UPDATE ON SUBSIDENCE AT WAIRAKEI

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ABSTRACT

Maximum subsidence at Wairakei reached 8.5 m in December 1980 with the centre of subsidence still subsiding at over 0.4 m/yr. By late 1982, the amount of subsidence will have exceeded all known cases of subsidence caused by any form of fluid withdrawal. The concentration of most subsidence within a 1 km^2 area has caused very high horizontal strain rates at the ground surface (up to 5×10^{-4} yr^{-1}). A zone of fissuring, cracking and ground sag can be traced intermitently around the area of subsidence. In the centre of subsidence, the rise in water level of Wairakei Stream has matched the amount of subsidence. Subsidence is linearly correlated with pressure in the steam zone, and can be explained by normal consolidation processes. The consolidating horizon is thought to be Huka pumice breccia which has a very high compressibility.

INTRODUCTION

Wairakei field has become noted for the large amount of subsidence which has accompanied exploitation (Hatton, 1970; Stilwell, et al. 1976; Pritchett, et al. 1978). However, the cause of subsidence has been controversial (Pritchett et al. 1980; Narasimhan and Goyal, 1979). In December 1980, a complete resurvey of Wairakei benchmarks was carried out by Ministry of Works and Development, enabling a reassessment. This paper reviews these latest measurements, and also other measurements of associated ground deformation. These provide some new insights on the cause of subsidence. Complete documentation of the data, and full discussion on their significance will be published later.

TOTAL SUBSIDENCE (1950-12/1980)

Most benchmarks were installed around the production borefield and the area of maximum subsidence during the mid-1960's. An estimate of the amount of subsidence during the earlier exploitation years has been made by comparison with the few old benchmarks. These old benchmarks typically show increasing subsidence rate between the late 1950's and early 1960's, with a slight decline occurring subsequently (Fig. 1). Exceptions to this trend are benchmarks around the Karapiti thermal area, approximately 3 km south of the production borefield. These benchmarks had a relatively high subsidence rate during the early 1960's but the subsidence rate has declined greatly since then (e.g. A77, Fig. 1). The implications of the subsidence in this area are discussed in a companion paper (Allis, 1982).

For most old benchmarks, the amount of subsidence prior to the mid-1960s can be estimated to within 20% by assuming the subsidence began instantaneously in 1959 with the mid 1960's subsidence rate. That is, the amount of subsidence prior to say 1965 was 6 times the amount of subsidence that occurred in 1965. The uncertainty caused by this estimation process becomes less than 5% when the total subsidence between 1950 and 1980 is considered. Relative uncertainties between nearby benchmarks will be much less than this.

The total amount of subsidence until December 1980 is shown in Fig. 2. The subsidence is relative to a benchmark outside the field near Aratiatia dam (about 4 km east of the production borefield). Maximum subsidence is 8.5 m, near Wairakei Stream and about 500 m from the eastern production borefield. This area is still subsiding at more than 0.4 m/yr. By the time of presentation of this paper (November 1982), maximum subsidence will have reached about 9.3 m. This apparently exceeds all other documented cases of subsidence caused by any form of fluid withdrawal. The

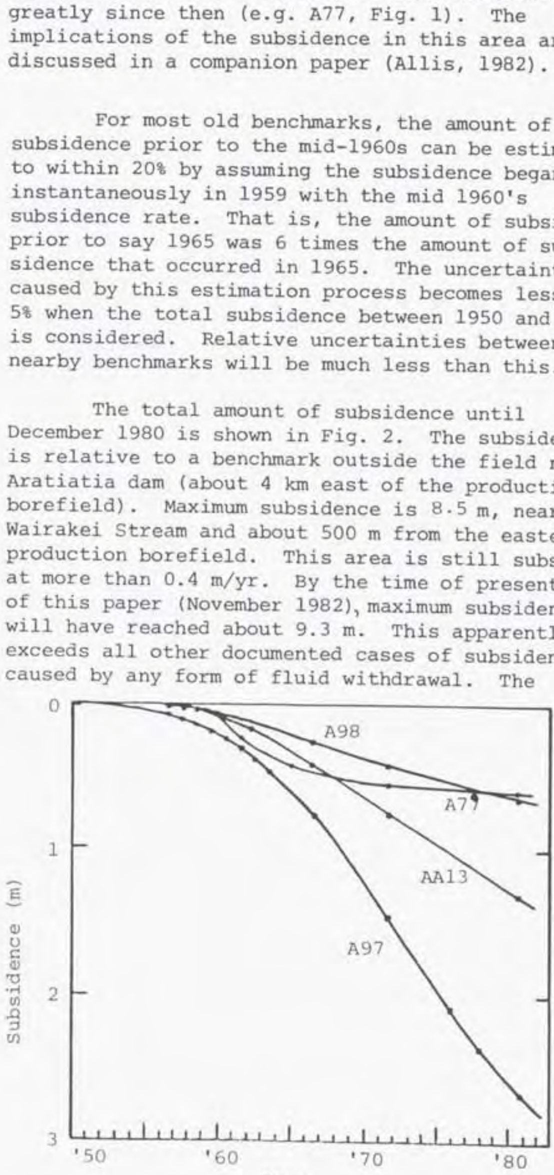

Fig. 1. Subsidence of selected benchmarks around Wairakei Field.

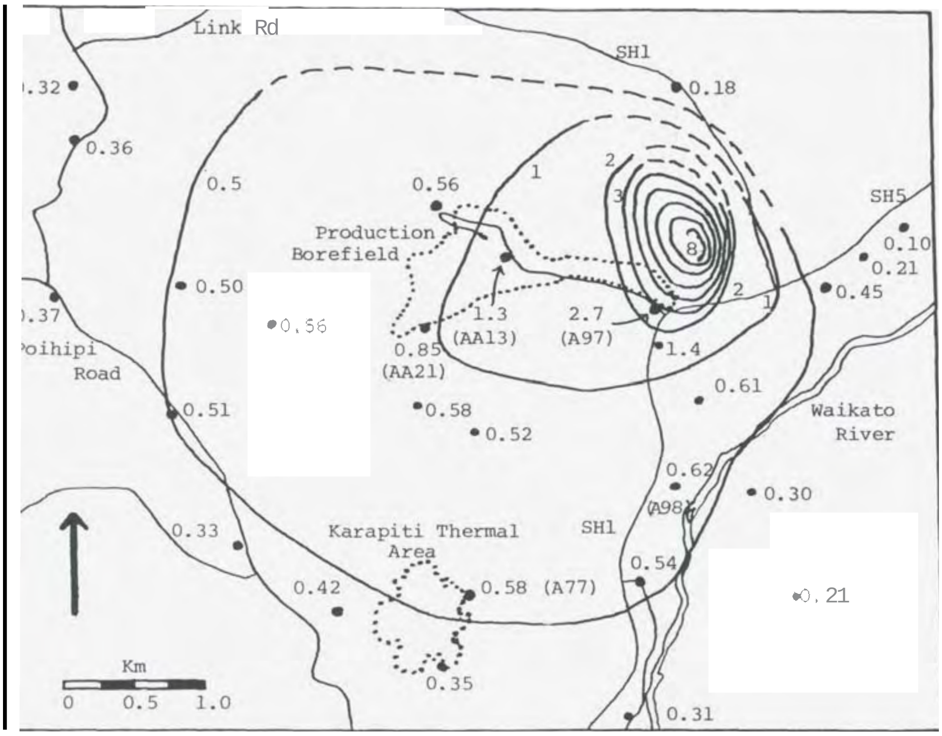

Fig. 2. Total subsidence at Wairakei Field (1950-12/1980). The location and amount of subsidence at numerous benchmarks within the production borefield and main subsidence bowl are not shown. Apart from 0.5 m contour, the contour interval is 1 m.

previously cited examples of extreme subsidence are at Wilmington, California (hydrocarbon withdrawal), Mexico City (groundwater withdrawal), and San Joachim, California (groundwater and hydrocarbon withdrawal). Between 8.5 and 9 m of subsidence occurred in each locality (Viets et al., 1979). What makes Wairakei subsidence *so* remarkable is that the area of intense subsidence (hereafter called the subsidence bowl) is restricted to an area of only 1 km^2. However, the 0.5 m contour encloses a roughly circular 15 km^2 area centred on the western production borefield, reflecting the lateral extent of drawdown in the reservoir.

Although most benchmarks have had a small decline in subsidence rate since the mid-1960's, those in the centre of the subsidence bowl and on its northern side show a 25% increase. There has been no significant change in subsidence rate on the east, south and west sides. This means NW-trending, elongate shape shape of the bowl has been accentuated with time.

SURFACE DEFORMATION

The comparatively large subsidence gradients around the sides of the bowl imply correspondingly large horizontal strain rates. A zone of cracking, fissuring and ground sag can be traced intermittently around the outer parts of the bowl (Fig. 3). This corresponds to the locus of maximum tension, or maximum convex curvature of the ground surface. The largest fissure, about 1 m wide, is on the east side of the bowl.

Possibly the most interesting features are just east of the original Geyser Valley, where steam is flowing preferentially to the surface along tension cracks. En echelon, NE-trending strips of bare, lightly steaming ground have appeared since the mid-1960's. This area was originally low grade thermal ground covered in stunted manuka. The strips of steaming ground range up to *50* m long and 5 m in width. A more localized zone of fissured steaming ground curves around the northern end of the strips. One explanation for this area is that the underlying Huka mudstones may originally have been cut by NE-trending faults. When the ground came under tension, the faults opened up, allowing steam to rise to the surface in linear zones and causing the strips of bare ground. With time the zone of tension has moved northward, and it is now marked by the fissured ground. Recent monitoring of the rate deformation across this whole area has confirmed that maximum extension is now occurring in the fissured zone at around 12 mm/yr.

Large changes have occurred to Wairakei stream where it traverses the subsidence bowl. As the ground has subsided water level has risen, causing flooding of the stream valley. Pine trees have fallen into the water as their roots have become water logged. The stream has become swamp-like, and rapid sedimentation is occurring because of the low velocity. A 3 m rise in water level has occurred where the drop structure

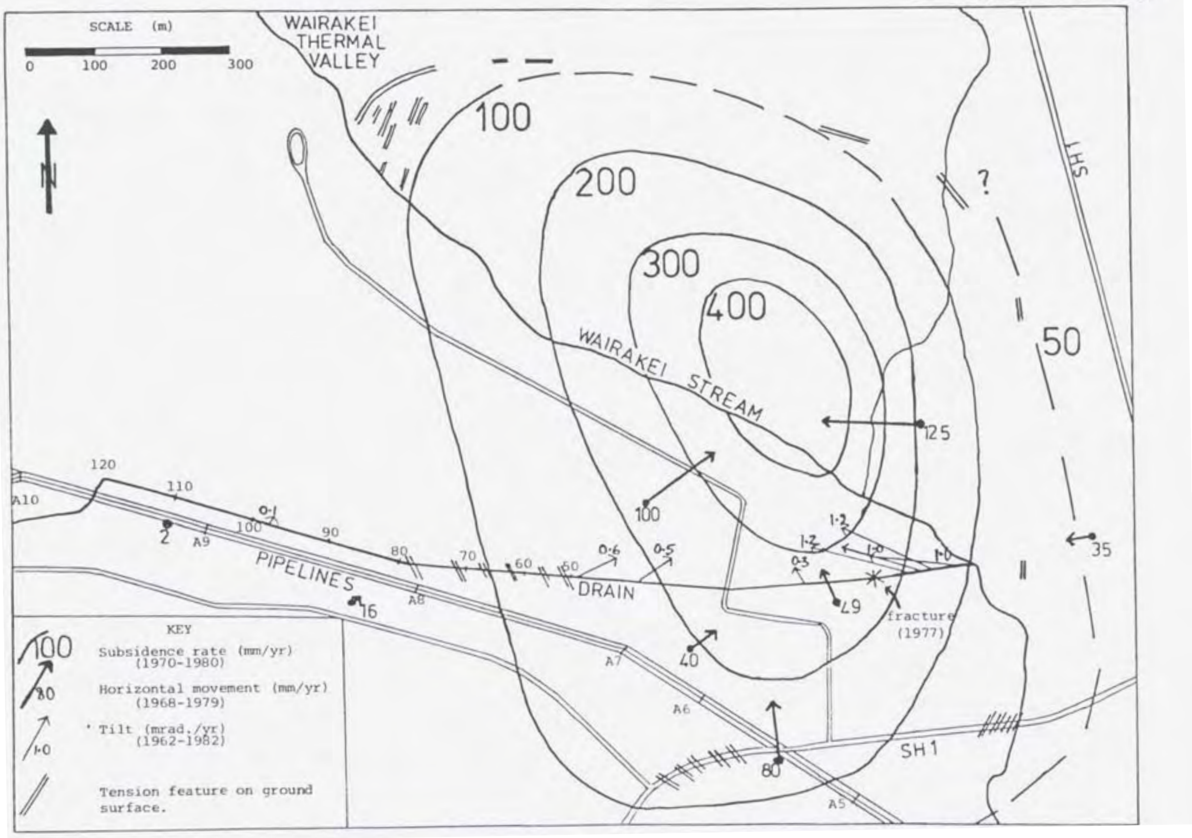

Fig. 3: Compilation of rates of deformation of the ground surface around the subsidence bowl. Small numbers along the drain are joint numbers (also shown on Fig. 4). A5 to A10 are anchor locations of the steam pipelines.

of the main drain terminates in the stream. This is approximately the amount of subsidence at that locality, suggesting that the rise in water level in the subsidence bowl has kept pace with subsidence.

HORIZONTAL STRAIN

The rate and direction of movement of 12 benchmarks has been monitored by the Ministry of Works and Development since 1968 (Fig. 3, Hookyaas, 1980). As expected, movement is towards the centre of subsidence, with maximum horizontal movement occurring in the region of highest subsidence gradient. Here, the ratio of horizontal to vertical movement reaches 0.7. The movement of two benchmarks on either side of the centre of the bowl implies an E–W shortening of over 0.2 m/yr, and a compressional strain rate of over 5 x 10^{-4} yr^{-1}. Maximum extension is occurring on the east side of the bowl, where the movement of 2 benchmarks indicates E–W extension of 0.09 m/yr (strain of 3.4×10^{-4} yr^{-1}).

The variation in strain rate on the western side of the subsidence bowl has been calculated from two sets of measurements. N.Z. Electricity Division has monitored movement of the steam pipe lines at the expansion loops since 1965. The average strain rate between 1965 and 1980 is shown in Fig. 4. The pipe movement was also averaged into three 5 year periods, but no consistent variation with time was found. Measurement of the width of joints on the main drain (every 9.14 m) has also given a record of average strain along the portion of the drain under tension (Fig. 4).

The latter set of measurements clearly shows that the strain has not been homogeneous, but has been concentrated over relatively short distances. This confirms that fissuring of the ground is occurring, even although it is not obvious in the borefield. N.Z. Electricity Division has also been monitoring the rate of movement of many of the joints on the drain since 1978. This has shown that most of the strain peaks between joints 50 and 80 (Fig. 4) reflect present day rate of movement, but the peaks at joints 87 and 91 were probably due to higher strain rates prior to 1978 (G. Morris, pers. comm.). Joint 57 has been opening at 3 mm/yr, so if this rate can be extrapolated backwards in time, the joint would have been closed in 1973. The transition from tension to compression on the drain occurs in less than 50 m. Close inspection of the joints here indicates that the open joints presently near the transition zone were never under compression. Therefore, the location of zero strain has probably not changed significantly since the drain was built (1962).

Compression on the drain is being released at two sliding joints near the down-stream end. The rate of movement on the one joint that existed

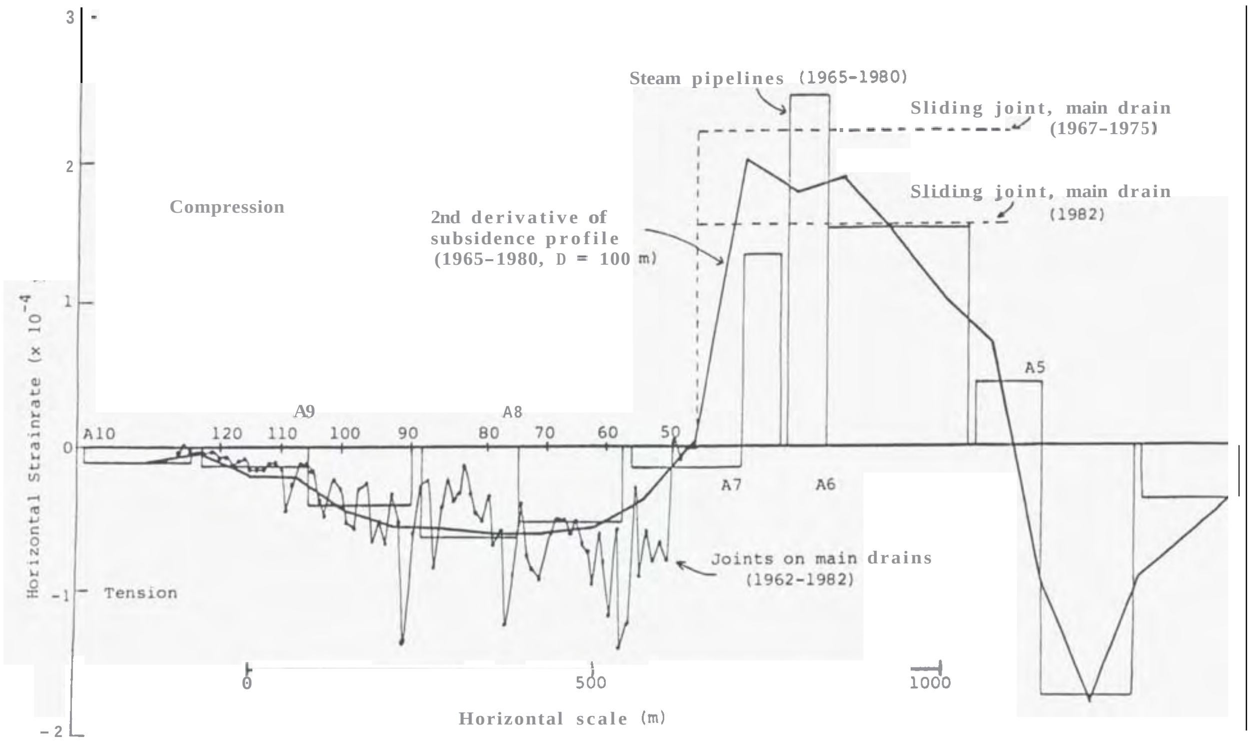

Fig. 4: Measured and inferred variation in horizontal strain rate along the main drain and the pipelines. A5 to A10 are pipeline anchor locations. 50–120 denote locations of joints on drain.

between 1967–75 was close to 10 cm/yr (Stilwell et al. 1976). Monitoring for two months in 1982 suggests an average of 6 cm/yr on the upper joint and 1 cm/yr on the lower joint. The appropriate strain rates are shown on Fig. 4. Monitoring is continuing to see whether the compressional strain rate has decreased with time, or whether seasonal effects such as varying height of the shallow water table affect the short-term strain rate.

Also plotted on Fig. 4 is the strain rate inferred from the second derivative of the subsidence rate profile along the steam mains. As Hatton (1970) noted, the surface strain rate and the surface curvature appear to be linearly correlated. This can be explained if the grornd above the consolidating horizon behaves as a bending beam or plate. If the horizontal strain decreases linearly with depth, the depth D to the zero strain plane is the ratio of surface strain to surface curvature. At Wairakei a good correlation exists when D≳100 m. This may be considered as a minimum estimate of the depth to the consolidating horizon.

TILT

Tilt along the main drain has been deduced by measuring the change in attitude of individual concrete sections since the drain was built. (Precise levelling in 1982 by P. Otway, D.S.I.R.). The tilt vectors are plotted on Fig. 3. The orientation and amplitude of most vectors are in good agreement with tilt calculated from the subsidence contours. The maximum measured tilt rate is 1 mrad/yr on 4 levels of the drop structure. This amounts to just over 1° of tilt since the drain was built in 1962.

In 1977, a major fracture occurred in the main drain (location in Fig. 3). Analysis of the variation in tilt rate along the drain shows that the break coincided with the maximum rate of change of tilt, or maximum curvature of the ground surface. Because the drain was repaired with rigid concrete sections as before, another fracture may eventually occur in the same location.

CAUSE OF SUBSIDENCE

Both Pritchett et al. (1980) and Narasimhan and Goyal (1979) compare the rate of subsidence at Wairakei with the deep, liquid pressure drop in the reservoir. This shows a highly non-linear response with time, interpreted as a pre-consolidation compressibility operating before 1966, and a very large virgin compressibility operating subsequently. However, simple modelling of the high subsidence gradient on the east side of the bowl suggests the consolidating zone should be within 100–300 m of ground surface. It cannot be shallower than 100 m because the upper liquid zone has had a very small pressure change (<1 bar generally, Allis, 1982). Confirmation of this depth range comes from casing damage in many wells of the eastern production borefield (Bixley and Hattersley, 1982). The consolidating zone is therefore within the Huka formation or the upper Waiora formation, and furthermore, is being controlled by steam pressure changes rather than the underlying liquid pressure changes. In contrast to deep liquid pressures which have almost stabilized, steam pressure has fallen steadily since the early 1960's. A plot of subsidence at 3 benchmarks in the production bore-field, against steam pressure in nearby monitor wells, shows a near-linear response since the first measurements in 1963 (Fig. 5).

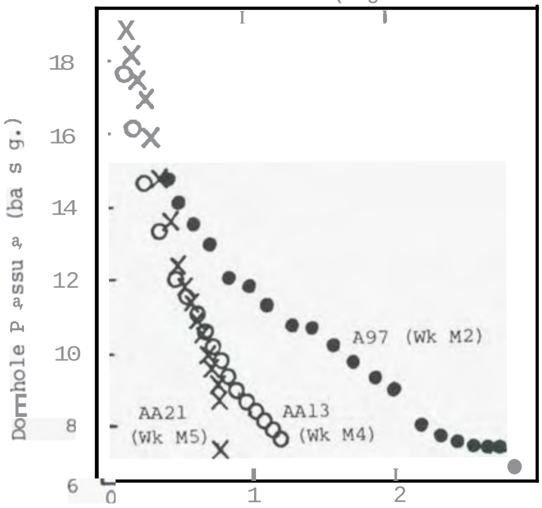

Fig. 5. Plot of steam zone pressure versus subsidence at 3 points in production borefield.

Pritchett et al. (1980) maintain that rock compressibility at Wairakei must be implausibly high to explain the subsidence. In fact, the compressibility should be in the range 0.5-2 kbar^{-1} (maximum consolidation rate of 0.5 m/yr; steam pressure decline of 0.5 bar/yr; 50-200 m thickness of the consolidating zone). Although this is significantly higher than the previously determined values for Huka mudstone and Waiora pumice breccia (0.25 and 0.024 kbar^{-1}, respectively) Wairakei pumice breccia did have a high compressibility at low pressure (Pritchett et al., 1976). We have examined the compressibility of pumice breccia by carrying out consolidation tests on samples of Wairakei pumice breccia (<50 m depth) and Huka pumice breccia (approximately 200 m depth) (Fig. 6). After passing through apparent preconsolidation pressures of around 10 to 30 bar, the samples indicated compressibilities of 23 and 8 kbar^{-1}. (Compression indices of 3.29 and 0.85). Either value is capable of explaining the observed subsidence.

The high compressibility of pumice breccia in the 10-30 bar effective pressure range can be deduced from the natural decrease in porosity with depth at Wairakei. Average porosity, without regard to rock type, is greater than 40% shallower than 300-400 m depth, whereas it is less than 30% at greater depth (Banwell, 1955). The porosity of pumice and pumice breccia at shallow depth may range between 50-80%, whereas the Waiora pumice breccia averages 23% (Whiteford and Lumb, 1975). This means there may be a depth window between about 100 and 300-400 m within which

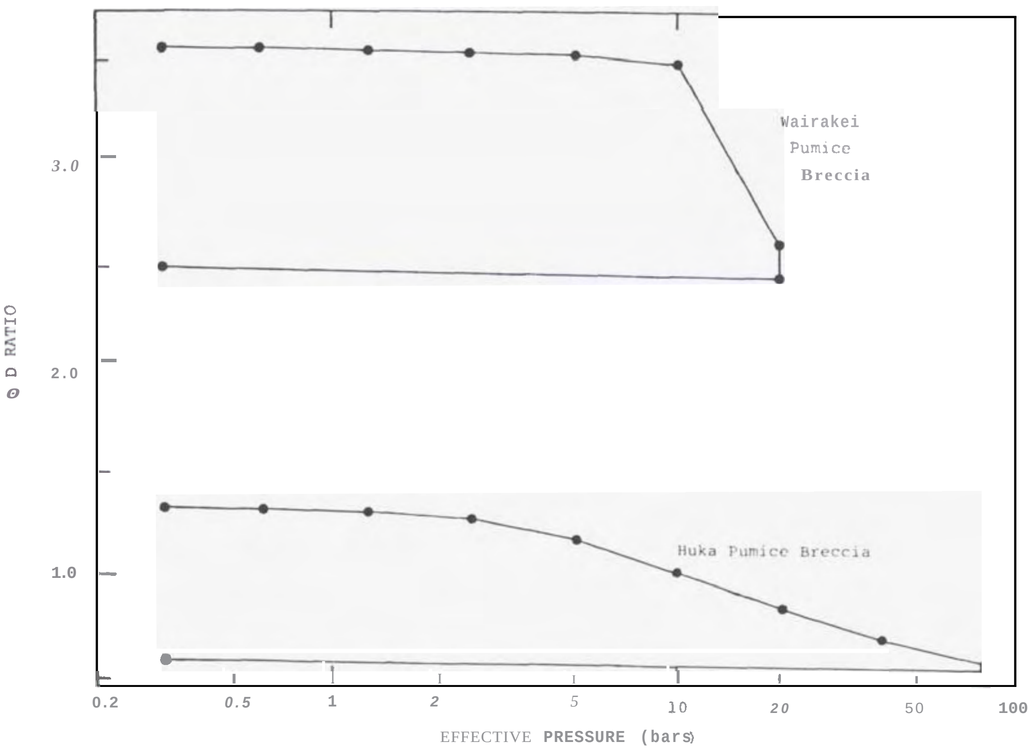

Fig. 6: Consolidation behaviour of 2 samples of pumice breccia. Wairakei pumice breccia (<50 m deep) had an initial porosity of 78%. Huka pumice breccia (~200 m depth) had an initial porosity of 87%.

considerable consolidation of pumice breccia is possible. With less than 100 m of overburden, the effective rock pressure may not rise high enough to cause consolidation, even if pore pressure is reduced to atmospheric pressure. Below 300-400 m, natural consolidation has already occurred.

The principal candidate for causing the extreme subsidence at Wairakei is Huka pumice breccia, which lies between the upper and lower Huka mudstones. Several early wells discharged from this horizon (1, 9, 14), and it became steam-dominant in the first few years of drawdown. It ranges in thickness from 0 in the western production borefield, to 50-60 m near the eastern end of the production borefield, and to over 200 m further east beneath the power station. However, near the power station its temperature was <100°C when drilled in 1951, and it has probably remained liquid filled since then.

Although we have shown that normal consolidation processes are capable of explaining the subsidence bowl, we can still only guess the exact reason for the location and shape of the subsidence bowl. The possibilities appear to be: (a) thick (≥200 m) Huka pumice breccia beneath the area. (b) A relatively sharp boundary to the steam zone within the Huka formation; at the boundary, steam pressure may be very low, causing large scale pore collapse. (c) some other factor causing anomalous compressibility. This uncertainty can probably only be resolved with a well near the centre of the subsidence bowl, and consolidation tests on core samples. These tests should also enable predictions of future subsidence in the area.

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