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PREDICTING FUTURE SUBSIDENCE AT WAIRAKEI FIELD, NEW ZEALAND

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SUMMARY - A releveling survey of Wairakei field during mid 1997 has confirmed that the magnitude of subsidence rates in the main subsidence bowl continues to reduce. Peak subsidence rates are now close to 200 mm/y, and are less than half the peak rates which were occurring during the mid 1970s. The maximum total subsidence is now 14 m. The greatest reduction in rates has occurred around the eastern margin of the bowl where it coincides with the field boundary. This is attributed to lateral inflow of cooler water at shallow depth maintaining or increasing pressure near the compaction zone. Near the power station, shallow injection since the early 1990s appears to have resulted in a reduction in the subsidence rates in a localized area. This contrasts with the western half of the field where ongoing steam pressure declines have caused subsidence rates to increase since the mid 1970s. 1-D coupled fluid flow-deformation modeling of the drainage process indicates that subsidence could continue for another 50 years, but with subsidence rates continuing to reduce. The total maximum subsidence is predicted to be in the range 20 ± 2 m assuming the present pattern of borefield management continues.

1. INTRODUCTION

Unusually high rates of subsidence at Wairakei field have been known since the mid-1960s, when it was realized that additional benchmarks were required northeast of the production borefield in order to delineate the subsidence associated with production (Hatton, 1970; Stilwell et al., 1976). The cause of the subsidence has been inferred to be due to the very compressible sediments within the Huka Falls Formation (HFF), a relatively low permeability formation which covers most of the field between about 100 m and up to 400 m depth. Allis and Barker (1982) and Allis (1990) suggested that a pumice breccia unit within the HFF with a compressibility of the order of 10 $kbar^{-1}$ (0.1 MPa^{-1}) could be causing the anomalous compaction. More recently, Allis et al (1997a,b) have suggested that mudstone units in the HFF are more likely to be causing most of the compaction. This was based on modeling of the compaction as well as comparisons with the nearby Ohaaki field, where relatively high rates of subsidence have also begun to occur with the development of the field for power production. In addition to high compressibilities (10 – 50 $kbar^{-1}$), the modeling indicated that the deforming sediments also must have relatively low permeability (~ 0.1 mD) for the high subsidence rates to have continued at Wairakei for around 40 years. In cold groundwater systems this compaction phenomenon is known as aquitard drainage (Helm, 1984).

During mid 1997, Wairakei field was releveled, and the processed data has recently become available. In this paper we review the new data in the area of maximum subsidence. The new data is added to some of the modeling scenarios of Allis et al. (1997) which were based on the data up to 1994. Finally, we investigate the model predictions for the center of the subsidence bowl and estimate the total maximum subsidence that is likely to occur in the future.

2. THE 1997 RESULTS

Maps of subsidence rates in the Wairakei subsidence bowl during the mid 1970s, and the mid 1990s, are shown in Figs. 1 & 2. The mid 1990s rates are largely derived from releveling surveys during 1994 and 1997. For approximately 10% of the benchmarks, data is absent from one of these surveys, and earlier survey data has been used for the map. Subsidence rates based on these earlier data have been scaled according to the gradually decreasing trend of subsidence rate during the 1980s and 1990s (Fig. 3).

The maximum subsidence rates of between 400 and 500 mm/y during the 1970s have declined to around 200 mm/y during the mid 1990s. Although the subsidence trends between the center of the bowl (benchmark P128) and the margins (e.g. benchmark A97 near southern margin, located on Fig. 1) suggest a similar pattern (Fig. 3), closer inspection of the rate

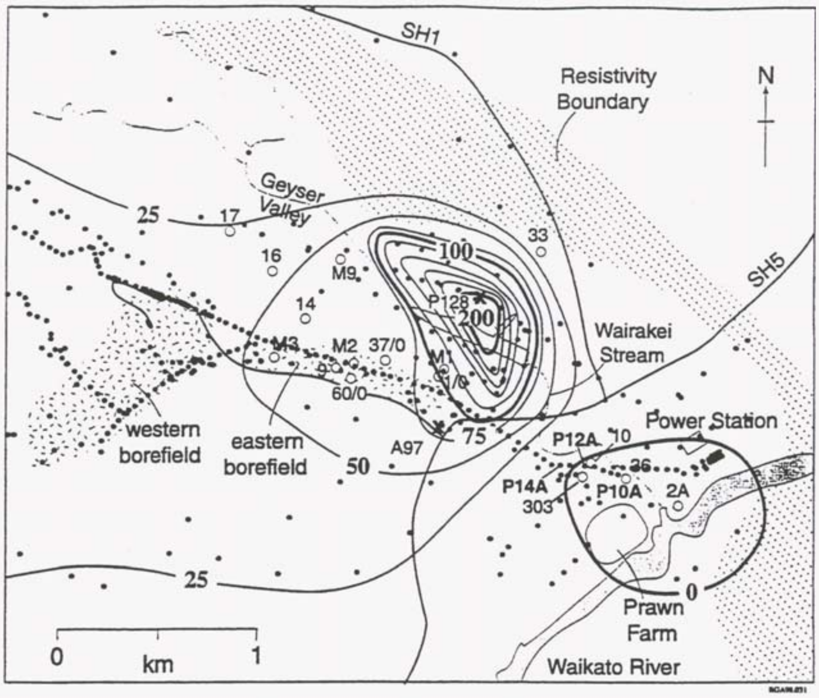

Fig. 1. Subsidence rates (mm/y) around the Wairakei subsidence bowl during the mid **1990s.** Most data is from repeat leveling in **1994** and **1997. Dots** are benchmarks with level changes. Benchmarks **A97** and **P128** are marked with crosses. **P10A, 12A** and **14A** are benchmarks referred to in Fig. **6.** Open circles are wells referred to in the text or other figures.

changes shows systematic differences (Fig. **4).** In the center of the bowl, the subsidence rate during the mid **1990s** is just under 50% of that during the mid **1970s.** This compares to **60%** at **A97** over the same period of time.

A compilation of the ratio of mid **1990s** subsidence rates to mid **1970s** subsidence rates is shown in Fig. 5. The greatest fractional change in rates occurs around **300** m west of the power station, with subsidence of **20 – 40** mm/y in the mid **1970s** decreasing and reversing to slight ground inflation of **1 – 5** mm/y in the mid **1990s.** All rates are relative to an origin near the Aratiatia Dam about **3 km** ENE of the power station. The greatest amount of subsidence rate reduction, however, occurs near the center and on the northeast margin of the bowl (around 200 mm/y reduction in rates). These changes coincide with the location of the resistivity (boundary around the northeastern margin of the field. This part of the field has been noted for large-scale cooling within the HFF (e.g. well **33)** after an initial pulse of heating during the **1960s** (Allis, **1982).** It has also been an area of gradual gravity increase since the late **1960s** (Allis and Hunt, **1986;** Hunt, **1995).** The changes are consistent with lateral invasion of cold water, with fluid pressures possibly recovering significantly after an initial pressure drawdown phase early in the development of the field.

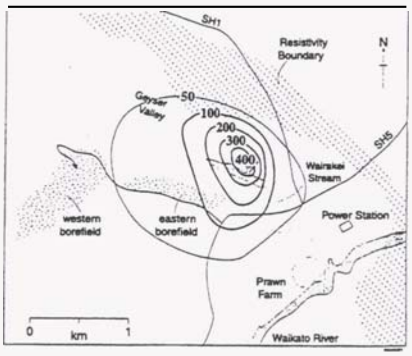

Fig. **2.** Subsidence rates (mm/y) around the Wairakei subsidence bowl during the mid **1970s.**

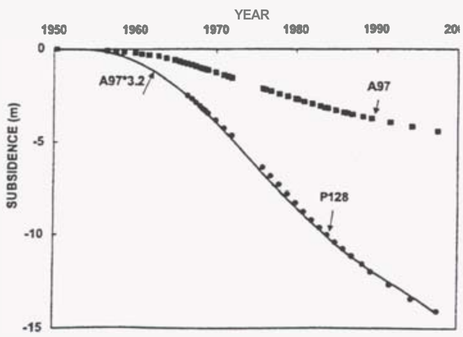

Fig. **3.** Subsidence histories at two benchmarks (located in Fig.1). The line through the **P128** data is **3.2** times the subsidence at **A97,** indicating similar trends around the bowl.

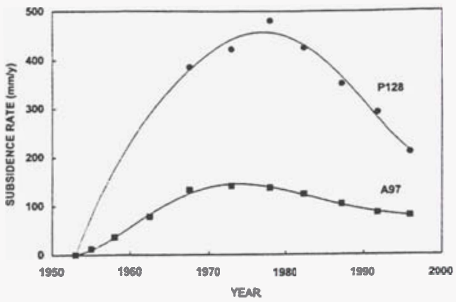

Fig. 4. Subsidence rate variations at A97 and P128, calculated at approximately 5 yearly intervals depending on the timing of the releveling surveys at each benchmark. The data are plotted at the mid point of the releveling interval, and 5^{th}-order polynomial trendlines have been fitted to the data.

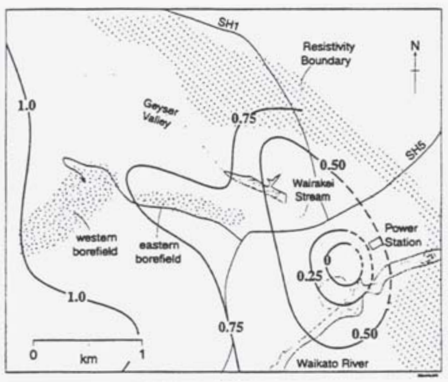

Fig. 5. Map highlighting the areas of greatest change in subsidence rate since the mid 1970s. The contours represent the ratio of the subsidence rate during the mid 1990s to that during the mid 1970s.

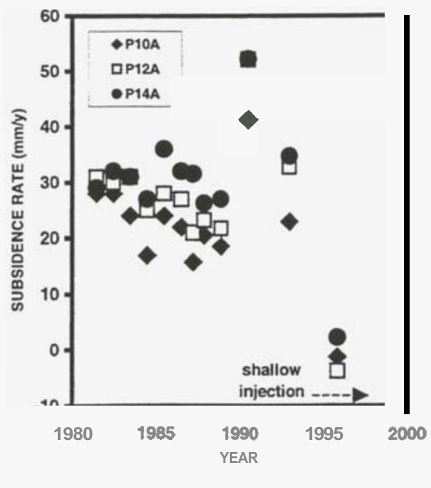

Fig. 6. Variation in subsidence rate near the power station since the early 1980s with data plotted at the midpoint between leveling surveys. The three benchmarks are located on Fig. 1. The arrow marks the time of hot injection into well **303,** near these benchmarks.

A second factor that appears to be influencing shallow pressures immediately west of the power station is injection into the HFF. Well **303** was drilled and injection tested with cold water in 1989-90. While shut, a strong downflow was present, with water flowing out of the pumice breccia unit of the HFF and down the wellbore to exit into the Waiora Formation. This outflow would have resulted in a depressurization **of** the HFF and hence the increase in subsidence rate seen in 1990 in Fig. ***6***. Since 1994 well **303** has been accepting injection of 126°C separated water at 220-270 m depth. Subsidence rates here decreased from around 35 to 20 mm/y during the 1980s to near zero after 1995, and the area is now showing slight ground inflation. The radius of inferred influence from the injection appears to be about 500 m.

In contrast to declining subsidence rates within the subsidence bowl and near the northeastern boundary of Wairakei field, the rates have been increasing in much of the western half of the field. The zone of no significant change in subsidence rates between the mid 1970s and the mid 1990s can be seen near the western edge of Fig. 5. Further west the ratio varies between 1 and 1.5. This trend of increasing subsidence rates appears to be closely related to the continuing decline in steam zone pressure at 200 – 500 m depth in the west of the field.

To summarize, Figs. 5 & ***6*** demonstrate that some areas of subsidence around the eastern margin of the subsidence bowl have experienced significant declines in subsidence since the mid 1970s. Lateral recharge to the field probably is occurring, at the eastern margin and it appears to be causing the subsidence rates to reduce more rapidly. There is also circumstantial evidence that shallow injection into a well near the power station has perturbed local subsidence trends and possibly stopped the subsidence in this area.

3. MODELING THE SUBSIDENCE

Details **of** the subsidence modeling are given in Allis et al. (1997) and are summarized here. A finite element code coupling compaction and fluid flow was applied to a one dimensional geological section comprising low permeability, relatively compressible mudstone sandwiched between relatively permeable pumice breccias. The geological justification for this is shown in the cross-section in Fig. **7.** Most of the compaction is thought to have occurred in the upper mudstone unit of the HFF between about 100 m and 200 m depth. The pumice

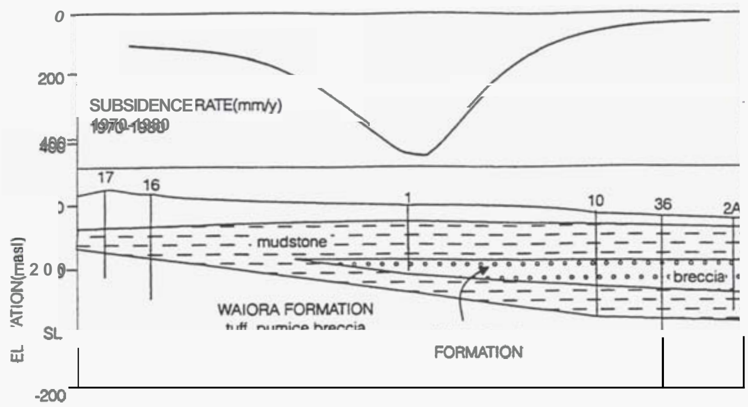

Fig. **7.** Northwest trending cross-section through the upper part of **the** Wairakei field in the vicinity of the Wairakei subsidence bowl. Cross-section can be located on Fig. **1** between wells **17** and **2A.**

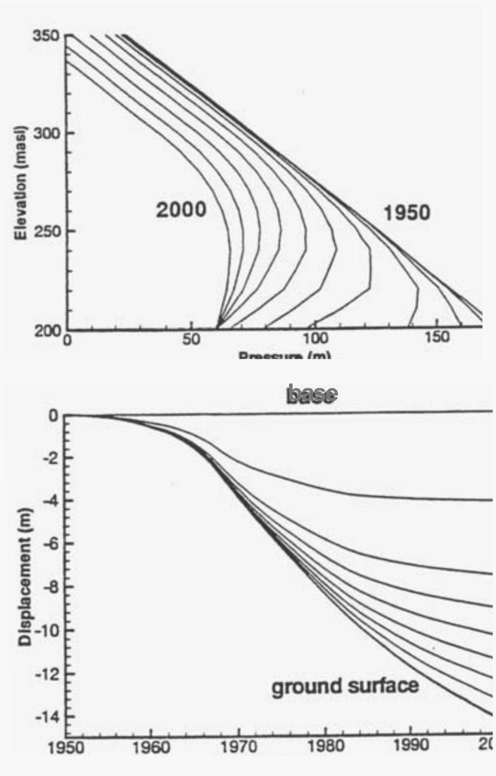

Fig. **8.** Pressure and displacement trends beneath **P128** calculated from the model assuming a mudstone compressibility of **45** kbar^{-1} and a permeability of **0.2** mD. The modeled subsidence closely matches observations, but little is known about shallow pressure changes in the area. The pressure-depth trends are at **5** year intervals; the displacement-time trends are at the base of the column **(200** masl), **225, 250, 260, 270, 280, 290, 300,** and the ground surface.

breccia unit within the HFF has a well-determined pressure history in the part of the subsidence bowl extending into the eastern borefield. The observed pressure decline of 11 bar (1.1 **MPa)** between **1960** and **1980** has been used as a boundary condition at the base of the geological column. The model calculates the decrease in pressure as it propagates upwards through the mudstone, as well as the resulting compaction caused by the decreasing pressure. The models discussed below for sites near benchmarks **A97** and **P128** have 100 m of mudstone overlain by 50 m of pumice and pumice breccia. This surface pumice unit is assigned a permeability consistent with its aquifer characteristics **(100** mD), and a moderate compressibility (1 **kbar^{-1}**). The permeability and compressibility of the mudstone are varied during the modeling in order to best fit both the observed surface subsidence and near-surface groundwater pressure changes, if known.

Modeling in the Eastern Borefield around **A97** implies a permeability of around 0.06 mD and a compressibility of **15** kbar^{-1} (Allis et al. **1997).** This produces the observed subsidence trend, and correctly predicts a pressure decline in the near-surface groundwater of **15** m by **1985.** In order to fit the three times greater subsidence in the center of the subsidence bowl **(P128),** the modeling requires a significantly greater compressibility of the mudstone (30 – **45** kbar^{-1}; Figs. 8 **&** 9). **A** higher permeability is also implied, indicating that the pressure decline may have propagated through the mudstone to a greater extent than is the case at **A97.** The lack **of** shallow pressure data in the groundwater of this region means that there is greater uncertainty in the model parameters at **P128** compared to **A97.**

4. DISCUSSION:

PREDICTIONS OF FUTURE SUBSIDENCE

Predictions of future subsidence must be treated cautiously. Non-uniqueness in the "best-fit" model parameters means that uncertainties and errors become amplified with increasing forward projection of the subsidence trend. In addition, the forward modeling assumes the hydrological boundary conditions remain constant, which in our model applies to the base of the mudstone column. The pressure here is assumed to have remained constant since the early 1980s. If lateral recharge causes pressure recovery, or there are future effects of production or injection in the vicinity of the compaction zones(s), then the model predictions clearly become unreliable. A possibly significant source of uncertainty in the model is the **1-D** assumption **of** pressure decline throughout the 100 m thickness of the mudstone unit. Zones of higher horizontal permeability within the mudstone could result in a more complex drainage process than single drainage through the base of the mudstone.

Given the above caveats, the forward projections of 3 models for the center of the subsidence bowl are shown in Fig. 9. The two models with the best fit to the subsidence data up to 1997 predict long term subsidence of 20 ± 2 m. It is not possible to distinguish between these two models. If the models are correctly representing the long term drainage and deformation beneath the subsidence bowl, then approximately half the total subsidence occurred within 25 years of commissioning of the power station. The subsidence rate subsequently declines gradually, and significant subsidence could conceivably continue for another 75+ years in this scenario.

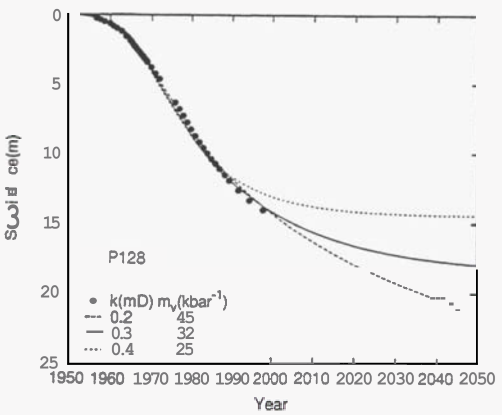

Fig. 9. Predicted subsidence trends for the centre of the Wairakei bowl (P128) for three sets of mudstone properties.

5. ACKNOWLEDGEMENTS

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