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Refining Geothermal Reservoir Models Using Repeat Microgravity Data

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ABSTRACT

High-precision gravity measurements can be a useful indicator of large scale changes in fluid mass within a geothermal reservoir related to production, reinjection or phase changes. In New Zealand, repeat microgravity surveys have been performed at a number of producing geothermal fields over the last 50 years. However, this data is not routinely incorporated into reservoir models used to manage these fields. The goal of this paper is to determine a methodology for calibrating a reservoir model against changes observed in microgravity, and to apply this to a high-temperature geothermal field.

We created a shallow reservoir model (to -900 masl) from a TOUGH2 heat and fluid flow model of a geothermal field which had been calibrated using well enthalpy and pressure data. Gravity changes were calculated at measurement locations using density values produced by the shallow reservoir model. The calculation was run multiple times using the PEST inverse modelling software, comparing calculated gravity with measured gravity at each iteration. A number of parameters were varied to find the best-fit model, for example fluid flux at the base of the model, the extent of deep fluid flow, and rock properties including porosity, permeability, fracture volume and fracture spacing.

The initial numerical model, which was calibrated only with well enthalpy and pressure data, captures first-order features detected by microgravity measurements. However, the average misfit in the microgravity data could be reduced by more than half by changing the bulk rock permeability and porosity, and the fluid enthalpy and flow rate at the base of the model. Although this represents a significant reduction in misfit, the model still does not replicate all the features of the gravity data. Therefore while repeat gravity surveys are most sensitive to changes in the shallow subsurface, they may also be influenced by large-scale changes in the deeper reservoir.

1. INTRODUCTION

Geothermal energy accounts for 14% of electricity generation in New Zealand (Ministry of Business 2013). It is important as the only renewable energy source that does not depend on the weather. To understand how heat and fluid flow through the geothermal systems used for electricity production, numerical models are routinely used. These models can also help to determine optimal locations and rates of production. They are generally calibrated from well temperatures and pressures but other data sets may be collected and incorporated to improve confidence in the models (Hunt and Kissling 1994; Nordquist et al. 2004). For example, gravity data is sensitive to changes in mass and can therefore be used to study fluid influx or outflux or changes in fluid phase (Atkinson and Pederseen 1988). In the Taupo Volcanic Zone, high precision gravity data has been collected since the 1960's (Hunt 1970; Hunt 1984) and is now collected at several geothermal fields every 1-10 years (e.g. Hunt 1995; Hunt and Bowyer 2007; Hunt et al. 2002). By calibrating a reservoir model with high-precision gravity data, we can refine and test conceptual models created based on well temperatures and pressures and improve our estimates of reservoir properties. The goal of this work is to calibrate a geothermal reservoir model in New Zealand with gravity data, refining the model and identifying which parameters gravity data is most sensitive to.

2. METHODOLOGY

2.1 Numerical Model

A numerical model of a geothermal field was created using the Petrasim interface to the TOUGH2 heat and fluid flow modelling code (Pruess et al. 1999). A dual porosity model was used to simulate fracture-dependent flow. The model was calibrated with well temperatures and pressures. Because gravity measurements are primarily sensitive to near-surface effects, a smaller model was created from the full-field model for gravity calibrations. The resulting model covered 7 km by 6 km and extended from the ground surface to -900 masl. The geology comprised a homogeneous bulk rock above a relatively impermeable clay cap. The cap had a small leak in the centre through which fluid could flow (Figure 1). Initial conditions were set according to the natural state of the calibrated full-field model and consisted of single phase liquid water and a two-phase zone. The top surface followed topography at between 287 and 526 masl and was fixed at 1.3 MPa and 40 °C to represent the top of the water table. Blocks of fixed pressure and temperature were utilized at the lateral edges of the model at -25 masl to establish a south to north groundwater flow consistent with measured data. Reinjection was simulated as fluid injection at 145 °C into a cell at -175 m. The temperature and pressure at the base of the model were allowed to vary during computation, starting from conditions derived from the full-field model (Figure 1). Hot fluid was injected through the leak in the clay cap at the base at varying rates to simulate the hot outflow from the deeper geothermal system. The injection rate and other model properties, listed in Table 1, were varied to try to minimise misfit between measured and modelled gravity data.

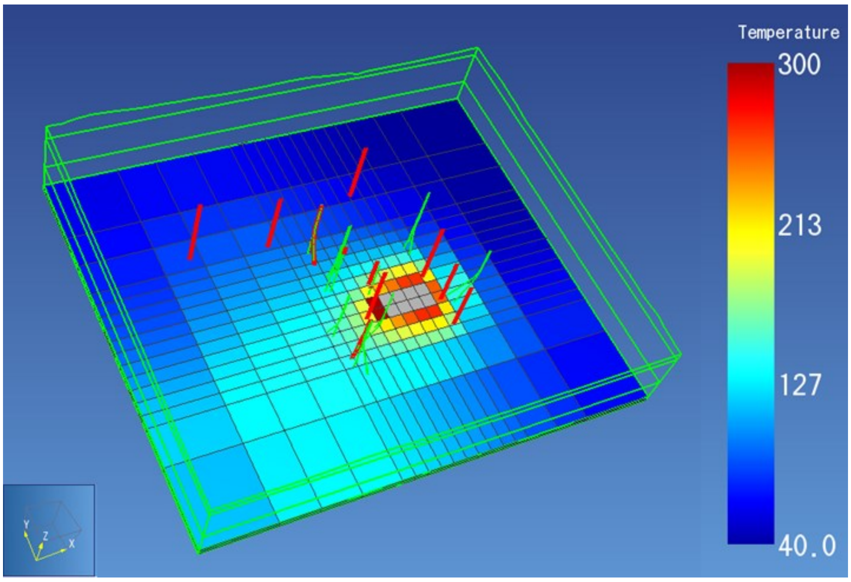

Figure 1. Setup of numerical model created to simulate the shallow part of a geothermal field. The colours represent the initial temperature (°C) for the bottom boundary condition of this model. Grey shows the area of fluid upflow correlating to a leak in the clay cap. Coloured lines correspond to well locations.

Table 1. Numerical model parameters varied during model calibration.

Symbol	Parameter	Parameter abbreviations				
q	Injection rate					
H	Injection enthalpy					
T	Temperature boundary condition	d – at depth	t - top			
φ	Porosity	f - fracture	m - matrix	b – bulk rock	c – clay layer	l - leak
k	Fracture permeability	xy - horizontal	z - vertical			
s	Fracture spacing					
v	Fracture volume					
kr	Relative permeability					

2.2 Gravity Data

Gravity measurements were collected on a semi-regular basis starting from 1997 and repeated in 2003, 2004 and 2009. A Lacoste and Romberg G-106 gravity meter was used following the method of Hunt et al. (1984). Sites were chosen to cover the entire geothermal reservoir and some distance beyond. Approximately 100 sites were measured in the study area, although some of these fell beyond the area of the gravity-related numerical model. The measurement sites consisted of benchmarks generally set in concrete in the ground between depths of 20 cm and 1 m.

Each site was measured during three separate visits, with the measurement repeated three times at each visit to ensure maximum accuracy. At least three hours, and preferably several days, elapsed between visits to ensure that erroneous data could be identified and instrument drift could be accurately determined and corrected for. Repeat levelling surveys done around the same time allowed for accurate corrections related to changes in location. This high-precision methodology resulted in measurement uncertainties of less than 20 µgal. As we are interested in changes in gravity, all measurements were compared to the initial, comprehensive survey carried out in 1997. Some areas were not returned to in later years due to access, time or budgetary constraints. The size of the area covered therefore varied considerably over the four surveys (Figure 2). All of the repeat surveys show that the gravity signal has increased over most of the reservoir since measurements began in 1997, with some decreases toward the outside of the field (Figure 2). The gravity increase also forms a fairly coherent bull's-eye, possibly due to resaturation of a 2-phase zone.

2.3 Gravity calculations

The gravity calculations were carried out as described in Franz (2013). The gravity at each station was calculated by summing the contributions from all of the individual model blocks. The contribution from each block was given by:

$$\boldsymbol{g = G * \rho * GF}$$

where G is the universal gravitational constant, ρ denotes the density of the block, and GF is a gravity factor between the block and the measurement station. The density is calculated by summing the contributions from the different MINC components (fracture and matrix in this case). The GF is a static factor calculated at the beginning, that is related to an integral of the distance between the measurement station and the block. It is not trivial because it depends not only on the shape of the block, but also its position and orientation with respect to a station. Analytical solutions are only known for certain shapes (Nagy, 1966) and so an algorithm was used to subdivide the blocks into a refined tetrahedral mesh until a point source approximation could be used (Franz 2013). In this way the calculation is independent of the shape and orientation of the blocks with respect to the measurement station.

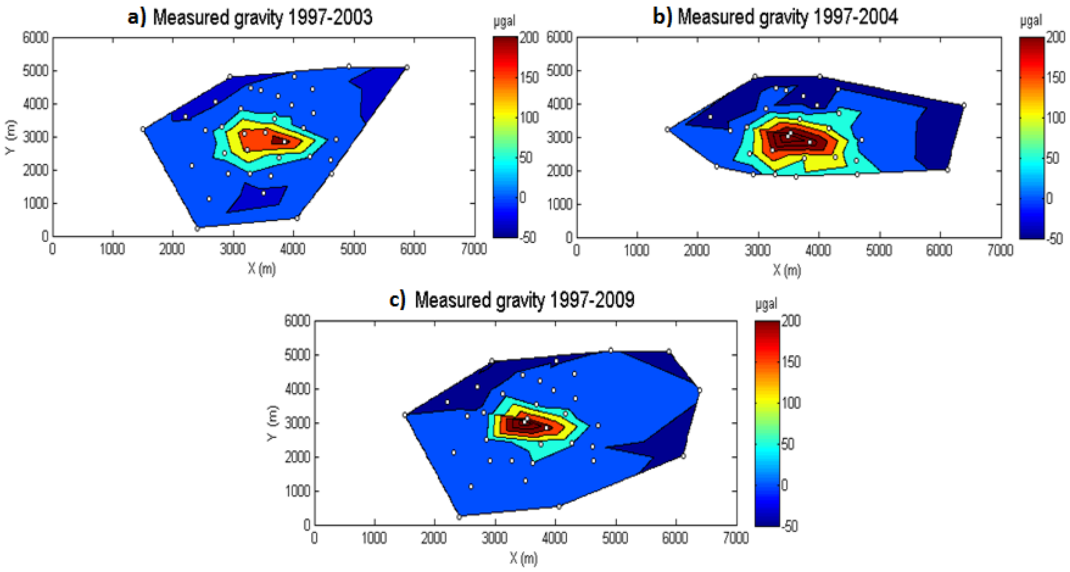

Figure 2. Changes in gravity measured between 1997 and a) 2003, b) 2004 and c) 2009. White dots correspond to measurement locations.

2.4 Calibration

The TOUGH2 model was calibrated against gravity data using a combination of Python and PEST (Doherty et al. 1994; Figure 3). For each iteration, the fluid density in each cell was read from the TOUGH2 output file and used in combination with the gravity factor to calculate the gravity signal at the measurement point as described above. The gravity signal from each block was summed to give the total gravity at a station. This was repeated for each station, and for each survey time. The change in gravity was then calculated between the measurement year and 1997. Finally, PEST was used to calculate the difference between measured gravity and modelled gravity for each iteration. Using a pre-assigned combination and range of parameters, PEST would modify the TOUGH2 input file to determine a new set of input parameters. The model would be rerun and the process repeated until the least squares objective function showed no further improvement.

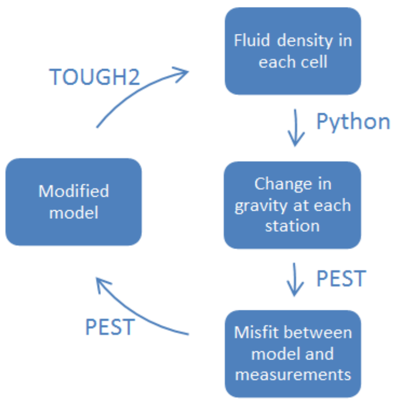

Figure 3. Flow diagram showing the calibration methodology.

3. RESULTS

The initial model created from well temperatures and pressures captures the overall bulls-eye shape of the change in gravity (Figure 4), but there is significant room for improvement. The maximum change in gravity calculated during the modelling process is in the wrong location, the shape of the anomaly is generally too diffuse, and the magnitude of the anomaly is far too small, with a maximum of around 50 µGal (Figure 4) instead of the 200 µGal measured (Figure 2). A variety of model parameters (Table 1) were therefore varied to improve the model fit to the measured data.

Initially, parameters were varied individually to determine which parameters gravity data was most sensitive to (Figure 5). Sensitivity was calculated using PEST sensitivity analysis (Watermark Numerical Computing 2004). Figure 5 shows that the lateral permeability in the bulk rock above the clay cap (k(b_xy)) is the parameter that gravity data is most sensitive to. The fracture volume (v) is also a sensitive parameter. To a lesser extent, the vertical permeability in the bulk rock (k(b_z)) and leak (k(l_z)), the porosity (φ) and the rate of fluid being injected into the leak (q) are also important (Figure 5). These parameters were therefore varied in combination, although other parameters like fracture spacing and fluid enthalpy were also modified.

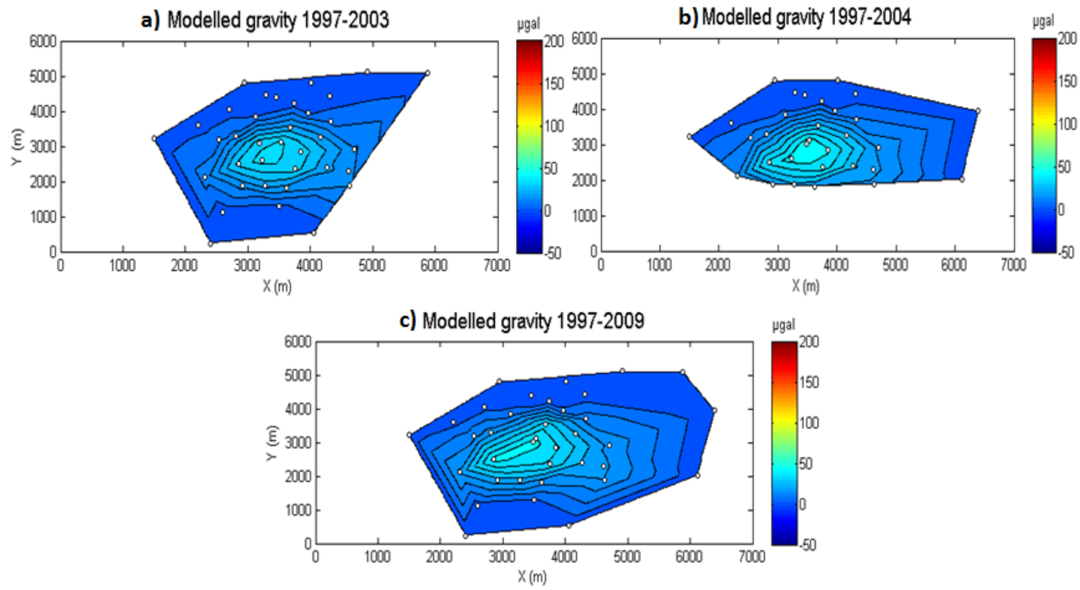

Figure 4. Changes in gravity modelled between 1997 and a) 2003, b) 2004 and c) 2009. The model was calibrated using well temperatures and pressures only.

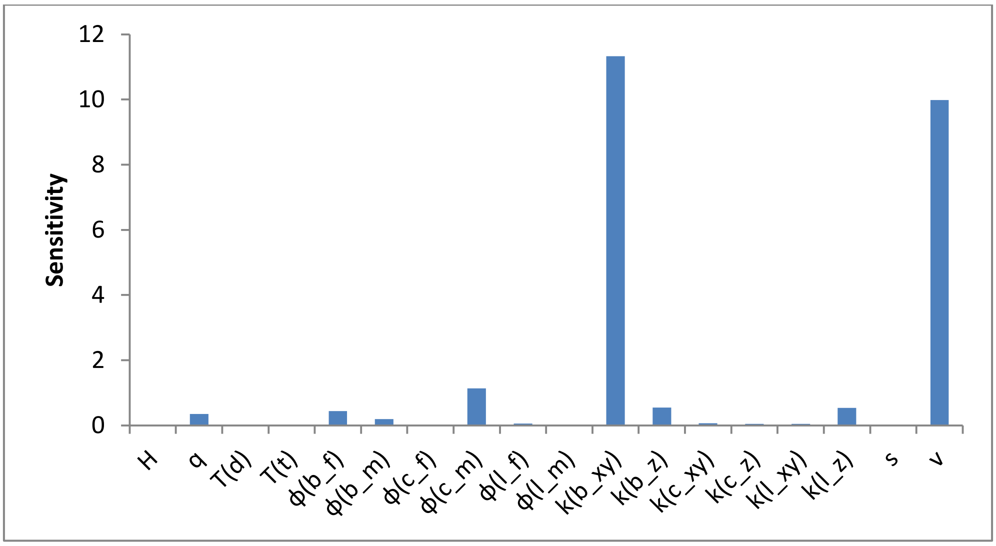

Figure 5. Model parameters that gravity data is most sensitive to. See table 1 for symbol meanings.

After changing many different properties, the best-fit model was identified where the objective function (the sum of squared misfit) was minimised (Figure 6). This best-fit model (Figure 7) shows a significant improvement over the initial model (Figure 4). It inverts for lateral permeability and porosity in the bulk rock, rate of injection into the leak in the clay cap, and enthalpy of the injected fluid. The greatest changes in gravity are on the order of 120 to 200 μGal (Figure 7) which is comparable to the measured 200 μGal (Figure 2). The shape and location of the gravity anomalies is also much closer to that measured (Figure 2), although the modelled signal is still too diffuse. The total misfit is reduced by more than 30% and the average misfit by half (Table 2).

4. DISCUSSION

A number of properties in the reservoir model were refined by calibrating against microgravity data (Table 3). For example, the amount of fluid flowing into the base of the model could be determined to within an order of magnitude . The enthalpy of the fluid could also be refined from the gravity signal as it affects the two-phase zone which gravity signals are most sensitive to. Lateral permeability in the bulk rock was important because it affected how much flow was horizontal compared to vertical. This changes whether the gravity anomaly has a smaller magnitude and is broad (with high lateral permeability), or is a more focussed, larger anomaly (with smaller lateral permeability). Vertical permeability in the fracture could also be refined by calibrating against microgravity data, although with large uncertainties (Table 3). The vertical permeability in the matrix was not sensitive in our model because it was already high at 5 x 10^{-14} m^2 and so fluid could flow relatively freely. Fracture volume and porosity had noticeable effects (Figure 5) because they control how much fluid is available to flow in each cell. Other parameters such as model boundary conditions or fracture spacing were relatively insignificant for this model.

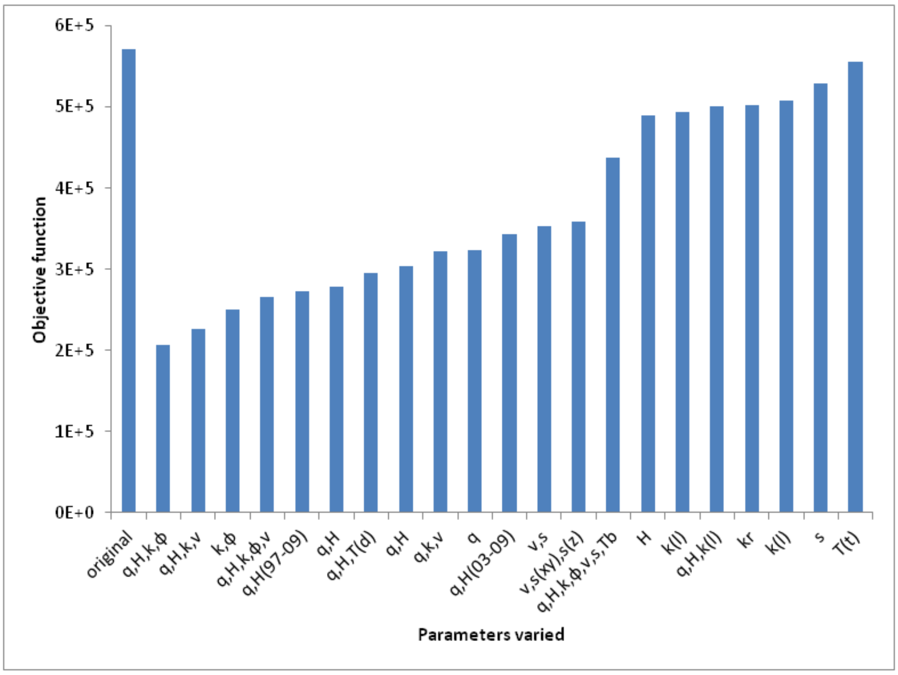

Figure 6. Graph showing the different model fits depending on the model parameters varied. The original model calibrated without gravity data has the highest objective function and is therefore the worst fit. See Table 1 for the key to parameters.

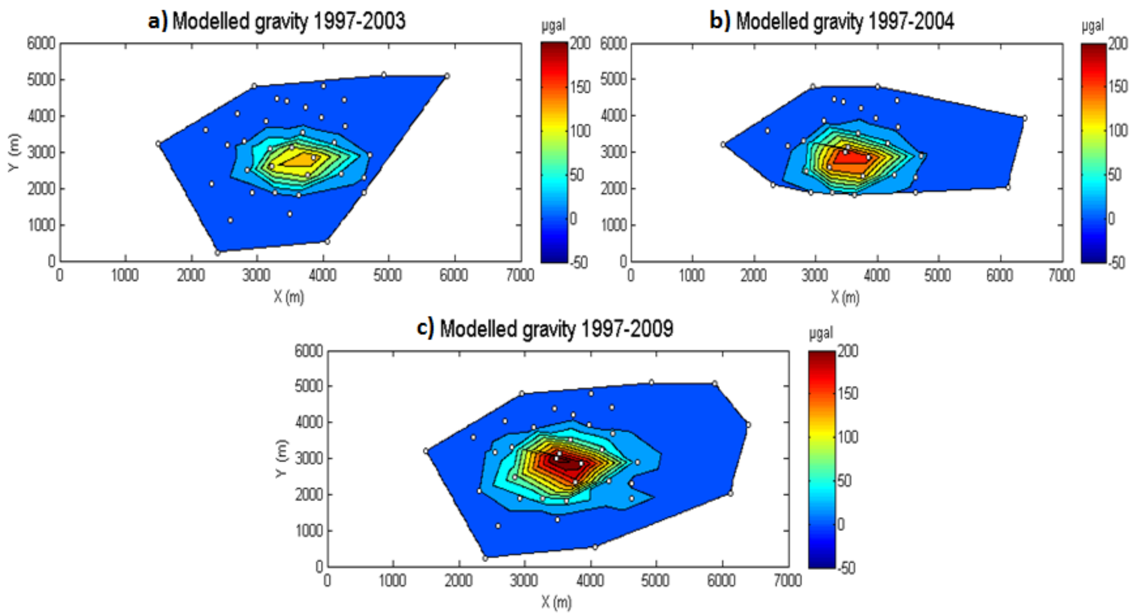

Figure 7. Change in gravity modelled between 1997 and a) 2003, b) 2004 and c) 2009 for the best-fit model calibrated against gravity data.

The misfit between measured and modelled gravity can be improved by varying one parameter, but much more so by varying several parameters concurrently (Figure 6). For example, the model fit was improved by varying either porosity (φ) or fracture volume (v) along with permeability (k) and fluid influx (q, H). However, there is a tradeoff; trying to invert for both porosity and fracture volume at the same time was less successful (Figure 6). This is because they have a similar effect and so the problem becomes underconstrained. If one of these parameters is well known the other can be inverted for, although this is very rarely the case. Either assumptions must be made, or other datasets like magneto-tellurics, temperature, pressure or geochemistry must be incorporated to gain information about more parameters at once. PEST makes this relatively straightforward and provides statistics to understand the results, but the modeller is still required to determine which parameters to vary and their likely ranges. A reasonably realistic initial model is also necessary and so although the process can be semi-automated, it still depends on the modeller.

Table 2. Misfit between measured and modelled gravity data. The original model was based on well temperatures and pressures alone, while the best-fit model was determined from calibration with gravity data.

Misfit	Total (µGal)	Objective function (µGal²)	Average (µGal)	Average absolute (µGal)	Median (µGal)	Maximum (µGal)	Minimum (µGal)	Smallest (µGal)
Original model	4272	555,581	30	41	13	313	-57	0.3
Best-fit model	2979	186,581	11	29	7	176	-111	0.3

Table 3. Parameters inverted for in best-fit model. See table 1 for symbol meanings.

Parameter	q (kg/s)	H (kJ/kg)	k(b_f_xy) (m²)	k(b_f_z) (m²)	k(b_m_xy) (m²)	φ(b_f)	φ(b_m)
Initial guess	1.28	1.38×10^{6}	1.10×10^{-14}	1.20×10^{-13}	4.10×10^{-16}	0.5	0.25
Final estimate	0.41	1.39×10^{6}	6.75×10^{-15}	5.01×10^{-14}	3.18×10^{-16}	0.1	0.24
Confidence limits	-2.53	-4.75×10^{5}	5.28×10^{-16}	2.12×10^{-27}	1.21×10^{-18}	-0.69	-0.095
	3.35	3.25×10^{6}	8.63×10^{-14}	1.19	8.35×10^{-14}	0.89	0.58

Our best-fit model has reduced the total misfit between modelled and measured gravity by 30% (Table 2). It supports the idea that increases in gravity are related to resaturation of a two-phase area above the leak. Over time, reinjection and production lead to changes in the pressure regime that result in the vapour-dominated zone becoming smaller (Figure 8). As vapour changes to water, the more dense fluid results in an increase in measured gravity. However, the model systematically underestimates this increase in gravity (Figure 9). It also does not explain the negative change in gravity measured at several stations toward the outside of the field (Figure 9). Therefore the conceptual model needs modification – either the shallow lateral flow or resaturation zone is not being captured correctly by the model, or the gravity data is sensitive to changes in the deeper system. The fact that the modelled gravity signal is too diffuse suggests that lateral flow may be overestimated. However, the fit gets worse if lateral permeability is reduced, suggesting that it is not simply a decrease in flow and that changes below -900 masl may also be having an effect.

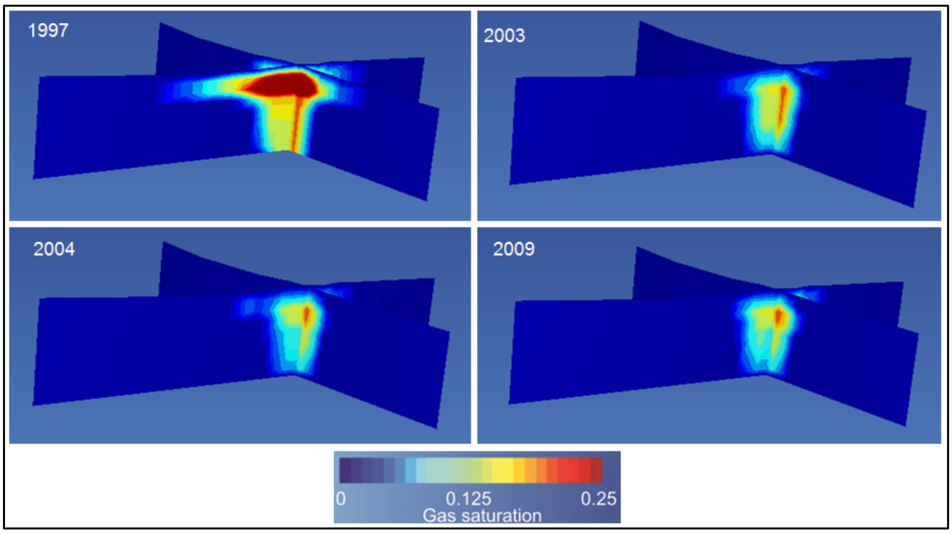

Figure 8. Modelled resaturation of a vapour-dominated zone that can cause most of the increase in gravity measured.

5. CONCLUSIONS

Gravity data helps to constrain the reservoir properties of a geothermal field. Calibrating a reservoir model against gravity data allows the permeability, enthalpy and flow of fluid into the system at depth to be refined. Additional parameters like porosity or fracture volume may also be refined, although there is a trade-off where variables have similar effects. Adding other complementary datasets like geochemistry, magneto-tellurics or temperature and pressure at the same time as gravity can help to further refine parameters and improve reservoir models.

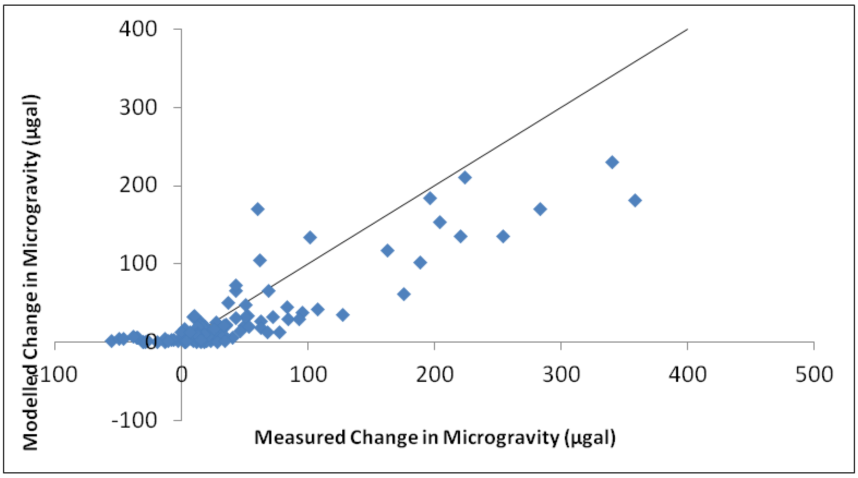

Figure 9. Comparison of modelled and measured data for the best-fit model. Points with zero misfit between measured and modelled data should plot along the straight line.

By adjusting a few parameters in a model, by less than an order of magnitude in our case, the total misfit between modelled and measured gravity data can be decreased by as much as 30%. However, our model consistently underestimates changes in gravity and does not replicate the decreases in gravity measured in some areas. Therefore the conceptual model needs some refinement. The model may not be correctly capturing lateral flow or the amount of resaturation, or the gravity data may be sensitive to changes in the reservoir deeper than -900 masl. In any case, the gravity data is sensitive to more than we expected and provides valuable information for understanding geothermal reservoir behaviour and improving reservoir modelling forecasts.

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