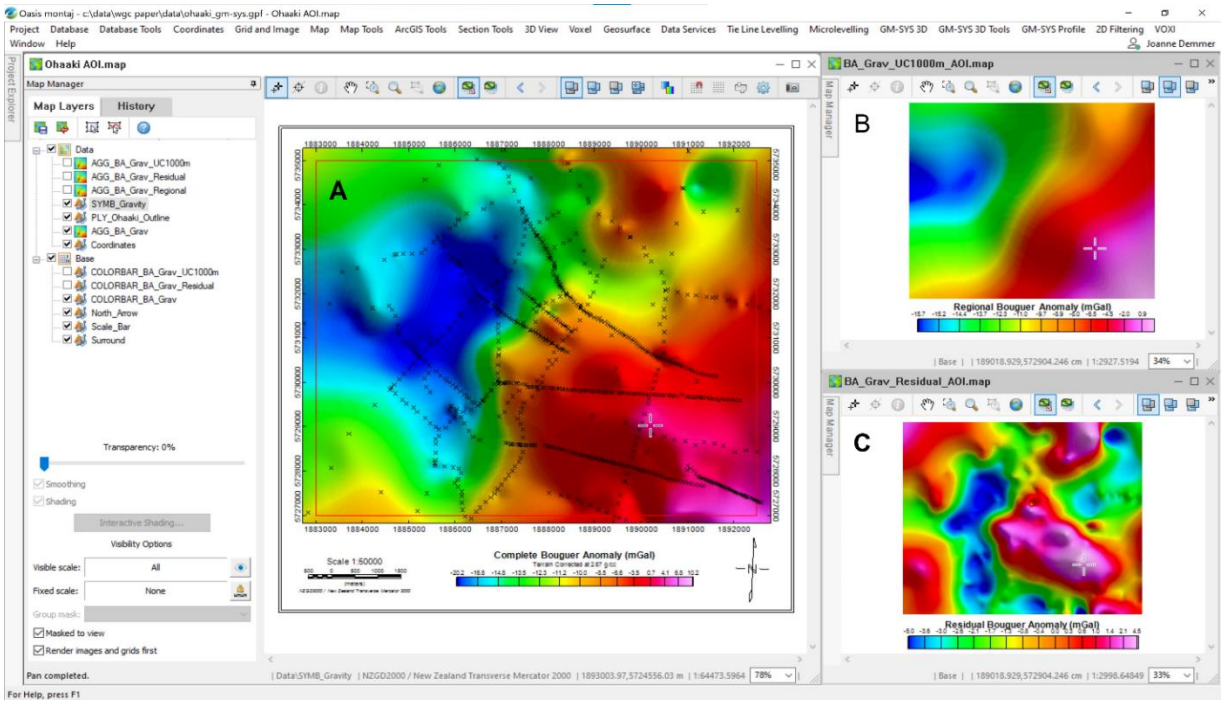


Figure 5: A screenshot of gravity anomaly grids shown in Oasis montaj a) complete Bouguer anomaly grid (mGal), with gravity measurement locations overlain in black dots, b) regional Bouguer anomaly, and c) residual Bouguer anomaly.

2.5 GM-SYS 3D™ Forward Model

Forward model calculations in GM-SYS 3D™ are performed in the wavenumber domain and are based on Pearson's implementation of Parker's algorithm (Parker 1972). Prior to the transformation into frequency domain, the Bouguer anomaly grid was expanded by 50% so that the very long wavelengths beyond the survey area could be modelled and edge artefacts reduced. The measured Bouguer anomaly has been reduced to the geoid (mean sea level) while the predicted response calculates the absolute gravity response of the model. To correct for this offset a DC shift was applied to the mean error using an auto best-fit method.

Due to the limited knowledge of the Ohaaki area, the unfiltered complete Bouguer anomaly grid was forward modelled first to ensure all wavelengths were modelled and the deep geological structure investigated. The residual anomaly was then modelled to inspect the shallower geological features. The predicted gravity response was compared with the observed gravity response from the survey data and the misfit (difference between the observed and predicted) was reviewed.

Figure 6 shows the results from forward modeling the unfiltered complete Bouguer anomaly grid. The observed response shows a long wavelength trend that dips SE-NW, high to low (Figure 6A). There is a high gradient in the center of the area. The predicted response (Figure 6B) suggests a central gravity low encircled by a gravity high on the western, northern and eastern sides, that peaks in the NW corner. The correlation between the predicted and observed response is poor at these long wavelengths (Figure 6C). This suggests that the regional structural geometry or the density of a mid to deep layer in the starting model is not correct. Parts of the model, such as the Pre-Whakamaru and Greywacke layers, that have been constructed with little to no supporting geological borehole information should be re-evaluated.

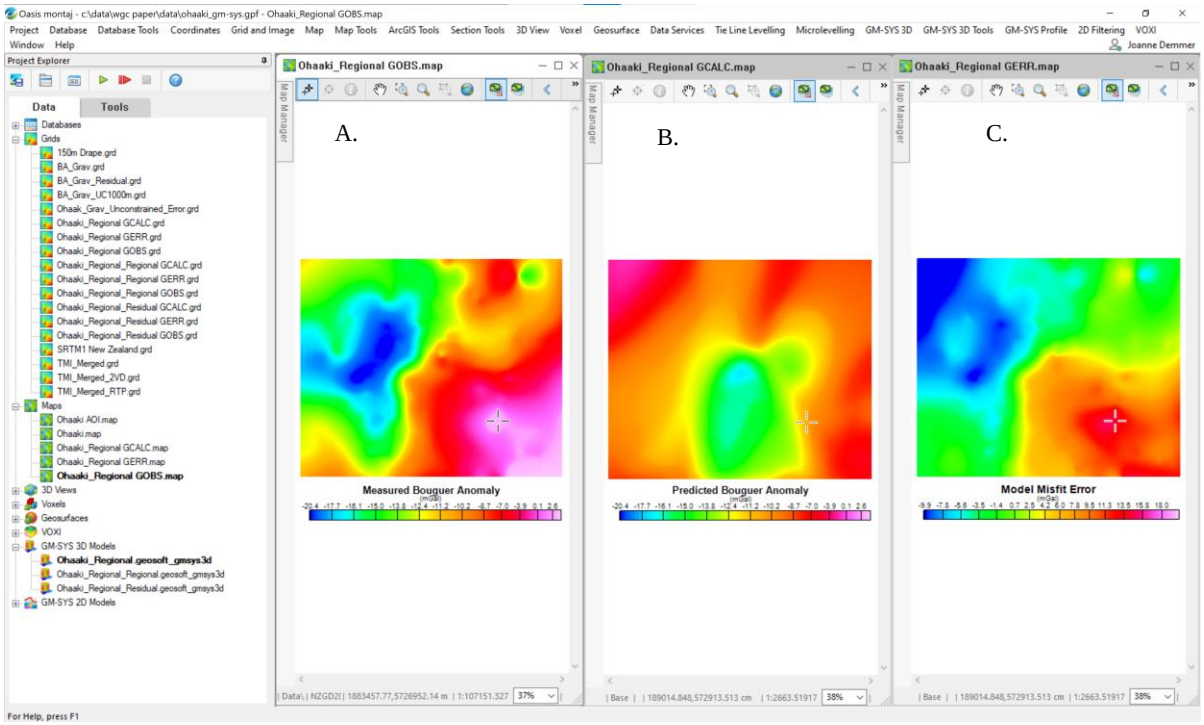


Figure 6: A screenshot showing forward model results of the unfiltered complete Bouguer anomaly displayed in Oasis montaj, A) observed response, B) predicted response, and C) model misfit error.

Figure 7 shows the results from forward modeling the residual Bouguer anomaly grid. The observed residual gravity anomaly (Figure 7A) shows a 5 km long gravity high that trends NW-SE. On its NW tip lies a N-S trending gravity low and 4 discrete gravity highs situated around the survey perimeter. The predicted response (Figure 7B) has some correlation to the observed response at these short (sub 10 km) wavelengths. The main source of error (Figure 7C) comes from the central N-S trending gravity low feature that corresponds with the subsurface dome. Forward modelling suggests that the orientation and density of this shallow lava body requires further investigation.

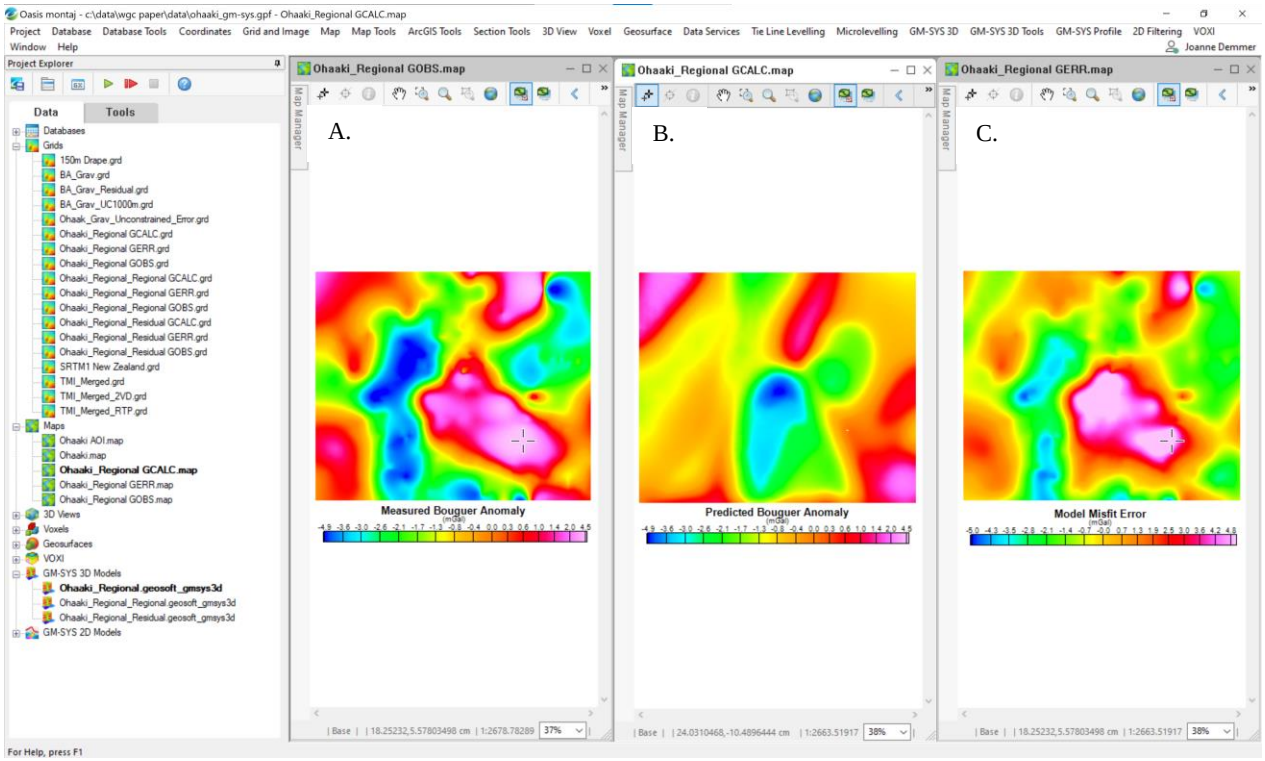


Figure 7: A screenshot showing forward model results of the residual Bouguer anomaly displayed in Oasis montaj, A) observed response, B) predicted response, and C) model misfit error.

2.6 GM-SYS 2D™ Forward Model

The GM-SYS 3D™ forward models suggest that the Pre-Whakamaru and Greywacke layers along with the lava dome are the main sources of error. This error can be used to make geologically reasonable updates to the starting model that will minimize the mean error. Any update needs to be evaluated with regard to known data observations. There are limited rock property data available in the Ohaaki region: the rock density ranges are broad, for dry rocks only and not known for all lithologies and the borehole information is scarce. Boreholes BR1 and BR2 provide the only subsurface lithological constraint in the study area. For this reason, sections that crosscut the boreholes and traverse the densely sampled ground gravity stations were extracted from the unfiltered complete Bouguer anomaly GM-SYS 3D™ model and brought into GM-SYS 2D™ (Figure 8). The surfaces that define the top of each geological unit were automatically brought across (except for the closed lava body).

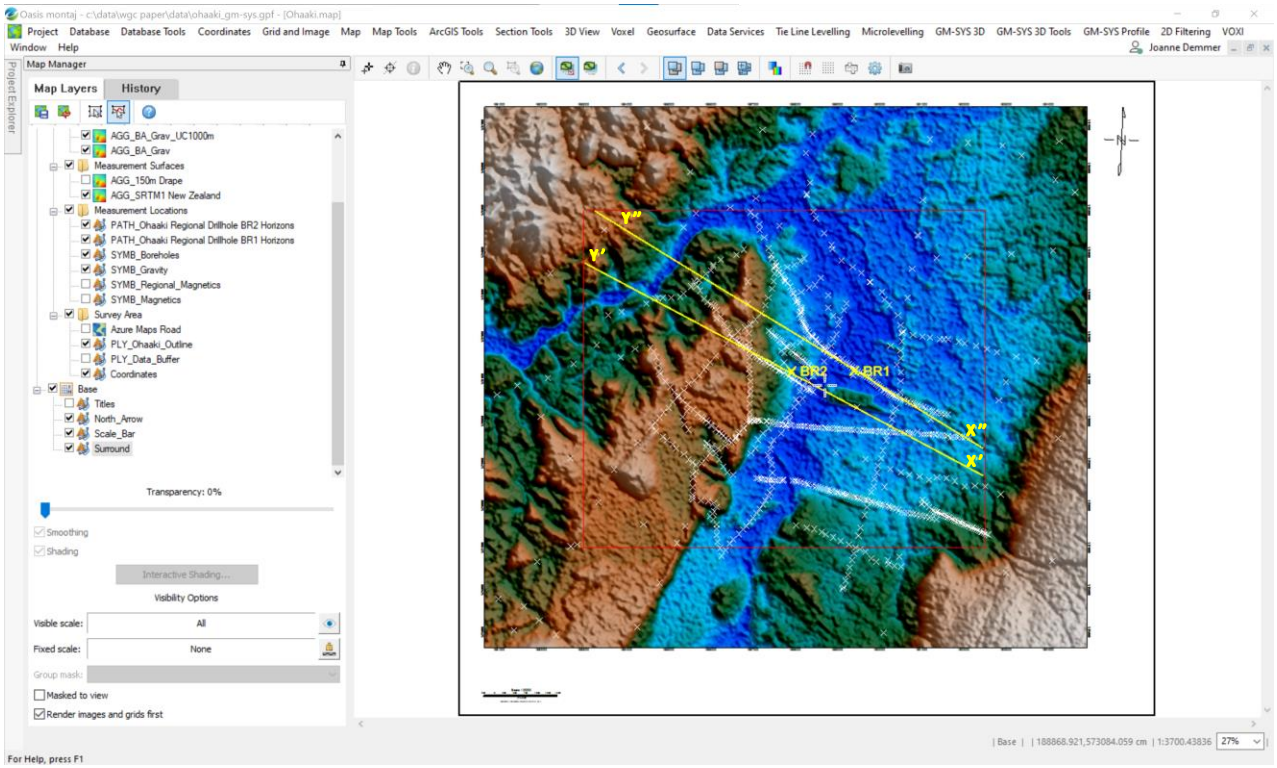


Figure 8: A screenshot of an Oasis montaj map showing the terrain with borehole BR1 and BR2 locations and cross-section profile lines overlain in yellow. Ground gravity station locations are shown in white.

In GM-SYS 2D™ the horizons and rock properties can be interactively updated until the error between the calculated model response and measured response is minimized. Forward calculations are run in real time so changes to the model can be rapidly tried and tested. For each profile, it can be seen in Figure 9 that the starting geological model with initial rock densities does not produce a predicted gravity response that matches the measured response, nor does it honor the borehole lithologies. Whilst some of this mismatch could arise from the missing lava dome that has not migrated across into GM-SYS 2D™, the long wavelength trends poorly correlate.

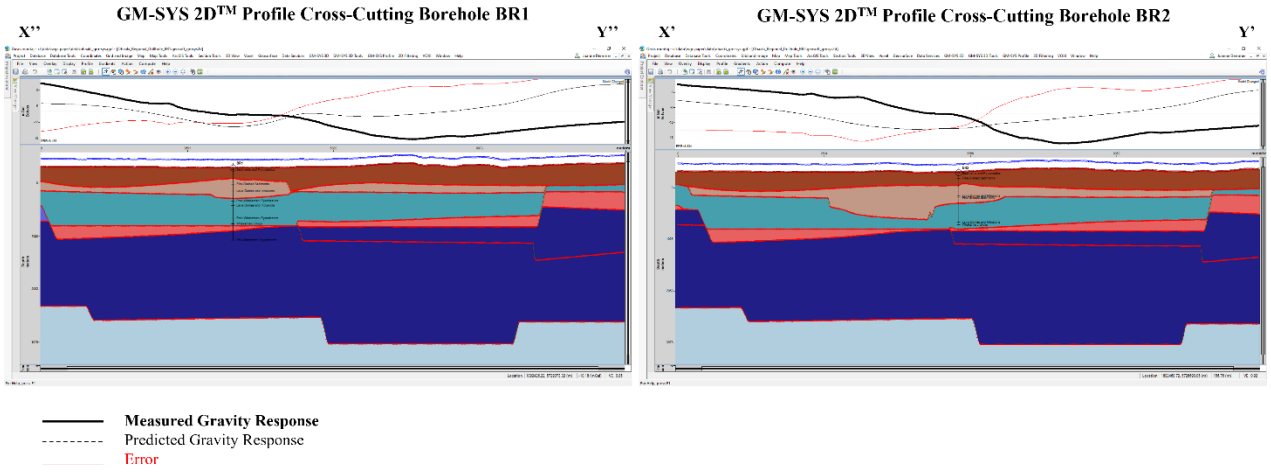


Figure 9: Screenshots of GM-SYS 2D™ sections of the starting geological model cross-cutting boreholes BR1 (left) and BR2 (right). Predicted gravity response of the model poorly matches the measured response and borehole lithologies.

To reduce the modelling error, updates to the starting geological model and rock densities were needed. The borehole lithologies from BR1 and BR2 were first used to constrain structural updates to the geological horizons. These updates were then extrapolated away from each borehole. Borehole BR1 does not penetrate the Greywacke layer and borehole BR2 does not penetrate the Pre-Whakamaru and Greywacke layers. Therefore, updates to these deep horizons were driven by the requirement to satisfy the longer wavelength gravity response by either adding or removing excess mass. This led to structural updates which included additional faults, revised fault offsets and the continuation of the Pre-Whakamaru layer (Figure 10). Rock densities were adjusted as outlined in Table 2 but kept within the published rock density ranges (Milicich et al. 2018).

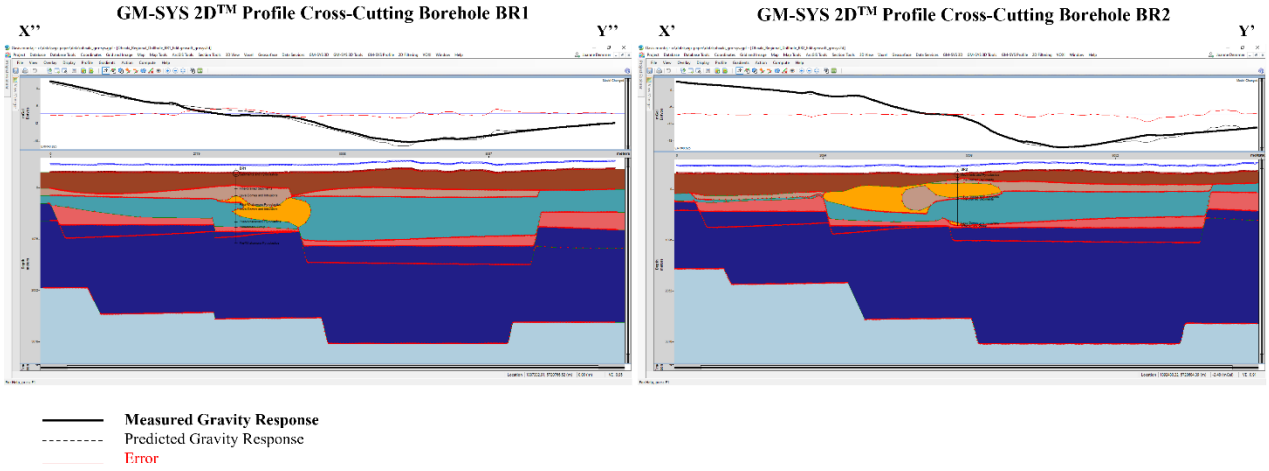


Figure 10: Screenshots of GM-SYS 2D™ sections of the updated geological model cross-cutting boreholes BR1 (left) and BR2 (right). Predicted model response closely matches the measured response and borehole lithologies.

Table 2: Average bulk densities used in the GM-SYS 2D™ forward model

Geological Unit	Original Dry Bulk Density (g/cm^3)	Revised Dry Bulk Density (g/cm^3)
Sediments and Pyroclastics	2.67	1.50
Fine-Grained Sediments	1.55	1.60
Post-Whakamaru Pyroclastics	1.75	1.70
Whakamaru Group	2.00	2.18
Pre-Whakamaru Pyroclastics	2.15	2.36
Greywacke	2.65	2.66
Lava Domes and Intrusions	1.8	2.10

3. OUTPUT

The revised GM-SYS 2D™ geological horizons were exported from each cross-section in Oasis montaj and brought into Leapfrog Geothermal. Figure 11 shows the revised GM-SYS 2D™ geological horizons overlain on top of the original Leapfrog Geothermal Hydrogeology Model. Incorporating the horizons back into the Leapfrog model gives the broader geological context required to assess the validity of the geophysics driven update. The modeler can then review their interpretation and decide to either incorporate or reject the change. This collaborative approach prompts dialog between the geophysicist and the geologist, which can lead to new ideas that direct future work.

In the example presented in this paper, the geologist had a regional structural understanding that was not portrayed in the cross sections. The cross sections indicated a graben structure whilst regional studies suggested a horst structure was more likely. A discussion between disciplines prompted a review of the geophysical modelling. It was decided to repeat the workflow but focus on delineating the greywacke basement to see if the gravity data supported this regional geological understanding.

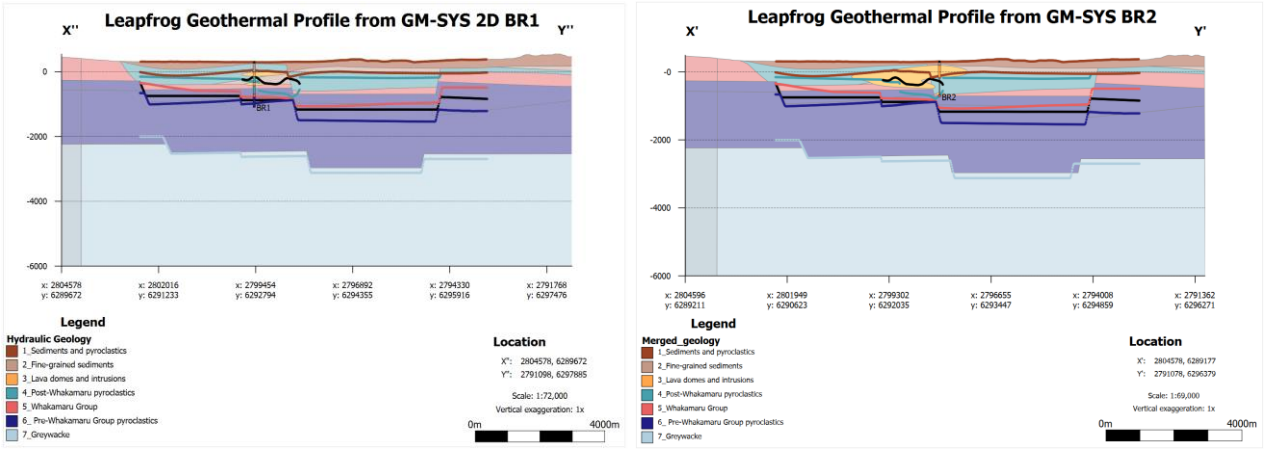


Figure 11: Original Leapfrog Geothermal geological cross-sections with revised horizons from GM-SYS 2D™ overlain.

4. DISCUSSION

In the exploration stage of a geothermal project, the geological model is often largely unconstrained and uncertain. The simplified hydrogeological model of the Ohaaki area is akin to an early-stage exploration project. It is a model built from limited borehole data then upscaled and extrapolated to present a geological hypothesis shaped by the regional setting. Forward modelling this hydrogeological model of the Ohaaki area and constraining it with gravity and borehole data has identified some areas of potential improvement that can be investigated. These include the Pre-Whakamaru, Greywacke and lava dome layers.

In this example, the first pass of the workflow sought to investigate all wavelengths of the Bouguer anomaly, in an attempt to identify misfit features at all depths. The scope was too broad. There were too many variables and assumptions which lead to an unreliable modelling result with little reduction in model uncertainty. This was because the rock density ranges were too broad, for dry rocks only and not known for all lithologies. In addition, borehole information was scarce; boreholes BR1 and BR2 provided the only lithological constraint. As a result, many Earth models could have produced the same gravity response.

At this phase of exploration, it was known that the geological model would be significantly more complex than described in the hydrogeological model but the details in the complexity at depth were more uncertain. The workflow succeeded in bringing multiple disciplines together to try and better understand this complexity. A more targeted approach, with a focus on one geological unit or body, would have yielded better results. In this example, it was learnt that constraining the forward model to focus on one update, the Greywacke basement, would have allowed us to test if the gravity data supported the hypothesized regional horst setting. This would have reduced uncertainty in the model at depths beyond the drilling extents.

The modelling methods adopted by GM-SYS™ are better suited to surface orientated layered earth models. These modelling tools are designed to update geological structure and density distribution but are optimal when only one layer is under investigation. Whilst this approach works well to refine the deep geological layers that are beyond the extents of drilling e.g., the Greywacke, it struggles to accurately update the closed body geometry and density of the lava dome. Depending on what geological feature is of interest, this software limitation should be considered when deciding which modelling approach to use.

The ability to easily transition from 3D to 2D allows interpretation to be focused and more data driven. This is because 2D profiles that crosscut densely sampled ground gravity stations and boreholes can be extracted. Updates along these profiles can be made with greater confidence and these changes can influence changes to other parts of the model. However, borehole data can pick up highly localized effects that can be misleading. Depending on the complexity of the geology, 2D interpretations may not be reliably extrapolated in 3D.

The workflow presented allows seamless collaboration between modeler and geophysicist. This makes it efficient to take the learnings from the initial run of the workflow and reapply them to the next run. As the geothermal project evolves, iterative updates to the geological and geophysical models can be made as new data is collected and incorporated. This streamlined workflow saves time and ensures everyone is working and collaborating on the most up to date data.

5. FUTURE WORK

This study iteratively updated the starting geological model in GM-SYS™, using the limited amount of known data available, until the predicted gravity response closely matched the observed gravity response. Another approach could be to run a gravity inversion in VOXI. VOXI can run more complex cloud-based inversions that would better update the discrete subsurface lava domes. Future work will be to compare results from these two workflows for input into the geology model.

6. CONCLUSION

The ambiguity of gravity data add uncertainty that makes modelling and interpretation more challenging. The workflow presented in this paper reduced modelling uncertainty by incorporating geological information that constrained gravity modelling toward a more geologically interpretable result. The results were incorporated back into the geological model with ease and interpreted.

In this example of the Ohaaki Geothermal Field area, the workflow was applied to an upscaled, loosely constrained exploration stage geological model. The workflow was successful in bringing multiple disciplines together to collaborate efficiently. While the initial

predicted Bouguer anomaly from the forward model did not align with the regional geological structure, areas of uncertainty and improvement were highlighted. These included the deep regional structural layers (Pre-Whakamaru and Greywacke) and the shallow lava dome layers. However, too many assumptions and variables led to an unfocused result. It was learnt that the workflow would retrieve better results if the forward modelling focused on one hydrogeological unit such as the Greywacke. This iterative workflow feeds the life cycle of a geological model; where the model is updated using multiple geoscience disciplines as and when new data is acquired, or new ideas formed. This workflow highlights the importance of having an efficient interconnected workflow that enables modelling updates to be tested with ease.

Improved collaboration across geoscience disciplines can lead to better data driven decisions that influence and direct future work. In the case of an exploration stage project, geophysics can improve geological understanding on all scales and help to refine updates to the geological model. These updates will in turn de-risk commercial decisions, such as expensive drilling programmes, that stem from the geological model.

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