RESERVOIR PROPERTIES AT WAIRAKEI DETERMINED FROM GRAVITY CHANGES DURING THE 1988-1989 REINJECTION TEST

Warwick Kissling and Trevor Hunt[1]
Applied Mathematics Group, DSIR Physical Sciences, P.O. Box 1335, Wellington
[1]DSIR Geology and Geophysics, Private Bag 2000, Taupo

SUMMARY - In this paper we examine gravity measurements taken in conjunction with the 1988 - 1989 reinjection trial in the Eastern Borefield at Wairakei. We derive a 'line source' model for the change in depth of the deep liquid level which gives a reasonable match to the gravity data. The permeability-depth (kh) for this model is 9.9 Darcy-metres (D-m), and the storativity (ϕch) of 9.2×10^{-6} mPa^{-1} is consistent with the assumption that the reservoir contains a free water surface. A better result is obtained with an anisotropic reservoir model, in this case the principal kh's are 18.2 D-m and 5.4 D-m respectively. The direction of largest kh is found to be at an azimuth of 82°. We have computed the transient behaviour of the gravity field using these models, and find that the gravity changes will remain detectable for 3 to 4 years after the cessation of injection. Values of kh and storativity have been obtained fkom pressure transients at WK53 and WK60. These are similar to the 'gravity' values, but it has not been possible to further reconcile the two sets of measurements. In addition a TOUGH simulation based on the homogeneous model is used to check our results and obtain a more realistic picture of the reinjection process, providing a basis for future work.

1 INTRODUCTION

The Eastern Borefield (EBF) reinjection test took place fkom April 1988 to May 1989. A good summary of the test itself, the data collected, and some early analysis is contained in Hunt et.al. (1990).

In this paper we study the gravity changes associated with the reinjection with the aim of using them to understand something of the hydrology of the EBF, and to estimate reservoir parameters which have traditionally (and independently) been obtained from pressure and other measurements.

The first precise gravity survey was carried out at Wairakei in 1961, and repeat surveys have been made at short intervals since then. Results of these surveys, as well as measurement and analysis techniques are given by Hunt (1975 and 1984). This paper uses published gravity data fiom surveys completed in 1988 and 1989.

Reservoir studies at Wairakei using gravity data have so far been based on models where large scale movements of fluid are deduced from changes in gravity, but no specific model for the mass flow is used. In studies of this type, Hunt (1977) used gravity data to determine recharge rates for the period 1958 - 1974, and Allis and Hunt (1986) examined gravity changes induced by exploitation.

The present study significantly extends this approach. The EBF reinjection trial is the first instance where gravity measurements have been made in conjunction with a ***controlled*** injection at Wairakei. The relative isolation of the EBF means that a specific (and hopefully realistic) model of the fluid flow can be proposed, and gravity changes calculated from this. With a flow model of this type we have a tool to understand both the spatial and temporal changes in the gravity, as well as (in principle at least) pressure and temperature data.

This paper starts with a short survey of the available data for the EBF reinjection trial. We then describe two flow models, one analytical and one numerical, followed a section detailing the calculation of gravity changes with these models. Finally we tabulate results and offer some discussion.

2 DATA SURVEY

In this section we summarise information relevant to the EBF reinjection test, the measurements made during the test, and the EBF itself. For more details see Hunt et.al. (1990).

Gravity and Pressure Measurements

Gravity measurements were made before and after the injection test at a number of benchmarks distributed throughout the Wairakei EBF area. They show that the changes in gravity (corrected for elevation changes and smaller 'background' gravity changes) were largest (greater than 100 μGal) near the injection site at WK62, and decreased to zero over distances of between 1 and 2 km, depending on direction (Hunt et.al, 1990).

Deep liquid pressures during the reinjection trial were available at three monitor wells, WK53, WK60 and WK213. WK53 and WK60 (194 m and 154 m respectively from the injection site) showed strong responses, (0.5 - 1 bars) indicating good permeability close to WK62. WK213 is 1.2 km from the injection site and showed only a weak pressure response.

The Eastem Borefield

In this paper we use a very simple model for the EBF, consisting of a two-phase zone overlying a deep liquid zone. Table 1. contains a list of properties of the EBF used in this study.

Parameter	Value	Units
Porosity	0.2	
Two-Phase Zone Saturation	0.5	
Two-Phase Zone Temperature	175	°C
Depth of Free Water Surface	310	m
Liquid Density	900	kgm^{-3}
Liquid Dynamic Viscosity	1.5×10^{-4}	Nsm^{-2}
Liquid Zone Temperature	200-210	°C

Table 1. Physical Parameters for the Eastern Borefield.

Flowrates

During the reinjection test some 5.2×10^{6} tonnes of fluid was injected at WK62. The flowrate was almost constant throughout, except for a short interval in early 1989 when the injection was halted. The temperature of the injected fluid was 130° C, with the depth of the injection feedpoint being 450 m. In this study we use idealised flowrates listed in Table **2.**

Time Interval	Flow (kgs^{-1})
Before 19/4/88	0
19/4/88 - 27/2/89	161
27/2/89 - 11/3/89	0
11/3/89 - 10/5/89	161
After 10/5/89	0

Table 2. Flowrates for Eastern Borefield Reinjection Trial.

3 ANALYTICAL MODEL

In this paper we are attempting to interpret observed gravity changes in terms of a physically reasonable model for the flow in the EBF induced during the reinjection trial. The simplest model with which we might hope to extract some information about the reservoir properties is the 'Theis' or 'line source' solution for the pressure in a radial, homogeneous reservoir of infinite extent, subject to a constant injection rate. This model has been used very successfully for the analysis of pressure transients, giving confidence that it will also apply to the gravity data. The pressure $P(r,t)$ at a particular radius r and time t is

$$P(r,t) = P_0 + qBE_1(r^2/4Dt), \qquad (1)$$

where P_0 is the initial (uniform) pressure and q is the volume flowrate. The function E_1 is the Exponential Integral, as defined in Abramowitz and Stegun (1965). The unknown parameters B (the pressure amplitude) and D (the diffusivity) are to be determined from the gravity data. These contain the parameters that we wish to derive: the permeability-depth (kh) and the storativity (ϕch) (Grant et.al., 1982).

For an anisotropic reservoir the Theis solution is modified to read

$$P(x_1,x_2,t) = P_0 + qBE_1(x_1^2/4D_1t + x_2^2/4D_2t), \qquad (2)$$

where the subscripts $_1$ and $_2$ refer to the principal directions of Diffusivity.

In this case the unknown parameters are B, which contains an effective permeability-depth, D_1 and D_2, the principal diffusivities, and an angle θ (which does not appear explicitly in equation **(2)**) which defines the alignment of the principal axis of diffusivity with respect to geographical North. The physical parameters of interest are then $(kh)_1$, $(kh)_2$ and ϕch.

In the EBF there is a free water surface, and we identify any pressure changes with a change in the water level $h(r,t)$, defined by

$$P_0 = P(r,t) + \rho_w g h(r,t), \qquad (3)$$

where ρ_w is the water density and g is the acceleration due to gravity (g = 9.81 ms^{-2}). The gravity change (Δg) due to the injected fluid is calculated by direct integration over the fluid volume defined by $h(r,t)$, as described in Section 5.

The homogeneous and anisotropic models described here contain free parameters to be adjusted to best match the gravity data. The best fit in each case has been obtained by minimising the sum of squares of the residual (observed - computed) gravity changes over all the benchmarks. The minimisations are non-linear in all the unknowns and we have used the NAG (Mark 12, 1987) subroutine E04JAF to find the solutions.

4 TOUGH MODEL

TOUGH is a variant of the well known geothermal simulator MULKOM, which solves multi-phase (liquid and vapour), multi-component (air and water) flow problems in porous media by the method of integrated finite differences. MULKOM was developed at Lawrence Berkeley Laboratory, and is described by Pruess (1982). In this study we have used TOUGH, despite the fact that air flow is not incorporated into our model, because a number of local enhancements to TOUGH were not yet available with MULKOM.

The TOUGH model was developed to give a more detailed understanding of the reinjection process. It describes the injection of cool fluid into a hot, deep liquid zone. The reservoir and fluid properties used in the model are listed in Table 1. We have used properties similar to those derived from the analytical model. The permeability was chosen to have a value of 25 mD to give a reasonable match to the gravity data, but no further parameter adjustment has been attempted.

One practical difficulty is the number of elements in the TOUGH model. For the computers available 2000 elements is a practical limit. For this reason we chose to model a homogeneous reservoir, where radial geometry can be used, saving a large number of elements. In spite of this reduction, the vertical resolution of the model was restricted to 10 m, in order to adequately cover the combined 500 m vertical extent of the deep liquid and 2-phase zones. The radial extent of the reservoir was taken to be 1.5 km , with elements staggered from 10 m at the centre to 100 m near the boundary. The limit of 1.5 km is almost certainly too large, but was chosen so that boundary effects would not influence the comparison with the analytical model (which assumes no boundary).

Despite these savings the computational time was still long. The reason appears to be the presence of the free water surface, which is displaced into the 2-phase zone as the reinjection proceeds. We have found that the direct linear equation solvers used by TOUGH do not perform well for problems of this type, and have used a bi-conjugate gradient solver due to Van der Vorst (personal communication) with excellent results.

The EBF is observed to be in an almost 'static' state, with a fixed water level and constant saturation in the 2-phase zone. To achieve this state the residual relative permeability was chosen to make the liquid water in the 2-phase zone immobile at a saturation of 0.5. This fixes the pressure to be steam static, close to what is observed.

We also require that the upper and lower boundaries of the model do not influence the fluid flow. Experiments show that a total depth of 500 m (200 m 2-phase zone, 300 m deep liquid) is adequate to meet this condition.

The output from TOUGH consists of pressures, temperatures, and liquid saturations for each element in the model at specified times. From these the density changes can be found. As a check on consistency the integral of the density changes over the whole reservoir was computed. It was found to equal the amount of injected mass to within about 1 %.

5 GRAVITY EFFECTS

Efficient computation of the gravity effect of a mass change of arbitrary distribution is essential for the modelling in this paper. Traditional computational methods, such as given by Talwani and Ewing (1960), have not been used in this paper. The reason is that for our numerical TOUGH model, where the computed density changes are complicated functions of position, direct evaluation of the integral defining the gravity effect is the obvious way to proceed. Furthermore, the problem is already naturally discretised in a manner which makes the integration very simple. While the method described by Talwani and Ewing could be used for our analytic models, the direct method has been maintained for convenience and consistency.

The gravity effect at a point due to a change of mass is the vertical component of the total gravitational attraction of that mass. It is defined by the integral:

$$\Delta g(x_o, y_o, z_o) = \int_V G\rho(z - z_o)/R^3 dV, \qquad (4)$$

where G is the Universal Gravitational constant (G = 6.67×10^{-11} Nm^2kg^{-2}), ρ is the density change, and R is the total distance from the observation point (x_o, y_o, z_o) to the volume element dV at (x, y, z). The vertical component of the attraction is obtained through the factor $(z - z_o)/R$. Contributions to Δg come from all regions where ρ is non-zero.

In the TOUGH model, the density change ρ is calculated for each element from the conditions in that element. For the Theis models we assume that the deep liquid level is displaced into the 2-phase zone according to equations (1), (2) and (3). In this case ρ will be approximately

$$\rho \simeq \phi(1-s)\rho_w. \tag{5}$$

For the values of ϕ (porosity), ρ_w (liquid density) and s (2-phase zone liquid saturation) listed in Table 1., ρ has a value of 90 kgm^{-3}. Uncertainties in these parameters mean that ρ might lie in the range **50** - 120 kgm^{-3}.

The gravity changes are extremely small, and the strict use of SI units is inconvenient. A more useful unit, and that used here, is the microgal (μGal), defined as 10^{-8} Nkg^{-1}.

6 RESULTS and DISCUSSION

We start this section with a brief discussion of the gravity data. Figure 1 shows the relationship between the observed gravity changes Ag and distance from the injection site at WK62. There is a decrease in the values of Ag with distance, indicating some radial symmetry in the data. For this reason, we chose, as a first approximation, the radial, homogeneous Theis model (equation 1) for the flow in the EBF, and the solid line in Figure 1 shows the best fit from this model.

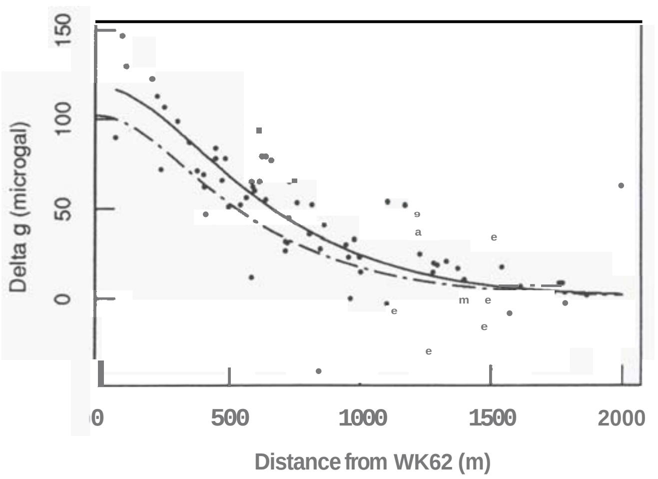

Figure 1. Plot of gravity changes (Ag) versus distance from WK62 at the end of the reinjection test. The solid line is the best fit radial 'Theis' solution. The dashed line comes from the TOUGH model.

Next, we note in Figure 1 a group of gravity observations between 1 and 1.5km from WK62, which appear to have high values of Ag. These points form two groups on the map of the benchmarks (+'s in Figure 2) - one to the East and the other to the West of the central region. These are interpreted as evidence for anisotropic permeability in the reservoir, ie. a higher kh in the (approximately) East-West direction, than in the North-South. We have tried to model this effect with equation (2). Figure 3 shows a plot of the contours of computed *Ag* for this model. Interestingly, the alignment (82° azimuth) of the direction of highest permeability does not correspond to the direction of faulting at Wairakei (about 45°) (Grindley, 1965), although, given the simplicity of the model, the agreement with a contours given by Hunt et.al. (1990) is excellent.

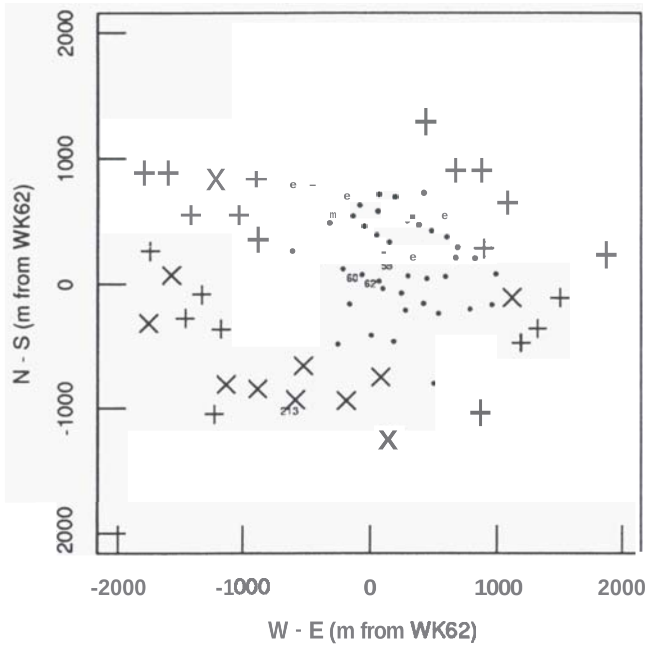

Figure 2. Locations of Gravity Benchmarks, Centered on WK62. +'s indicate points in the East-West groups and ×'s show benchmarks where Ag is negative.

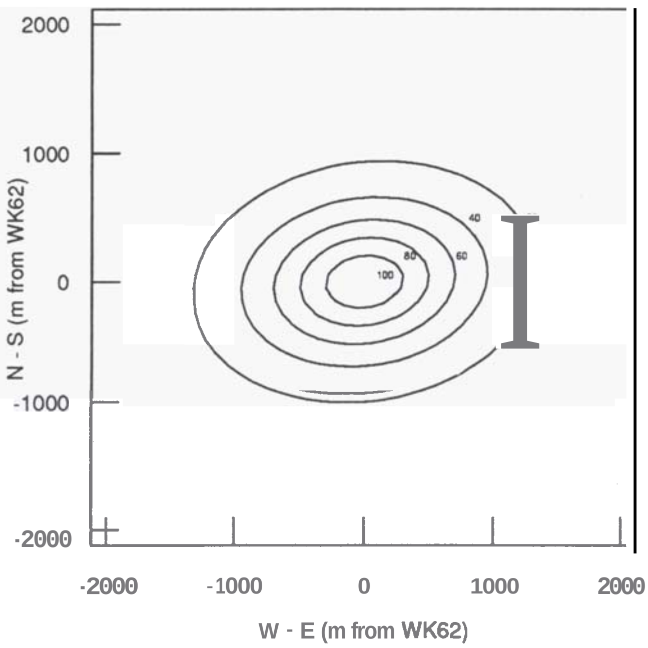

Figure 3. Contours of Ag computed from anisotropic model. The contour values are in μGal.

Figure 4 shows the best fit Theis solutions to the main pressure transient at WK53 and WK60. The fits are excellent. The pressures have been adjusted by an arbitrary amount so that they fit onto a single plot.

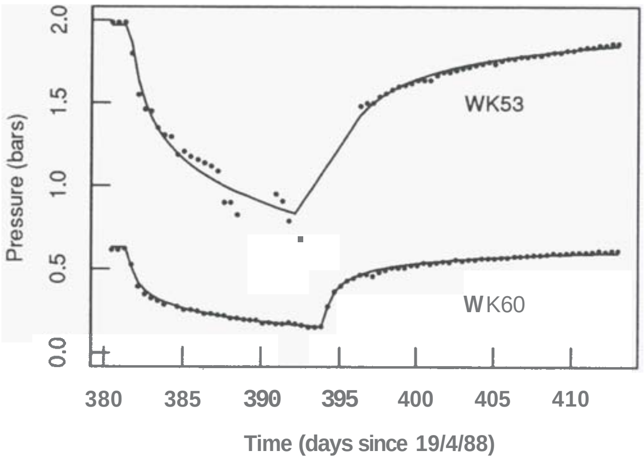

Figure 4. Fitted Pressure Reponses at WK53 and WK60. The pressure scale is arbitrary.

Table **3** lists the parameters derived from the two gravity models, and for the pressure transients. The values of kh derived from the pressure tests are much greater than those from the gravity data. The reverse is true for the values of ϕch. These differences can be simply explained. **As** the pressure transients occur quickly they access only the *fracture* system in the EBF, and we see short timescale responses characterised by high permeabilities and low porosities. On the other hand the gravity data 'sees' the long timescale behaviour due to 'blocks' and fractures acting together. To reconcile these two types of response it will be necessary to use a more complex model such as a double porosity model, (McGuinness, 1986).

Model/Data	kh (D-m)	ϕch (mPa^{-1})
Homogeneous Gravity	9.9	9.2×10^{-6}
Anisotropic Gravity	18.2, 5.4	8.7×10^{-6}
WK53 Pressure	69	6.2×10^{-7}
WK60 Pressure	232	8.3×10^{-7}

Table 3. Summary of Derived Reservoir Parameters.

The fit shown in Figure 1 is moderately good, although the data is quite 'noisy'. Hunt et.al.(1990) consider the significance level of the gravity measurements to be less than 20μGal, and the scatter in the plot about the best fit curve seems to support this. One result of this is that the measures of goodness of fit are misleading. The scaled sum of squares of residuals are 0.86 and 0.79 for the homogeneous and anisotropic models respectively. Despite this modest improvement, we are confident that the structure shown in Figure 2 is real.

We also note in Figure 1 a region centered about at 1.25 km where many of the measured gravity changes are negative. This implies a mass deficit in this area, which cannot be accommodated with our present simple models. The benchmarks involved lie predominately to the West and South-West of WK62, and are shown in Figure 2 as $\times$'s.

Figure 5 shows the transient behaviour of the gravity anomaly, computed with the Theis model, for various times after the end of the reinjection trial. The maximum value of Δg declines to 20μGal about **3** years after the end of the reinjection, thus becoming only marginally detectable. The observation of this transient behaviour would have provided confirmation of the models used in this paper, and a basis for further, more detailed modelling, but unfortunately no data is available.

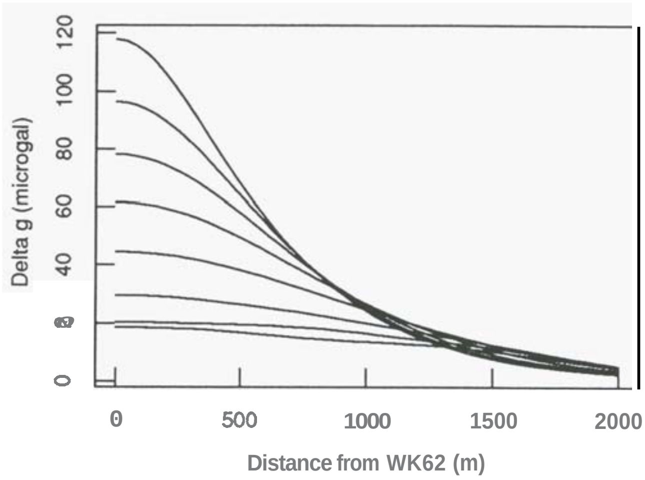

Figure 5. Transient behaviour of the gravity changes, computed from the Theis model. Times for each curve, from top to bottom, are approximately 0,.1,.25,.5,1,2,3 and 4 years, measured from the end of the reinjection test.

Figure 6 shows the density difference at the end of the reinjection test as a function of position, as computed by the TOUGH model. There are two regions of increased density. The first, surrounding the injection point (x) has a density change of about 20 kgm^{-3} and is due to the cooler temperature of the injected fluid. The second region (y) is where the deep liquid level has been displaced into the 2-phase zone. Region (y) has a rather larger density change (90 kgm^{-3}) and is closer to the surface, and therefore dominates the gravity signal. Although not well defined in this plot, it is *precisely* this region that is represented by our analytical models. **A** third region (z) experiences a slight decrease in density (up to 2 kgm^{-3}) due to the deep hot fluid displacing the cooler water near the free surface, which in turn is displaced into the 2-phase zone.

The gravity change computed from the TOUGH model at the end of the reinjection trial is plotted (dashed line) in Figure 1. The discepancy between this and the 'Theis' solution is probably due to the rather poor resolution (large elements) of the TOUGH model. The obvious ‘steps’ in the water level in Figure 6 show that the 10 m vertical resolution of the TOUGH model is also inadequate for matching pressure histories. It implies that the smallest pressure change that can be modelled is about 1 bar.

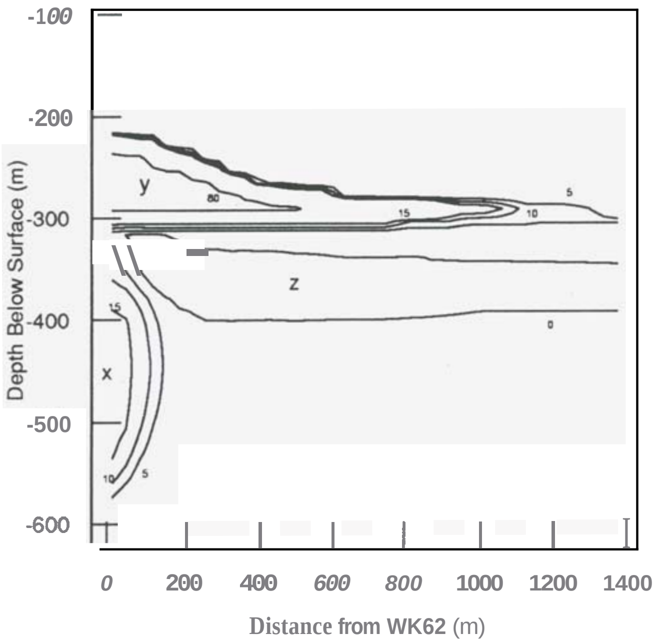

Figure 6. Regions of density change at the end of the reinjection trial, computed from the TOUGH model. Contour values are in kgm^{-3}. Some contours have been omitted for clarity.

7 ACKNOWLEDGEMENTS

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