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RECENT INTERFERENCE TESTS AT NGAWHA AND OHAAKI

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ABSTRACT

Interference tests conducted at Ngawha geothermal field in New Zealand in October and November 1983 show that, as was apparent in previous tests, the field is rather poorly modelled by an infinite homogeneous reservoir. A bounded double porosity model is found to more successfully fit the observed pressure responses.

Extensive interference testing of the highly permeable rhyolite formations overlying the western Broadlands geothermal field has indicated a previously unconfirmed division of the rhyolites into two groups, which are not in good communication with each other.

NGAWHA

The pressure responses in wells NG4, NG8, NG9 shallow, NG11 and NG12 to discharge from NG13 and injection into NG3 were measured during October and November, 1983. Figure 1 indicates the relative locations of these wells. The responses from NG8, NG9 shallow and NG11 were similar in timing and scale of response. Those in NG4 were affected by gas buildup, and an unexplained linear trend affects part of the response from NG12. Gaps in the data are attributable largely to the ravages of cows and wild pig.

As indicated in Figure 2, the Theis or line-source solution to the infinite homogeneous reservoir model gives a remarkably poor fit to the pressure data. Since there is a variable flow rate at two source wells, the fit was accomplished by superposition and by minimising the residual sum of squares numerically. The results say very little except that Ngawha is not behaving like an infinite homogeneous reservoir. Fits of this model to previous tests at Ngawha were also not very successful (Bradford et al., 1983; McGuinness et al., 1984).

All wells show a rapid response to injection or production, observable within an hour at distances of 2 km. This suggests that any boundaries to the reservoir will have an appreciable influence within a short time. Noting that the reservoir material is fractured greywacke, it would seem reasonable to attempt to model the reservoir as a double porosity medium with a boundary. This approach is also suggested by the responses to the long-time production of NG13, which are almost linear in time, but indicate recharge from somewhere (e.g. low permeability blocks of greywacke).

FIGURE 1

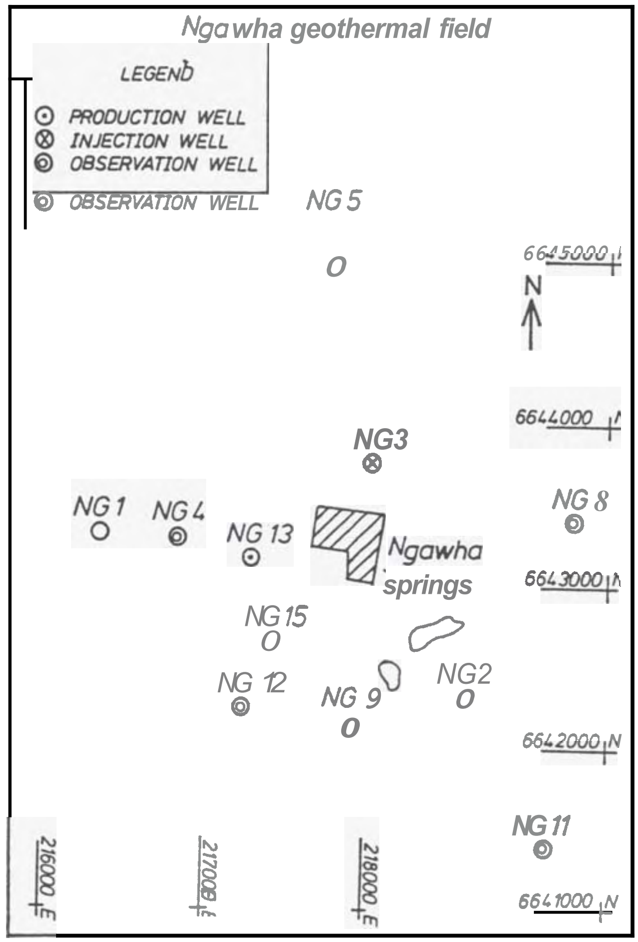
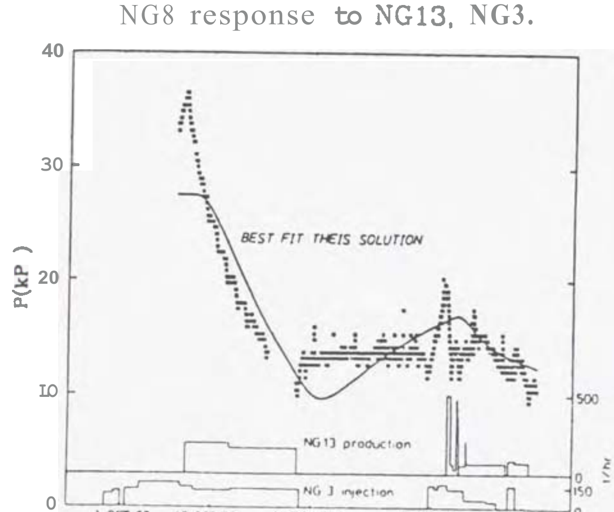


FIGURE 2

NG8 response to NG13, NG3.



A BOUNDED DOUBLE POROSITY MODEL

The model settled on is an adaptation of one analysed by McNabb (1978). The reservoir is modelled by a porous medium composed of a homogeneous distribution of fractures and blocks. The fractures partition the medium into a matrix of blocks, each of characteristic length scale ε, over which the fracture pressure is assumed relatively constant. The fractures are of low porosity and high permeability, while the blocks are of high porosity and low permeability. The blocks then act as sources of fluid, connected to each other and to the wells and the boundaries by the fracture system. At short times after a well is produced somewhere in the fracture system, the reservoir behaves like a low porosity high permeability homogeneous reservoir, with only the fractures affecting the pressure distribution. This regime is not usually observable in practice, as the time is so short. In the absence of boundaries, an intermediate regime follows, as the pressure disturbances penetrate the blocks. This is followed by a long-time regime in which the reservoir behaves like a homogeneous reservoir with a composite diffusivity (with approximately the permeability of the fractures and the porosity of the blocks). There is no evidence for this long-term regime in the data from Ngawha, suggesting that boundary effects become important during the intermediate regime.

A crucial assumption in the model used here is that flow from each block is normal to the block boundary. This assumption is valid for times much less than the time taken for a pressure disturbance to reach the centre of a block. The advantage of this assumption is that it allows the model to be solved without specifying the block geometry.

The notation used is as follows:

$p_f(x,t)$ = the fluid pressure at point x in the fractures at time t.

$p_m(x,y,t)$ = the fluid pressure at point y and time t in the matrix block in the neighbourhood of x.

k_f, ϕ_f = fracture permeability and porosity.

k_m, ϕ_m = block permeability and porosity.

c = compressibility of water.

μ = dynamic viscosity of water.

Assuming homogeneity in each block, the usual approach for single-phase flow yields

$$\phi_m \mu c \frac{\partial p_m}{\partial t} = k_m \nabla_y^2 p_m \ , \quad y \in V_x \ ,$$

$$p_m(x,y,t) = p_f(x,t) \ , \quad y \in S_x \ , \qquad (1)$$

where V_x is the volume and S_x is the boundary surface of the block in the neighbourhood of x, and ∇_y^2 is the Laplacian in y.

Assuming the fractures form a homogeneous medium, the blocks act as sources to give

$$\phi_f \mu c \frac{\partial p_f}{\partial t} = k_f \nabla_x^2 p_f + S(x,t) \ ,$$

$$S(x,t) = \frac{k_m}{V_x \mu} \iint_S \nabla_y p_m(x,y,t) \cdot d\sigma, \ y \in S_x . \qquad (2)$$

$S(x,t)$ is the source strength of fluid flowing into the fractures from the block near point x, at time t.

The model is solved in three dimensions, for a homogeneous spherical reservoir. (For a two-dimensional infinite reservoir, see Najurieta (1980).) The boundary condition at radius $r = 0$ is that for a fluid source of strength q, turned on at $t = 0$:

$$p_m = p_f = 0 \ , \qquad t = 0 \ ,$$

$$\lim_{r \to 0}\left(4\pi r^2 \frac{k_f}{\mu}\frac{\partial p_f}{\partial r}\right) = q \ , \quad t > 0 \ , \qquad (3)$$

where $r^2 \equiv \sum_{i=1}^{3} x_i^2$, and q is a volume flow rate.

A boundary is imposed at a radius R:

$$\frac{\partial p_f}{\partial r} = 0 \ , \quad r = R \ , \quad \text{for all } t \ . \qquad (4)$$

When equations (1) and (2) are transformed to Laplace space, they factor (McNabb, 1978). Assuming normal flow in the blocks, they may be solved subject to boundary conditions (3) and (4) (McNabb solves for the infinite reservoir case). The solution in Laplace space does not invert analytically. The inversion integral is

$$p_f(r,t) = \frac{1}{2\pi i}\int_C \frac{e^{st}}{r}[A \exp(\alpha r) + B \exp(-\alpha r)]ds \ , \qquad (5)$$

where

$$A = \frac{-q\mu}{4\pi k_f s}\left(\frac{\alpha R + 1}{\alpha R + 1 + (\alpha R - 1)\exp(2\alpha R)}\right) \ ,$$

$$B = \frac{q\mu}{4\pi k_f s}\left(\frac{\alpha R - 1}{1 - \alpha R - (1 + \alpha R)\exp(-2\alpha R)}\right)$$

$$\alpha = \lambda_f \sqrt{s + b\sqrt{s}} \ ,$$

$$\lambda_f^2 = \phi_f \mu c / k_f \ ,$$

$$b = \frac{A}{V}\frac{k_m}{k_f}\frac{\lambda_m}{\lambda_f^2} = \frac{A}{V}\frac{\sqrt{k_m \phi_m}}{\phi_f \sqrt{\mu c}}$$

$$\lambda_m^2 = \phi_m \mu c / k_m \ ,$$

A = the surface area of a typical block,

V = the volume of a typical block,

and C = a vertical line to the right of any singularities in the s plane.

A small time approximation to p_f is obtained by expanding the integrand for large values of $Re\ s$, and is (McNabb, 1978)

$$p_f(r,t) \sim -\frac{q\mu}{4\pi k_f r}\exp(-\lambda_f b r/2)\, \mathrm{erfc}\left(\frac{\lambda_f r}{2\sqrt{t}}\right),$$

$$t \to 0 \ .$$

This is the classical porous medium solution with the fracture values of permeability and porosity, modified by an exponential factor which is independent of time and involves both fracture and block properties.

A long-time approximation to $p_f(r,t)$ follows from a consideration of its Laplace transform $\overline{p}_f(s,t)$ in the neighbourhood of $s = 0$. Noting that $\overline{p}_f(s,t)$ is analytic except at $s = 0$, where it has a branch point, and that in the neighbourhood of $s = 0$

$$\overline{p}_f(s,t) \sim a_0 s^{-3/2} + a_1 s^{-1} + a_2 s^{-1/2} + \ldots ,$$

$$s \to 0 ,$$

where a_0, a_1, a_2 are independent of s, and replacing the path of integration in the inversion integral by a path wrapped around the negative half of the real axis, a large-time asymptotic expansion for p_f may be obtained (e.g., Carrier et al., 1966) as

$$p_f(r,t) \sim -\frac{3q\mu V}{2\pi\sqrt{\pi}R^3 k_m A\lambda_m} t^{-\frac{1}{2}}$$

$$-\frac{3q\mu}{8\pi R^3 r k_f}\left(\frac{r^3 + R^3}{3} - \frac{3rR^2}{5}\right)$$

$$+\frac{3q\mu}{4\pi R^3}(k_f\lambda_f^2)\frac{V^2}{(k_m A\lambda_m)^2}$$

$$-\frac{3q\mu V^3 k_f^2 \lambda_f^4}{4\pi\sqrt{\pi}R^3 k_m^3 A^3 \lambda_m^3} \quad t^{-\frac{1}{2}} + \ldots , \quad t \to +\infty . \tag{6}$$

To leading order, only the block properties affect the long-time behaviour, and there is no dependence on r. That is, the reservoir is behaving like a box of blocks, all in perfect communication via the fractures (to this order), with the rate of bleed of fluid from the blocks controlling the pressure in the box (in the fractures). This lack of dependence on distance from the source is apparent in the data from Ngawha.

Equation (6) will be valid for times short enough that flow in the matrix blocks is still normal to the block boundary, and long enough that just the first two or three terms arc important in the expansion. Despite these restrictions, fitting the three terms in (6) to the observed pressure response in NG9 gives a much better fit than the homogeneous infinite model as depicted in Figure 3. A computer program was written to superpose the effects of the various flow-rate changes in NG13 and NG3, and to linearly regress the resulting model on the NG9 data. The fit is not expected to be good at short times after a significant flow-rate change. To allow for this, an iterative 'robust' regression program was used (Davies, 1984) which gives less weight to outlying residuals, and has the effect of giving very little weight to the pressure data at these short times. Figure 3 is the result of such a fit.

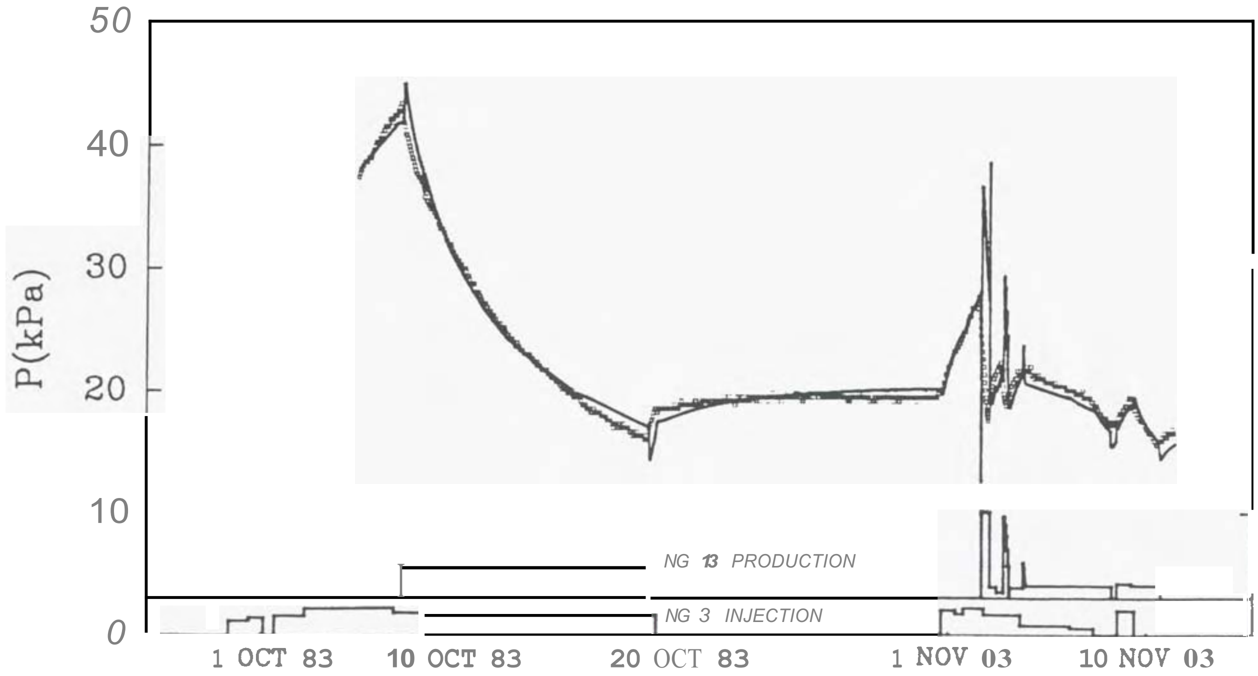
It is found that only the leading term in the asymptotic expansion (6) may be used to determine reservoir parameters. This conclusion is indicated by the lack of statistical significance in fitting the injection well contribution to the second term, and by the ill-conditioning that arises when two or three terms are used (it is then possible, in principle, to solve for k_f, ϕ_f and R, but the difference between two numbers close in value leads to errors of several hundred percent, and to unphysical values for k_f). A non-robust linear regression on the first term accounts for 82%of the variance of the data. Adding the second term improves this to 91%, and adding the third term only improves this to 935. Using the fitted coefficient of the first term gives

$$\alpha = \frac{4}{3}\pi R^3 \frac{A}{V}\sqrt{\frac{k_m}{\phi_m \mu c}}\,\phi_m$$

$$= (1.7 \pm 0.3) \times 10^6 \ m^3.s^{\frac{1}{2}} , \tag{7}$$

FIGURE 3

NG9 response to NG13, NG3, and fitted double porosity model.



where to leading order

$$p_f \sim -\frac{q}{c\alpha}\ t^{\frac{1}{2}}\ , \quad t \to \infty . \tag{8}$$

α is the volume of fluid accessed in the blocks in unit time after the turning on of a source in the reservoir.

OHAAKI

The Ohaaki (western Broadlands) geothermal reservoir is overlain by highly permeable rhyolite formations, which carry cooler water and are known to be in good communication with the deeper reservoir (Grant, 1982). These rhyolites extend laterally beyond the neighbourhood of the Ohaaki reservoir to communicate with groundwater. The possibility that the rhyolites could provide an easy path for substantial quantities of cooler water to enter the Ohaaki reservoir under exploitation prompted a series of interference tests of the Ohaaki reservoir and rhyolites during Nov 1983 - May 1984. Wells BR33, BR11 and BR40 were discharged at various times, while groundwater wells BR3/0, BR9/0 and BR18/0, rhyolite wells BR5I, BR6, BR37S, BR39, M4, M7, M8, M9, M10 and M11, and Ohaaki reservoir wells BR12, BR13, BR23 and BR34 were monitored (Figure 4).

The observed pressure responses give a clear indication that the rhyolites fall into two groups that are not in good communication with each other, in support of a conjecture by Grant, 1982. As in Figures 4 and 5, group 1 includes the feed-points of wells BR11, BR33, M10, M11. Deep reservoir wells BR13 and BR23, and groundwater wells BR9/0 and BR18/0 show some response to production from group 1. Group 2 includes the feedpoints of wells BRSI, BR6', BR39, BR40, M4, M8 and M9.

FIGURE 4 OHAAKI RHYOLITE GROUPING PLAN

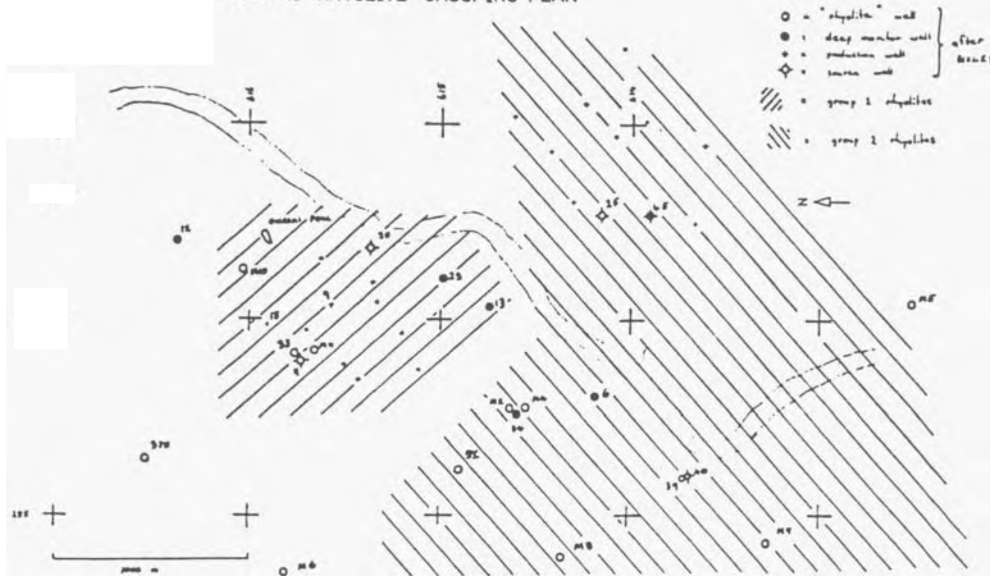


FIGURE 5 OHAAKI GEOLOGY bfter Bixley) & RHYOLITE GROUPING SECTION

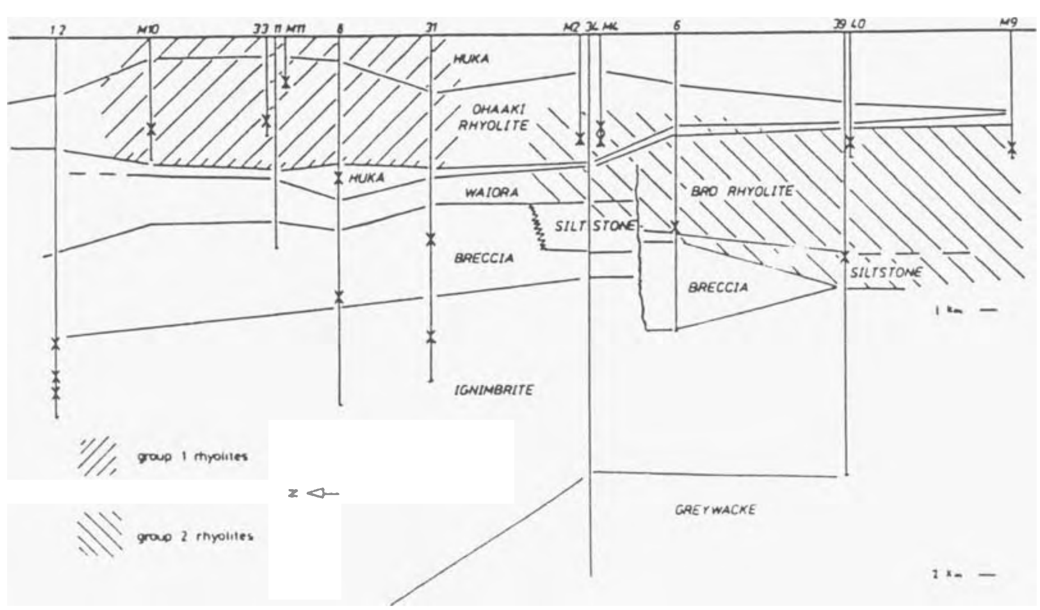
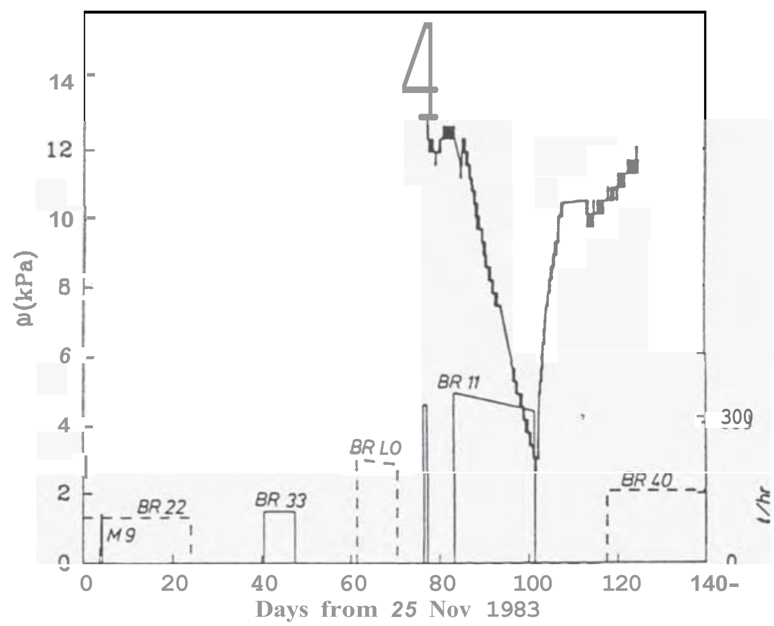


FIGURE 6

BR33 response to M9, BR11, 22, 33, 40



There are no observable responses across the border between these two groups. Furthermore, the drawdowns of the rhyolite wells in group 1 are all quite closely approximated by a linear response in time (e.g. Figure 6), modelled by withdrawal from an open box of fluid. Table 1 presents results basedonsuch a model. The responses in group 2, on the other hand, are closely approximated by the line-source solution for an infinite homogeneous reservoir (Figure 7). Aquifer parameters estimated by fitting the line-source solution are presented in Table 2.

TABLE 1

GROUP 1 RHYOLITE

Linear Responses to BR11

obs. well	$\frac{dP}{dt}$ (Pa/s)	ϕA (km²)	A (km²)
M10	3.8×10^{-3}	0.25	1.3
M11	5.9×10^{-3}	0.17	0.9
BR33	6.2×10^{-3}	0.16	0.8
BR9/0	4.4×10^{-3}	0.22	1.1

These values are obtained using flow-rate 0.107 m^3/s, T = 140°C, ρ = 925 kg/m^3. A is computed assuming ϕ = 0.2. Uncertainties are ±10% in all results.

FIGURE 7

BR39 response to BR40

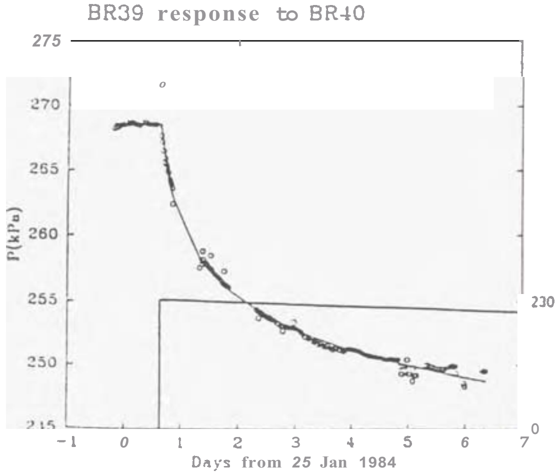


TABLE 2

GROUP 2 RHYOLITE

Line-source Responses to BR40

obs. well	r (m)	kh (d-m)	ϕh (m)	Comments
BR39	401	220	150	r is distance between feeds
BR6	630 710	180 260	70 20	
M9 M8	810	630	3000	M8 feed near shallow water table.
M4	940	1050	510	Atmospheric response making results suspect.
BR51	1200	420	970	Atmospheric effects removed.

The values ν = 0.207 x 10^{-6} m^2/s and C = 0.75 x 10^{-9} Pa^{-1} for 140°C water were used. Values of kh, ϕh were obtained both by a semilog analysis and by fitting the line-source solution numerically.
The fitted values are presented, and the semilog analyses suggested uncertainties of about 20% in these values.

There is evidence of a boundary effect in the response of BR51 to discharge of BR40 (group 2 rhyolite). This effect is apparent when atmospheric effects are removed fromthedata. Cross-spectral analysis (Davies, 1984) shows no evidence of any lag in the response of wellbore pressures to atmospheric pressure, so that a linear regression may be used to remove atmospheric effects. Figure 8 shows the result of fitting both the line-source solution and atmospheric pressure to the data preceding a time from discharge of 350 hours. The residuals in Figure 9 suggest infinite reservoir behaviour up to a time of about 400 hours, and semi-steady state after about 700 hours. Matthews et al., 1967, show that the radius of investigation, taking t = 550 ± 150 hours, is (using parameter values from Table 2):

$$r_{inv} = \sqrt{\frac{4kt}{\phi\mu c}} = 5.0 \pm 1.4 \text{ km} . \qquad (9)$$

This radius is smaller than the radius of the equivalent cylindrical reservoir that would give the pressure response of an infinite reservoir up to this time, and larger than the radius of the equivalent cylindrical reservoir that would give a semi-steady state response by this time. It may be regarded as an order of magnitude estimate of the size of the group 2 rhyolites.

FIGURE 8

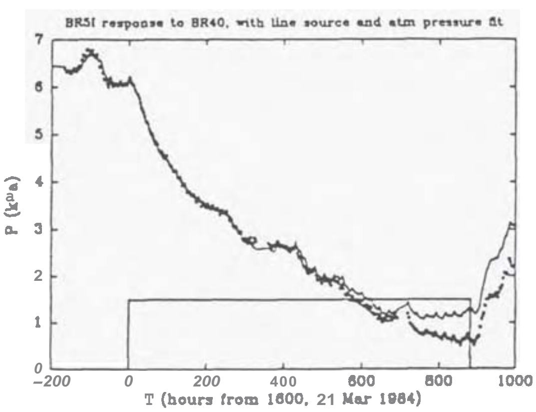
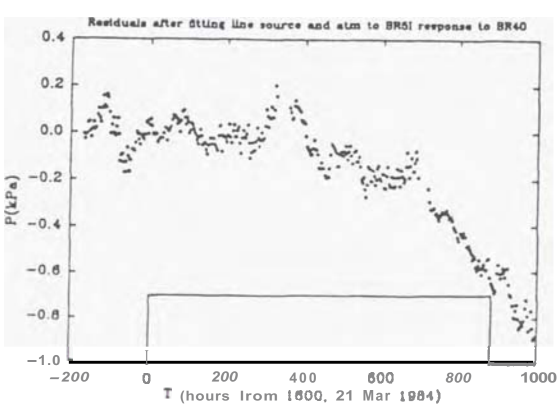


FIGURE 9



These results, besides reassuring us that the group 1 rhyolites are unlikely to channel cooler fluid into the Ohaaki reservoir, have been useful for reinjection considerations at Broadlands. In particular, reinjection of a portion of the waste geothermal fluid into group 2 rhyolites will be implemented, at some saving over the deep reinjection alternatives.

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