CHARACTERISTICS OF CYCLIC ACTIVITY IN FRYING PAN AND INFERNO CRATER LAKES, WAIMANGU

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SUMMARY

Frying Pan Lake and Inferno Crater Lake occupy craters formed on 10 June 1886 when a basaltic dike was intruded into the Waimangu area. These lakes are the largest and most spectacular hot springs in New Zealand, and display interrelated cyclic variations over a 38 day cycle.

The discharge from Frying Pan Lake varies inversely with the water level of Inferno Crater Lake by 20.2 ± 2.7 litre sec^{-1} and has decreased from 122.2 to 104.1 litre sec^{-1} between 1972 and 1990. The temperature also responds to the 38 day cycle, but shows no correlation with discharge volume. Ambient air temperature strongly influences the discharge temperature which ranges annually between 44.3 and 56.6°C with a mean of 50.2°C.

The lake occupying Inferno Crater fluctuates from overflow to about 8 m below overflow and back to overflow over 38 days. The temperature fluctuates sympathetically with the water level in the range 35.0 to 84.5°C. Four stages are recognised.

INTRODUCTION

Surface hydrothermal activity at Waimangu is dominated by the two large crater lakes, Frying Pan and Inferno, which occupy explosion craters formed on 10 June 1886 as part of the 1886 Tarawera Rift eruption (Fig. 1).

Okataina Volcanic Centre (OVC) is believed to provide the heat source for the Waimangu hydrothermal system (Nairn 1981, Scott 1991). It is the most recently active of the rhyolite eruptive centres recognised within the Taupo Volcanic Zone, and incorporates all recently active volcanic vents east of Rotorua. The most recent volcanism at the OVC was the basaltic Tarawera eruption on 10 June 1886.

Surface outflow features of the Waimangu hydrothermal system, developed in and about the 1886 craters where no surface hydrothermal activity had been described before the 1886 eruption. Within a few months of the June eruption newly developed activity reportedly waned, but between 1888 and 1896 surface activity gradually increased and became permanently established (Keam, 1980).

CYCLIC ACTIVITY

A unique aspect of the hydrothermal activity at Waimangu is its cyclic nature. Perhaps this was initially displayed by the Waimangu Geyser which erupted relatively regularly from 1900-1904 (Stanton, 1978), and is evident today at Inferno Crater Lake and Frying Pan Lake, which display interrelated cyclic variations.

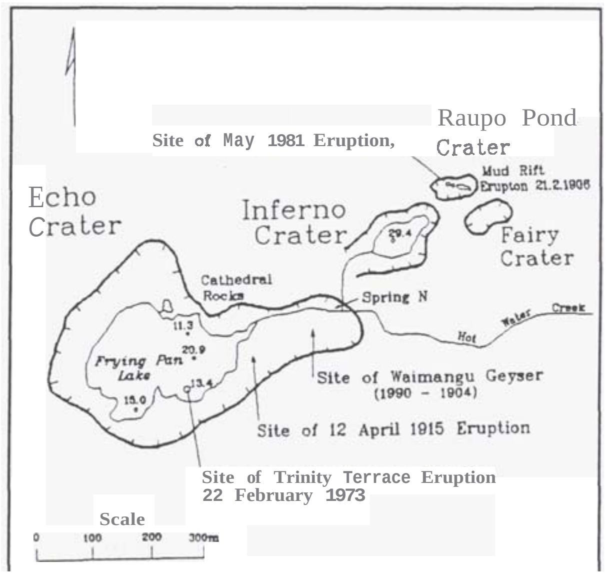

Figure 1. Sketch map of Echo-Inferno Crater area, Waimangu.

The lakelet in Inferno Crater has exhibited water level variation since at least 1901, when the lake level rose and fell in step with the Waimangu Geyser cycle. Instrumentation was installed at Waimangu in 1970 to investigate and quantify aspects of the hydrology associated with the cyclic behaviour of Frying Pan and Inferno Crater lakes. Lloyd (1973, 1974) presented the first records and clearly demonstrated that an inverse relationship exists between the water level of Inferno Crater Lake and the discharge of Frying Pan Lake.

POST 1900 HYDROTHERMAL ACTIVITY

In 1900 Waimangu Geyser commenced erupting in the northeastern portion of Echo Crater and continued intermittently to 1904 (Fig. 1). Eruption heights up to 450m are reported. Following the demise of Waimangu Geyser many small hydrothermal eruptions occurred, particularly within Echo Crater, and a moderately large event on 21 February 1906 (NZ Herald, February 22 1906) formed the Mud Rift in Raupo Pond Crater (Fig. 1). On 12 April 1915 a larger event occurred south of Waimangu Geyser basin. The largest post 1886 hydrothermal eruption occurred on 1 April 1917. It re-excavated and enlarged southern Echo Crater, and destroyed an accommodation house 600 m to the SW (Morgan, 1917) - two lives were lost. By 26 June 1918 a lake, called Frying Pan, almost filled the sub-craters formed by this event (Lloyd & Keam 1965).

A further eruption from near the lake centre occurred on 29 August 1924, then on 22 February 1973 the Trinity Terrace area on the SE shore of Frying Pan Lake was destroyed by a smaller hydrothermal eruption (Lloyd & Keam 1974). During the night of 23-24 February 1978 an event occurred at Raupo Pond Crater and Inferno Crater Lake (Keam 1979, Scott 1991). Inferno Crater Lake was completely discoloured, while at Raupo Pond Crater the Mud Rift was in eruption (Fig. 1). A bathymetric survey on 14 March 1978 revealed a new depression of about 600 m^3 volume NE of Matua vent (Keam 1981a). In May 1981 eruptions at Raupo Pond Crater created two small craters, deepening and destroying the Mud Rift (Scott 1982, Scott & Lloyd 1982).

Today, Waimangu is an area of diverse and intense hydrothermal activity with two of the largest and most spectacular hot springs in New Zealand. Frying Pan Lake occupies the 1917 sub-craters within Echo Crater and Inferno Crater Lake occupies an 1886 crater blasted through the side of Mt Haszard. This paper defines the cyclic characteristics of the hydrothermal activity in these lakes using data from instrumental records.

INSTRUMENTATION

Most records of temperature, flow, and water level at Wairnangu have been obtained from mechanically operated analogue chart records. The instrumentation at Frying Pan Lake records the lake discharge through a Parshall flume, and the temperature of the discharging fluid. At Inferno Crater a gas purge is used to detect the water level, and a Parshall flume the periodic discharge.

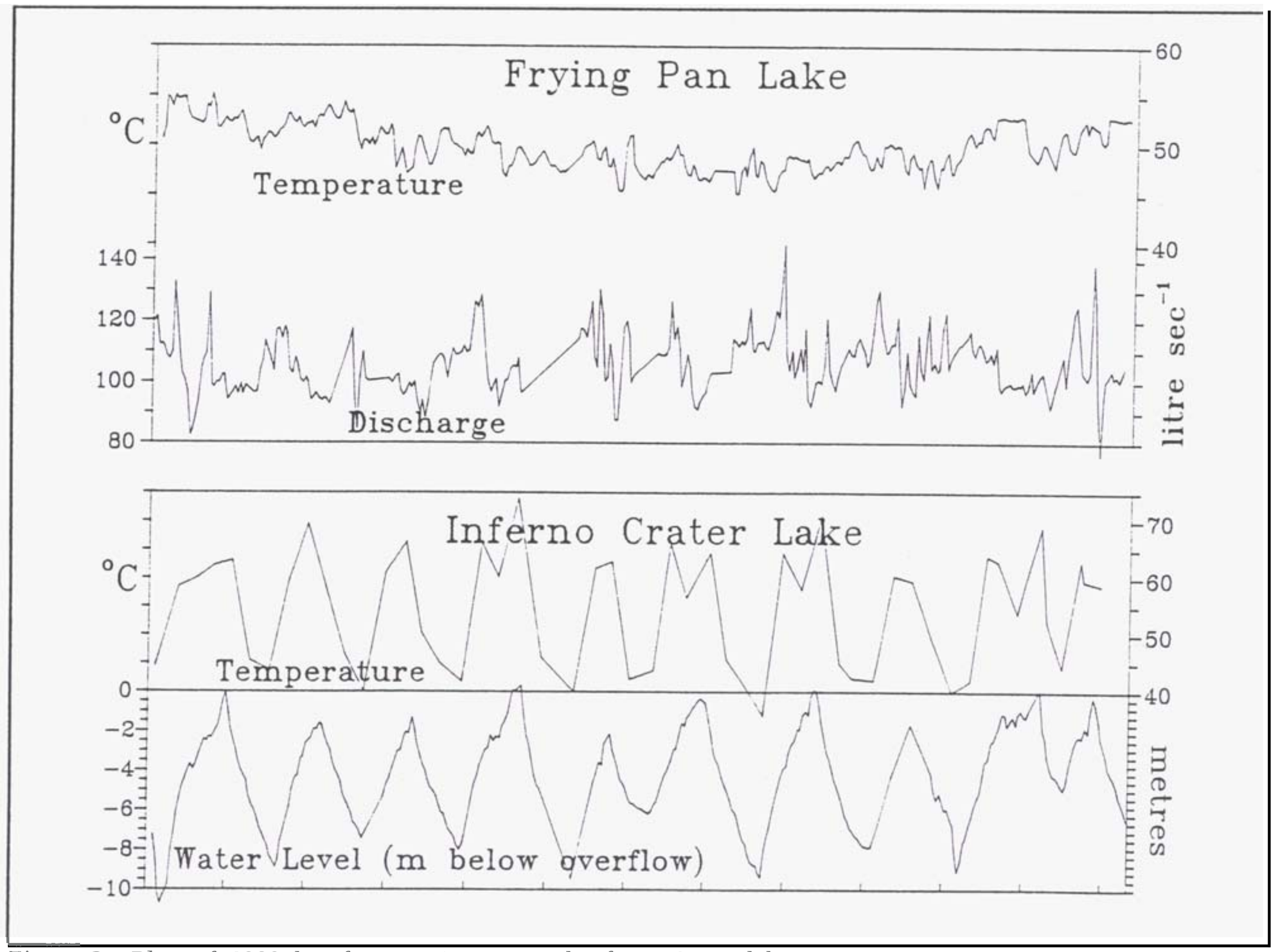

Figure 2: Plots of 1989 data from Frying Pan and Inferno Crater lakes.

The estimated errors associated with the various recording systems in use at Waimangu as assessed by Scott (1991) are:

Frying Pan Lake	**Error Estimate**
Discharge	
Elliot recorder	± 5.5 litre sec^{-1}
Stevens recorder	± 3.6 litre sec^{-1}
Temperature	
Elliot recorder	± 1.6 "C
Inferno Crater Lake	
Water level	
Foxboro recorder	± 0.090 m
Temperature	
Thermometer readings	± 0.2 °C
Electronic recorders	± 0.2 °C
Overflow	
Stevens recorder	± 3.6 litre sec^{-1}

FRYING PAN LAKE

Frying Pan Lake occupies the 1917 craters in the western subcrater of Echo Crater. The lake has a surface area of 38 000 m^2, a relatively flat floor at 6 m below overflow, except for the four deep vents (> 11 m) that descend to a maximum measured depth of 20.88 m. Bathymetry (Keam 1981b) indicates that the lake has a volume of 200 000 m^3. The lake overflows continuously into Hot Water Creek draining from the NE corner. The discharge rate and temperature are recorded at a monitoring station about 90 m downstream of the outlet (Fig. 1).

Temperature of the Discharge

Frying Pan Lake discharge temperature displays a strong diurnal fluctuation, up to 6°C on hot sunny days (Wilson 1981). The mean daily temperatures used in this study tend to smooth the diurnal fluctuation which appears entirely as a solar radiation effect. Wilson (1981) calculated an average enthalpy of 876 ± 8.5 kJ kg^{-1} for the period 5 December 1979 to 20 January 1980, while Scott (1991) obtained a mean of 749 ± 19 kJ kg^{-1} for the 1971 to 1990 period. Having ranged annually from 1152 to 702 kJ kg^{-1}.

A prominent seasonal variation of the mean daily discharge temperature is apparent (Fig.2). This is further examined in Figure 3 where the monthly mean of the daily discharge temperatures are plotted against the monthly mean air temperature recorded at Waiotapu 3.5 km SE of Frying Pan Lake, for the period 1971 to 1989. A strong correlation is apparent between these parameters (r^2 = 70.9%).

Short-term variations superimposed on the yearly seasonal cycle are also apparent in Figure 3, and these have been tested by Fourier analysis using 1989 data Figure 4. These show previously unrecognised cycles especially about 18, 50 and 65 days duration. The cycle of about 40 days duration is related to the cycle of similar length in Inferno Crater

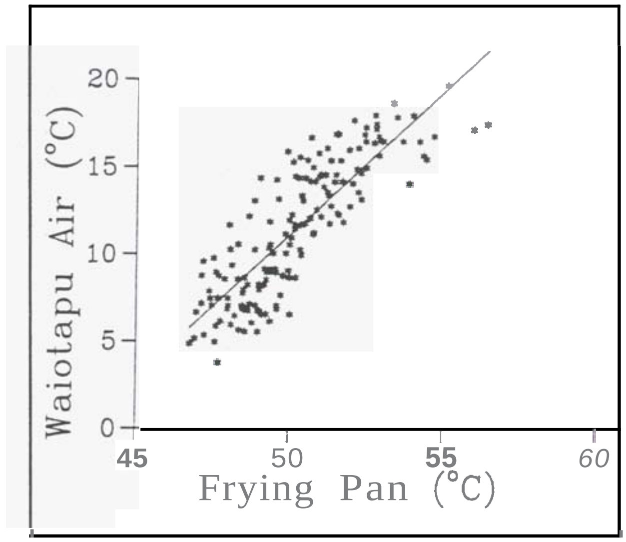

Figure 3: Plot of mean monthly Frying Pan Lake temperature verses mean monthly air temperature at Waiotapu.

Lake. The origin of the other cycles is unclear.

The discharge temperature has ranged from 42.1°C (19 July 1977) to 58.9°C (6 January 1973) and the mean daily temperature (1971-1990) is 50.2 ± 2.4°C.

Frying Pan Lake Discharge

Fluctuations in the discharge of Frying Pan Lake from both climatic and hydrothermal influences are recognised. The mean daily discharge has ranged from 65.7 litre sec^{-1} (27 March 1989) to at least 219 litre sec^{-1} (30 April 1982). The peak discharge associated with the Trinity Terrace eruption was estimated to exceed 230 litre sec^{-1} (Lloyd and Keam, 1974).

Figure 2 shows high amplitude flows which are usually short lived (1-3 days), and also lower amplitude signals of about 40 days duration. The short-term, high amplitude fluctuation are attributed to rainfall - induced surface runoff within Frying Pan Lake catchment. To examine the characteristics of the longer-term cycle a Fourier analyses has also been made of the 1989 discharges data, Figure 4. This analyse identifies cycles similar to those in the temperature data. The amplitude of the dominant 35-45 days cycle has been quantified by Scott (1991) at 20.2 ± 2.7 litre sec^{-1}.

The mean annual discharge has decreased from 122.2 litre sec^{-1} in 1972 to 98.9 litre sec^{-1} by 1988 (19.0%), with a small rise in 1989-90. This long term trend was examined in detail by Scott (1991) and shown to be strongly related to the long term rainfall trend, suggesting this trend is caused by climatic rather than hydrothermal influences.

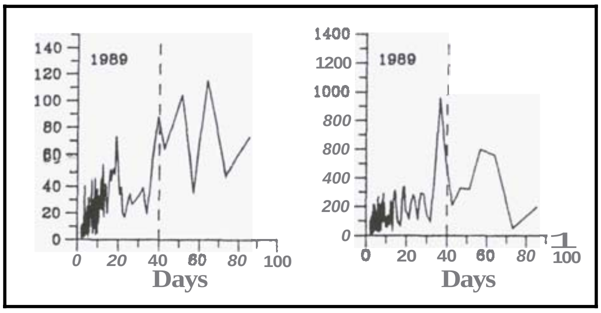

Figure 4: Frequency verses amplitude plots of 1989 (Fig.2) Frying Pan temperature and flow data.

INFERNO CRATER

Inferno Crater was formed on 10 June 1886 when a basaltic dike was intruded into the rhyolite dome of Mt Haszard. Today the crater is occupied by a lake whose water level has been recorded to regularly fluctuate over 12 metres with respect to its overflow level. This periodic behaviour, comparable to geyser cyclicity, is one of the most remarkable hydrothermal phenomena known.

The cyclic nature of the hydrothermal activity is clearly recognisable in Figure 2. When overflowing the lake has a volume of about 65 200 m^3 and a surface area of 7500 m^2. The primary source of energy and mass for the lake is a vent called Matua (Keam 1981a) in the crater floor. McLeod (1983) calculated an average enthalpy of 800 kJ kg^{-1} for the period 25 June to 1 July 1982, while Scott (1991) obtained 1097 ± 117 kJ kg^{-1} for the 1971 to 1990 period. Having ranged annually from 910 to 1471 kJ kg^{-1}.

Instrumental data obtained since 1971 shows the period between overflows has ranged from 2 days (March 1986, February-July 1990) to 188 days (May-December 1973). During the later, four cycles are recognised but for three of them, overflow level was not reached. Cycles which do not include an overflow are termed incomplete cycles. The mean cycle length between water level minimum, regardless of whether an overflow occurred or not, is 37.7 ± 9.7 days. The length of cycle between overflows, which contain one or more incomplete cycles is 97.7 ± 31.7 days, ranging from 56 to 188 days (incomplete cycles range from 1 to 4). Cycle length between commencement of overflows average 38.4 ± 10.9 days.

Distinct stages in the cyclic behaviour of Inferno Crater Lake were first described by Scott (1976) from a study of seismic noise, and were ordered from the end of an overflow. Stanton (1978) chose to commence the cycle at the lowest water level (i.e. lowest energy state) and his ordering is now adopted. Four stages are recognised:

Stage 1 - steady rise from a low water level
Stage 2 - oscillations
Stage 3 - overflow
Stage 4 - recession to a low level

Stage 1

It lasts 7.7 ± 1.8 days and the water level rises 4.7 ± 1.4m an average rise of 0.6 ± 0.1 metre day^{-1} (Fig.5). A lake volume increase of about 23 800 m^3. The temperature rises 17.3 ± 4.5°C (2.2 °C day^{-1}) and has ranged from 10.0 to 27.2 °C. The lake temperature at the start of Stage 1 averages 42.5 ± 3.4 °C, having ranged from 35.6 to 50.9 °C. There is a moderate correlation between the stage duration and the depth at which the water level rise commenced (r^2 = 40.8%).

Stage 2

This stage lasts 14.7 ± 5.9 clays, and the water level rises 3.89 ± 1.14 m. This has ranged from 1.15 to 6.43 m. The temperature rises and falls with water level, but remains about a mean of 60.7 ± 2.2 °C. This near constant temperature is maintained until Stage 3 when it rises substantially. In contrast the water level oscillations are superimposed on a gradually rising water level, although the rate of rise decreases through the stage (Fig.5).

Stage 3

Stage 3, the major overflow commences at the start of the water level rise which culminates in the flow and terminates at cessation of overflow. Over 140 flows have been reliably recorded since 1980 and two distinct families are recognised; (1) flows associated with the normal 38 day cycle, and (2) those associated with prolonged high water levels. In the latter case small flows recur every 2-3 days.

Typically flows associated with the 38 day cycle last for 51.3 ± 26.1 hours. The mean flow rate is 79.1 ± 11.0 litre sec^{-1} (range 60.4 to 105.5 litre sec^{-1}). The average total flow volume is 14.0 ± 5.6 x 10^6 litres (14.0 x 10^4 m^3). Peak flow rates average 96.0 ± 21.2 litre sec^{-1}, the largest of 192 litre sec^{-1} occurred on 10 December 1981 during the longest recorded overflow.

Flows associated with prolonged high water level stands last 9.9 ± 8.2 hours. The mean flow rate is 70.8 ± 9.7 litre sec^{-1}, while peak flow rates range 46.9 to 191.5 litre sec^{-1}. The mean total flow volume is 2.7 ± 2.1 x 10^6 litres.

Temperatures during an overflow range from 58.0 (14 May and 18 September 1972) to 84.5°C (24 February 1978). At the commencement of a flow the temperature has ranged from 58.0 to 79.5°C (mean 66.5 ± 5.1°C), and at the end from 64.3 to 84.5°C (mean 71.9 ± 5.0°C). The range during a flow is 5.6 ± 4.3°C and the mean during overflow is 70.6 ± 5.1°C.

Stage 4

Stage 4 is the recession. Mean water level recession is 7.9 ± 2.0 m below overflow and the temperature falls 26.4 ± 6.1 °C. The lake has receded to below 12 m on six occasions, 12.79 m (June 1971), 12.30 m (August 1971), 12.68 m (October 1971), 12.81 m (November 1971), 12.41m (July 1981), and 12.21 m in August 1982. Duration is 15.1 ± *5.6* days, giving fall rates of about 0.52 m, and 1.8°C day'', and a lake volume decrease of 45 600 m^3.

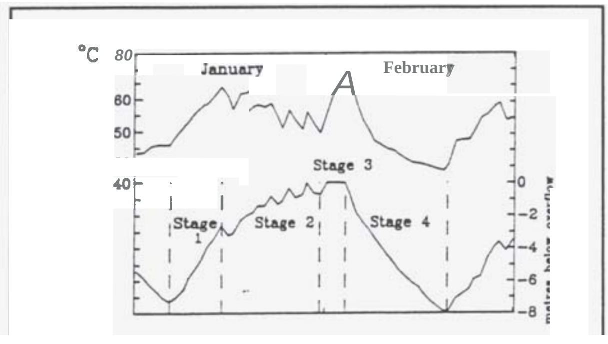

Figure 5: Temperature and water level of Inferno Crater Lake showing the 4 stages (Jan-Feb 1973).

DISCUSSION AND SUMMARY

Monitoring the two largest surface discharging features at Waimangu since 1971 has shown that the hydrothermal system is cyclic and responds to both hydrothermal and climatic signatures.

Frying Pan Lake has displayed a significant decline in discharge with time from 122.2 litre sec^{-1} in 1972 to 98.9 litre sec^{-1} by 1988, correlating (r^2 = 55.5%) with long term rainfall trends. The discharge temperature has prominent seasonal range of 8.9 ± 1.6 °C and a near constant mean annual temperature, which is well correlated (r^2 = 70.9%) with air temperature. Thus indicating that climatic conditions are strongly superimposed over hydrothermal ones. Fourier analyses of both the discharge and temperature data (Fig.4), clearly reflect the 38 day cycle of Inferno Crater Lake. The discharge from Frying Pan Lake exhibits an inverse flow variation of 20.2 ± 2.7 litres sec^{-1}.

In contrast to Frying Pan Lake, Inferno Crater Lake is a much more complex system. Its smaller size, higher mean temperature and variable water level tend to override the climatic influences, and only primary hydrothermal signals are reflected in the data. The typical 38 day cycle is divided into four distinct stages, which are discussed above.

The most striking feature of the Waimangu hydrothermal system is the inverse correlation between water level and temperature of Inferno Crater Lake, and discharge of Frying Pan Lake. The latter displays a 20.2 ± 2.7 litre sec^{-1} variation through a cycle, while Inferno Crater Lake water level varies on average 7.9 m with respect to overflow level. The temperature of Frying Pan Lake discharge cannot be correlated with any other parameters, although Fourier analyses reflect the 38 day cycle.

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