GEOLOGIC CONTROLS ON SHALLOW HYDROLOGIC CHANGES AT WAIRAKEI FIELD

R.G. Allis

Geophysics Division, D.S.I.R., Wairakei

ABSTRACT

A significant decline in groundwater level at Wairakei has apparently only occurred between the production borefield and Geyser Valley, and within the Karapiti thermal area. Over most of the production borefield, groundwater temperature is now at boiling point for depth, and the top of the steam zone which underlies the groundwater, is now near the top of the Huka mudstone. Consideration of recent gravity increases in the production borefield and decreasing steam zone pressure, suggests the permeability contrast at the top of the mudstone is now a controlling factor on the depth extent of the steam zone. The only clear evidence of cold groundwater movement towards the borefield is to be found on the northeast boundary, near the region of intense subsidence.

INTRODUCTION

Drawdown of Wairakei field has caused a steam zone to form between the deeper liquid reservoir and overlying groundwater. Although deep liquid pressures have almost stabilized, indicating mass flow equilibrium, steam zone pressures and groundwater levels within the production borefield are still declining (Fig. 1). The continued fall in steam zone pressures could be caused by both downflowing groundwater and direct exploitation. This paper documents and analyses the shallow hydrological changes, and investigates the relationship between the steam zone and the overlying groundwater.

GROUNDWATER LEVEL CHANGES

Groundwater levels have been measured intermittently by M.W.D. since 1954. These are generally in wells which range from 20 to 50 m deep. Weekly measurements during the early years showed seasonal effects could cause variations up to about 1 m in amplitude. This is probably the minimum level change that can be soley attributed to exploitation.

Significant changes in water level appear to be confined to the production borefield and Geyser Valley (Fig. 2). Although water level wells are widely spaced outside the production borefield, these all show little change. The continued flow of springs immediately to the west, and northwest of the production borefield confirm this observation.

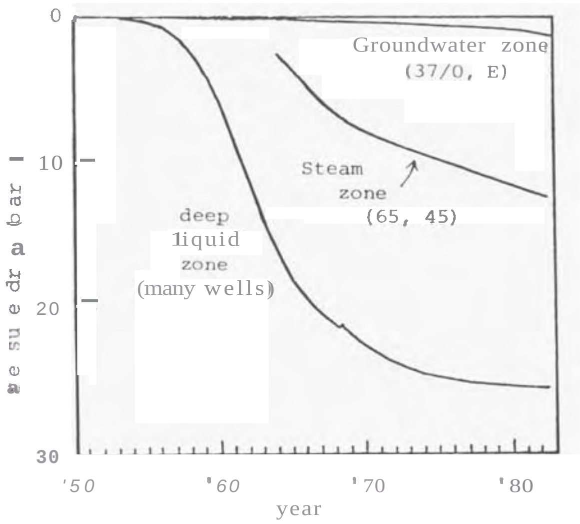

Fig. 1: Pressure trends at different depths of Wairakei field. Numbers in brackets are wells used for drawing trends.

Maximum decline in water level appears to have occurred in the vicinity of Geyser Valley (Fig. 2). Water level in Champagne Cauldron was measured down to 21 m below overflow in 1966 before it became inaccessible (Glover, 1977). Wairakei Stream is now perched as it flows through Geyser Valley. The rate of fall of groundwater level in wells closest to Geyser Valley was very irregular, with short-term rises and falls of many metres occurring. These fluctuations probably indicate a close connection between the groundwater and the deep reservoir in this area. This may be due to the NE-trending faults which originally channelled the chloride water towards Geyser Valley. The large decline in chloride concentration of deep wells in this area (wells 8A, 21, 31) during the 1960's also reflects flow of groundwater into the deep reservoir. In the eastern production borefield, the rate of fall of groundwater level has steadily increased with time.

Approximately 1 km downstream from Geyser Valley, water level has risen by over 5 m. This is in the region of maximum subsidence which now exceeds 9 m (Allis and Barker, 1982). Ponding of the stream has flooded its valley, and presumably has also raised groundwater level thoughout the area of intense subsidence.

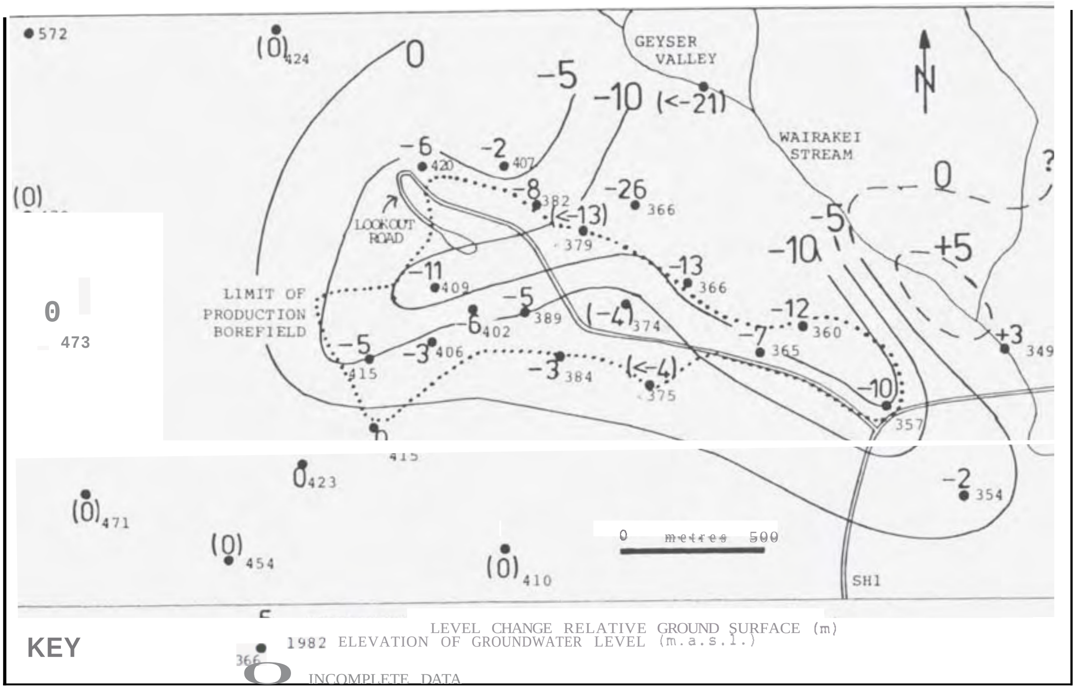

Fig. 2: Measured groundwater level changes in the vicinity of the production borefield.

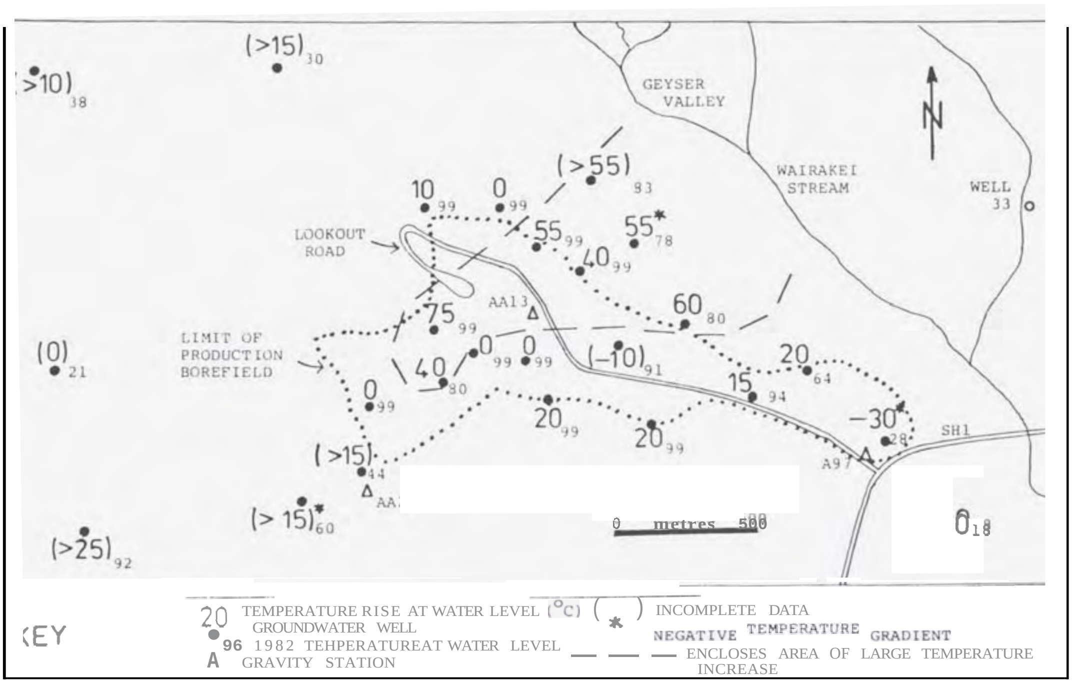

Fig. 3: .Temperature changes at the water level in groundwater wells in the vicinity of the production borefield.

Despite these water level changes, the regional hydraulic gradient is still eastwards towards Waikato River. However there now also appears to be a local northeast gradient across the production borefield towards Geyser Valley.

GROUNDWATER TEMPERATURE CHANGES

During the 1950's and 1960's M.W.D. measured groundwater temperature at the water level. Bottom-hole temperature in these wells was also meausred by G.E.K. Thompson in 1968 (Geophysics Division files). All wells were remeasured in 1982 to determine the extent of changes (Fig. 3).

The temperature changes have been rounded to the nearest 5°C increment, in line with probable uncertainties. The general pattern is of large temperature increases at the water level. A comparison of bottom-hole temperatures in 1968 and 1982 confirms the trend of increasing steam heating of the groundwater. In the central production borefield, the groundwater is now at boiling point for depth. Originally the groundwater surface in this area was around 50°C, presumably because of cross-flowing cool water at shallow depth. The area of greatest temperature increase coincides with the area of greatest drawdown of groundwater. There is no evidence of widespread invasion of cold water flowing from Wairakei Stream in Geyser Valley towards the production borefield. In fact the groundwater hydraulic gradient is probably in the reverse direction. The two wells closest to Geyser Valley (17/0; 16/0) are relatively shallow, so cooler water could be present at greater depth. Well 16/0 has a negative temperature gradient.

The only evidence of substantial cooling was in one well (E) at the eastern end of the production borefield. An inversion now exists in this well, with temperature decreasing from 50°C above water level, to 28°C in the 2 m of water at the bottom of the well. In 1968, the temperature in the well was constant at 86°C. The cool water in this well is probably flowing from the southwest towards Wairakei Stream. The temperature trend with time in this well follows the surface heat flow trend for all of Wairakei field. During the 1950's and early 1960's a large increase in heat flow (i.e. steam flow) took place. Subsequently, surface heat flow has declined as the rate of deep liquid drawdown has declined.

WELL 33

Well 33 is a 480 m-deep well situated on the northeast side of Wairakei field (located on Fig. 3). With well 32, 1 km further north, it defines the only sharp pressure boundary known at Wairakei field. The wells are cased into the Waiora formation and have shown only 2 bars of drawdown since 1960. Well 33 is cold at depth, but has a warm zone within its casing, indicating it is (or was) on the edge of a shallow outflow zone of the field. The well showed a pronounced heating pulse during the 1960's, and subsequent cooling and invasion by cold groundwater (Fig. 4). In 1959 maximum temperature was around 40°C at the top of the Waiora formation. The temperature peak rose to 95°C during the mid-1960's but has subsequently declined to 12°C. This behaviour suggests some permeability at this depth, and cold water is presumably now flowing towards the production borefield. Conductive cooling is still occurring in the lower Huka formation because of the low permeability of the mudstone. High permeability undoubtedly exists within the Huka formation because drilling fluid losses occurred, and silicified pumice breccia was encountered over a 20 m interval at 100 m depth (M.W.D. files). Relatively little temperature change appears to have occurred at this depth since 1959.

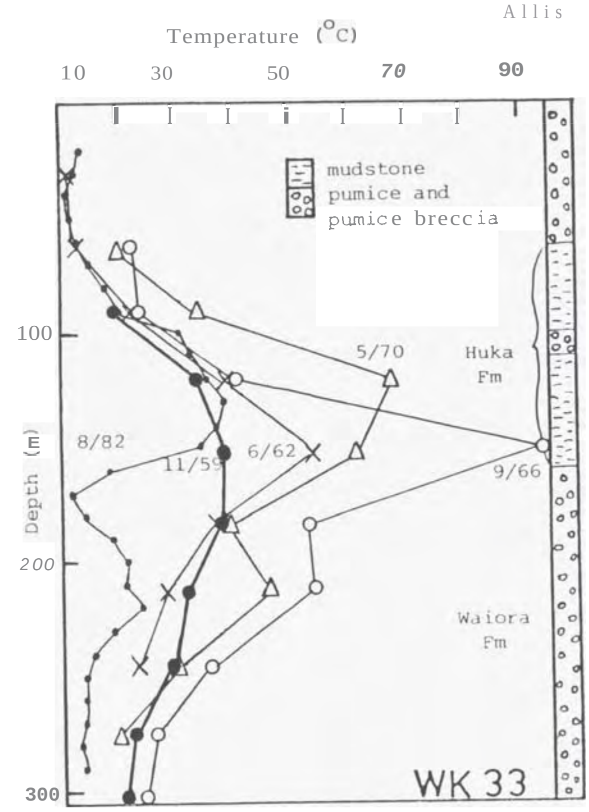

Fig. 4: Changes in temperature profile in well 33 since 1959.

Two hot springs originally existed in the section of Wairakei Stream between well 33 and the production borefield. Heat outflow from these 'springs' was still occurring in 1978 (Allis, 1981). However a subsequent rise in water level of Wairakei Stream appears to have quenched these features. This, and the temperature changes in well 33, suggest considerable cold water may now be entering Wairakei field on its northeastern flank. The cold water invasion may also be contributing to the intense subsidence by quenching the steam zone in, or beneath the Huka formation in this locality (Allis and Barker, 1982).

LOCATION OF THE GROUNDWATER-STEAM INTERFACE

Steam zone pressure has always been highest in the west of the field, decreasing towards the production borefield (Grant, 1982). This mostly reflects changing depth to the base of the relatively impermeable Huka mudstones. In the far west (well 222) this depth is over 400 m below surface; in the production borefield it is less than 200 m depth. The initial pressure of the steam zone which formed beneath the Huka formation was close to hydrostatic from groundwater level (35 bars in the west; >15 bars beneath the production borefield).

In the production borefield the Huka formation is relatively thin and shallow, and a delicate balance exists between the steam zone and the overlying groundwater. The depth of the transition between the two can be inferred by extrapolating hydrostatic gradient downwards and steamstatic gradient upwards. This assumes that a relatively sudden transition does exist. It is possible that the transition is actually blurred with local downflowing 'fingers' of water and local upflowing 'fingers' of steam. However the prevalence of boiling point for depth conditions in the groundwater over much of the production borefield suggests that steam flow upwards dominates water flow downwards.

A typical pressure gradient profile beneath the production borefield is shown in Fig. 5, and is compared with the initial profile before exploitation. The present day profile has a steam pressure gradient in the western production borefield (after Grant, 1982) and includes a slightly lower steam pressure in the Huka pumice breccia beneath the eastern borefield,

The transition from hydrostatic to steam zone pressure occurs at the top of the Huka formation, suggesting it is geologically controlled. The reason is clearly the large permeability contrast at the contact betweeen mudstone and pumice breccia. Within the low permeability mudstone, any downward flux of water is apparently insufficient to quench steam-dominant conditions. The hydrostatic to steamstatic transition may therefore be stable at any depth within the mudstones, its location depending mostly on steam zone pressure. The transition cannot move upwards into the relatively permeable Wairakei pumice breccia because the steam zone would be rapidly quenched by lateral groundwater flow.

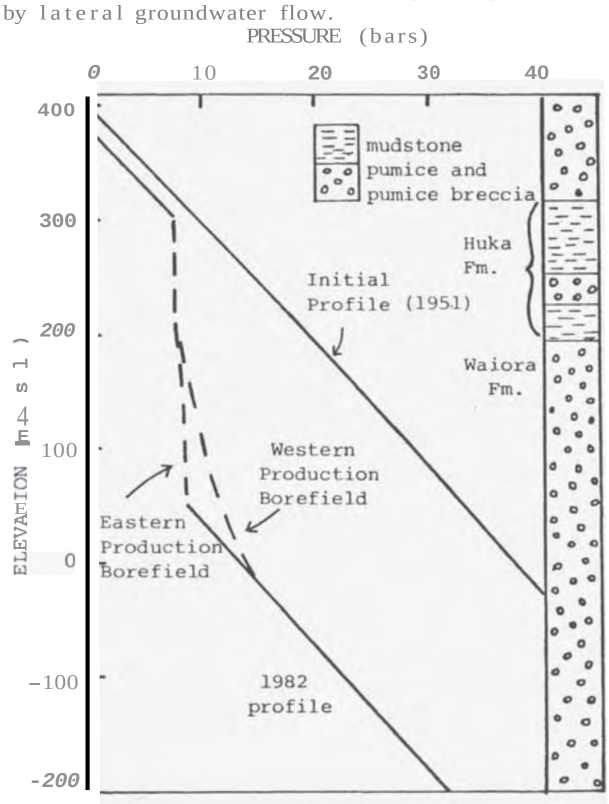

Fig. 5: Change in pressure profile beneath production borefield due to exploitation. Typical geologic column also shown.

The vertical changes in the steam zone beneath the production borefield are sketched in Fig. 6. For simplicity the Huka formation is depicted as a single low permeability layer separating zones of high permeability. With initial rapid drawdown of the deep liquid, the steam zone expands predominantly downwards beneath the low permeability layer. However as the rate of liquid pressure declines and is exceeded by the rate of steam pressure decline, the steam zone begins to migrate upwards. Depressuring of the low permeability layer gradually occurs, Eventually this depressuring reaches the permeable groundwater zone, and pressure changes in the steam zone are then seen as water level changes in the groundwater. Local faulting of the low permeability layer, which would presumably allow downflow of groundwater into the steam zone, would accelerate pressure transmission to the surface.

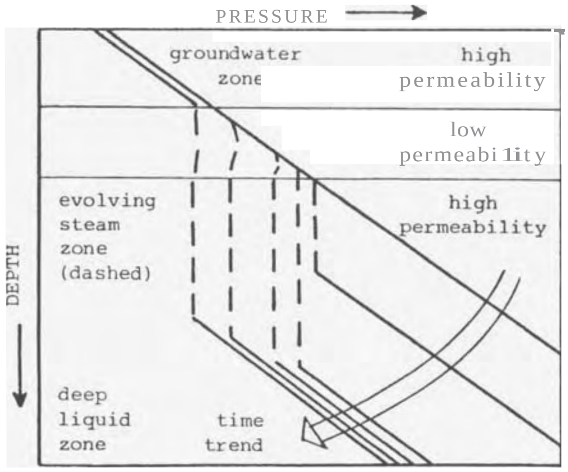

Fig. 6: Illustration of changes in steam zone caused by initial rapid liquid drawdown followed by steam pressure drawdown.

GRAVITY CHANGES

The saturation changes caused by an expanding or contracting steam zone also cause gravity changes. The gravity decrease, Ag, caused by formation of a steam zone by a deep liquid pressure drop, AP, will be given by (modified from Allis, 1981):

$$\Delta g = 2\pi \frac{G}{g} \phi (1 - So) \Delta P$$

where $g = 9.8$ m/s^2; G = gravitational constant (6.67×10^{-11} Nm^2 kg^{-2}); ϕ = porosity in steam zone; and So = residual saturation. Inserting values for the constants and expressing the equation in familiar units gives:

$$\Delta g(\text{mgal}) = 0.434\ (1 - So)\Delta P(\text{bar})$$

The gravity changes at Wairakei for the period 1961-1974 have been described by Hunt, (1977)(only one gravity station has a pre-exploitation value). During this period a liquid drawdown of 15 bars occurred across a central 10 km^2 area of Wairakei field. The gravity change across this same area ranged between -0.25 and -0.55 mgal. Applying the above equation to these changes gives $\phi(1 - So)$ as 0.04 to 0.09. Since the average porosity of the Waiora formation is around 0.25, So is therefore 0.6 to 0.8. This means that most of the pore volume in the steam zone was still liquid-filled in 1974.

Repeat gravity readings have recently been made at 5 benchmarks within the production borefield (pers. comm. A. Carman, Geophysics Division, D.S.I.R.). The gravity trends for 3 of the benchmarks are shown in Fig. 7 (located in Fig. 3). Gravity changes at the other two benchmarks are similar to that at the benchmarks AA13 and A97 (since 1971, the time of their first measurement the benchmarks are located between AA13 and A97).

A smooth curve has been drawn through the observed readings (gravity values are relative to Taupo Fundamental value of 100 mgal). This was then corrected for elevation change of the benchmarks since the first measurement. A further correction was then made for the decline in groundwater level in the vicinity of the benchmark. The correction was assumed to be one dimensional, i.e.

$$\Delta g_{corr} = 2\pi G\phi(1 - So)\rho_w\Delta h$$

where ρ_w = density of water; and Ah = water level decline. The porosity of the surface pumice deposits was assumed to be 0.6, and So was assumed to be 0.3, similar to that for soils (Cherry and Freeze, 1979).

Benchmark AA21 in the southwest of the production borefield is the only one still showing decreasing gravity. The other 4 benchmarks indicate increasing gravity since the 1970's. However the time when the increase began, and the rate of increase, vary greatly for each benchmark. The average gravity increase since the early 1970's at these 4 benchmarks is 0.13±0.05 mgal. The most likely factors causing this increase are a pervasive increase in saturation of the steam zone; decreasing thickness of the steam zone, and a large decrease in temperature (increase in density) in either of the liquid zones. The last factor is probably the least important because a large temperature decline of the deep liquid zone has not occurred, and in general, shallow groundwater temperatures have increased. As an extreme example however, if groundwater is 100 m thick, with an average temperature of 150°C originally, and 100°C subsequently, the increase in gravity would be about 0.1 mgal.

Possibly the main factor is decreasing thickness of the steam zone. As steam pressure continues to fall while deep liquid pressure remains almost constant, the bottom of the steam zone is rising while the top is held fixed in the upper Huka formation. Decreasing gravity at AA21 has a similar explanation. In the western production borefield, steam zone pressure increases with depth, probably because of proximity to the liquid upflow zone. Because steam pressure near the top of the steam zone has fallen at a greater rate than that at the bottom, the steam zone has increased in thickness, and gravity has therefore decreased.

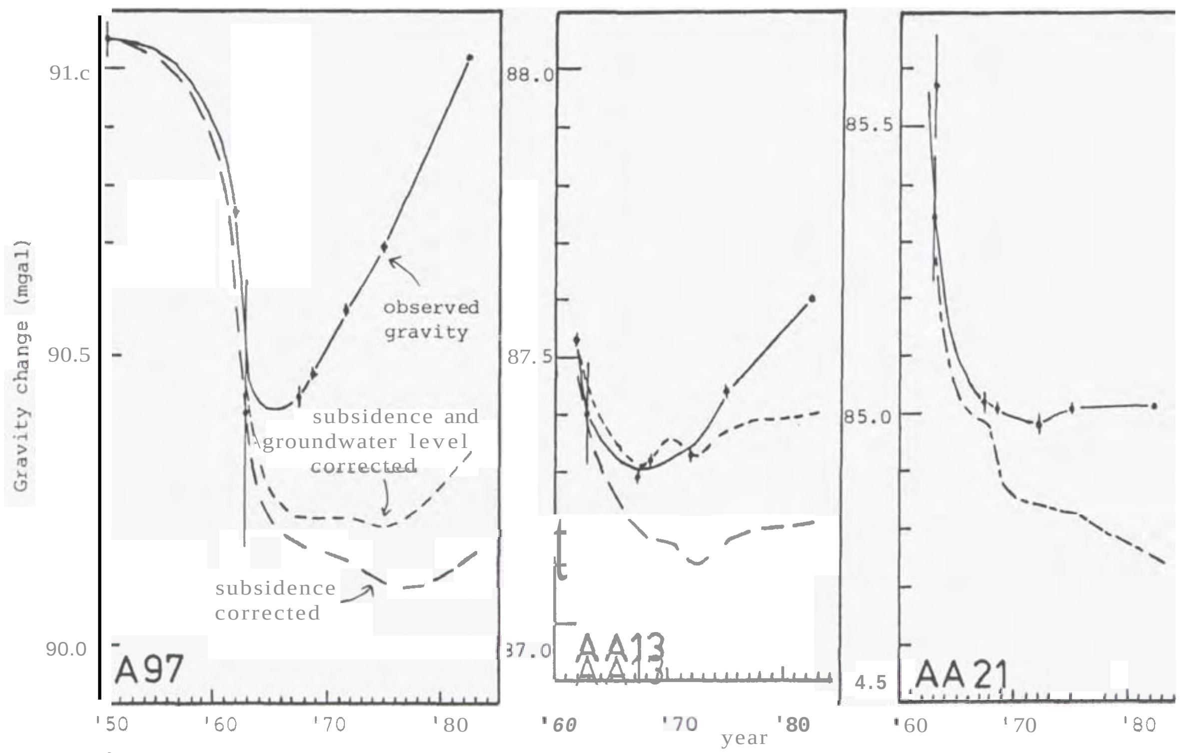

Fig. 7: Gravity changes at 3 benchmarks within the production borefield.

HEAT FLOW CHANGES

A detailed discussion of the heat flow changes at Wairakei field has been given in Allis (1981) and space does not permit a review here. However what is particularly relevant to this paper is the cause of the spectacular increase in heat flow at Karapiti thermal area (about 3 km south of the production borefield). Heat flow increased from 40 MW to a peak of 420 MW by the mid 1960's, and has subsequently decreased to around 220 MW. In contrast to the rest of Wairakei field, there is no Huka mudstone here. Liquid drawdown of the deep reservoir has probably caused drawdown from the groundwater surface. The heat flow pulse from the thermal area therefore follows closely the rate of deep liquid drawdown (Fig. 8). This is due *to* extra boiling that occurs as the 2-phase liquid zone migrates downwards into hotter rock. A long-term increase in heat flow is superimposed on the heat flow peak because of the increased flow of 260°C water towards the production borefield. Steam separates in the upflow area west of the production borefield, and flows towards Karapiti in the fractured upper part of the Karapiti rhyolite.

The benchmarks around Karapiti are the only ones at Wairakei field for which the subsidence mimics the deep liquid pressure drop (Fig. 8). Over the rest of the field subsidence correlates with steam pressure decline. Around Karapiti thermal area, the lack of low permeability rocks near surface has caused steam pressures to remain low, so little compaction has occurred since deep liquid pressure stabilized in the early 1970's.

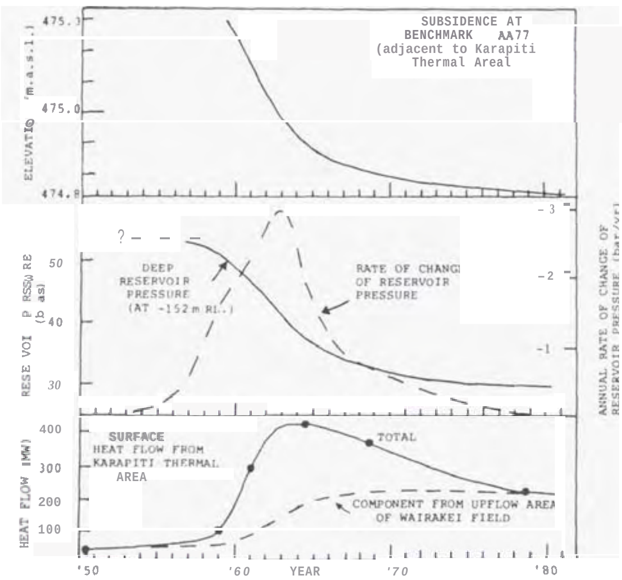

Fig. 8: Heat flow changes and subsidence at Karapiti thermal area compared with deep reservoir pressure changes.

CONCLUSIONS

The changes that have occurred around Karapiti thermal area emphasize the important influence of the Huka mudstone on near-surface hydrology elsewhere at Wairakei. What is still unclear is the role of faults in the mudstone, and whether downflowing groundwater is a significant component of the heat and mass budget of the field. The general trend of increased surface heat flow and increased groundwater temperature suggest that fluid flow in the mudstone is dominated by upflowing steam rather than downflowing water. A careful study of the rate increase of gravity and the decrease of steam pressure in the production borefield is required before downflowing ground-water can be ruled out as a major cause of the steam zone pressure decline. Such a study needs to include the effects of upward movement of the steam zone into the higher porosity mudstones; and the boiling of residual pore water as steam temperature and pressure declines. Both factors should cause a decrease in gravity, and may make the observed gravity increases more significant.

ACKNOWLEDGEMENTS

Ministry of Works and Development (M.W.D.) are thanked for supplying many of the well measurements mentioned in this paper. I also thank Andrew Carman, Geophysics Division, D.S.I.R. for remeasuring gravity at 5 benchmarks at Wairakei.

REFERENCES

Allis, R.G. 1981: Changes in heat flow associated with exploitation of Wairakei geothermal field, New Zealand: N.Z. Journal of Geol. and Geophys., 24, 1-19.

Allis, R.G. and Barker, P. 1982: Update on subsidence at Wairakei: Proc. 4th N.Z. Geothermal Workshop, 1982.

Cherry, J.A. and Freeze, R.A. 1979: Groundwater: Prentice-Hall International.

Glover, R.B. 1977: Chemical and physical changes at Geyser Valley, Wairakei, and their relationship to changes in borefield performance: N.Z. D.S.I.R. Bulletin 218, 19-26.

Grant, M.A. 1980: The initial state and response to exploitation of Wairakei geothermal field: unpublished manuscript.

Grant, M.A. 1982: Recharge to the Wairakei reservoir: Proc. 4th N.Z. Geothermal Workshop, 1982.

Hunt, T.M. 1977: Recharge of water in Wairakei geothermal field determined from repeat gravity measurements: N.Z. Journal of Geol. and Geophys., 20, 303-317.