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ANALYSIS OF SUBSURFACE COMPACTION AND SUBSIDENCE AT WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

Using the simple theory of one-dimensional consolidation, close agreement between calculated compaction and observed subsidence was found for Wairakei Geothermal Field. The crucial parameters in the analysis are the compressibilities and thicknesses of the various formations and the magnitude of the observed decline in pore pressure and the level of the water table. The compaction of the surficial pumice and the underlying Wairakei Breccia and Huka Falls Formation accounts for most of the observed subsidence.

The reservoir pressure has always been lower in the eastern part of the Wairakei Field than in the western part. Production of steam from shallow wells and cold water intrusion at relatively shallow levels in the eastern borefield contributes substantially to the reduction in steam pressure, which induced compaction in the Huka Falls Formation. The decline in the level of the water table results from the pressure reduction and causes the compaction of the two layers above the Huka Falls Formation.

Precise modelling of subsidence at Wairakei is difficult because of the lack of data regarding the nature and thickness of the compaction-prone deposits and the uncertainty about subsurface conditions in the area of maximum subsidence, which lies outside the main production zone. Since deformable lacustrine sediments are also found at Ohaaki Geothermal Field, attention is drawn to the problem of potential subsidence at Ohaaki.

INTRODUCTION

Compaction of the main aquifer (Waiora Formation) cannot account for most of the observed subsidence at Wairakei. However, the compressibility of the shallower deposits was found to be 2 to 3 orders of magnitude greater than that of the Waiora Formation by Allis and Barker (1982), who suspected that an unlithified pumice breccia layer in the Huka Falls Formation was responsible for both the unusual location and the large magnitude of the subsidence at Wairakei.

In the current study, the physical properties of the shallow deposits at Wairakef have been investigated further, as well as the state of stress in those deposits. Equations for the increase in effective stress were derived for each stage in the exploitation history of Uairakei. Compaction calculations were made based on the theory of one-dimensional consolidatfon (Terzaghf, 1925) and the results have been compared with the observed subsidence. Surface manifestations which have appeared since the onset of Subsidence were analysed to determine whether their locatfon and continued movement are related to a local or regional stress field.

Finally, the location of the main subsidence area has been re-examined. The implications of subsidence for field management and reinjection strategies are discussed, and suggestions for future studies are made.

PHYSICAL NATURE OF SHALLOW DEPOSITS

The production zone within the Waiora Formation in the Wairakei reservoir is a dense, competent unit, consisting largely of a highly mineralised pumice breccia (Grindley, 1965; Steinet, 1977). The compressibility of this formation was found to be quite low; Pritchett et al. (1976b) report a value of 0.025 kilobar-1. Such a low compressibility does not yield a compaction which matches the observed subsidence, even though the Waiora Formation has experienced the greatest pressure drop of any of the formations at Wairakei.

The Waiora Formation is overlain by the essentially unaltered lacustrine sediments of the Huka Falls Formation (Grindley, 1965; Steiner, 1977). In the eastern borefield beneath the area of maximum subsidence, this formation consists of mudstones with thin interbedded pumiceous sandstones (Hu_1), pumice breccia (Hu_2), and interbedded mudstones and pumiceous sandstones (Hu_{3-4}).

Allis and Barker (1982) reported a compressibility value of 8.0 $kilobar^{-1}$ for Hu_2, which is thickest in the eastern and southeastern areas of the field. Consolidation tests were performed by the author on fresh core samples of Hu_2 and Hu_{3-4} obtained from well WK301, and old core samples of Hu_2 from well WK33 (see Figure 5 for well locations). The results of the consolidation tests (Table 1) indicate that the compressibility of Hu_2 and Hu_{3-4} are of the same order of magnitude, but slightly lower than that reported by Allis and Barker (1982). Pritchett et al. (1976b) report a significantly lower value (0.25 $kilobar^{-1}$) for the compressibility of the Huka Falls mudstone.

Other samples of the Huka Falls Formation (all members) were also tested for dry density, saturated density and effective porosity. Similar values were obtained for all members. The average values of dry density, wet density and effective porosity were found to be 0.99 g/cm^3, 1.49 g/cm^3m and 0.57 respectively.

The Huka Falls formation is overlain by the tuffaceous sandstones of the Wairakei Breccia (Grindley, 1965), which are commonly affected by argillic alteration, and in some places, by supergene alteration (Steiner, 1977). Consolidation tests indicate that the compressibility of thfs formation is 23.0 $kilobar^{-1}$ (Allis and Barker, 1982). Its porosity is also very high; the average value of five samples was 0.72. High porosity generally indicates high compressibility. The surficial pumice layer is also extremely porous, but has not been tested for compressibility to date.

TABLE 1: Experimental values of uniaxial compressibility

Well	Depth (m)	Formation	C_m (kil... -1)
WK301	85	Hu_{3-4}	1.16 ± 0.2
WK301	85	Hu_{3-4}	2.14 ± 0.1
WK301	138	Hu_2	0.90 ± 0.15
WK301	138	Hu_2	1.20 ± 0.1
WK33	120	Hu_2	1.75 ± 0.2
WK33	120	Hu_2	2.42 ± 0.1
WK4/1	?	Hu_2	8.0*
WK4/1	?	Wr	23.0*

* Allis and Barker, 1982

State of Stress within the Wairakei Reservoir

According to the theory of one-dimensional (uniaxial) consolidation (Terzaghi, 1925) the intragranular or effective stress P' inside a rock mass (i.e. the load supported by the rock matrix) is equal to the total geostatic stress (P_{total}) at that point (due to the weight of rock and water above it) minus the pore pressure (u):

$$P' = P_{total} - u. \tag{1}$$

Compaction may occur by the transfer of stress from the pore fluid to the rock matrix when the pore pressure is decreased. It follows that the change in effective stress is given by:

$$\Delta P' = \Delta P_{total} - \Delta u. \tag{2}$$

As the increase in effective stress is responsible for compaction by rearranging, distorting, or breaking the rock grains, the effect of changing reservoir conditions on effective stress will be discussed. All equations for $\Delta P'$ below are derived by calculating $\Delta P_{total} - \Delta u$ at various levels of the reservoir and summing the cumulative stresses.

The pore pressure profile of a semi-confined, unexploited, liquid-dominated geothermal reservoir with a parasitic vapor-dominated zone is shown in Figure 1a (u_0, reservoir state 0). With production, the level of the hot water table is drawn down, the steam-dominated zone ("steam zone") expands, pore pressures decline, and the level of the overlying water table (∇) drops because the confining layer or "cap rock" is leaky (u_1, reservoir stage 1). The decline in both the water table and the pore pressure cause an increase in effective stress. $\Delta P'$ throughout the various zones (Figure 1b) are:

1. Above ∇_1 : $\Delta P' = 0$

2. Between ∇_1 and ∇_2:

$$\Delta P' = \rho_{w(c)} g[1-n_1(1-s)]a, \tag{3}$$

where $\rho_{w(c)}$ is the density of the cool groundwater, g is gravitational acceleration, n_1 is the porosity of the uppermost layer, s is the residual saturation (fractional volume of pores filled with immobile water which remains after the water table has been drawn down), and a is the depth from ∇_1 to the point in question.

3. Between ∇_2 and the top of the semi-confining layer:

$$\Delta P' = \rho_{w(c)} g \Delta h_1[1-n_1(1-s)], \tag{4}$$

where Δh_1 is the total drop in groundwater level.

4. In the semi-confining layer, $\Delta P'$ is affected by the decline in groundwater level, the steam pressure drop, and dry-out of the steam zone. Dry-out occurs when immobile pore water is boiled off, using heat from the rock as pressure and temperature drop along the saturation curve (Grant et al., 1982). $\Delta P'$ in this part of the reservoir is given by:

$$\Delta P' = \rho_{w(c)} g \Delta h_1[1-n_1(1-s)] - (\rho_{w(h)} - \rho_s) g n_2 \Delta s_1 b + \Delta u_{s(1)} \tag{5}$$

where $\rho_{w(h)}$ is the density of the hot, immobile pore water, ρ_s is the density of the steam, n_2 is the porosity of the semi-confining layer, Δs_1 is the change in residual saturation of the steam zone due to dry-out, b is the depth from the top of the semi-confining layer to the point in question, and $\Delta u_{s(1)}$ is the decline in steam pressure.

5. In the portion of the main aquifer which is steam-filled in both the initial and exploited states, a term must be included for the dry-out of the main aquifer, giving:

$$\Delta P' = \rho_{w(c)} g\, h_1[1-n_1(1-s)] - [(\rho_{w(h)} - \rho_s) g][(n_2 \Delta s_1 x) + (n_3 \Delta s_1 c)] + \Delta u_{s(1)}, \tag{6}$$

where x is the thickness of the semi-confining layer, n_3 is the porosity of the main aquifer, and c is the depth from the top of the main aquifer to the point in question. The same amount of dry-out is assumed to occur in both the semi-confining layer and the portion of the main aquifer which was originally filled with steam.

6. In the portion of the main aquifer which was in either the liquid-dominated ("boiling") zone or hot water zone and is now in the steam zone, $\Delta P'$ is affected by the change in groundwater level, dry-out through the steam zone, the change in pore pressure at the point in question, and the amount of immobile water remaining in the pores after drawdown of the hot water table. This gives:

$$\Delta P' = \rho_{w(c)} g \Delta h_1[1-n_1(1-s)] - [(\rho_{w(h)} - \rho_s) g][(n_2 \Delta s_1 x) + (n_3 \Delta s_1 y) + (n_3 s' d)] + \Delta u_{s(1)} + (\Delta u_h - \Delta u_{s(1)}) d/z, \tag{7}$$

where y is the original thickness of the steam zone in the main aquifer, s' is the residual saturation following drawdown of the main aquifer, d is the depth from the original hot water level to the point in question, Δu_h is the pore pressure drop in the hot water zone, and z is the increase in thickness of the steam zone in the main aquifer. The difference in fluid density between the boiling zone and the hot water zone is assumed to be negligible.

7. In the remainder of the aquifer:

$$P' = \rho_{w(c)} g \Delta h_1[1-n_1(1-s)] - [(\rho_{w(h)} - \rho_s) g][(n_2 \Delta s_1 x) + (n_3 \Delta s_1 y) + (n_3 s' z)] + \Delta u_h \tag{8}$$

In reservoir state 2, deep recharge has caused the deep liquid pressure to stabilise. However, steam preseures still decline due to lowering of temperature at the flash point, extraction of steam by shallow wells, and cold water intrusion. Because the steam pressure continues to decline, there is an additional drop in groundwater level.

The equations describing the increase in effective stress during reservoir state 2 are similar; however, terms must be added to account for the additional groundwater level decline (Δh_2), changes in residual saturation (Δs_2) due to dry-out ($\Delta s_2 > 0$) or resaturation ($\Delta s_2 < 0$) of the steam zone, additional steam pressure decline ($\Delta u_{s(2)}$), changes in residual saturation following drawdown of the main aquifer (s"), and perhaps additional pressure decline in the

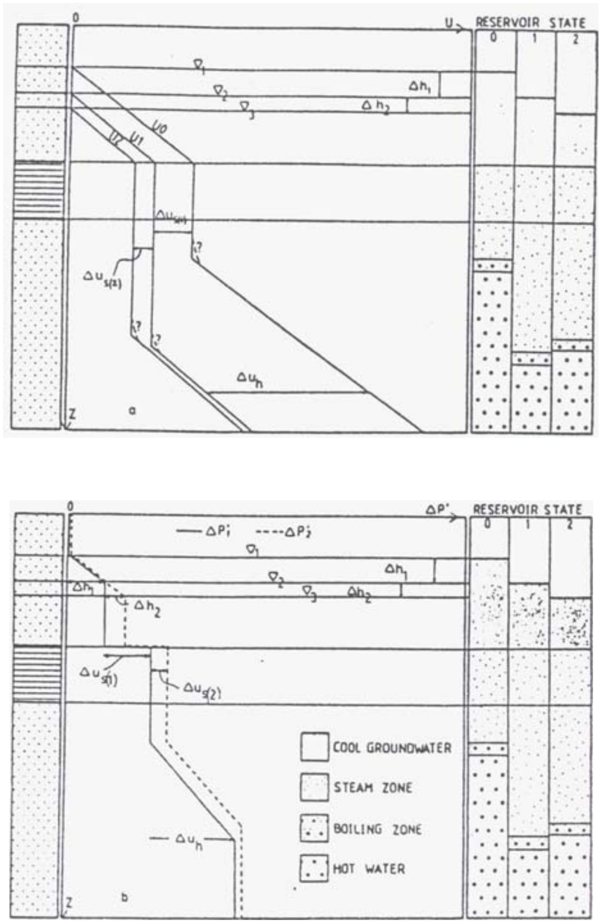

FIGURE 1: (a) Plots of pore pressure (u) vs. depth (z) and (b) increase in effective stress (P') vs. depth for a semi-confined, liquid-dominated geothermal reservoir in the initial state *(0)* and exploited states (1 and 2). indicates the top of the water table, h is the decline in the level of the water table, u_s is the decline in steam pressure and u_h is the decline in hot water pressure.

The Wairakei reservoir has evolved in a similar manner to the theoretical reservoir described above. Although it was not present initially, a steam-dominated zone quickly developed in the eastern borefield (Figure 2), where the pore pressure gradient is aptly described as steam-static overlying near-hydrostatic (Grant and Horne, 1980). In the western borefield, the development of the steam zone has been much more limited, and the progression towards the development of such a zone is less clear (Figure 3).

COMPACTION IN THE WAIRAKEI RESERVOIR

Calculated compaction is compared to observed subsidence at two of the most frequently-levelled benchmarks in the field: A97 and AA13. Subsidence at A97 and AA13 are typical of the eastern and western borefields respectively.

Benchmark A97 (eastern borefield)

Pritchett et al. (1976a) noted the non-linear relationship between Subsidence and time at bench mark A97 (Figure 2), and they attributed this to an increase in the compressibility of the Waiora Formation uith time. Calculations in which a constant compressibility for the Waiora Formation throughout the production history of the reservoir is used, suggest, however, that a change in compressibility has not occurred. The following assumptions were used in the calculations:

1. The generalised stratigraphy and reservoir pressure declines are adequately represented by Figure 2.
2. The cumulative groundvater level decline (Ah) is 3m for each time Interval considered (1952-1962, 1962-1972, 1972-1982).
3. Porosities of the surficial pumice and Wairakei Breccia, Huka Falls Formation (all members), and Walora Formation are *0.6, 0.5* and 0.3, respectively.
4. The residual saturation following both the vater table decline (s) and the drop in the hot vater table in the reservoir (s') is *0.5.*
5. Dry-out of the steam zone occurred between 1962 and 1972, and the change in residual saturation (As) was *0.2.*
6. Resaturation of the steam zone occurred between 1972 and 1982; Δs during this time period was -0.2.
7. If the Increase in effective stress ($\Delta P'$) is not constant throughout the thickness of a given layer, the average value of $\Delta P'$ is used for the entire layer (i.e. $\Delta P'$ at the midpoint of the layer).

Using these assumptions, compaction (Δt) of each layer is calculated using the equation:

$$\Delta t = \Delta P' C_m t, \qquad (9)$$

where C_m is the coefficient of uniaxial compressibility and t is the thickness of the layer; AP' *is* calculated using equations 3-8 above. The results are presented in Table 2.

Bench mark AA13 (western borefield)

The generalised pressure changes shown in Figure 3 Indicate that the development of the steam zone in the west has been restricted, and the progression toward the development of such a zone is less clear. For this reason, it is difficult to estimate changes in residual saturation. However, using the values for residual saturation following drawdown used above and a water table decline of 8m, it is possible to calculate the total estimated compaction (Table 3).

There is close agreement between the calculated compaction and the observed subsidence. The key parameters influencing the calculated compaction are the choices of compressibilities, the thicknesses of the formations, and the magnitudes of the pore pressure drop and the water table decline. The compaction of the surficial pumice and of the Wairakei Breccia is significant in all calculations; conversely, the Waiora Formation contributes little to the total compaction, except for the compaction during 1952-1962 at A97. As the steam zone migrates upward through the various members of the Huka Falls Formation, the contribution to the total compaction made by these layers becomes apparent. Thus, the argument that subsidence is related to the decline in steam pressure after the mid-1960's. rather than to the decline in deep liquid pressure, is valid (Allis and Barker, 1982, and Figure *4).* This is particularly the case in the eastern borefield, where the development and enlargement of the steam zone is very clear.

ANALYSIS OF SURFACE FEATURES

The surface manifestations of subsidence (Figure *5)* are located mainly in the zone of ground tension (Allis and Barker, 1982). The horizontal strain in the vicinity of several steaming cracks and bare patches, and one active normal fault which have appeared since the onset of subsidence were analysed to determine if their location and continued movement are related to a regional (i.e. tectonic) stress field or local (i.e. subsidence-induced) stresses.

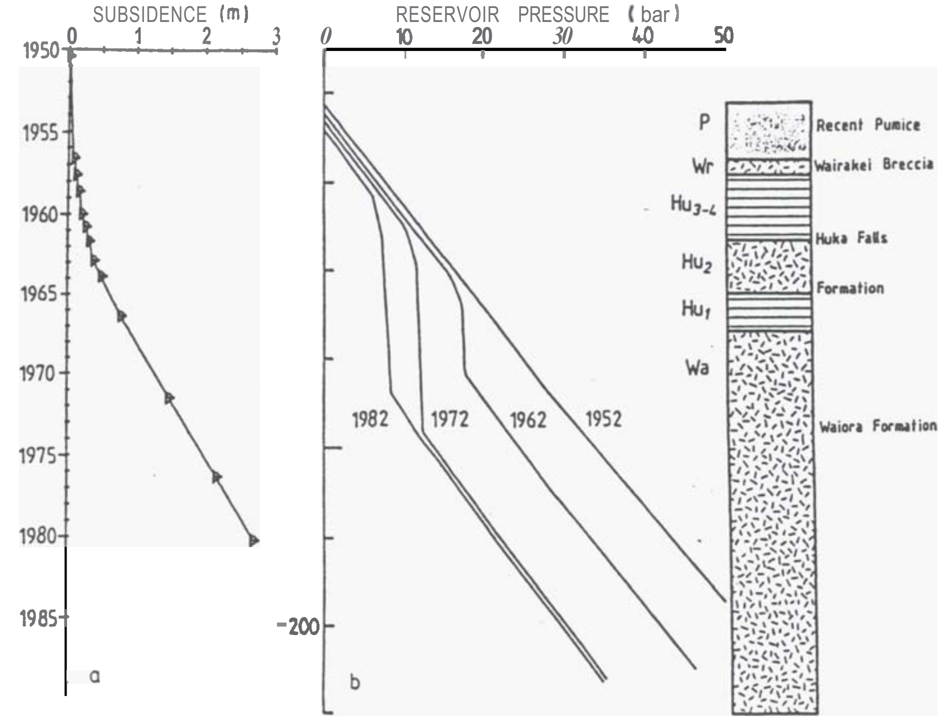

FIGURE 2 : (a) Plot of subsidence vs. time at bench mark A97. (b) Pressure of change8 and generalized stratigraphy in the eastern borefield (modified from Allis, in prep.).

TABLE 2 : Reservoir compaction near A97

Formation	t (m)	ΔP'(kb)	C_m (kb^{-1})	Δt (m)	% total compaction	
P	3	0.00011	23[a]	0.008	52	
P, Wr	75	0.00022	23[a]	0.380		
Hu_{3-4}	70	0.00022	2.14±0.1	0.033i0.002	4	1952-1962
Hu_2	65	0.00022	1.75i0.2	0.075t0.003	3	
Hu_1	35	0.00459	1.1620.2	0.186i0.033	25	
Wa	40	0.00784	0.024[b]	0.008	16	
Wa	460	0.00984	0.024[b]	0.109		

Δt_{total}= 0.749 m ± 0.112 m . Calculated subsidence rate- 0.075±0.011 m/year
Observed subsidence. 0.30 m Observed subsidence rate = 0.030 m/year

Formation	t (m)	ΔP'(kb)	C_m (kb^{-1})	Δt (m)	% total compaction	
P	3	0.00011	23[a]	0.038	33	
P. Wr	72	0.00022	23[a]	0.364		1962-1972
Hu_{3-4}	70	0.00022	2.14±0.1	0.033±0.002	3	
Hu_2	65	0.00380	1.75±0.2	0.432t0.050	38	
Hu_1	35	0.00457	1.16±0.2	0.186±0.033	17	
Wa	110	0.00486	0.024[b]	0.013	9	
Wa	390	0.00963	0.024[b]	0.092		

Δt_{total}= 1.128 m ± 0.169 m Calculated subsidence rate= 0.113±0.017 m/year
Observed subsidence= 1.23 m Observed subsidence rate = 0.123 m/year

Formation	t (m)	ΔP'(kb)	C_m (kb^{-1})	Δt (m)	% total compaction	
P	3	0.00011	23[a]	0.008	22	
P. Wr	69	0.00022	23[a]	0.349		
Hu_{3-4}	70	0.00274	2.14t0.1	0.410t0.020	26	1972-1982
Hu_2	65	0.00511	1.75±0.2	0.581r0.066	36	
Hu_1	35	0.00534	1.16±0.2	0.216±0.03	14	
Wa	70	0.00580	0.024[b]	0.010	2	
Wa	430	0.00230	0.024[b]	0.024		

Δt_{total}= 1.598 m ± 0.240 m Calculated subridence rate- 0.160t0.024 m/year
Observed subsidence. 1.38 m Observed subsidence rate = 0.138 m/year

[a] Allis dnd Barker. 1982

[b] Pritchett et al., 1976b

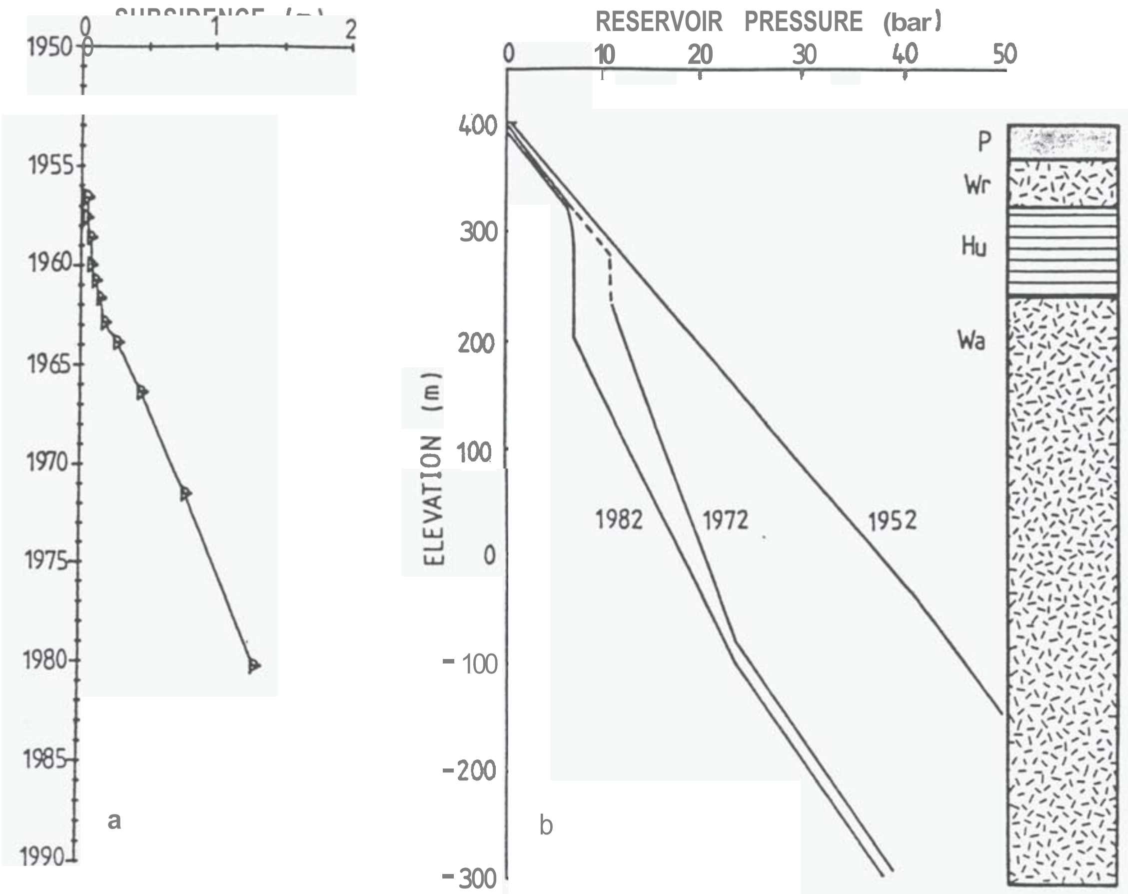

FIGURE 3 : (a) Plot of subsidence vs. time at bench mark AA13. (b) Pressure changes and generalized stratigraphy in the western borefield (modified from Allis, in prep.).

TABLE 3 : Reservoir compaction near AA13 (1952-1982)

Formation	t (m)	ΔP'(kb)	C_m (kb^{-1})	Δt (m)	% total compaction
P	8	0.00028	23[a]	0.052	43
P, Wr	55	0.00056	23[a]	0.708	
Hu	85	0.00749	1.16±0.2	0.739±0.127	42
Wa	50	0.01301	0.024[b]	0.016	15
Wa	450	0.02201	0.024[b]	0.238	

Δt_{total} = 1.753 m ± 0.263 m

Observed subsidence= 1.41 m

[a] Allis and Barker, 1982

[b] Pritchett et al., 1976b

Wooden pegs were set out in triangular patterns around these features (Figure 6) and the distance between the pegs vas periodically remeasured, using the same fiberglass tape and a spring balance to ensure that a constant pull vas exerted on the tape.

A method of strain analysis derived from a graphical construction by Ramsay (1967) was employed to determine the value and direction of the major principal strain from the changes in length of the three sides of the triangles. Quadratic elongations and shear strains vere calculated, and a Mohr diagram was constructed to determine the orlentations and values of the principal strains For each triangle.

The results (Table 4) show that the subsidence is responsible For the ongoing strain; the direction of principal extension for the steaming fissures and bare patches ranges from 114° to 180°, vith an average value of 135°. This direction is nearly at right angles to the subsidence contours at this locality.

Similar results were obtained from the strain analysis of movements near the Lault. The direction of principal extension therefore is 217°, which is a bearing pointing directly towards the center of maximum subsidence.

The steaming cracks form an en-echelon pattern, and their location coincides with the eastern extension of a E-W trending fault which traverses Geyser Valley. These features may have formed over incipient faults which have opened due to subsidence-induced ground tension (Allis and Barker, 1982). The fault does not appear to be related to any underlying structure; its location is solely due to the tensional stresses resulting from the subsidence, as are the horizontal strains measured near surface manifestations.

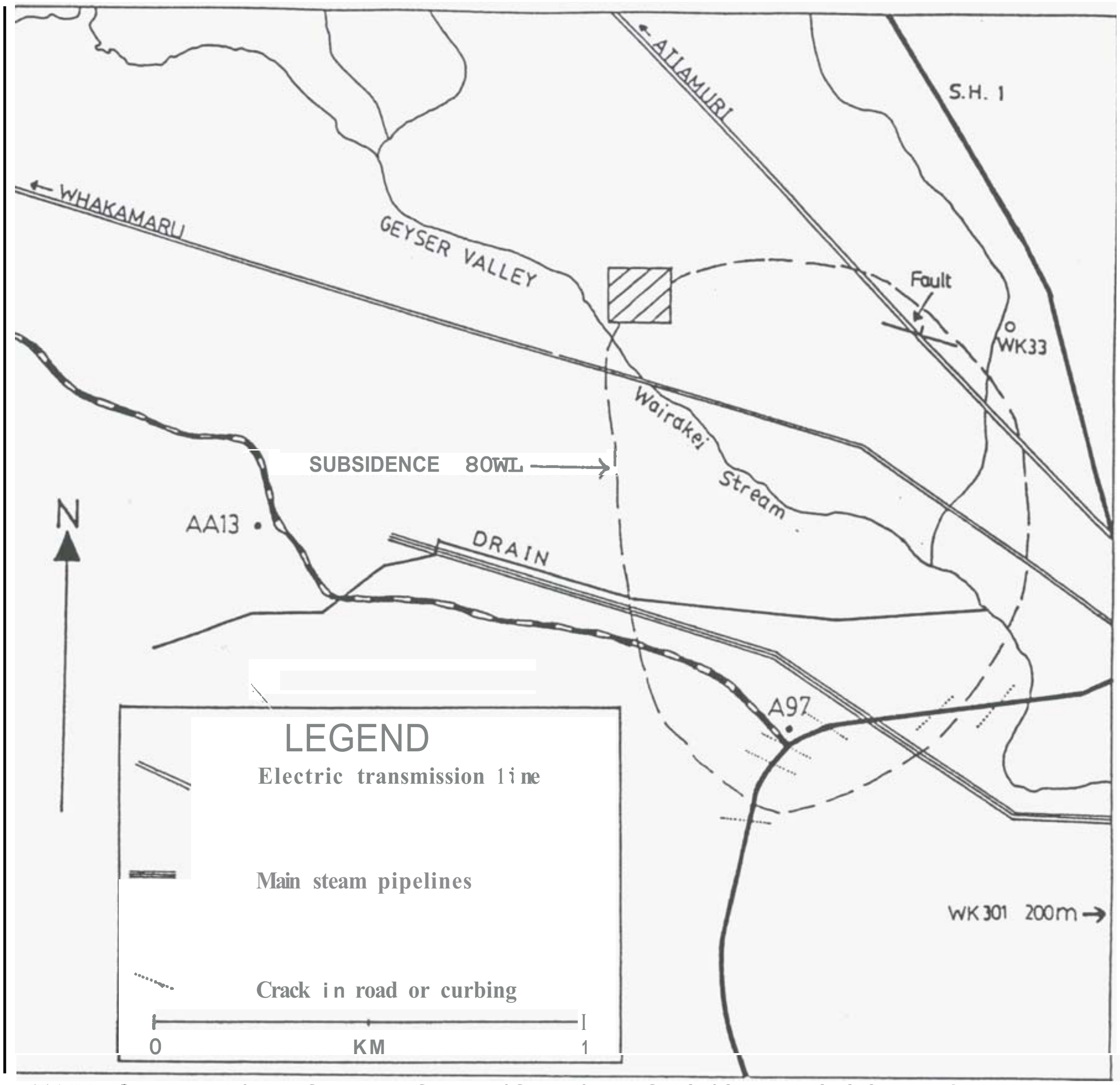

FIGURE 5 : Locations of some surface manifestations of subsidence. Shaded area shown in detail in Figure 6.

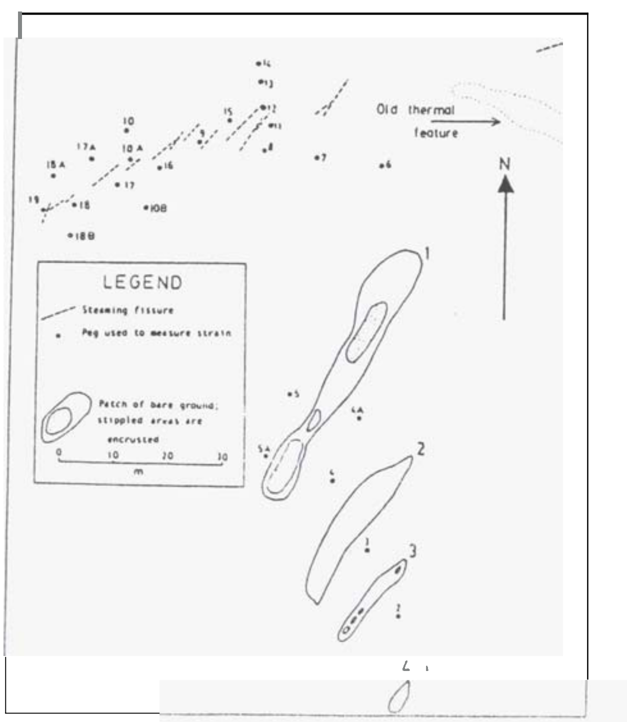

FIGURE 6: Location of pegs used for strain analysis of fissured ground east of Geyser Valley.

TABLE 4 : Principal extension directions derived from strain analysis of fissures

Triangle	Direction of principal extension
19 -18A-18	126°
19 -18 -188	119°
17 -17A-16	150°
17 -16 -10	114°
17 -10A-10B	140°
17 -10A-16	168°
10A-16 -10B	127°
17 -16 -10B	120°
9 -15 -8	131°
15 -11 -8	117'
15 -12 -11	130'
15 -12 -8	180'
5A -5 -4	119°
5 -4 -4A	130'

LOCATION OF THE AREA OF MAXIMUM SUBSIDENCE

The main subsidence area at Uairakei is located near Geyser Valley, which was one of the surface discharge areas for ascending geothermal fluids during the unexploited state of the reservoir. Since production began, major changes have occurred at Geyser Valley, and cool surface waters are now thought to be entering the reservoir through fault conduits (Glover, 1977).

The proximity of the subsidence area to Geyser Valley has two implications:

1. As Geyser Valley is an area with a direct and long-established connection to the deep reservoir, it has experienced the full effects of pressure drawdown.

2. As the "Geyser Valley Fault" and associated faults to the east may be the entry point of cool ground-water, the steam zone in the east is becoming resaturated and the steam pressure continues to fall, causing the continued compaction beneath the subsidence area.

The subsidence area is located approximately half way between Geyser Valley (and associated faults to the east) and the eastern borefield. The Huka Falls Formation is less than 40m thick beneath Geyser Valley, and thickens towards the southeast. The pressure drop has been greater beneath Geyser Valley than in the eastern borefield. Thus, there is an interplay between the thickness of the compressible deposits of the Huka Falls Formation and reservoir pressure decline; the subsidence bowl is located in an area which is affected by both phenomena.

The reservoir pressure has always been lower in the eastern borefield than in the west (Bolton, 1970), and the development and enlargement of the steam zone in the east is clearly visible in Figure 4. Although most production comes from the western borefield, where the formation of the steam zone has been limited, a large pressure drop accompanied by boiling and extensive steam formation has occurred in the eastern and northeastern area of a the field. As the steam zone ascended into the compressible deposits (i.e. the Huka Falls Formation), compaction started. Steam pressures continue to decline beneath the main subsidence area, and the water table continues to drop; thus, compaction continues.

IMPLICATIONS OF STUDY

In terms of subsidence control, production from the steam zone by shallow wells is the most detrimental field management policy. Many of the eastern wells at Wairakei originally produced hot water; however, following drawdown of the deep water table, many of these wells produced increasingly from the steam zone. Although production in the west would still induce a pressure decline in the east, without the added component of production in the east, the severity of this pressure decline may be lessened. Three 200-series wells in the west were recently brought on line, and future target areas are also in the west, reflecting the fact that the productivity of the eastern borefield is declining.

As the hydraulic gradient is toward the south, reinjection in the main subsidence area would probably cause an enthalpy decline in the eastern wells. If a management deciston were made to halt production in the eastern borefield, reinjection into the main subsidence area could be an attractive propositton. The primary advantage to drilling a reinjection well in the subsidence area would be that the geologic structure and stratigraphy would be knovn, and that fresh cores could be obtained for consolidation tests. Surface rebound following reinjection would yield information regarding the physical nature of the deposits. In addition, water levels, reservoir pressure and steam distribution could be ascertained.

The necessity for a thorough study of the sedimentology and engineering properties of the Huka Falls Formation is indicated by the results of this study. Although not detailed here, other compaction calculations by the author (Robertson, 1984) indicate: that there is a lateral variation in compressibility in this formation. Considering the rapid, spatial and temporal lithologic changes observed in the cores from Wairakei and Tauhara, this result is not surprising. As shallow, post-eruption lacustrine sediments are common in the geothermal areas of the Taupo Volcanic Zone, a study of the Huka Falls Formation would have implications for other geothermal fields; in particular, the Ohaaki Field.

A large part of the production area at Ohaaki lies at an elevation which is only a few meters above the level of the Waikato River. Subsidence of a similar order of magnitude as that which has occurred at Wairakei could. cause substantial flooding of the production area by the Waikato River. The lacustrine sediments at Ohaaki, tentatively correlated with the Huka Falls Formation, should be sampled and tested in order to determine physical properties. For subsidence prediction, the most important of these properties is the uniaxial compressibility. Accurate values for the compressibility of all shallow layers are essential for realistic Subsidence prediction.

A mathematical model of subsidence at Wairakei is currently underway. A realistic model of the subsidence at Wairakei would be unique in that it would be the only such model to predict both the location of the subsidence, which is offset from the main production area, and the magnitude of subsidence, which does not result from reservoir compaction in the main production zone- A realistic model would shed some light on the nature of the rheology of the shallow deposits, which appears to be very complex. For further discussion of the requirements of such a model, refer to Robertson (1984).

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