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PRECURSORY CHANGES TO NATURAL THERMAL FEATURES DURING TESTING OF THE WAIRAKEI AND BROADLANDS-OHAAKI FIELDS

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SUMMARY - Exploitation of geothermal fields in New Zealand has led to moderate to severe, but localised, effects on natural thermal features, such as geysers and hot springs. These effects have been caused primarily by decreases in reservoir pressure associated with mass withdrawal and net mass loss.

Small, but now clearly identifiable, precursors for some of these effects were observed during pre-production testing at Wairakei and Broadlands fields, but their significance was not recognised at that time. Precursors of changes to natural thermal features were: decline in flow rate from springs, decline in chloride content and temperature of emerging fluids, and an increase in the eruption period of geysers.

1. INTRODUCTION

In the last decade, concern has mounted about the environmental impacts resulting from the development of energy resources and all new power generation proposals are now subject to intense environmental scrutiny. Geothermal is generally regarded as a benign energy source; particularly when compared to nuclear, coal and oil. However, experience shows that there can be environmental problems associated with its exploitation. These problems are becoming of increasing concern, and to an extent which may be limiting developments. A recent example of this concern has been the rejection of a Resource Consent application for test drilling of the Reporoa Field. (At time of writing, an appeal is being made to the Planning Tribunal). A major reason for the rejection was that no guarantee could be given there would not be any effects on natural features within the field, or on the features in neighbouring Waiotapu Field which are a major tourist attraction.

History shows that hiding or ignoring such problems can be counterproductive to development of an industry because it may lead to a loss of confidence in that industry by the public, regulatory, and financial sectors. If our aim is to further the use of geothermal energy, then possible environmental effects should be clearly identified, and countermeasures devised and adopted to avoid or minimise their impact. Techniques have already been developed to avoid or minimize most of the impacts associated with drilling operations and gas discharges during production (Brown, 1995).

However, in the public perception, the effects on natural physical features, such as geysers and hot springs, are of major concern. One step in addressing this concern is to establish whether such effects have any precursory signs (changes) during discharge testing of exploration wells in the early stages of development. This may allow developments to proceed, at least through a testing stage, after which rational and informed decisions could be made as to whether, and how, full-scale development could be done with minimum impact on such features.

Questions about precursors that need answers are:

- what are they?
- what is their magnitude?
- how soon can they be identified?
- do they occur everywhere in the field?
- do they always occur?
- in what order do they occur?
- how much testing is needed?
- are any reversible?

We also need to know what does not change; i.e. what are not good precursory indicators.

Answers to all these questions are beyond the scope of this paper. Here we present historical observations made during discharge testing of the Wairakei and Broadlands (Ohaaki) fields to show what changes occurred, and their magnitude. We hope, at a later date, to address the other questions about precursors.

Surprisingly, there has been little previous documentation of the changes which have occurred in these fields. The only significant published papers have been Glover (1977), who describes mainly the chemical changes at Wairakei, and Thompson (1957) who records physical changes (up to 1955). The flow rate, chemistry and temperature data presented here have been taken from the files of the Institute of Geological and Nuclear Sciences (inherited from the former DSIR) and of Downer Energy Services Ltd (formerly Ministry of Works).

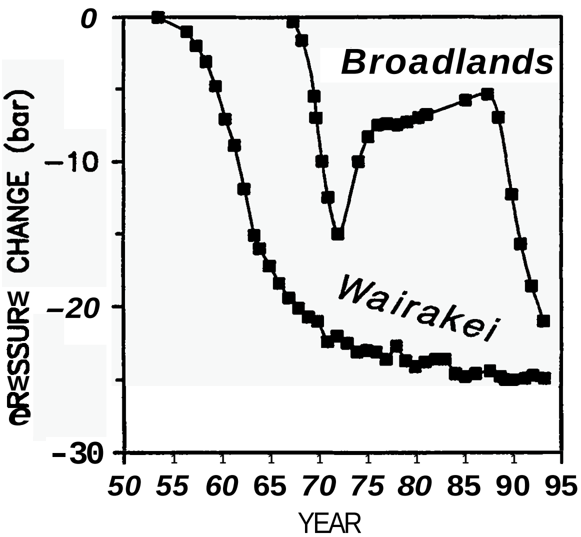

Fig. 1: Changes in deep liquid pressures at Wairakei and Broadlands fields. Data from ECNZ (1990), Hunt (1995), and Clotworthy *et al.*, (1995).

2. FIELD DEVELOPMENT HISTORIES

At Wairakei, exploratory drilling began in 1950 and 69 prospecting holes had been drilled and test discharged by December 1958. During this "Test Discharge Period", mass withdrawal increased to about 20 Mt/yr. The Wairakei Power Station (original installed capacity 192 MWe) was progressively commissioned from November 1958 to October 1964, during which time the annual mass withdrawal rose from about 20 to 75 Mt/yr, after which it declined and has remained at about 45 Mt/yr since 1975. The time since November 1958 is referred to as the "Production Period". All the fluid withdrawnhas been discharged into the nearby Waikato River or into the atmosphere (except for about 5 Mt reinjected during tests).

At Broadlands, drilling began in 1965, and by 1971, 25 deep wells had been drilled. From the middle of 1967 until the start of 1972, test discharges were conducted during which time the annual mass withdrawal increased to about 10 Mt/yr. During this "Test Discharge Period" all the fluid withdrawn was discharged into the Waikato River or the atmosphere; there was no reinjection. In the following 16 years, a further 18 holes were drilled but no extensive testing was done; the average mass discharge was only 1.5 Mt/yr and did not exceed 3.5 Mt/yr. This time is known as the "Recovery Period". Commissioning of the Ohaaki Power Station (116 MWe installed capacity) began in August 1988 and was completed in November 1989. Mass withdrawal rose to 16.2 Mt in 1990, and has remained at similar values since then. Since commissioning, most of the waste fluid has been reinjected (mainly around the periphery of the production areas) and net mass loss has been about 6 Mt/yr.

3. PRESSURE CHANGES

Prior to development of the fields, the reservoirs were liquid-dominated with fluid generally at or near boiling point for depth. At Wairakei, a 2-phase zone existed in the upper part of the reservoir (Grant and Home, 1980). Over-lying each reservoir is a zone of cold ground-water, locally heated by fluids escaping upwards to supply natural thermal features at the surface.

At Wairakei, the withdrawal during the Test Discharge Period resulted in deep-liquid pressures decreasing by about 3 bar (0.3 MPa). However, this value must be treated with caution because some of the data were not obtained by direct down-hole measurements but calculated from well head pressures in wells standing shut and full of water (Grant and Home, 1980). During the early stages of production (1960s), large pressure decreases extended across most of the field leading to the expansion (both vertical and horizontal) of the 2-phase zone, followed by the formation of a vapour-dominated region in the upper part of this zone. By the mid-1970s deep-liquid pressures had settled at about 25 bar (2.5 MPa) below pre-production values (Fig. 1).

At Broadlands, deep-liquid pressures decreased by about 15 bar during the Test Discharge Period, but recovered by about 10 bar in the Recovery Period before decreasing again after production began (Fig. 1). Considering the test periods at each field, the pressure changes at Broadlands were much greater (15 bar) than at Wairakei (3 bar), despite the mass withdrawal rates at Broadlands being smaller than at Wairakei (10, 20 Mt/yr, respectively).

4. ENVIRONMENTAL EFFECTS

No environmental effects were foreseen during the planning and initial development of Wairakei Power Scheme. At that time (early 1950s) the environment was not such an important consideration (relative to the demand for energy) and Environmental Impact Reports were not required. Indeed, the technology for measuring many environmental parameters was still in its infancy. Furthermore, the conceptual models prevalent at that time for geothermal systems, were that the fluid obtained from the bores was of deep, magmatic origin, and not closely related to surface or near-surface geothermal fluids (Wilson, 1976). It was envisaged that any fluid withdrawn from the upper part of the reservoir would be rapidly replaced by hot fluid from deeper in the reservoir, and that the natural features would be unaffected (Wilson, 1976). Most of the natural features were in Geyser Valley, about 0.5 - 1 km distant from the production wells, so it was thought that mass withdrawal from depths of less than 0.5 km would not affect the features. Despite reports of diminishing thermal activity and other environmental changes in the mid-1950s, it was not clear at that time whether the changes were a result of the test discharges or merely natural variations. However, while the Wairakei Power Station was being commissioned it became apparent that severe environmental effects were happening, but by that time it was too late to modify the development programme.

Information obtained from Wairakei during the 1960s and 1970s led to a better understanding of the relationship between surface features and the geothermal reservoir. It is now recognised that the thermal features were fed by fluids escaping from the upper part of the reservoir, along faults or fissures. Withdrawal of fluid from the upper part of the reservoir, through production bores, and concomitant pressure decrease led to a decrease (with time) in the amount of this fluid feeding the features (Glover, 1977; Allis, 1981).

During the planning stages of the Ohaaki Power Scheme, it was recognised that environmental effects might occur, and an Environmental Impact Report was prepared. In this report (NZED, 1977) the effects of chemical and gas discharges, noise, and thermal pollution on the climate, natural waterways, flora and fauna, were assessed and steps taken to mitigate the effects. The possible effects of exploitation on natural thermal features were not mentioned in the Impact Report, despite a fall in water level in the Ohaaki Pool during the Test Discharge Period and the changes which were known to have occurred at Wairakei.

5. DECLINE OF NATURAL THERMAL FEATURES

Prior to development, Wairakei was a major tourist attraction noted for a wide variety of natural thermal features which included geysers, fumaroles, hot springs, hot pools, and sinter slopes (Herbert, 1921; Wilson, 1976). Most of these features were located in two adjacent valleys: Geyser Valley (Wairakei Stream) and Waiora Valley (Kiriohinekei Stream). Exploratory drilling began in the Waiora Valley, and it was here that most production wells were located; no wells have been drilled in the Geyser Valley. Names and numbers for the features follow that of Thompson (1957).

Regular observations and measurements (flow rate, chloride content and temperature) of selected thermal features did not begin until November 1952, after exploratory drilling and well discharges had begun. Initially, the effects of mass withdrawal on the natural features were small and isolated, and were thought at that time to be caused by natural climatic variations. This was, in part, because the data showed that although some features changed during the testing period, others did not show any change. For many people the rapid decline of the thermal features in Geyser Valley following the large increase in mass withdrawal after commissioning came as a surprise.

Prior to exploitation the Broadlands Field had few natural thermal features (cf. Wairakei); the largest and most significant feature being the Ohaaki Pool, a boiling pool with a surface area of about 850 m^2. This pool has cultural significance for the local Maori people, and is noted for its beautiful fretted sinter lip and surrounding sinter apron. Prior to test drilling the pool generally overflowed. During the Test Discharge Period the flow rate decreased until it ceased overflowing, and then the water level fell. At the start of the Recovery Period the water level in the pool rose, but it did not begin to overflow again until 1981. Overflow stopped and the level in the pool again fell when production began in 1988, and it is now kept full and overflowing by the addition of bore water.

6. PRECURSORY CHANGES

Measurements made during the Test Discharge and early part of the Production Periods, at both fields, show that the main precursors of the decline in natural thermal features were:

6.1 Decrease in flow rate from springs and pools

Measurements show that there were large decreases in the flow rate from many springs and pools in Geyser Valley at Wairakei during the Test Discharge Period. Examples are shown in Figure 2. At Waitangi Pool (SP55) in Nov. 1953 the outflow rate was about 1.2 l/s, which decreased to about 0.2 l/s in late 1957. Another example is Spring 29: in Nov. 1952 this discharged periodically, but in October 1953 the periodicity ceased, and the rate of discharge steadily declined until April 1954 when the discharge ceased (Thompson, 1957). The water level then decreased until it was 1.5 m below the edge, at which point measurements could no longer be made (Fig. 2). These changes occurred as a result of pressure drop of less than 3 bar (0.3 MPa) in the reservoir beneath the main production borefield.

Prior to exploitation the Ohaaki Pool generally overflowed with a flow rate of about 9 l/s (Lloyd, 1957). During the Test Discharge Period at Broadlands, the outflow rate from the Pool decreased when nearby wells were discharged, recovered when the discharges stopped, and decreased again when the bores were reopened (Fig. 3). This effect was also noticed during small discharge tests in 1976, during the Recovery Period (Grant, 1982).

6.2 Decrease in chloride content of springs

Prior to exploitation, fluids in the upper part of the Wairakei reservoir had a chloride content of about 47.5 mM/l (1680 ppm, 265°C, enthalpy 1160 kJ/kg; Brown et al., 1988) which, after adiabatic steam loss, would have a content of about 70.9 mM/l (2506 ppm, 99°C)

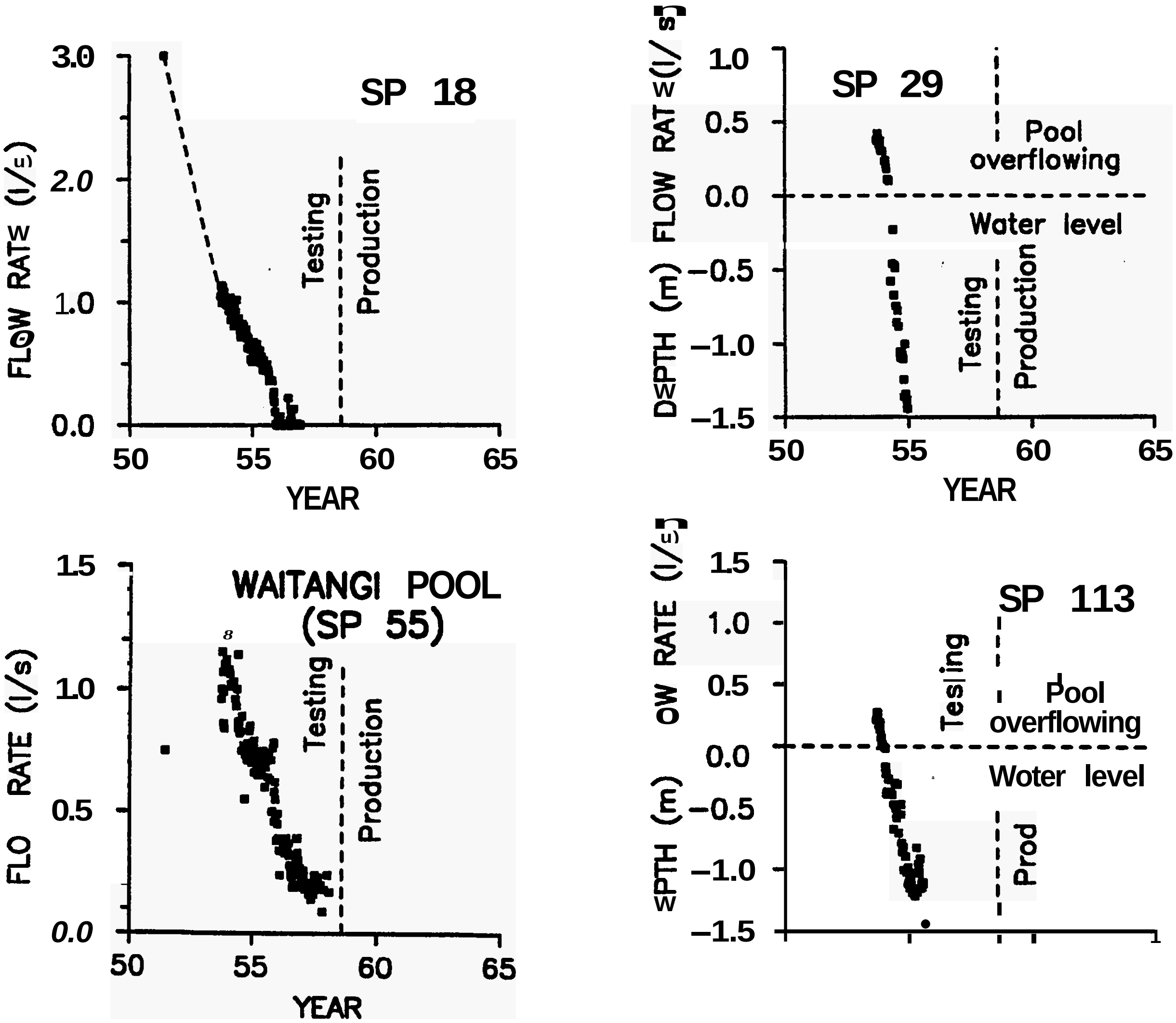

Fig. 2: Changes in flow **rate** and water level of hot springs and pools in Geyser Valley at Wairakei. Note the rapid changes with time during the Test Discharge Period.

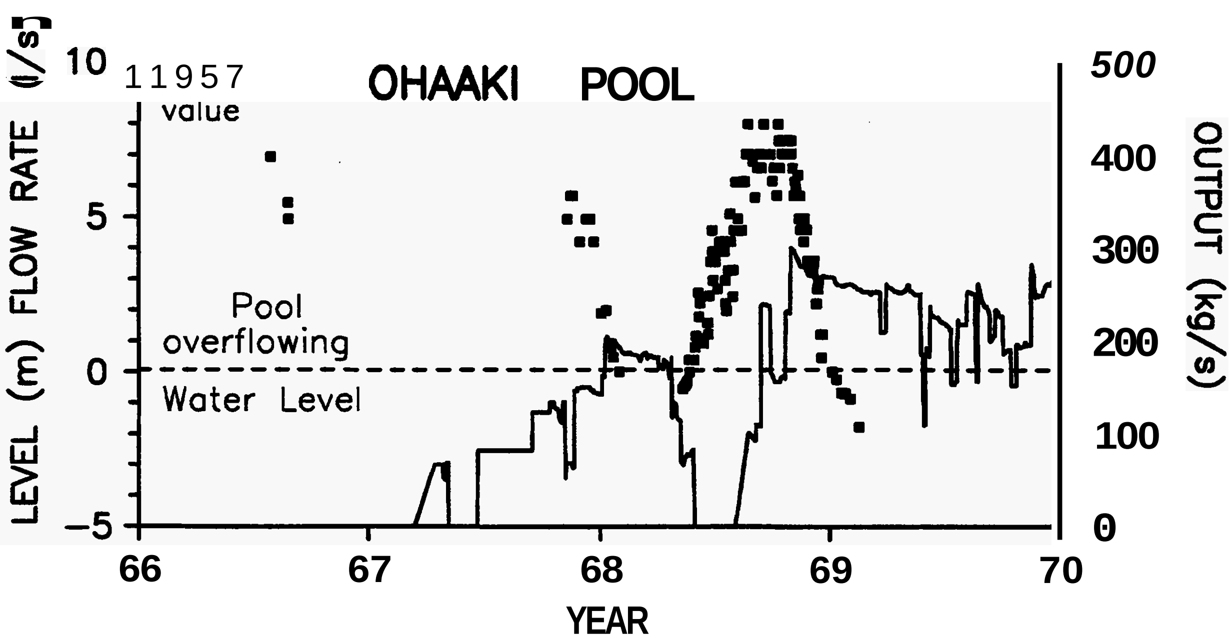

Fig. 3: Changes in flow rate and water level (solid dots) of the **Ohaaki** Pool and output **fkom** nearby bores (line), at Broadlands. Note the decrease in flow rate when nearby bores were open and discharging, and the increase when these bores were shut. Scatter in the **data** is largely **caused** by atmospheric pressure variations.

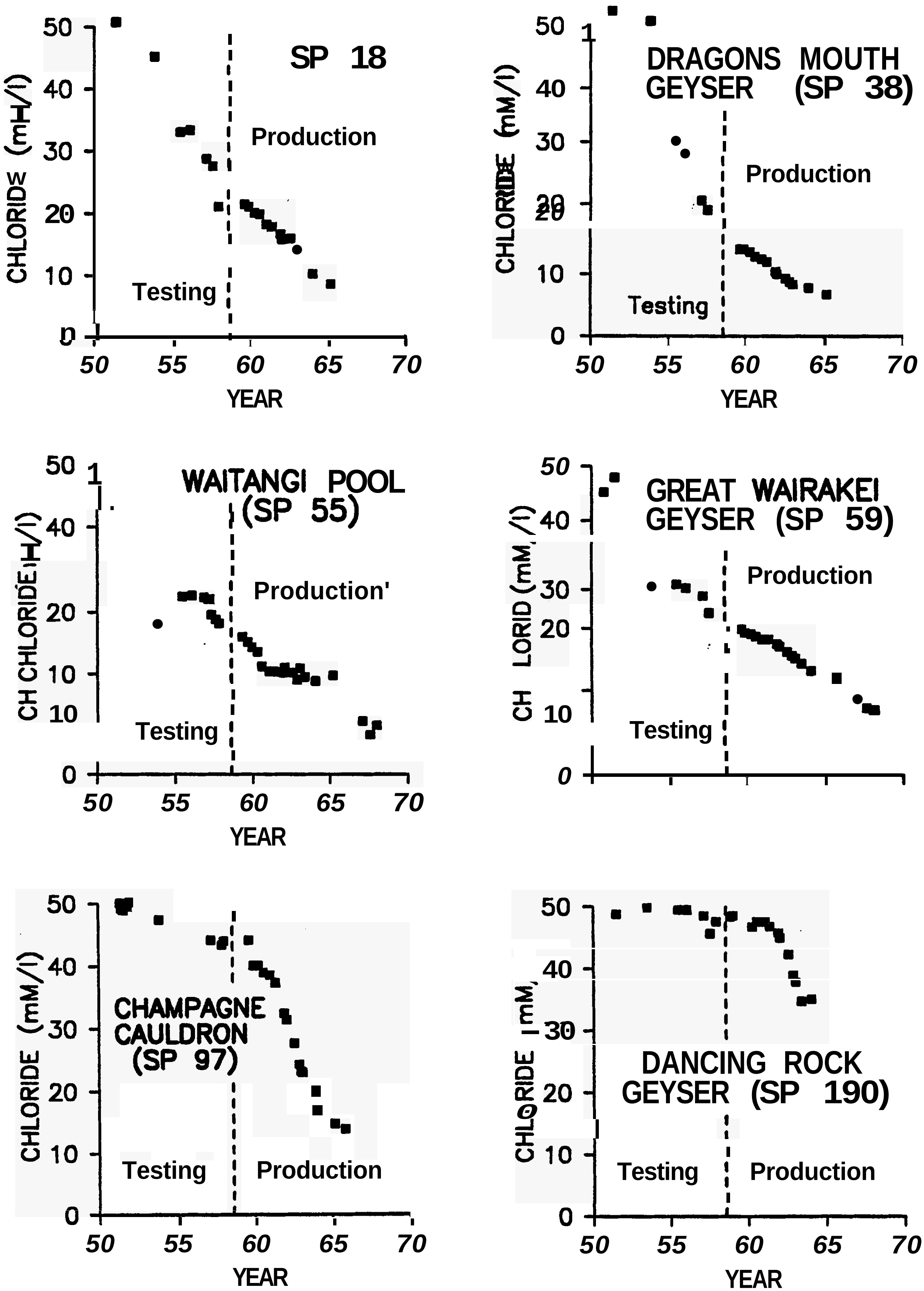

Fig. 4: Changes in chloride content of hot springs in Geyser Valley at Wairakei. Note that some springs responded quickly to the test discharges, but for others the changes did not occur until after production began.

at the surface. Most fluids emerging fiom natural features at Wairakei had a chloride content of about 45 - 50 mM/l, indicating some dilution by warm (150°C) near-surface groundwaters containing about 8.5 mM/l (300 ppm) chloride (Brown *et* al., 1988). As the deep-liquid pressures declined, so too did the chloride content of emerging waters, indicating increased dilution of the upflowing geothermal fluids by groundwater.

Many springs in Geyser Valley showed rapid decreases in chloride content during the Test Discharge and early part of the Production Periods (Fig. 4). The largest (measured) decreases in the Test Discharge Period were at Springs 18 and 38 (Dragon's Mouth Geyser), where the chloride content declined from about 50 mM/l in 1951 to about 20 mM/l in 1957 (Fig. 4); i.e. a decrease of more than 50%. In general, the highest (topographically) springs showed the earliest change. Springs which were at lower elevations, and had larger flow rates, had the smallest change during the Test Discharge Period; for example in Champagne Cauldron (Tuhuatahia; Spring 97) the chloride decreased by only about 20% during the Test Discharge Period (Fig. 4). However, during the early 1960s the chloride content decreased fiom about 40 mM/l to about 15 mM/l in 3 years.

At Broadlands, there was little change in chloride content of the Ohaaki Pool during the Test Discharge Period: prior to testing it was 29.4 - 32.0 mM/l (av. 8 samples = 30.6 ± 0.9), and during testing it was 29.1 - 29.7 mM/l (av. 7 samples = 29.4 ± 0.3). Such data led Hochstein and Henrys (1988) to the conclusion that there was a large subsurface outflow from the pool.

6.3 Increase in eruption period of geysers

Little quantitative data are available about the decline of the geysers at Wairakei. It is known that the eruption period (time between start of successive eruptions) of two geysers increased during the Test Discharge Period, before geysering ceased. The eruption period of Bridal Veil Geyser (Spring 199) increased from about 38 min. in Nov. 1952, to about 55 min. in Dec. 1953, to about 65 min. in Dec. 1954 (Fig. 5). Another example is the Great Wairakei Geyser (Spring 59): during the Test Discharge Period the eruption period increased fiom about 12 to more than 30 hrs, before the feature stopped geysering in 1954 (Fig. 5). Comparison of the eruption period data with rainfall measurements (Fig. 5) shows that the increases in period were not caused by a decrease in rainfall. Similarly, the reductions in flow rate from springs could not have been caused by changes in rainfall.

6.4 Decrease in temperature of springs and pools

Some hot springs and pools at Wairakei showed temperature declines of up to 30°C during the Test Discharge Period: these included SP18 and SP178 (Fig. 6). However, the temperatures of some other features in Geyser Valley showed little change: these included Rainbow Pool (SP197) and Ocean Geyser (SP198) (Fig. 6). These features maintained temperatures near boiling, while flow rates decreased significantly, because the upflowing geothermal fluids were diluted by warm (>100°C) groundwater.

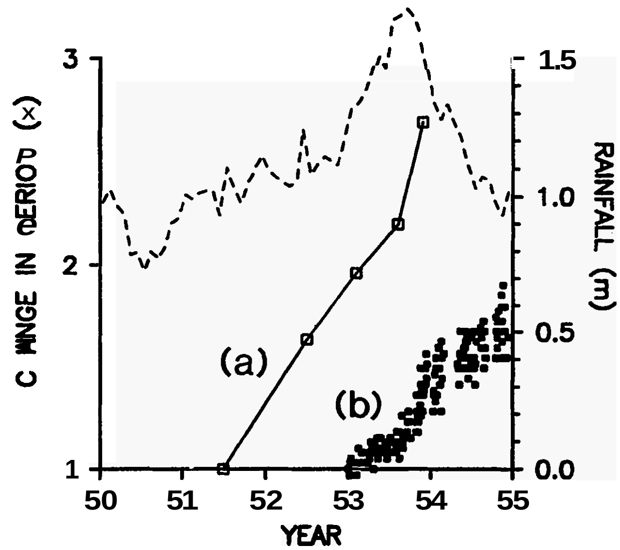

Fig. 5: Changes in eruption period (T/To) of geysers in Geyser Valley at Wairakei during the Test Discharge Period. (a) Great Wairakei Geyser (data from Grant *et* al., 1985); (b) Bridal Veil Geyser (data from Thompson, 1957). Periods are normalised to To = 12.5 hr for Great Wairakei, and 39 min. for Bridal Veil. Broken line shows monthly running total of rainfall in previous 12 months.

At Broadlands, there are fewer data. Prior to testing, the temperature of the Ohaaki Pool varied by up to 25°, but it is clear that during the initial part of the Test Discharge Period (when the overflow rate decreased) that temperatures fell to about 65°C, although they subsequently recovered (Fig. 7). During the Recovery Period, temperatures in the pool fluctuated in response to *small* test discharges from nearby wells.

Data from both fields suggests that the absence of temperature changes in a single hot spring or pool may not be a reliable indication that there will be no future environmental impact.

7. CONCLUSIONS

- Moderate to severe impacts on natural thermal features occurred at Wairakei and Broadlands fields, caused primarily by exploitation-induced pressure decreases in the upper parts of the reservoirs.

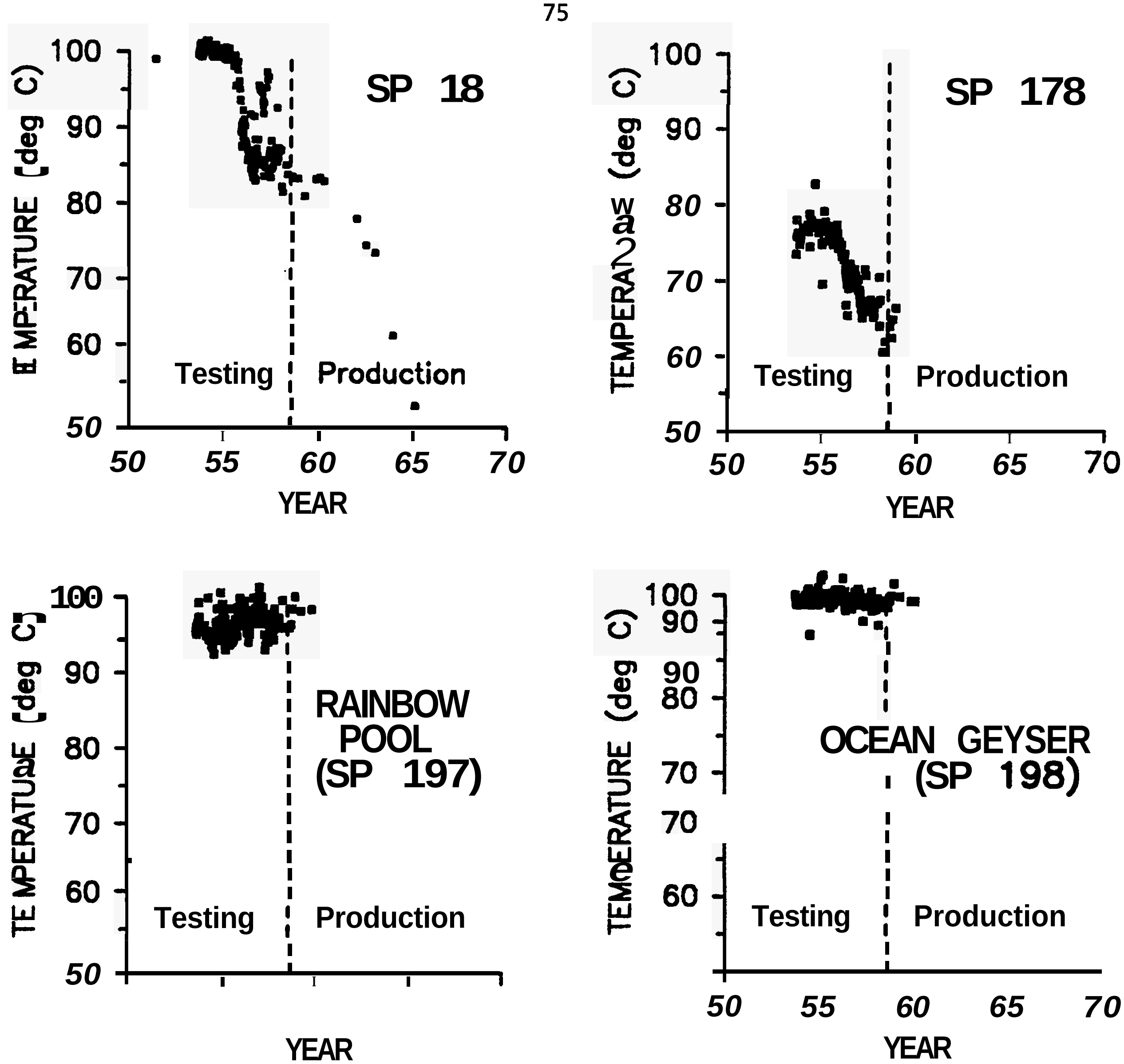

Fig. 6: Changes in temperature of fluid fiom hot springs and pools in Geyser Valley at Wairakei during the Test Discharge Period and early part of the Production Period.

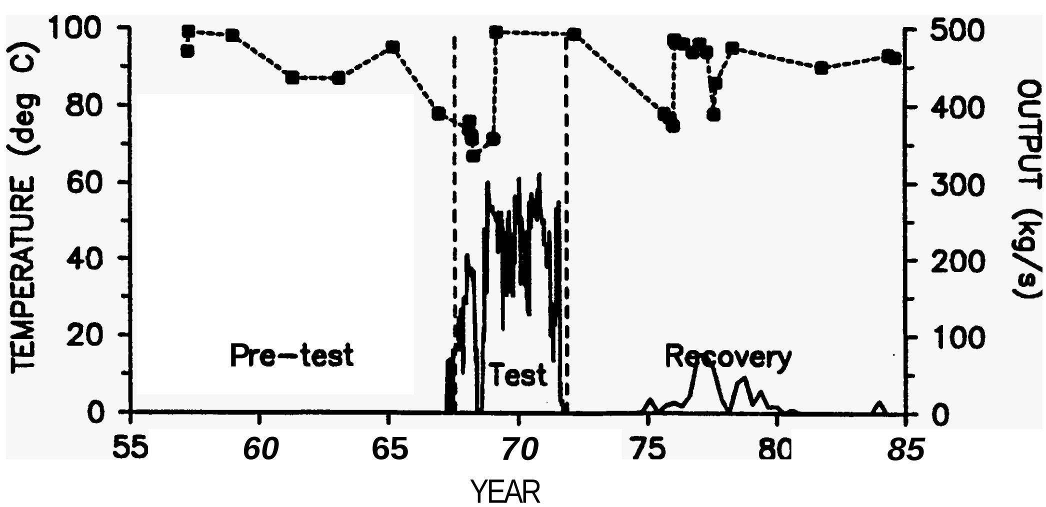

Fig. 7: Changes in temperature (solid symbols) of Ohaaki Pool at Broadlands. Solid lines indicate total mass discharge rate from nearby bores.

- The extent and severity of the impacts were dependent on local conditions.
- Small, but now clearly identifiable, precursors occurred during pre-production testing, but their significance was not recognised at that time.
- The most significant precursory signals of future impacts were:

(i) **decline in flow rate from natural** features - in some cases the flow stopped within 2 years;

(ii) **decline in chloride content** of spring waters - decreases of up to **60%** occurred during testing;

(iii) **increase in the eruption period** of geysers - in two cases, these doubled over a **2-yr** interval;

(iv) **decline in temperature** of emerging fluids - some decreased by up to **20°C** over a **5-yr** period.

8. ACKNOWLEDGEMENTS

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