

Estimation of reservoir permeability using gravity change measurements

Trevor M. Hunt^a and Warwick M. Kissling^b

^a Institute of Geological and Nuclear Sciences, Wairakei Research Centre,
Private Bag 2000, Taupo, New Zealand.

^b Institute for Industrial Research and Development, P O Box 31 310,
Lower Hutt, New Zealand.

ABSTRACT

Exploitation of a liquid-dominated geothermal system generally results in a transfer of mass that causes measurable changes in gravity. When the rate of mass transfer is controlled by the permeability of the reservoir rocks then analysis of measured gravity changes, using numerical reservoir simulation models, can yield values for reservoir properties. One such case is during the early stages of exploitation, during the formation and expansion of a 2-phase zone.

Calculations using MULKOM models show that for Wairakei field the gravity changes associated with permeabilities of 50 and 100 md would be clearly distinguishable (> 50 microgal) in less than 2 years. A measured gravity change of -415 microgal between 1950 and 1961 suggests a permeability of 100 md for rocks in the upper part of the 2-phase zone. This value is consistent with those obtained from well tests.

INTRODUCTION

The best documented behaviour of a liquid-dominated geothermal system during exploitation is probably that for Wairakei Geothermal Field where continuous production has taken place since 1958. In its natural (unexploited) state, Wairakei is believed to have contained a thin liquid-dominated 2-phase zone overlying a 1-phase deep liquid zone (Grant and Horne 1980; Donaldson et al 1983). The nomenclature used here is that used by Allis and Hunt (1986).

When exploitation began, production was mainly from the deep liquid zone beneath a small area (1 km^2) known as the Main Production Borefield (Fig. 1). Removal of fluid resulted in a pressure drop which caused boiling to occur in the upper part of the reservoir. The 2-phase zone expanded both laterally and vertically, and by the early 1970's was about 500 m thick. The 2-phase zone also divided into an upper zone ("steam zone" or "vapour-dominated zone") in which steam is the main

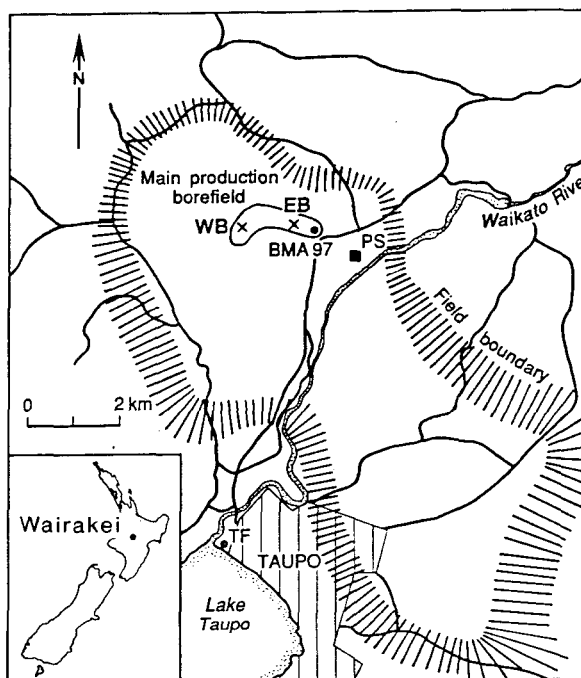


Fig. 1: Map of Wairakei Geothermal Field showing the location of the Main Production Borefield and its parts. EB = Eastern Borefield; WB = Western Borefield; TF = Taupo Fundamental benchmark; PS = geothermal power station.

pressure-controlling phase, and a lower zone ("liquid-dominated zone") in which liquid water is the continuous phase but boiling conditions exist and some steam is present (Allis and Hunt, 1986). The boundary between these zones is believed to be gradational, but there is little information available about the vertical distance over which the changes occur. The steam and liquid-dominated zones may not be homogeneous; liquid saturation in the steam zone may be smaller at the top of

the zone than at the bottom (Hunt, 1988). Pressures in the deep liquid zone fell by up to 2.5 MPa (25 bar), but have been relatively stable in most parts of the field since the early 1970's. However, gravity and pressure data suggest that in the Eastern Borefield (Fig. 1) the deep liquid level has risen by nearly 100 m since the early 1980's (Hunt, 1988).

Measured gravity changes have been used in New Zealand geothermal fields to: determine recharge over the whole field (Hunt, 1977); estimate changes in saturation in the steam zone in different parts of the field (Allis and Hunt, 1986); check the validity of numerical reservoir simulation models (Blakeley and O'Sullivan, 1985; Hunt et al, 1990a); and determine the path of reinjected fluid (Hunt et al, 1990b). In this paper we extend the application of gravity change measurements further by showing how, under certain circumstances, they can be used to determine the permeability (k) or permeability-thickness (kh) of the reservoir rocks. We use Wairakei field as an example because of its well-documented pressure and gravity data.

PERMEABILITY MEASUREMENTS AT WAIRAKEI

The response of pressure in wells in the outer parts of the Wairakei field to changes in discharge from wells in the borefield is very rapid, and pressure changes over most of the field have been uniform, indicating very high values for horizontal permeability (Bolton, 1970).

Values of permeability (k) and permeability-thickness (kh) at Wairakei (Table 1) have previously been determined from (in approximate order of importance):

- Well tests such as interference and injection tests. Most published values are for the Eastern Borefield, and the results are poorly documented. Values range from 4-500 md for k, and from 10-170 d-m for kh.
- Reservoir simulation models which match response of the field to exploitation. Early models were 1-D matched only to pressure changes for a 5-10 year period; later models were 2½ or 3-D and matched pressure, temperature, recharge and enthalpy data over more than 20 years. Most later models were consistent with values of 25 - 50 md for horizontal permeability and 10 - 20 md for vertical permeability. Other modelling studies at Wairakei (Mercer et al, 1975; O'Sullivan et al, 1983) assumed values for permeability, and adjusted other parameters, (e.g. recharge coefficient and reservoir area).
- Laboratory measurements on core samples. All these measurements showed $k \ll 1$ md, however, they measure only pore permeability and do not take into account fracture permeability which is of much greater significance.

GRAVITY CHANGES

The main causes of gravity changes resulting from mass changes in the reservoir according to Allis and Hunt (1986) are (in approximate order of importance):

- Liquid drawdown in the 2-phase zone.
- Saturation changes in the 2-phase zone (dry out due to steam loss, or cooling and condensation from invading groundwater).
- Changes in deep liquid density due to temperature changes.

The gravity effects of changes in deep liquid density due to pressure changes, pore compaction, and silica precipitation are generally negligible (Allis and Hunt, 1986).

The first two causes are associated with the transfer of large amounts of mass into or out of the 2-phase zone. In some cases (but not all) the rate of transfer of this mass is controlled, or at least significantly influenced, by the permeability of the rock in the 2-phase zone. The rate of mass transfer, together with fluid density and geometric factors, determine the rate of gravity change. Hence from the rate of gravity change, fluid density change, and the geometry of the 2-phase zone it is possible to calculate the permeability in the vicinity of the region of mass change.

MODELLING

Conceptual Model

The conceptual model for the development of the 2-phase zone as a result of production from the reservoir at Wairakei is of a boiling front expanding, both laterally and vertically (Fig. 2). Large density changes are associated with this development of the 2-phase zone and result mainly from the conversion of liquid water to steam. These density changes give rise to gravity changes.

Numerical Model

To determine the permeability from gravity change data we set up a simple numerical reservoir simulation model for the initial exploitation of the Wairakei field and computed the theoretical gravity changes for different values of horizontal permeability.

The calculations were made using the simulator MULKOM (Pruess, 1983). To minimise computational time we chose for the model a homogeneous reservoir having radial geometry. The radius of the model was initially taken as 3 km, with element dimensions ranging from 100 m at the centre to 250 m near the boundary; each model element was 10 m thick and the total

TABLE 1: Summary of published values of permeability (k) and permeability-thickness (kh) of reservoir rocks at Wairakei Geothermal Field. v = vertical, h = horizontal, 1 md = 10⁻¹⁵ m².

k (md)	kh (d-m)	Details	Reference
WELL TEST VALUES			
100-500	*	No details given	Elder 1966
4 h	*	Pressure response at WK223 to borefield production changes	McNabb et al 1975
4 h	*	Pressure transients at WK33 and WK36	
*	15-75	Pressure build-up test on 4 dry steam wells	Grant 1978
*	14-33	Steam fed wells WK4/2, 36, 42 (Eastern Borefield)	Grant 1980
50-500	*		Elder 1981
*	3	Injection test on impermeable well WK301	Allis et al 1985
*	10-100	Interference tests during initial development	Electricorp 1990
*	100-150	Measurements in monitor wells, Eastern Borefield, 1988-89	
*	100-170	Injection test in Eastern Borefield	Hunt et al 1990b
VALUES DETERMINED FROM RESERVOIR SIMULATION MODELS			
25 v	*	Simple 1-d model	Marshall 1966
11	*	Simple 1-d steady state flow model	Donaldson 1968
12 v	*	From model for natural discharge	Grant 1970
4	*	Calculated from temperature decrease due to production	McNabb et al 1975
7 h	*		
8 v	*	From pressure drop in field	
		Calculated from natural output of whole field	
25	*	Gross permeability from single-phase model	Grant 1977
50	*	Simple single-phase model of whole field	Robinson 1977
50	*	Lumped parameter model with instantaneous drainage; pressure match	Sorey and Fradkin 1979
25	*	Lumped parameter model with slow drainage; pressure match	
40	18	Unconfined aquifer model	Zais and Bodvarsson 1980
45	*	Lumped parameter model with instantaneous drainage; pressure match	Fradkin et al 1981
27	*	Lumped parameter model with slow drainage; pressure match	
35 h	30 -35	Confined aquifer model, based on effects at Tauhara	Wooding 1981
20-300 h	*	Distributed parameter, 2D model; pressure, enthalpy, recharge match	Blakeley and O'Sullivan 1982
20 v			
5 v	*	Calculated from natural output of field and pressure gradient	Donaldson et al 1983
VALUES FROM LABORATORY MEASUREMENTS			
1	*	30 specimens of various rock types, using water	Elder 1966
0.01-0.05	*	Cores from WK37 (Eastern Borefield), pore pressure 100 bar, confining pressure 150-250 bar; using water	Pritchett et al 1978

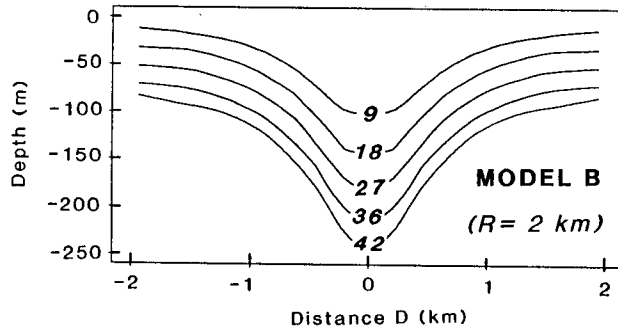
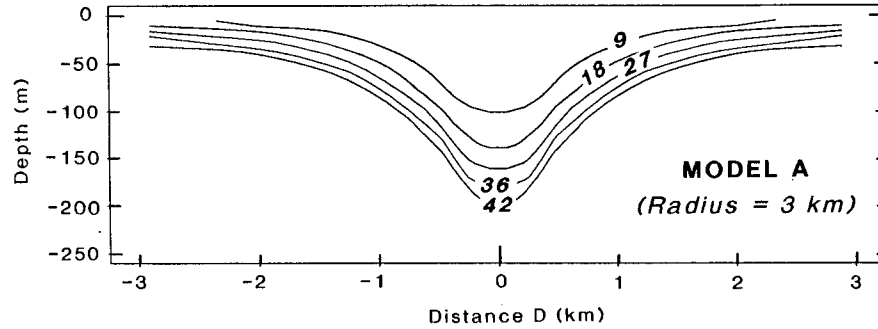


Fig. 2: Development of 2-phase zone (saturation = 0.9) at Wairakei according to MULKOM models for $k = 100$ md. Values in italics (9, 18, . .) indicate months after start of production. Depths indicate thickness of zone beneath the top of the reservoir; vertical exaggeration is 8x.

thickness was taken to be 500 m. The region of fluid withdrawal was taken to be 200 m thick, 900 m in diameter, located at the bottom centre of the model. The discharge rate was assumed to be 1200 kg/s; actually, mass output at Wairakei rose from about 460 kg/s in early 1958 to 1620 kg/s at the end of 1960 (Electricorp, 1990). The temperature of the liquid was taken (initially) to be 200°C, the (connected) porosity of the reservoir rocks to be 0.2, and pressures to be hydrostatic. Natural mass discharge from surface features was assumed to balance recharge: the natural discharge rate for the period 1958 - 1962 was about 400 kg/s and mass inflow into the 2-phase zone was 200 - 700 kg/s (Allis, 1981). Permeability was assumed to be isotropic. Saturation changes in the 2-phase zone were allowed to develop in the model with the residual liquid saturation set at 0.3 (Blakeley and O'Sullivan, 1985).

The output from MULKOM consists of values of pressure, temperature, and liquid saturation for each element in the model at specified times after production commences. From these values the density change ($\Delta\rho$) in each element for different periods of time was determined (Hunt et al, 1990a). The gravity effects (Δg) of the density changes in all the elements were then calculated by direct evaluation of the integral:

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

where G is the Universal Gravitational constant ($6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$), and R is the distance from the observation point (x_o, y_o, z_o) to the volume element dV at (x, y, z) .

Theoretical gravity changes with time, at the centre of the field, were calculated for reservoir permeabilities of 50, 100, and 200 md, for a period of 42 months from the start of production. The results (Fig. 3A) clearly show that gravity changes of greater than 100 microgal would be expected in the area above the production zone in 3-6 months from the start of production. More importantly, the size of the changes soon differs greatly for the assumed values of permeability. For example, after only 12 months the gravity change at the centre of the borefield is predicted to be nearly -330 microgal for a permeability of 50 md, and -180 microgal for a permeability of 200 md. After 36 months of production the difference in predicted gravity changes at the centre of the borefield, for permeabilities of 50 and 200 md, is about 300 microgal. The size of the theoretical changes, after a relatively short time, clearly exceed the errors in gravity change measurement and gravity changes that are likely to occur as a result of shallow groundwater level changes, topographic changes, or other influences (about 50 microgal). This shows that measurements of gravity change in the borefield area are a powerful tool for estimating reservoir permeability.

To check if the results were strongly model dependent we repeated the calculations for a model with radius 2

km (Model B, Fig.2), and at points 1 and 2 km from the centre (Fig. 3B, C). This data suggests that the gravity changes are most sensitive to differences in reservoir permeability at points close to the centre of the model, and here are not particularly dependent on the radius of the model. At distances of more than 1 km from the centre, however, discrimination is poor and the theoretical gravity values are influenced by the radius.

RESULTS AT WAIRAKEI

Unfortunately, no precise gravity survey was made at Wairakei before production began; the first such survey was not made until August 1961, about 3.5 years after production had commenced. The only data available in the borefield area spanning the period of 2-phase zone development is a gravity change of $-415 (\pm 100)$ microgal between 1950 and 1961 at benchmark A97 (Hunt, 1977). This benchmark is located close to the centre of production in the early 1960s (Fig. 1). If it is assumed that there was no significant mass withdrawal before 1958, and the value of -415 microgal is plotted on Figure 3A, the point lies close to the theoretical gravity change curve for a permeability of 100 md. In view of the simplifications and assumptions made in setting up the model and the large error in the gravity change, this value for permeability must be considered only approximate. The value of 100 md is, however, consistent with values obtained by well tests and some previous simulation models and suggests that the method is viable. If gravity values at a few selected points in the borefield area had been measured immediately before production started and the measurements repeated at 6 to 12 month intervals for several years after production had begun, then a much better estimate of permeability could be made, especially if a more detailed model was used for the numerical simulation.

ACKNOWLEDGEMENTS

This work was financed by the New Zealand Foundation for Science Research and Technology (Output Area 21 - Energy).

REFERENCES

- Allis, R.G.; Currie, S.A.; Leaver, J.D.; Sherburn, S. 1985: Results of injection testing at Wairakei Geothermal Field, New Zealand. 1985 International Symposium on Geothermal Energy: 289-294.
- Allis, R.G. and Hunt, T.M., 1986: Analysis of exploitation induced gravity changes at Wairakei geothermal field. *Geophysics*, 51: 1647-1660.
- Bolton, R.S. 1970: The behaviour of the Wairakei Geothermal Field during exploitation. *Geothermics Special Issue*, 2: 1426-1449.

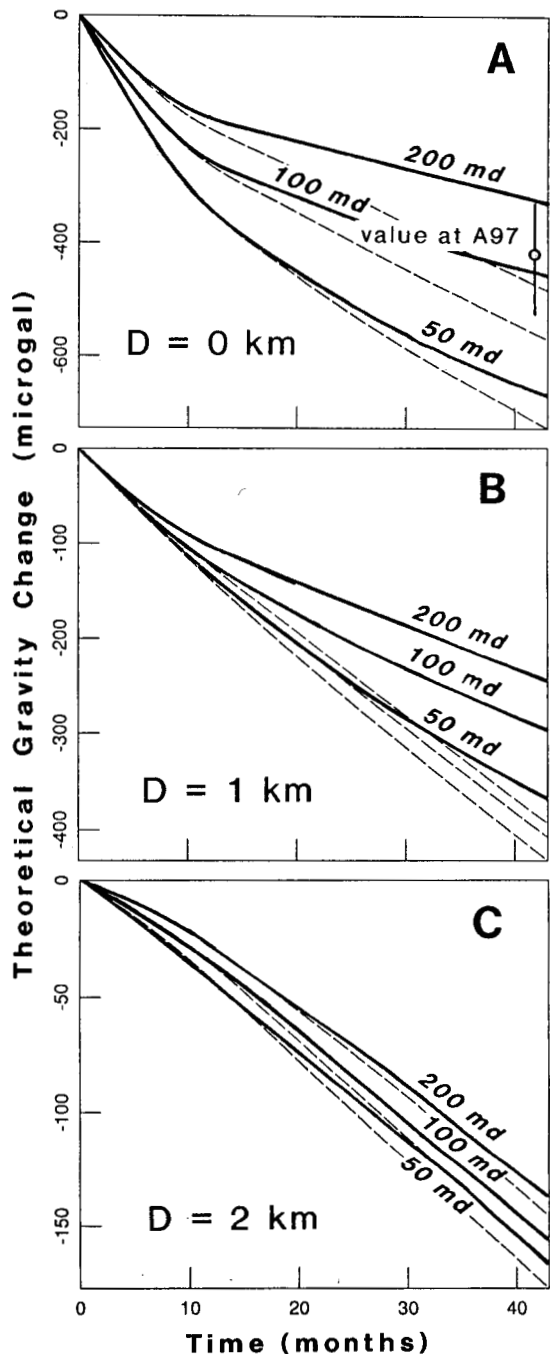


Fig. 3: Theoretical gravity changes for the 2-phase zone development at Wairakei for various values of permeability calculated using the MULKOM models (A, B). Solid lines indicate gravity changes calculated for Model A ($R = 3$ km); broken lines for Model B ($R = 2$ km). For clarity, only the lines for Model A are labelled with the values of permeability used. Note how quickly the difference between the lines exceed the significance level of the gravity measurements (approx. 50 microgal) for a point at the centre of the model.

- Blakeley, M.R. and O'Sullivan, M.J. 1982: Modelling of production and recharge at Wairakei. Proceedings 4th NZ Geothermal Workshop: 23-31.
- Blakeley, M.R. and O'Sullivan, M.J. 1985: Gravity changes predicted by numerical models of the Wairakei Geothermal Field. Proceedings 7th NZ Geothermal Workshop: 49-53.
- Donaldson, I.G. 1968: The flow of steam water mixtures through permeable beds: a simple simulation of a natural undisturbed hydrothermal region. N.Z. J. Science, 11: 3-23.
- Donaldson, I.G.; Grant, M.A.; Bixley, P.F. 1983: Nonstatic reservoirs: the natural state of the geothermal reservoir. Journal of Petroleum Technology, Jan 1983: 189-194.
- Elder, J.W. 1966: Heat and mass transfer in the earth: hydrothermal systems. New Zealand DSIR Bulletin 169.
- Elder, J. 1981: Geothermal Systems. Academic Press, London.
- Electricorp 1990: Water right applications and impact assessment. Electricity Corporation of New Zealand.
- Fradkin, L.J.; Sorey, M.L.; and McNabb, M.A. 1981: On identification and validation of some geothermal models. Water Resources Research, 17: 929-936.
- Grant, M.A. 1977: Approximate calculations based on the simple one-phase model of a geothermal field. N.Z. J. Science, 20: 19-25.
- Grant, M.A. 1978: Pressure changes in the two-phase zone at Wairakei. Geothermal Circular MAG 20. Unpublished internal report, Applied Mathematics Division, DSIR, Wellington.
- Grant, M.A. 1980: Notes on Wairakei Wells 1-63. Geothermal Circular MAG 28. Unpublished internal report, Applied Mathematics Division, DSIR, Wellington.
- Grant, M.A.; Donaldson, I.A.; and Bixley, P.F. 1982: Geothermal Reservoir Engineering. Academic Press, London.
- Grant, M.A. and Horne, R.N. 1980: The initial state and response to exploitation of Wairakei Geothermal Field. Geothermal Resources Council Transactions, 4: 333-336.
- Hunt, T.M. 1977: Recharge of water in Wairakei Geothermal Field determined from repeat gravity measurements. N.Z. Journal of Geology and Geophysics, 20: 303-317.
- Hunt, T.M. 1988: Update on gravity changes in the main production borefield at Wairakei. Proceedings 10th N.Z. Geothermal Workshop: 129-132.
- Hunt, T.M.; Allis, R.G.; Blakeley, M.R.; and O'Sullivan, M.J. 1990a: Testing reservoir simulation models for the Broadlands geothermal field using precision gravity data. Geothermal Resources Council Transactions, 14: 1287-1294.
- Hunt, T.M.; Bixley, P.F.; Carey, B.S.; McCabe, W.M.; and Young, R.M. 1990b: Results of a 13-month reinjection test at Wairakei Geothermal Field, New Zealand. Geothermal Resources Council Transactions, 14: 1192-1200.
- McNabb, A.; Grant, M.A.; and Robinson, J. 1975: Permeability estimates. Technical Report 34. Applied Mathematics Division, DSIR, Wellington, New Zealand.
- Marshall, D.C. 1966: Preliminary theory of the Wairakei geothermal field. N.Z. J. Science, 9: 651-673.
- Mercer, J.W.; Pinder, G.F.; and Donaldson, I.G. 1975: A Galerkin-Finite element analysis of the hydrothermal system at Wairakei, New Zealand. J. Geophysical Research, 80: 2608-2620.
- O'Sullivan M.J.; Zivoloski, G.A.; and Blakeley, M.R. 1983: Computer modelling of geothermal reservoirs. Report 318. Department of Theoretical and Applied Mechanics, Auckland University, New Zealand.
- Pritchett, J.W., Rice, L.F. and Garg, S.K. 1978: Reservoir engineering data, Wairakei Geothermal Field, NZ. Systems, Science and Software, La Jolla, California (3 vols).
- Pruess, K. 1983: Development of the general purpose simulator MULKOM. Report LBL-15500, Lawrence Berkeley Laboratory, University of California, Berkeley, United States of America.
- Robinson, J.L. 1977: An estimate of the lifetime of the Wairakei geothermal field. N.Z. J. Science, 20: 27-29.
- Sorey, M.L. and Fradkin, L.J. 1979: Validation and comparison of different models of the Wairakei geothermal reservoir. Proceedings 5th Workshop on Geothermal Reservoir Engineering, Stanford: 215-220.
- Wooding, R.A. 1981: Aquifer models of pressure drawdown in the Wairakei-Tauhara geothermal region. Water Resources Research, 17: 83-92.
- Zais, E.J. and Bodvarsson, L. 1980: Analysis of production decline in geothermal reservoirs. Report LBL - 11215. Lawrence Berkeley Laboratory, University of California, Berkeley, United States of America.