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TEMPERATURE SURVEY IN 5m HOLES ACROSS THE WHITFORD WARM WATER PROSPECT (SOUTH AUCKLAND)

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Abstract

Constant temperature gradients have been observed in deeper wells which penetrate the almost impermeable 80-100 m thick Tertiary cover at Whitford. The gradients vary between 0.02 and 0.45°C/m. An attempt has been made to obtain the undisturbed near-surface gradient from repeated temperature measurement in a series of shallow, 5 m deep holes, allowing for an iterative reduction procedure described by Risk and Hochstein (1973). Results show that representative near-surface temperature gradients can be obtained which, together with best fit values of the mean thermal diffusivity, allow an assessment of the vertical heat flux at shallow depths.

Introduction

The warm water prospect near Whitford (South Auckland) was discovered when a few groundwater wells drilled for farm supply intersected a warm water reservoir at the contact between almost impermeable Tertiary sediments and a fractured greywacke basement. The thermal water has a maximum temperature of 55°C at 80-100 m depth; its geochemistry has close affinity with that of thermal fluids in other warm water prospects in the Greater Auckland area that discharge thermal water from greywacke basement (Hochstein and McKee, 1986). The natural heat discharged at Whitford is small - of the order of 0.5 MW (conductive losses); no thermal fluids are discharged in the natural state at the surface. At present, it is thought that the Whitford prospect is a fracture zone reservoir associated with re-activated fracture zones trending NNW and ENE; a gravity survey of the area has been described by Simpson and Tearney (1987). Efforts to outline the concealed basement reservoir by resistivity surveys have not been successful (Mohamed, 1988; Yang and Hochstein, 1989).

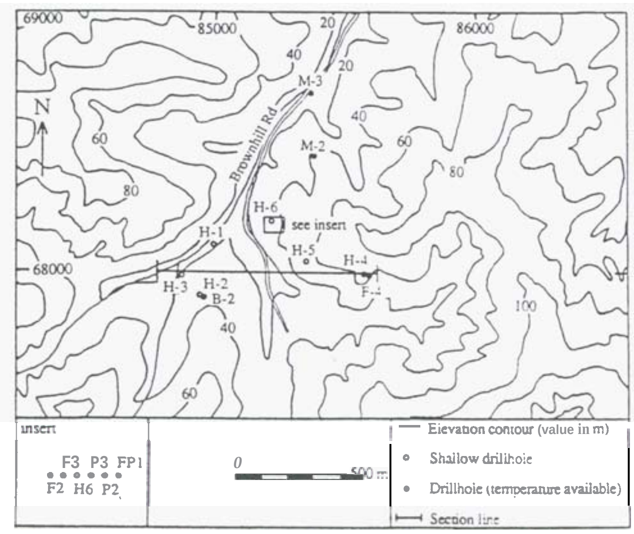

Fig. 1: Location of shallow and deep wells drilled over the Whitford warm water prospect.

Until now, the only data that approximately define the extent of the thermal reservoir are temperature data (Xin, 1986; GCNZ, 1987) in irregularly-spaced, up to 100 m deep, wells. The location of six wells which intersected the thermal reservoir is shown in Fig. 1; temperature profiles of 4 wells lying in the southern part (B-2, FP-1, F-3, F-4) are shown in Fig. 2. It can be seen from this figure that the temperature gradient in the low permeability Tertiary rocks is almost constant (for depth to basement. see Fig. 5).

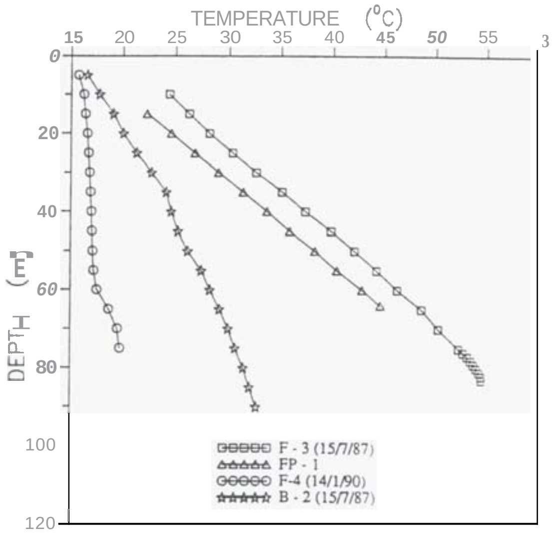

Fig. 2: Temperatures in selected deep wells in the southern part of the Whitford prospect.

In principle, it should therefore be possible to map the extent of the prospect by drilling a number of, say, 20 m deep temperature gradient holes. It is likely that at least 20 gradient holes would be required to outline in detail the extent of the prospect. However, in view of the limited economic potential of the prospect, any survey using 20 m deep temperature gradient wells is too expensive. We tried therefore to obtain information about the temperature gradient from temperature surveys in shallow (4-5.5 m deep) holes. Such holes are inexpensive and can be drilled quickly with a hydraulic post-hole borer. However, one cannot obtain the undisturbed temperature gradient directly as the temperatures are disturbed by annual and short-period seasonal temperature variations. These variations are shown in Fig. 3 for one of the shallow holes (H-4) drilled close to the deeper well F-4 (for locality see Fig. 1). Fig. 3 shows that both positive and negative temperature gradients can be observed at the bottom of the hole, depending on the time of year. To obtain the undisturbed gradient, appropriate reductions have to be applied to the data, which are described in the following paragraph.

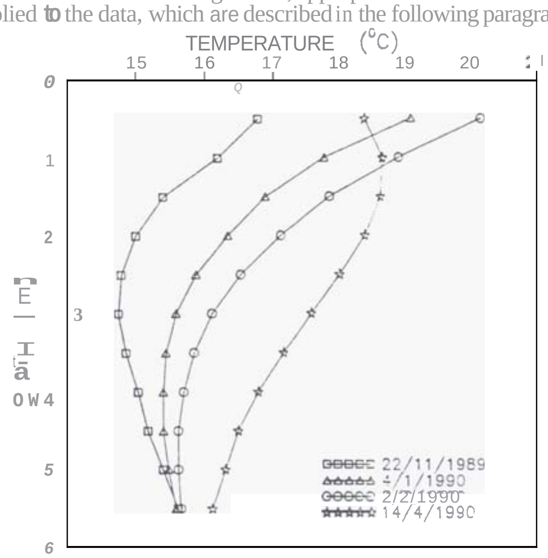

Fig. 3: Temperature variations between 22.11.89 and 14.4.90 in shallow hole H-4B (for locality see Fig. 1).

Analysis of temperature data in shallow holes

Heating during the summer and cooling during winter causes the surface temperatures at Whitford to fluctuate, with a peak to peak amplitude of more than 7°C. The actual wave form is quasi-sinusoidal. The temperature at the surface (z=0) can be expressed by a Fourier series of the form:

$$T(o,t) = T_o + \sum_{n=1}^{\infty} A_n \cos(n\omega t + \varepsilon_n) \quad (1)$$

where T_o is the average surface temperature, t the time, A_n and ε_n the amplitude and phase respectively of the nth Fourier component, and $\omega = 2\pi/365.25$ (rad/day) is the fundamental radian frequency. The temperature $T(z,t)$ at depth, according to Carslaw and Jaeger (1959), is given by:

$$T(z,t) = az + T_o + \sum_{n=1}^{\infty} A_n \exp(-kz\sqrt{n}) \cos(n\omega t + \varepsilon_n - kz\sqrt{n}), \quad (2)$$

where $a = \Delta T/\Delta z$ is the undisturbed vertical temperature gradient, $k = (\omega/2\alpha)^{1/2}$, and a the thermal diffusivity of the rocks. If the bulk density ρ and the specific heat capacity c of the rocks can be assessed, one can obtain the thermal conductivity λ, since:

$$h = \rho \alpha c. \quad (3)$$

With known values of α and h, the vertical heat flux can be obtained. Assuming that a number of temperature measurements $T(z,t)$ have been made at various times t, throughout the year, and that these measurements were taken at the same depths z, the unknown parameters in equation *(2)* can be obtained from a least-square curve fitting procedure which has been described by Risk and Hochstein (1973). The unknown parameters a, T_o, k (and hence a), A_n and ε_n can be determined by an iterative procedure where the residuals *are* reduced to minimum values involving mamx inversion of an overdetermined system containing all data *or* subsets of data measured in one hole.

The method has been used with success to determine the terrestrial heatflow in a 7.5 m deep well in solid basalts in Antarctica (Risk and Hochstein, 1973), although it has not been used for similar observations in a series of shallow holes where thermal constants might change laterally. For the analysis of the Antarctic data, measurements taken over a period of *2.4* yr were available, whereas at Whitford data could only be collected over a period of 0.75 yr.

Changes of thermal constants at shallow depths

The analysis of temperatures observed in a shallow hole during a period of a year gives representative data for the vertical temperature gradient and thermal diffusivity if these constants do not change with depth. If the analysis is extended to data collected in shallow holes which stand in rocks where the saturation coefficient S varies with depth ($S = 0$ for completely *dry* rocks and $S = 1$ for fully saturated rocks), thermal constants will also vary with depth.

All constants in equation (3) vary with porosity ϕ and saturation S. In the case of the bulk density p, one finds that it lies between the extreme values of:

$$\rho_d = (1 - \phi)\,\rho_p \text{ (for } S = 0) \text{ and } \rho_w = (1 - \phi)\,\rho_p + \phi \text{ (for } S = 1),$$

where the indices d, w, p refer to *dry*, wet (saturated) and particle density, respectively. For any other value of S, the bulk density is given by:

$$\rho = (1 - \phi)\,\rho_p + S\,\phi. \quad (4)$$

The specific heat capacity also varies with saturation and porosity, and is given by:

$$c = (1 - \phi)\,c_p + S\,c_w\,\phi, \quad (5)$$

where c_p is the heat capacity of the rock mamx and c_w the heat capacity of the pore water.

Because of interface effects, no simple equation can be given for the thermal conductivity λ and thermal diffusivity a of a porous rock. In practice, one determines one of these constants in the laboratory (or 'in situ', in our case) and computes the other constant using equation (3). Because of the changes in 'bulk' density and 'bulk' heat capacity with porosity and saturation, the thermal conductivity of *dry* and moist porous rocks is usually about *2* to 3 times lower than that of the saturated rock; the same applies for the thermal diffusivity. Since the vertical temperature gradient is a linear function of thermal conductivity for constant vertical heat flux q, namely:

$$q = \lambda\,(\Delta T/\Delta z), \quad (6)$$

changes in a, and hence λ, affect the value of $a = (\Delta T/\Delta z)$ in equation (2).

At Whitford the situation is complicated by the fact that many shallow holes stand partly in saturated rocks (water table only about *2* m below the surface in holes H-1, H-3 and H-6) and partly in moist rocks. The degree of partial saturation of moist rocks above the water table was not known. Most of the shallow holes stand in weathered Tertiary rocks; a thin layer of Alluvium (1-2 m thick) lies on top of the Tertiary rocks in holes H-1 and H-6.

Description of survey

Since at the *start* of the survey it was uncertain whether the analysis of the temperature data in shallow holes would give representative values for the undisturbed vertical temperature gradient, we drilled three shallow holes close (within 3 m) to deeper wells for which the temperature gradient below the water table was known, namely H-4 near F-4, H-6 near FP-1 and F-3, and H-2 near B-2 (see Fig. 1). The shallow holes were drilled as a 0.25 m wide hole (usually 5 to 6 m deep) into which plastic pipes of 2.5 cm diameter were inserted; each hole was then back-filled. To check for reproducibility and measurement errors (random *or* systematic), two narrow pipes were inserted in holes H-4, H-5 and H-6. Since temperature measurements made with a thermistor probe in air take some time before equilibrium conditions are reached, one pipe in each of these holes was sealed at the bottom and filed with water (A-series holes); the other one was sealed but not filed with water (B-series holes).

Unfortunately, only one of the A-series holes remained tight during the experiment (H-6A); the water in the other two drained to the water table. A 10 m long four-conductor thermistor probe was used, which allowed separate measurements of cable resistance and cable plus thermistor resistance. The thermistor was calibrated in a standard water bath before and after the survey, covering a period of 9 months. The error in absolute temperature was found to be ±0.1°C over the range of measured values (13 to 23°C); since different calibration thermometers were used, it is uncertain whether this error is caused by changes in the thermistor or thermometer type. The reading error (using a high impedance multimeter) was ±0.01°C; the readings were reproducible within ±0.05°C below 1 m depth during any day of the survey.

Temperatures in the six shallow holes and three deep holes were measured between 29.9.89 and 30.6.90 at 4 to 8 week intervals. Measurements were taken at 0.5 m depth intervals (downhole logging mode). The water level was also monitored.

Results of data analysis (annual cycle only)

The data were analysed initially using only the fundamental (annual) component (i.e. A_1, ε_1) of the Fourier series in equation (2), assuming that all temperature variations are caused by a sinusoidal annual temperature cycle. The computed best fit data and observed temperatures for hole H-5A are shown in Fig. 4a. It can be seen that the degree of fit for temperatures below 1 m depth is already acceptable. Temperatures at half metre intervals (i.e. at z = 0.5 m, 1.0 m, 1.5 m, etc.) are not shown, to avoid crowding of data points.

Results of the analysis for all shallow holes are summarized in Table 1. The data indicate the following:

(a) The computed vertical gradient (column *2)* is close to the gradient of the nearby deeper wells, namely: 0.015°C/m in H-4 versus 0.03°C/m in the deep well F-4; likewise 0.15°C/m in H-2 versus 0.2°C/m in *B-2* and 0.3°C/m in H-6B versus 0.45°C/m in FP-1 and F-3.

(b) Reproducibility of all reduced parameters is good for sires where measurements were made in two pipes (i.e. H-4A,B; H-5A, B) except for site H-6 where significant differences occur between a and A_1 in holes H-6A and 6B *(see* Table 1).

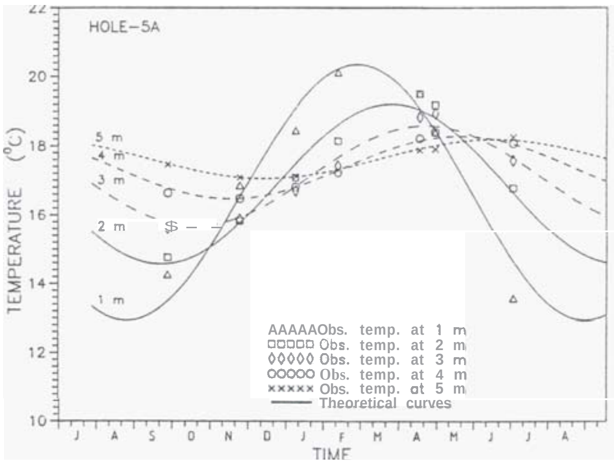

Fig. 4a: Best fit curves of temperatures between 1 and 5 m depth in hole H-5A; reduction restricted to first Fourier component in equation (2).

Table 1: Solution for theoretical parameters in quation (2) using the fundamental (annual) Fourier component (all depths).

hole Nr	a (°C/m)	T_0 (°C)	a ($10^{-6}m^2/s$)	A_1 (°C)	ε_1 (rad)	mean v^2 $(°C)^2$	elev (m)	P.L. (m)
H-1	0.33	17.35	0.68	5.3	4.2*	0.1	21	19.5
H-2	0.15	16.9	0.38	5.3	4.4	0.15	34.1**	32?
H-3	0.111	17.05	0.45	5.9	4.45	0.4	25	23.5
H-4A	0.01	16.0	0.42	5.5	4.25	0.05	65.8	43.8
H-4B	0.02	15.9	0.44	5.5	4.25	0.1	65.8	43.8
H-5A	0.24	16.4	046	5.9	4.15	0.15	50	<44
H-5B	0.25	16.4	0.46	5 9	4.15	0.15	50	<44
H-6A	0.27	16.4	0.95	4.5	4.15	0.3	37.0	35.0
H-6B	0.30	16.3	0.82	5.1	4.2	0.3	37.0	35.0

* Since measurements started an 28.9.89, a phase of 4.2 rad indicates a Tmax value for 27.1.89 which agrees with climatological records.

** Shallow water table is probably below 4 m depth at H-2 whvh lies on a hill. although he piezometric level in the cased deeper well (B-2) is 32 m.

(c) The average annual amplitude A_1 shows some scatter, at site H-6 the amplitude A_1 is significantly lower than that at other sites. Since the average annual amplitude should be constant for such a small survey area, the differences in A_1 can be interpreted in terms of effects caused by short periodic temperature variations.

(d) The mean annual temperature varies by 1.5°C between all sites; T_0 decreases almost linearly with elevation.

(e) The values for ***a*** are of the right order of magnitude. Since holes H-2, H-4 and H-5 stand above the water table, the values of 0.38 to 0.46 x 10^{-6} m^2/s are representative for the thermal diffusivity of most surface rocks at Whitford. The value of ***a*** increases in holes where water-saturated sediments occur below **2** m depth (**i.e.** H-1 and H-6). Water-saturated rocks were encountered at the bottom of **H-3;** the low value for α is probably affected by the thin alluvial cover at this site.

On the whole, the results of the first analysis are encouraging; the result that the temperature gradient in **5** m-deep holes is close to that of the deeper wells indicates that, in principle, it is possible to map anomalous temperature gradients for the whole prospect by using repeated measurements in shallow holes.

Results of data analysis (higher order components and analysis of data subsets)

The mean residual error v^2, given by the difference between computed best fit data and observed temperatures after the last iteration using the algorithm by Risk and Hochstein, can be further reduced. The error becomes smaller if ones uses either higher order Fourier components in the analysis, where (A_2,ε_2), (A_3,ε_3), (A_4,ε_4) relate to temperature changes with period of $1/2$, $1/3$ and $1/4$ yr respectively, or if data subsets are used. Data obtained for depth intervals of 0.5 to 2 m and 2.5 to 5 m constitute depth interval subsets. If the observation period is sufficiently long, one can also create data sets for different observation periods. The observation period of 0.75 yr, however, is too short to create time interval subsets in the case of the Whitford survey.

The effect on curve fitting using higher Fourier components (n up to 4) is shown for hole H-5A in Fig. 4b.

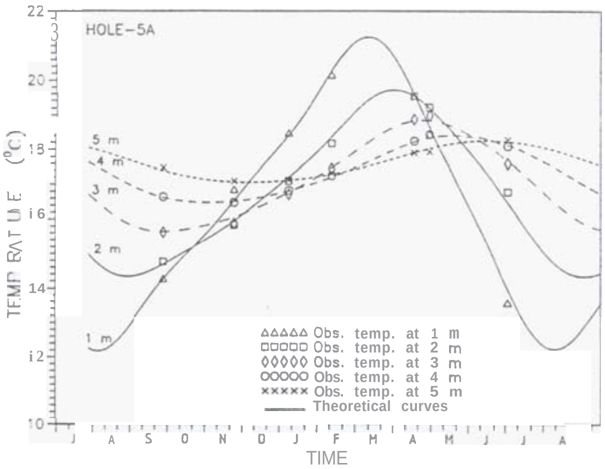

Fig. 4b: Same as Fig. 4a; reduction extended by using four Fourier components (n=1, 2, 3, 4) in equation (2) with A_2 = -1.5°, ε_2 = 3.55 rad; A_3 = -1.5°, ε_3 = 2.7 rad; A_4 = +0.5°, ε_4 = 1.9 rad, other values are listed in Table 2 (3rd row).

Table 2: Solution for theoretical parameters in quation (2) using different numbers of Fourier components and different data subset (different depth intervals).

hole Nr	a (°C/m)	T_0 (°C)	a ($10^{-6}m^2/s$)	A_1 (°C)	L (rad)	n	z range (m)	mean residual v^2 $(°C)^2$
H-5A	0.24	16.4	0.46	5.9	4.2	1	0.5-5	0.13
H-5B	0.25	16.4	0.46	5.9	4.15	1	0.5-5	0.13
H-5A	0.24	16.4	0.45	6.3	4.2	4	0.5-5	0.02
H-5B	0.25	16.35	0.44	6.2	4.2	4	0.5-5	0.02
H-5A	0.20	16.45	0.38	6.3	435	4	0.5-2	0.02
H-5B	0.24	16.4	0.37	6.2	4.25	4	0.5-2	0.03
H-5A	0.26	16.3	0.62	5.1	3.9	4	2.5-5	<0.01
H-5B	0.25	16.3	0.65	4.8	3.9	4	2.5-5	<0.01

The best fit curves in Fig. 4b match the observed data more closely; the amplitude A_1 increases (see also Table 2). The effect of higher Fourier terms fits on the computed values of a and T_0 is small; this also applies to the same analysis of data in the other shallow holes. However, comparing the results between holes, it was found that the scatter in amplitude values for **A2, A3, A4** increases with n. For 4 Fourier terms, the mean error in A_2 between sites is already ±30% and increases to almost **±50%** for **A3;** phase differences for the same terms between sites are significant (>1 month) from ε_3 onwards. Since it is unlikely that shorter seasonal temperature fluctuations vary in amplitude and phase **across** the survey area, the errors in A_n and ε_n of the higher Fourier components point to the effect of random fluctuations and errors in the observed data. Similar results were obtained when the analysis was extended to depth interval data subsets (see Table 2).

The data in Table 2 indicate that the mean temperature gradient **a**, the mean surface temperature T_0, and the phase ε_1 are least affected if a more detailed analysis is used, whereas A_1 and α show larger variations. This probably indicates that the observational period of *0.75* yr is still too short to obtain reduced data which closely agree in amplitude and phase between different holes. The temperature minimum in Figs. 4a, b, is, for example, not yet well defined by observed data.

For interpretation of the data it was decided to use only the values computed with the first Fourier term (**i.e.** data in Table 1) and to neglect the results of more detailed reduction until additional data become available. The scatter in the components between sites is smaller for the simple analysis shown in Table 1 than for other more detailed analyses listed, for example, in Table 2.

Interpretation of results

Best fit parameters describing the annual temperature variations as listed in Table 1 can be used for interpretation assuming that any error in these parameters is randomly distributed. The computed best fit values for ***a*** can be used to obtain the thermal conductivity λ and hence the heat flux q. For this, equation (3) can be used if appropriate values for the effective bulk density and effective thermal capacity can be obtained, i.e. using equations (4) and (5). The average saturated density of 5 cores from deeper wells in the

Whitford area is 2.26 fo.l E 3 kg/m^3, the average porosity is 0.25 ±0.05 (GCNZ, 1987). Since the saturation coefficient S of moist rocks above the shallow water table is probably about 0.3, one obtains a range for the bulk density with equation (4):

$$\rho \approx 2.085 \text{ E } 3 \text{ kg/m}^3 \ (S = 0.3) \text{ and } \rho = 2.26 \text{ E } 3 \text{ kg/m}^3 \ (S = 1).$$

For the specific heat capacity of the same rocks, equation *(5)* gives:

$$c \approx 915 \text{ J/kg K } (S = 0.3) \text{ and } c = 1650 \text{ J/kg K } (S = 1).$$

For this estimate, it was assumed that c_p of the rock mamx is 800 J/kg K and c_w of the pore water is 4200 J/kg K.

Since the depth range of moist and fully saturated rocks is known, an effective mean bulk density (ρ_{eff}) and effective mean specific capacity (c_{eff}) can be assessed for each shallow hole. This, in turn, allows estimates of the mean-thermal conductivity $\bar{\lambda}$ and the mean vertical heat flux $\bar{q}$, using equations *(5)* and (6) respectively. The results axe listed in Table 3.

							2
H-3	0.45	0-15	1.5-4	2.19	1.37	1.35	0.24
H 4 A	0.42	0-5.5	-	2.085	0.915	0.80	0.01
H-4B	0.44	0-5.5	-	2.085	0.915	0.84	*0.02*
H-5A	0.46	0-5	-	2085	0.915	0.88	0.21
H-5B	0.46	5 5	-	2.085	0.915	0.88	0.22
H-6A	0.95	0-2	2-4.8	2.19	1.34	2.79	0.75
H-6B	0.82	0-2	2-4.8	2.19	1.34	2.41	0.72

The data in Table 3 indicate that the mean thermal ('in situ') conductivity of rocks in moist or *dry* holes (i.e. H-2, H-4, H-5) lies between: $0.72 < \bar{\lambda}_d < 0.88$ (W/m K).

For holes which stand at least 2.5 m in saturated rocks (i.e. H-1, H-3, H-6), the values lie in the range: $1.35 < \bar{\lambda}_w < 2.88$ (W/m K).

The large range of $\bar{\lambda}_w$ values mainly reflects errors in the reduction of the observed temperatures and minor errors in the inferred bulk density and bulk heat capacity. Assuming that these errors are random, one obtains an average value for $\bar{\lambda}_w$ of 2.15 ±0.5 W/m K. This value is close to the average thermal conductivity of 5 saturated cores (2.1 fo.2 W/m K) of the Waitemata Group sediments taken from wells in the Brownhill Rd area (GCNZ report, 1987). Similar values of $\bar{\lambda}_d$ and $\bar{\lambda}_w$ are also cited in Touloukian and Ho (1981) for sandstones of similar porosity. It appears that the average of the computed thermal constants of near surface rocks in the Whitford area listed in Table 3 are representative values although any value for a single hole listed in this table might contain a significant error term. The vertical heat flux for each hole can therefore be estimated from the vertical temperature gradient (Table 1) and the mean thermal conductivity (Table 3) data. The heat flux estimates *arc* listed in the last column of Table 3.

East-west extent of the Whitford prospect, micro-climatic implications

If one plots the *best* fit temperature gradient obtained from the analysis of the shallow temperature survey together with the temperature gradient in the deeper wells along a profile running from H-4 to H-3 (approximately E-W direction, see Fig. 1), one finds that the centre of the wann water reservoir lies close to the valley, i.e. close to Brownhill Rd (Fig. *5).*

Since the temperature gradient in the Tertiary rocks is almost constant down to the basement (see Fig. 2), one can use the data in the upper part of Fig. *5* to predict *temperatures* down to the level of the deepest well. The extrapolated temperature field for the section is shown in the lower part of Fig. *5;* such extrapolation is justified for this setting. Without the data from deeper wells, extrapolation of temperatures from gradients in shallow holes can produce erroneous temperature sections as described by Salveson and Cooper (1981) for the Heber Field (US).

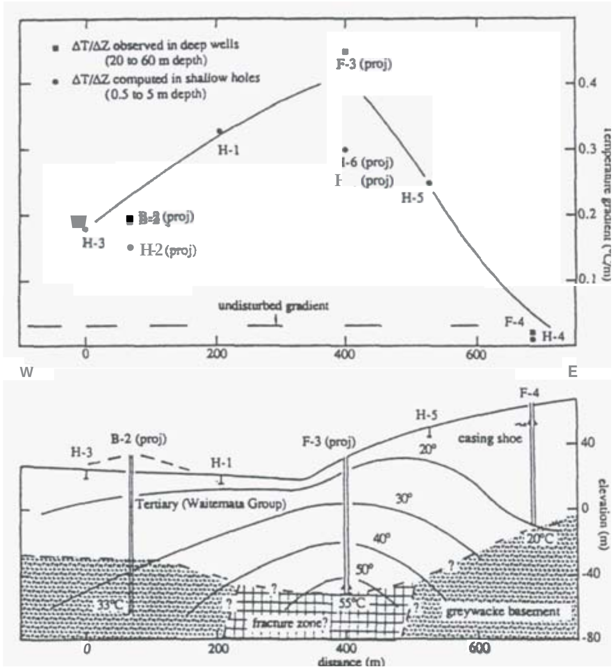

Fig. *5:* Vertical temperature gradient of shallow and deep holes across an E-W profile through the S part of the Whitford prospect (for location of profile, see Fig. 1). Also shown are extrapolated temperatures for a section of the profile (lower part).

The temperature contours in the section show some updoming to the east of well H-6 (F-3) which is probably caused by the combined effects of terrain and groundwater movement in the Tertiary. The temperature log of the easternmost well F-4 (Fig. 2) indicates a secular movement of slightly cooler watcr to the west between 20 and 60 m depth (the water level is about 9 m higher in F-4 than that in F-3). This cooling effect explains the steeper easterly dip of the 20°C temperature contour in Fig. 5. Since diluted thermal water occurs in the Tertiary cover (Xin, 1986; *GCNZ* 1987). there is also a very *small* upward movement of thermal water above the basement fracture zone which, however, is not sufficient to cause any distortion of the temperature profile in the hot well F-3.

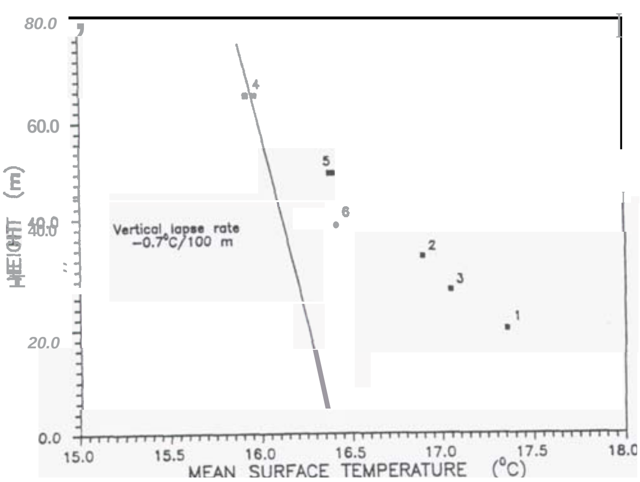

Fig. 6: Computed mean surface temperatures T_0 versus elevation (data taken from Table 1). The line through holes H-4A, B is the mean atmospheric lapse rate of -7°C/km.

The error in T_0 is rather small (as shown by comparison of T_0 data in Tables 1 and 2), one can therefore analyse the variation of T_0 as a function of elevation (Fig. 6). If one plots a normal (wet adiabatic) lapse rate of −7°C/km and assumes that the ground temperatures at H-4 (F-4) *are* undisturbed, one finds that the T_0 values at sites in the valley are all slightly higher than indicated by the atmospheric lapse rate. One can interpret this result by infemng that the soil temperatures in the valley near Brownhill Rd have been increased by up to 1°C by cooling thermal waters. The study indicates that soil warming can occur over low temperature prospects.

Acknowledgement

Mr A Turner (Motor Holdings, Auckland) kindly gave permission to undertake temperature surveys on Motor Holdings land and to cite results of some deeper wells (Fig. 2); farmers along Brownhill Rd also supported the study. B. Simpson (GCNZ) conmbuted to the planning of the shallow holes; Mr A. Franklyn (Geothermal Institute) arranged the drilling of the holes.

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