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COMPARISON OF SUBSIDENCE AT WAIRAKEI, BROADLANDS AND KAWERAU FIELDS, NEW ZEALAND

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Abstract. Exploitation has caused over 9 m of subsidence at Wairakei since 1950, up to 30 cm at Broadlands between 1968 and 1974, and up to 25 cm at Kawerau since 1970. Despite these differences and large differences in the rate and amount of mass withdrawal, there are similarities in the pattern of subsidence at all 3 fields. In each field, pressure drawdown in the production zone can be identified as a nearly circular area of consolidation centred on the production borefield. The circular shape suggests that the predominant fault direction may not be the main factor controlling horizontal permeability. In addition to production zone consolidation, each field has a small area of relatively intense subsidence originating from shallow depth. The area of shallow consolidation is near to the natural outflow zone where geothermal water originally rose to near-surface and dispersed in highly compressible formations. Early identification of such areas in other fields is important because the high rate of consolidation at shallow depth can cause large horizontal strain and tilt of the ground surface. There is also evidence of cool groundwater inflow near the area of shallow consolidation in all three fields. Shallow reinjection into these areas may mitigate the effects of subsidence and groundwater invasion.

Introduction. Wairakei field has become renowned for the amount of subsidence which has been caused by production (Hatton, 1971; Stilwell, et al., 1976; Allis and Barker, 1982). An unusual feature of the subsidence is the area of maximum subsidence being displaced from the production borefield. The explanation for this has been controversial (Pritchett, et al., 1980; Narasimhan and Goyal, 1979). However, recent study has shown that the subsidence can be readily explained by conventional consolidation behaviour of the reservoir with most of the consolidation occurring in the steam zone (Allis and Barker, 1982). The purpose of this paper is to show that although the magnitude of the subsidence at Wairakei may be unique, there are broad similarities between the subsidence at Wairakei, Broadlands and Kawerau geothermal fields. All three fields lie within the active volcanic zone of the North Island, New Zealand, and their production zones (generally 500-1000 m depth) comprise Quarternary rhyolitic-andesitic volcanics and sediments. Because of space limitations, only a brief summary of the subsidence history and modelling of each field is given here. More detailed descriptions can be found in the references cited.

Wairakei field. The total amount of subsidence at Wairakei has now exceeded 9 m, with the area of maximum subsidence still subsiding at >0.4 m/y (Allis and Barker, 1982). This exceeds all known cases of subsidence caused by any form of fluid withdrawal. A map of the subsidence since exploitation of the field began in 1950 is shown in Fig. 1. The area of intense subsidence covers less than 1 km^2 and this is centred close to the northern boundary of the field, about 0.5 km from the eastern production borefield. Subsidence ranges between 1 and 2 m across most of the production borefield, and over the rest of the field, it is mostly within 0.5 ± 0.1 m. Fig. 2 shows an E-W cross-section which summarizes the relationship between subsidence, the geology and temperature variations within the field, and the pressure and gravity changes caused by exploitation. Modelling of the area of maximum subsidence, using the analytical solutions for consolidating circular disks (after Geertsma, 1973), suggests the top of the consolidating zone is at about 150 m depth. This places the consolidation zone in Huka pumice breccia, a relatively permeable unit deposited between the upper and lower lacustrine mudstone units of the Huka formation (Grindley, 1965). The modelling suggests about 15 m of consolidation has caused the 8.5 m of surface subidence up to December

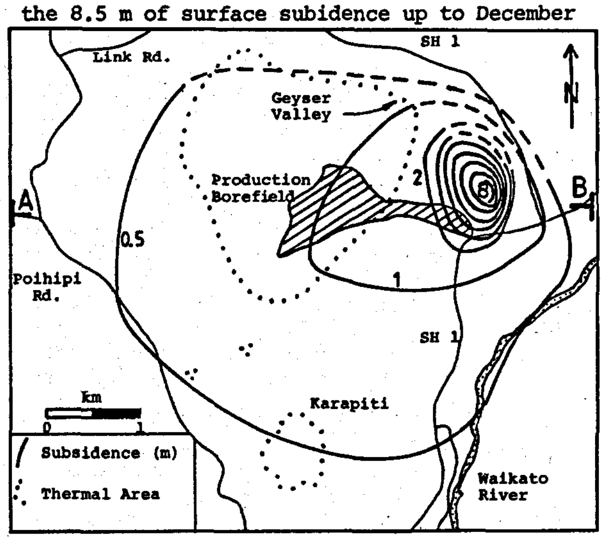

Fig. 1: Subsidence at Wairakei field between 1950 and December 1980. Contour interval is 1 m apart from 0.5 m contour.

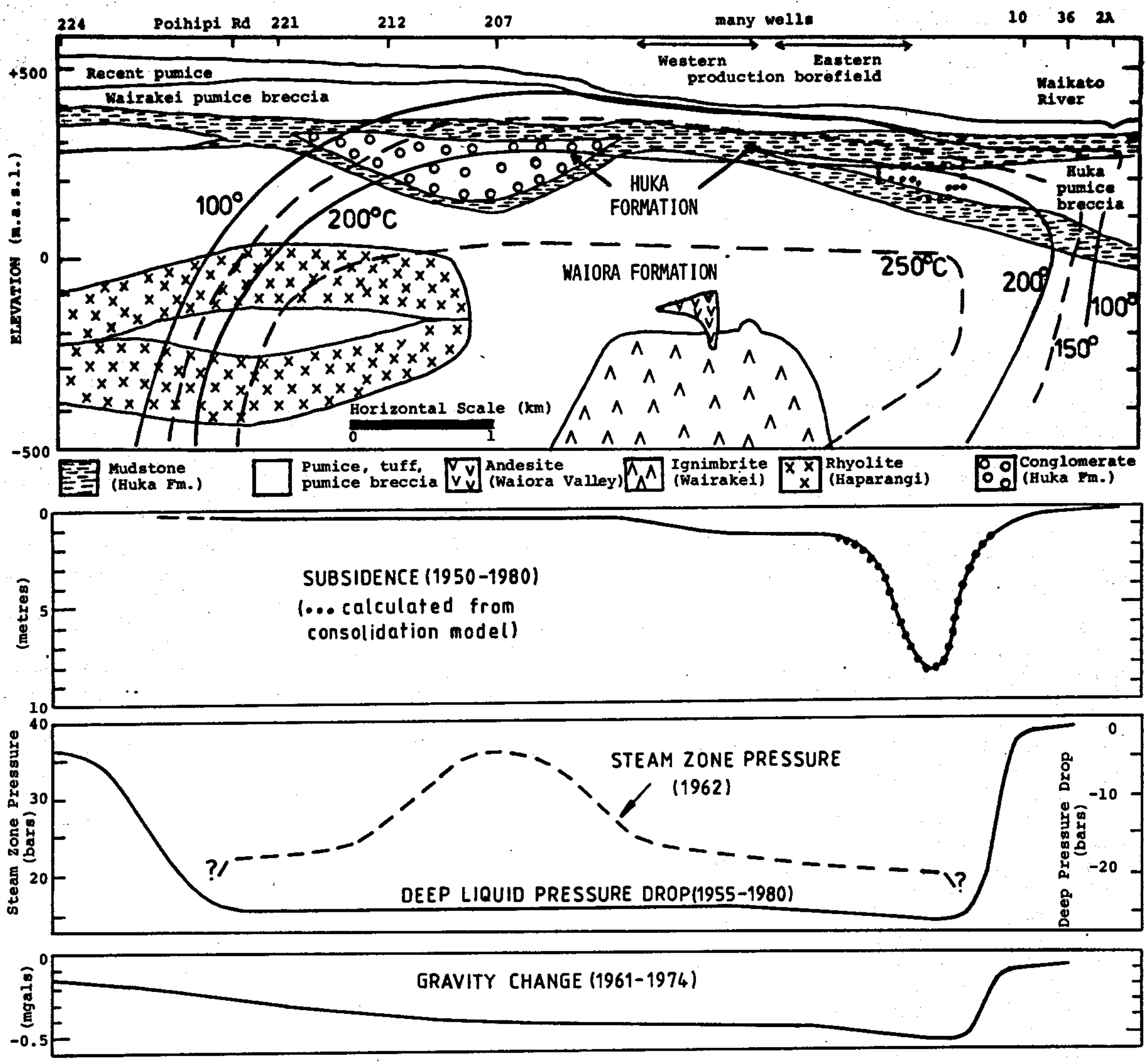

Fig. 2: Cross-section of Wairakei field showing relationship between geology and temperature, and the subsidence, pressure changes and gravity change caused by exploitation. The 1962 steam pressure is from Grant (1982); the gravity change is from Hunt (1977). Dotted area on cross-section is the consolidation model that fits the area of maximum subsidence.

1980 (Poisson's ratio assumed to be 0.25). Assuming the pumice breccia unit is 220 m thick beneath the area of maximum subsidence, and fluid pressure has dropped by 10 bars, the compressibility of the unit must be around 8 $kbars^{-1}$. Laboratory compressibility measurements on cores of pumice breccia confirm this, with compressibility ranging between 8 and 17 k $bars^{-1}$ for an effective pressure increase of 5-15 bars (Allis and Barker, 1982). The high compressibility of near-surface pumice breccia is due to its high porosity (50-80% typically). The deeper Waiora pumice breccia generally has a porosity of <30% and a compressibility 2 to 3 orders of magnitude less than near surface pumice breccias. The 0.5 m of subsidence across a large area of Wairakei field can be accounted for if the consolidation occurs in a 500 m-thick zone with an average compressibility of 0.02-0.03 $kbars^{-1}$ (pressure drop of 25 bars). However, much of this consolidation may be occurring in a thinner zone of more compressible material near the top of the Waiora formation. This is because subsidence linearly correlates with pressure decline in the steam zone, rather than pressure decline in the deeper liquid zone (Allis and Barker, 1982). Steam zone pressure has steadily fallen by 10-15 bars since the steam zone formed around 1960. The pressure continues to fall at 0.2-0.5 bars/y despite deeper liquid pressure being almost constant since the early 1970's.

Broadlands field. Extraction of fluid from Broadlands began in 1967, and rapidly rose to a peak equivalent to 100 MW (electrical) in 1971. Subsequent discharge of production wells has been intermittent, with the annual average being less than one tenth of the peak in 1971. This discharge history caused pressure to fall by 15 bars between 1967 and 1971, and pressure has subsequently recovered by about 8 bars (Hitchcock and Bixley, 1976). In contrast, benchmarks in the centre of the production borefield subsided

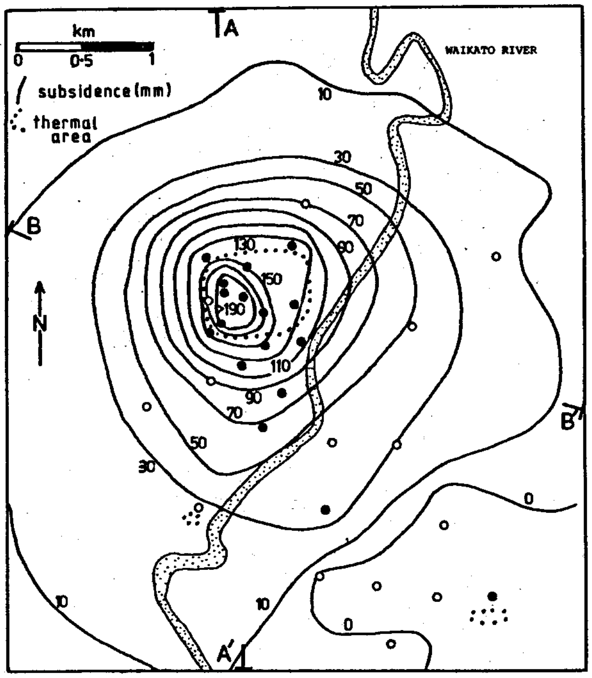

Fig. 3: Subsidence at Broadlands field between 1968 and 1974 (in mm). The black circles are wells discharged during this time. Open circles are other production wells

by 15-30 cm between 1968 and 1971, and there has been relatively little subsidence since then. The lack of rebound of benchmarks, despite a 50% recovery in reservoir pressure, indicates that consolidation is occurring as permanent pore collapse rather than elastic compression (Allis, 1982a). This behaviour was also observed in the laboratory compression measurements on pumice breccia from Wairakei. The amount of subsidence between 1968 and 1974 is shown in Fig. 3. Most of the subsidence had occurred by 1971, the time of the maximum pressure decline. A model for the subsidence is shown in Fig. 4. This assumes a uniform compressibility of 0.025 $kbars^{-1}$. Pressure drawdown in the production zone (500-1000 m depth) is incapable of explaining the relatively small area of maximum subsidence in the centre of the bore-field. Part of the discrepancy can be accounted for by modelling drawdown above the production zone (100-500 m depth). However, even this cannot fit the entire subsidence profile, and an area of relatively high compressibility at shallow depth (probably <100 m depth) is required in the centre of the borefield. The 0.8 km^2 area of drawdown above the production zone coincides with an area of low resistivity at <100 m depth, and with an area of relatively high surface heat flow and chloride outflow prior to 1968. Since 1968 this area has become notable for decreased groundwater levels, increased gravity (up to 0.3 mgal) and decreased downhole temperature and chloride concentration in production wells (Allis, 1982a). These changes are consistent with a downflow of cool groundwater into the production zone. The area of shallow consolidation at Broadlands was originally the main area of geothermal fluid outflow prior to exploitation, and this has changed to an area of groundwater downflow with production.

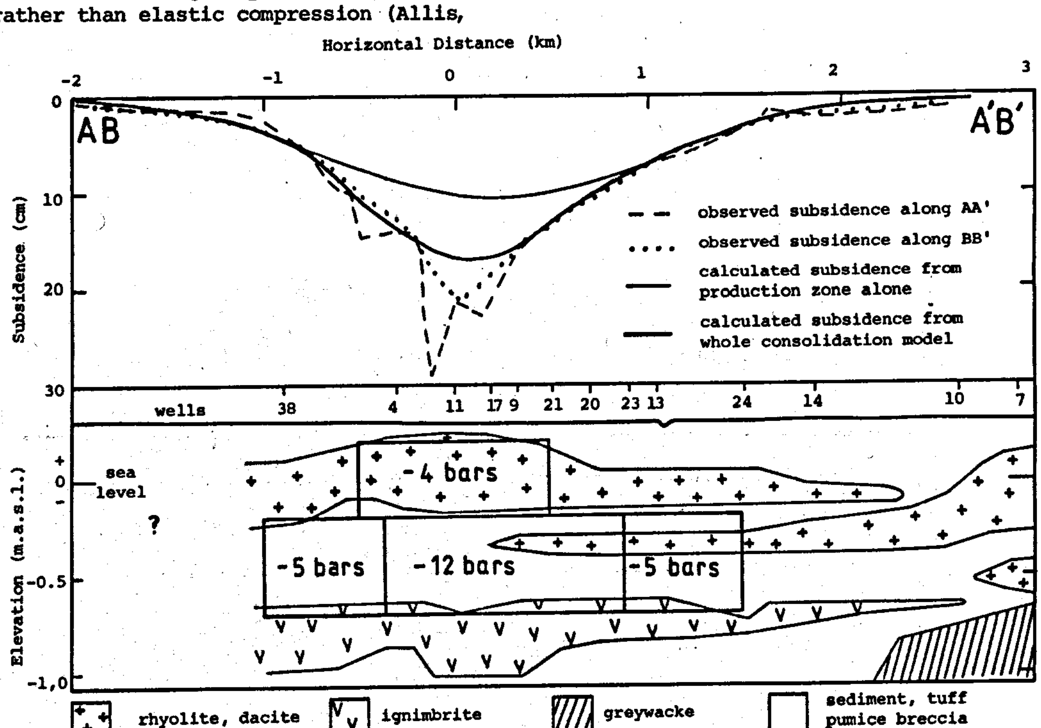

Fig. 4: Consolidation model for the Broadlands field. Production zone compaction is modelled as a central disk with 12 bars of pressure drawdown, and an annular zone surrounding this with 5 bars of drawdown. A circular area of consolidation above the production zone with a drawdown of 4 bars is included in the model.

Kawerau field. Although the first wells at Kawerau were discharged during the 1950's, the field was not levelled until 1970. Since this time, the rate of mass withdrawal has been almost constant at 7×10^9 kg/y and the maximum rate of subsidence has also not varied greatly, ranging between 15-20 mm/y. There has been no measurable drawdown in the production zone (600-1200 m depth; pressures to ± 1 bar). The subsidence pattern is asymmetric, with maximum subsidence occurring on the NE side of the field (Fig. 5). An E-W cross-section (Fig. 6) shows clearly that the subsidence is composed of two components: a broad zone of consolidation probably occurring in the production zone, and a small area of consolidation from shallow depth (Allis, 1982b). Modelling of the subsidence profile confirms this, with the top of the production zone anomaly occurring at about 50 m depth, and the shallow anomaly occuring at about 200 m depth. The shallow anomaly could have been modelled at <200 m depth, but consideration of the geology suggests it may originate in an explosion breccia unit at that depth. According to the model, production zone consolidation is occurring at 8 mm/y, while the shallow zone is consolidating at 17 mm/y. The depth extent of the two consolidation zones shown in Fig. 6 is inferred from the geology because of uncertainty in both the compressibility and the rate of pressure decline. Many of the Kawerau production well discharges have suffered declines in the enthalpy and chloirde content, indicating invasion by cooler water. The possibility that the subsidence is being caused by thermal contraction has been investigated and found to be untenable (Allis, 1982b). The observed cooling rates of several °C/y means that the cool water is entering the field along restricted paths, such as faults or down the outside of well casing, and the bulk of the reservoir rock remains close to its original

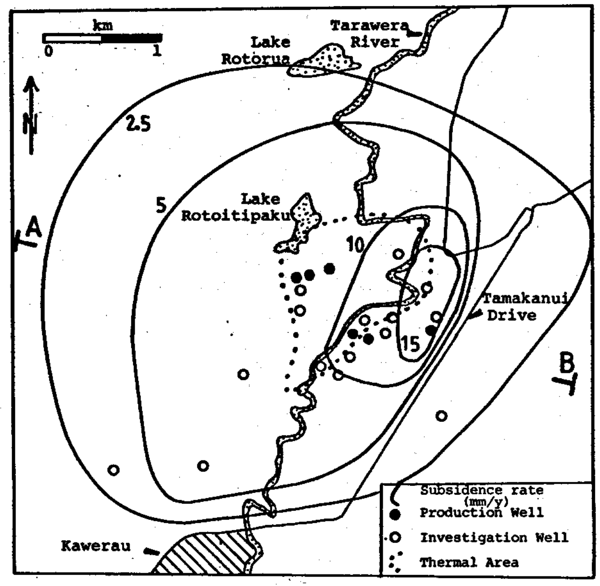

Fig. 5: Rate of subsidence at Kawerau field between 1978 and 1982 (in mm/y).

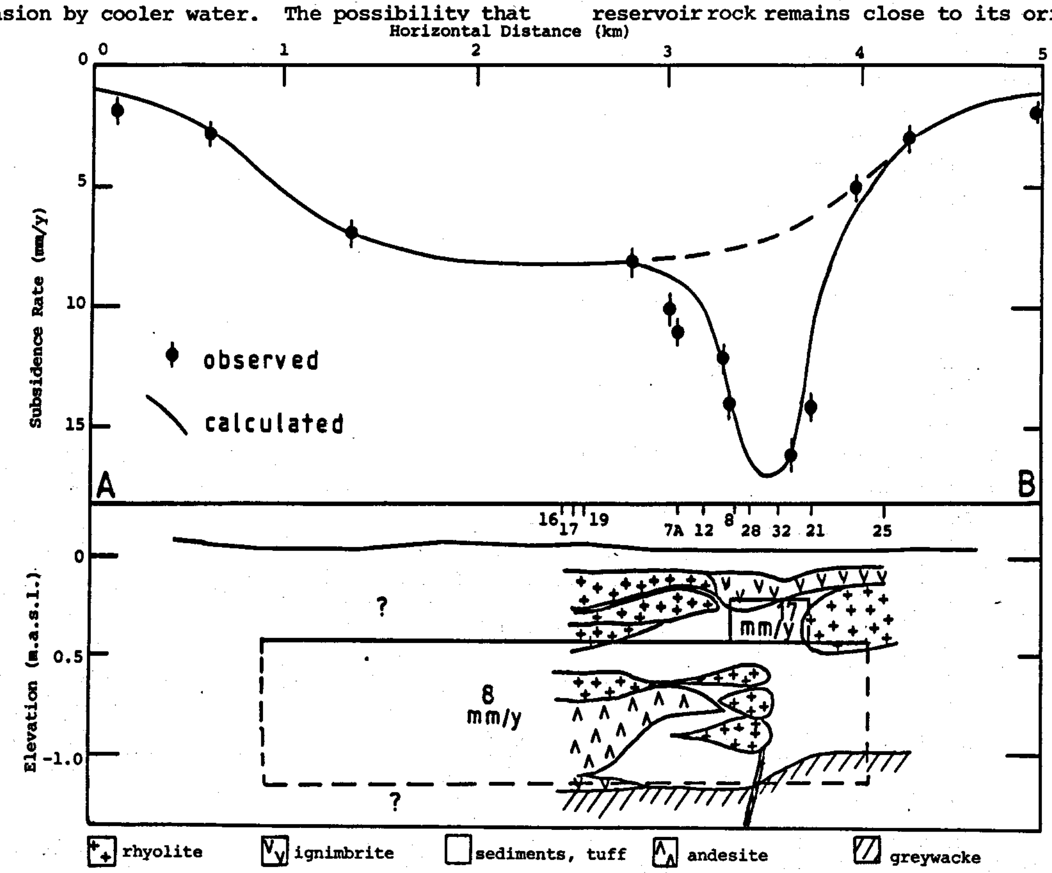

Fig. 6: Consolidation model for Kawerau field. Geological cross-section is simplified from Nairn (1982).

temperature. Although the pressure drop at production depths has been less than 1 bar, the cooling feed-zone temperatures could mean a larger pressure drop has occurred at shallow depth. This would be the case if the water is being drawn down from shallow depth. In the area of maximum subsidence, there has been a small but systematic variation in the rate of subsidence since 1970 which relates to the amount of production from nearby wells. This implies that near-surface water is being drawn down to production depths, because the subsidence in this area is dominated by consolidation at shallow depth. A cooling of 30-40^{o}C in the feed zones, with no pressure change at production depths, would cause near-surface pressure to fall by about 3 bars. Pivoting of the pressure depth curve with time implies that production zone consolidation may be restricted to the upper part of the production zone.

<u>Discussion and Conclusions</u>. An unexpected feature of the subsidence at the 3 fields is the roughly circular shape of the outer subsidence contours. These contours are concentric about the region of maximum mass withdrawal, and they reflect the lateral extent of drawdown in the production zone. The predominant faults in each field are normal faults trending NE-SW. If these faults were controlling permeability, elliptical contours with NE-trending major axes would have occurred. The circularity of the contours suggests that the production zones have uniform horizontal permeability and that they are behaving as homogeneous (horizontally), porous-permeable media. Possibly it is only the deep (>1 km) upflow parts of these fields where permeability is strongly fault controlled. At these depths compressibility is relatively small, and there is little contribution to the subsidence.

Modelling of the subsidence in all 3 fields has shown that there are 2 components: a zone of consolidation associated with the production zone which is comparable in the area to the area of the field; and a relatively small area of more intense consolidation at shallower depth. The depth of these two consolidation zones cannot be determined uniquely from the modelling, but it appears likely that the shallow component is occurring at less than 300 m depth, whereas the production zone component may be at about 500 m depth. The characteristics of the 2 consolidation zones in each field are summarised in Table 1. The consolidation potential in the right hand column of Table 1 is a measure of sensitivity to drawdown. It is equal to the product of the average compressibility and the average thickness of the consolidation zone.

The characteristics of the shallow consolidation zones make them very important when considering the environmental or engineering consequences of subsidence. In all 3 fields, the maximum horizontal strain and tilt occur around the boundaries of these zones. The extreme examples of this are at Wairakei, where horizontal strain reaches 5×10^{-4}/y, the maximum ratio of horizontal to vertical movement is 0.7, and maximum tilt is around 1 mrad/y (0.05^{o}/y) (Allis and Barker, 1982). Clearly, the prediction or identification of similar zones in other fields is essential during the initial stages of field development. A common feature appears to be their proximity to chloride-bearing springs and seeps. In addition, these areas have low resistivity at shallow depth. This is probably caused by the presence of chloride water in the sediments rather than acid-sulphate waters or a clay-rich steam zone. The chloride water means that the consolidation zone is in a natural outflow part of the field, and therefore it may have a direct, liquid connection to the reservoir at depth. Once the reservoir is under production, such areas may experience the full effects of drawdown. A second feature is the presence of material with a high compressibility. At both Wairakei and Kawerau the shallow consolidation appears to be occurring in a pumice breccia or explosion breccia which may have been rapidly deposited and poorly consolidated. Early dectection of potential areas of high consolidation may be possible if compressiblity measurements are made on core

	Period of Data	Mass Discharged	Maximum Subsidence	Amount of Consolidation	Area of Consolidation	Pressure Decline	Consolidation Potential
Production zone WAIRAKEI shallow anomaly	1950-80	1400×10^{9} kg	8.6 m	500 mm 15000	10 km^2 0.5	25 bars 10-15	20 mm/bar 1000-1500
production zone BROADLANDS shallow anomaly	1968-74	30×10^{9} kg	0.3 m	100 mm 150	5 km^2 0.8	12 bars 1-5?	8 mm/bar 30-150?
production zone KAWERAU shallow anomaly	1978-82	7×10^{9} kg/y	0.25 m	8 mm/y 17	9 km^2 0.4	0.1-0.2? bars/y 0.1-0.5?	40-80? mm/bar 34-170?

Table 1: Summary of subsidence characteristics. Production zone and shallow anomaly refer to the 2 consolidation zones causing the subsidence in each field.

from all formations, with particular emphasis on core from <300 m depth.

There is evidence in all 3 fields of cold water inflow near the shallow consolidation zone. At Wairakei, cold water may be flowing down the faults which originally channelled the hot water towards Geyser Valley (Allis, 1981). In addition, a cold intrusion at shallow depth has been identified in a well just outside the area of maximum subsidence (Allis, 1982c). The evidence at Broadlands has already been discussed. At Kawerau the cold intrusions may by more widespread. However, wells near the area of maximum subsidence originally had the hottest temperatures at shallow depth, but their shallow feed zone had suffered significant temperature declines by 1960, and the wells have had to be deepened (Grant, 1977). The only way of mitigating the effects of cold intrusions may be reinjected of waste borefield water into the inflow region. Reinjection into the shallow consolidation zone has the added advantage of possible repressuring of this zone, and reducing the maximum rate of subsidence in the field.

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